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Systematic and Quantitative Approaches to Assess the Probability of Extreme Weather and Resilience Risks for TxDOT Highways and Bridges

Technical Report 0-7191-R1

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16. Abstract

This research develops a quantitative framework to assess flood-related risks and resilience for Texas highways and bridges. The study reviewed current practices and gaps, applied GIS-based methods with statewide flood datasets, and evaluated exposure of pavements and bridges across multiple return periods and climate scenarios. Risk assessments quantified both acute and chronic flood impacts, including fragility curves and life-cycle cost projections that capture deterioration in different pavement types. Results show flooding is the most significant climate-related hazard to Texas transportation assets, with surface-treated pavements particularly vulnerable and rigid pavements more resilient. The framework provides TxDOT with scalable tools for district- and statewide prioritization, enabling identification of vulnerable assets, estimation of long-term costs, and integration of resilience into maintenance, rehabilitation, and investment strategies. By incorporating these methods into the 2026 Transportation Asset Management Plan, TxDOT can systematically embed resilience into planning, design, and decision-making processes.

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SYSTEMATIC AND QUANTITATIVE APPROACHES TO ASSESS THE PROBABILITY OF EXTREME WEATHER AND RESILIENCE RISKS FOR TXDOT HIGHWAYS AND BRIDGES

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DISCLAIMER

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1. INTRODUCTION

This report summarizes work conducted as part of Texas Department of Transportation (TxDOT) Research Project 0-7191: Develop Systematic and Quantitative Approaches to Assess the Probability of Extreme Weather and Resilience Risks for TxDOT Highways and Bridges. The goal of this project was to develop a quantitative risk framework that could be implemented in TxDOT's forthcoming Transportation Asset Management Plan (TAMP).

A TAMP is a federally mandated document that all state departments of transportation (DOTs) must develop for the Federal Highway Administration (FHWA). TAMPs are designed to present a clear view of the extent and condition of a state's transportation assets (with a minimum requirement to cover roads [pavements] and bridges) and the financial implications of managing, maintaining, and replacing these assets. TAMPs also set and discuss performance-based targets for the condition of infrastructure and discuss sources of risk to both the efficient operation of the transportation system (e.g., cyber risks, staff retention) and the infrastructure from hurricanes, earthquakes, or other natural or human-made hazards.

TxDOT's current TAMP was developed and submitted in 2022; an updated version is due in 2026. Over time, the content and requirements of state DOT TAMPs have been updated in response to legislative changes as well as trends in transportation practice.

The most recent legislative change that affects the TAMP occurred with the Infrastructure Investment and Jobs Act (IIJA, also known as the Bipartisan Infrastructure Law or BIL), which was signed in November 2022. The IIJA introduced new requirements for the TAMP that focused on managing transportation assets in response to extreme weather events. The IIJA also officially uses and defines *resilience* as a broad methodological concept useful for protecting and developing infrastructure and systems in the transportation domain and a variety of other related fields (e.g., power grids, pipelines, information technology, water systems).

WORKING DEFINITIONS AND CONCEPTS

Resilience

FHWA defines resilience as "… the ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions" (Federal Highway Administration 2014).

The concept of resilience has become increasingly important for transportation planners and practitioners. The common use of the word is related to its original Latin root, *resilire*, which means to recoil or bounce back. In transportation and many other fields, the concept of bouncing back or regaining shape or function after a physical disturbance, such as an extreme weather event, has become a useful planning and management concept that has progressively turned into formal definitions, policies, and laws.

The resilience concept alludes to the idea that change and disruptions are inevitable properties of systems, including transportation systems. As such, it encourages transportation engineers to plan for disturbances and design systems that can rapidly recover from them. While resilience is often used as a descriptor of how assets should be designed and managed, developing a resilient system requires *resilience thinking* and includes the following actions:

- Identify stressors and disturbances and conceptualize or model them in terms of their frequency and their potential for damage.
- Measure or conceptualize normal or expected operational performance.
- Measure or conceptualize the loss of service resulting from a specified disturbance or stressor and compare this against *normal* performance.
- Develop strategies to reduce the loss of service following a disturbance or stressor (i.e., implement strategies to improve resilience).

Figure 1 illustrates this concept graphically. The black horizontal line represents the normal function of the system measured by a carefully chosen system performance metric over time. The dashed vertical line represents a pulsed disturbance that occurs at a specified point in time (e.g., a flood event). The yellow and red lines illustrate alternative responses to the performance of the system following the disturbance (e.g., a road section or bridge on a road network, or a series of assets such as a corridor).

Relevant transportation examples of system performance include travel time, asset condition, or maintenance cost. The orientation of the curves in Figure 1 would dictate the need for inverse correlates of many of the suggested metrics. System recovery from a disturbance could occur naturally (e.g., the dissipation of water following flood) or with some human intervention (e.g., the clearing of obstructed drainage or repair of the system). System resilience is the difference between its normal function (black line) and its time-dependent performance due to its response to the specified disturbance (yellow and red lines).

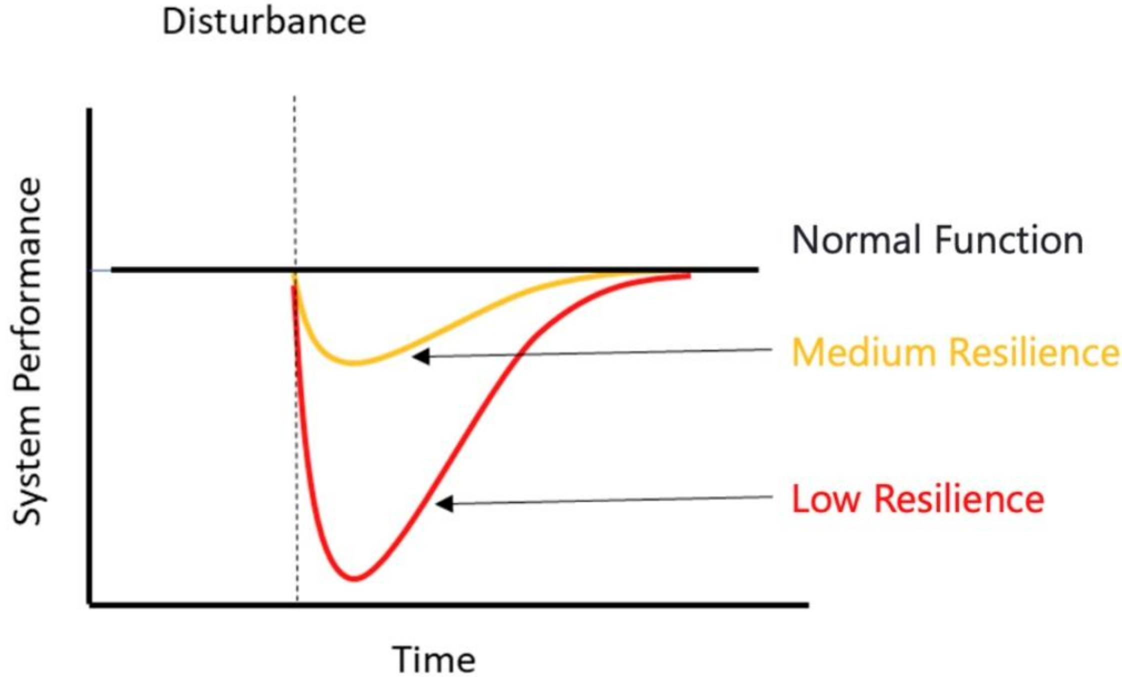

Figure 1. Simplified Resilience Concept.

Disturbance or Stressor

The conceptual view of resilience described previously requires a definition of *disturbance* or *stressor*. This project considered extreme weather or other related natural events that are, at least in part, driven by extreme weather. For example, flooding is driven by a combination of variables that include rainfall, topography, land use, and existing drainage infrastructure. Similarly, wildfire is driven by high fuel load, low humidity, low rainfall, and high wind speed, which drive the ignition and spread of fire depending on their levels.

In some fields, researchers classify disturbances into *pulse* and *press* categories. Pulse disturbances are characterized by relatively infrequent, discrete events that vary considerably from normal conditions (e.g., tropical storms, hurricanes). Press disturbances occur slowly and gradually. These gradual changes have the potential to change the *business as usual* or *equilibria* of a given system. Climate change and electric vehicle adoption are two press disturbances relevant to transportation. In some cases, press and pulse disturbances can coexist and interact. For example, gradual climate change (press disturbance) potentially leads to an increase in the frequency and intensity of specific rainfall and flood events (pulse disturbance).

Systems theory offers another way of distinguishing a *disturbance* from a *normal* or *business as usual* event. Disturbances can be viewed as events that are external to a normally functioning system (Birt and Coulson 2015). For example, state DOTs design hydraulic structures to prevent roadway flooding using a risk-based approach. These structures are designed to ensure that surface flooding occurs no greater than a specified probability (e.g., 1 year out of 50 years). In this context, a disturbance (e.g., a flood) can be defined as an event that causes an asset to operate outside of a design standard. Another way of defining disturbances based on system theory is that they are *external* variables that affect a system of interest but are not (directly) affected by the system itself. For example, a weather event can affect transportation assets, but those assets do not directly affect future weather (at least not in ways that could be modeled effectively). This definition of disturbance suggests that they are driven by forces that are external to the system of interest or are currently considered to be external because knowledge and technology prevents them being understood as internal components of a system. In line with concepts of resilience and resilience thinking, disturbances cannot be prevented. Instead, systems should be developed to effectively withstand or bounce back from such disturbances.

Risk

Consistent with Title 23, Section 515.5 of the Code of Federal Regulations (23 CFR §515.5), FHWA defines risk and risk management, in the context of transportation asset management, as follows (American Association of State Highway and Transportation Officials 2025):

- **Risk:** The positive or negative effects of uncertainty or variability upon agency objectives.
- **Risk management:** The processes and framework for managing potential risks, including identifying, analyzing, evaluating, and addressing the risks to assets and system performance.

In many fields, risk is conceptualized through a consistent model that varies only in terminology and detail among different practices. This model can be formulated as follows:

$$\text{Risk} = P_{event} \times P_{damage} \tag{1}$$

where P_{event} is the probability or likelihood of an event occurring, and P_{damage} is the probability or range of damage that occurs because of the specified event. FHWA's concept of risk includes positive as well as negative events, while in colloquial and most scientific uses, risk is typically reserved for potentially harmful and unpredictable events.

Risk assessment can be performed quantitatively or qualitatively. In quantitative assessments, the risk components (P_{event} and/or P_{damage}) can be represented probabilistically or by an average value. In the language of mathematical probability, the P_{damage} is conditional upon the specified event occurring. In qualitative, semi-quantitative, or categorical risk assessment, P_{event} and/or P_{damage} can be categorized (e.g., on a scale from 1 to 5) to yield a useful estimate of overall risk.

Often, the term *risk* is used in place of its two components; *risk* is used widely, used in many different settings, and used both scientifically and colloquially. This usage is also consistent with the mathematics of risk (Equation 1); setting either of the P_{event} or P_{damage} variables to a constant value (e.g., 1 indicating that insufficient information is available to provide an explicit value) still yields a useful estimate of risk. Put simply, a risk assessment is still valid and useful even if it only explicitly considers one of the P_{event} or P_{damage} elements.

The formalization of risk into two separate components is, however, operationally useful. It effectively enables the two components of risk to be conceptualized, researched, and estimated independently/separately. For example, for a risk assessment of extreme rainfall effects on a road asset (of specified design and construction), one team of researchers could quantify the likelihood of extreme rainfall events near the asset of interest while another research team could independently develop models of damage following flood events.

This risk modeling approach requires that its two components are modeled in a scientifically and logically defensible way. This approach provides the following advantages:

- It enables estimation of risk for assets and systems where damage has never occurred.
- It enables an effective division of skill sets and research expertise (in the previous example, environmental scientists and pavement engineers).
- It provides a consistent and relatively simple concept that enables stakeholders at any level of an organization to understand risk and how to calculate it.

Proxy Indicator

In transportation, a proxy indicator is an indirect measure used to estimate the performance of a system that can be reliably used in place of a direct measurement when the latter is not available or is difficult or prohibitively costly to measure.

The concept of a proxy indicator is likely derived from the concept of proxy variables used in statistics or other scientific disciplines. For example, the spacing of tree rings (representing annual growth increments) are often used as a proxy measure for climate patterns that occurred in the past, before direct measurements of temperature or rainfall were available.

In disciplines such as agriculture, proxy indicators can be used to *signal* adverse changes to growing conditions. For example, plants that are sensitive to environmental conditions are sometimes planted at the entrance crops provide an early warning signal of crop damage. Similarly, agriculturists are trained to be able to detect a wide range of plant stresses using indirect measures of plant health such as leaf color. The presence of proxy signals may be used to either treat risks directly or trigger a more detailed, costly investigation.

In the transportation field, examples of proxy indicators of damage include pavement surface wear that indicates pavement substructure wear. Proxy indicators of future flooding include river channel flow (a proxy to potential flooding), rainfall or hurricane forecasts, current dryness or saturation of soils (affecting runoff), etc.

LEGISLATIVE BACKGROUND

TAMPs are a requirement of the National Highway Performance Program (NHPP), established under the Moving Ahead for Progress in the 21st Century Act (MAP 21) in 2012 and continued under both the Fixing America's Surface Transportation (FAST) Act of 2015 and the IIJA of 2021. Figure 2 shows the legislative history of the NHPP and TAMPs.

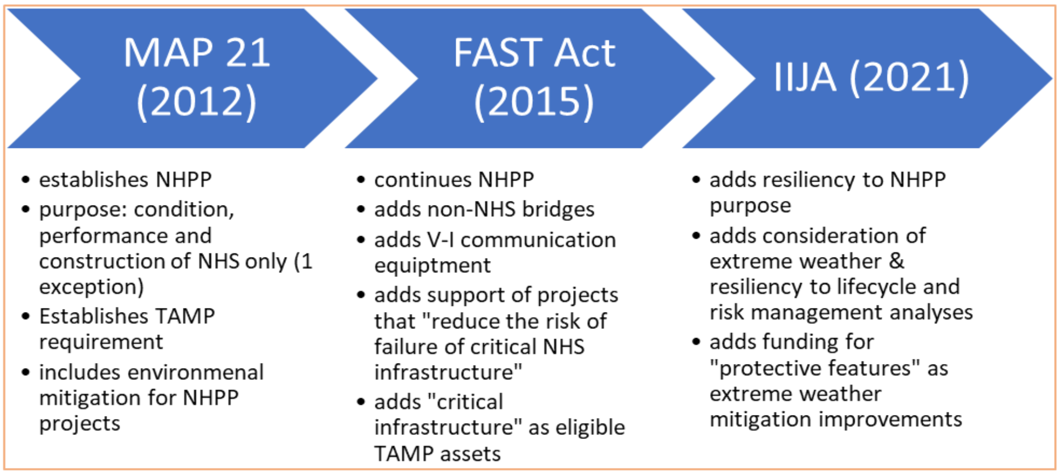

Figure 2. Legislative History of the NHPP and TAMPs.

At the federal level, 23 CFR §515.5 defines asset management as follows:

> Asset management means a strategic and systematic process of operating, maintaining, and improving physical assets, with a focus on both engineering and economic analysis based upon quality information, to identify a structured sequence of maintenance, preservation, repair, rehabilitation, and replacement actions that will achieve and sustain a desired state of good repair over the life cycle of the assets at minimum practicable cost.

Since its establishment in the MAP 21 Act, the NHPP has required each state DOT to develop a TAMP documenting National Highway System (NHS) pavement and bridge conditions. At the federal level, 23 CFR §515.5 defines an asset management plan as follows:

> Asset management plan means a document that describes how a State DOT will carry out asset management as defined in this section. This includes how the State DOT will make risk-based decisions from a long-term assessment of the National Highway System (NHS), and other public roads included in the plan at the option of the State DOT, as it relates to managing its physical assets and laying out a set of investment strategies to address the condition and system performance gaps. This document describes how the highway network system will be managed to achieve State DOT targets for asset conditions and system performance effectiveness while managing the risks, in a financially responsible manner, at a minimum practicable cost over the life cycle of its assets. The term asset management plan under this part is the risk-based asset

> management plan that is required under 23 U.S.C. 119(e) and is intended to carry out asset management as defined in 23 U.S.C. 101(a)(2).

IIJA Overview

The 2021 IIJA provided for historic levels of investment in America's infrastructure, with the highest funding levels since the National Interstate and Defense Highways Act of 1956 (the Federal-Aid Highway Act), which authorized construction of the interstate highway system in the United States. The IIJA was the first infrastructure law to address the climate crisis and include a dedicated climate title, "Subtitle D—Climate Change" (U.S. Department of Transportation 2022). Previously in 2013, *Executive Order 13653: Preparing the United States for the Impacts of Climate Change* also explicitly mentioned climate change resilience and adaptation in the context of transportation (Executive Office of the President 2013). Throughout the IIJA, an emphasis exists on building resilience into infrastructure, either by creating new programs and requirements or by integrating resilience into existing program purposes and goals (Georgetown Climate Center 2022). While the focus of this project was transportation resilience, the IIJA supports infrastructure resilience in five other major sectors including energy, building, and development; natural resources, ecosystems, and agriculture; water infrastructure; coastal protection; and preparedness and emergency response.

Legislative Definition of Resilience from the IIJA

Although many practices that support resilient infrastructure have been in use across multiple sectors responsible for infrastructure for decades, the term *resilience* has not been defined in statute prior to the IIJA (Humphreys 2022). Per Title 23, Section 101(a)(24) of the U.S. Code (23 USC §101[a][24]), the IIJA defines resilience as follows:

> … a project with the ability to anticipate, prepare for, or adapt to conditions or withstand, respond to, or recover rapidly from disruptions, including the ability— (A) (i) to resist hazards or withstand impacts from weather events and natural disasters; or (ii) to reduce the magnitude or duration of impacts of a disruptive weather event or natural disaster on a project; and (B) to have the absorptive capacity, adaptive capacity, and recoverability to decrease project vulnerability to weather events or other natural disasters.

The U.S. Department of Transportation (U.S. DOT) notes that this definition is "[the] first ever legislative definition of resilience" (U.S. Department of Transportation 2022), while the Georgetown Climate Center suggests that "… this is the first time the federal government has put forward a legislative definition of *resilience* in the context of transportation infrastructure and weather events and natural disasters" (Georgetown Climate Center 2022).

According to congressional legal analysts, definitions are "[a]mong the most important features of a bill" (Killion 2022). The significance of a codified definition is that, regarding a particular bill or section of existing code, the definition provides unequivocal direction about how and where Congress intended the term (vocabulary) within a bill to apply, rather than its ordinary meaning in everyday speech (Killion 2022) or by a dictionary. In the case of the IIJA that ties funding to projects and programs that increase the resiliency of the transportation system (U.S. Department of Transportation 2022), it is important to understand exactly what is meant by this term because funding is contingent upon it.

The IIJA definition of resiliency focuses on projects that support infrastructure challenged by harm brought on by climate conditions (weather or natural disasters), as opposed to harm brought on by human-made risks like cyber threats or poor financial planning. (Cyber security is also supported in the IIJA but is not included in the definition of resiliency.) Arguably, these somewhat narrow definitions challenge some of the currently accepted academic and policy definitions of resilience, which could include any type of stressor or disturbance (including human-made and natural, pulsed, and press disturbances). As the legislation becomes increasingly interpreted and disseminated via guidance, it remains to be seen whether the resilience concept is broadened to include other disturbances.

Policy Originating from the IIJA

Shortly after the IIJA was signed, FHWA sent a memorandum (Federal Highway Administration 2022) to all state DOTs regarding the impact of the new laws on TAMPs, which stated the following:

> State departments of transportation (State DOTs) are required to consider extreme weather and resilience as part of the life-cycle planning and risk management analyses within a State transportation asset management plan (TAMP) resulting from Section 11105 of the Bipartisan Infrastructure Law's changes to Title 23, United States Code, Section 119(e)(4) that took effect on October 1, 2021.

The content of 23 USC §119(e)(4) refers explicitly to state performance measurement and the TAMP as follows (requirements for extreme weather and resilience are in bold):

> (e) State Performance Management.
> (…)
>> (4) Plan contents. A State asset management plan shall, at a minimum, be in a form that the Secretary determines to be appropriate and include:
>>> (A) a summary listing of the pavement and bridge assets on the National Highway System in the State, including a description of the condition of those assets;
>>> (B) asset management objectives and measures;
>>> (C) performance gap identification;
>>> (D) **life-cycle cost and risk management analyses, both of which shall take into consideration extreme weather and resilience;**
>>> (E) a financial plan; and
>>> (F) investment strategies.

Section 11105 of the IIJA refers to the NHPP. Its signing has resulted in several other code amendments to 23 USC §119 including the following (again, requirements for extreme weather and resilience are in bold):

> (4) To provide support for activities to **increase the resiliency** of the National Highway System to mitigate the cost of damages from sea level rise, extreme weather events, flooding, wildfires, or other natural disasters.
>
> > (R) **resiliency improvements on the National Highway System, including protective features described in subsection (k)(2)**;
>
> (3) In subsection (e)(4)(D), by striking "analysis" and inserting "analyses," **both of which shall take into consideration extreme weather and resilience**.

The previously referenced *protective features* eligible for funds apportioned under 23 USC §119 include the following:

> (A) raising roadway grades;
> (B) relocating roadways in a base floodplain to higher ground above projected flood elevation levels or away from slide prone areas;
> (C) stabilizing slide areas;
> (D) stabilizing slopes;
> (E) lengthening or raising bridges to increase waterway openings;
> (F) increasing the size or number of drainage structures;
> (G) replacing culverts with bridges or upsizing culverts;
> (H) installing seismic retrofits on bridges;
> (I) adding scour protection at bridges, installing riprap, or adding other scour, stream stability, coastal, or other hydraulic countermeasures, including spur dikes; and
> (J) the use of "natural infrastructure" to mitigate the risk of recurring damage or the cost of future repair from extreme weather events, flooding, or other natural disasters.

PEER STATE DOT TAMPS REVIEW

As part of this project, the research team reviewed the 2022 TAMPs developed and published by several peer states. The purpose of this review was to familiarize the research team with the organization and content of TAMPs and develop an understanding of the types of activities other states were engaged in related to asset management, extreme weather, and resilience. The 13 state TAMPs that were reviewed included Alabama, Arkansas, California, Florida, Georgia, Louisiana, Michigan, Mississippi, New Mexico, North Carolina, Oklahoma, South Carolina, and Tennessee. Key findings from this review included the following:

- Each of the 13 states reviewed included pavements and bridges in their TAMPs. Some states mentioned other assets such as ports, traffic signals, guardrail, sound walls, and other infrastructure. However, none of the reviewed states, except California, included these assets as part of the 2022 TAMP. Two states reported that they may incorporate these other assets in future TAMPs.

- The state TAMPs generally defined the scope of pavement and bridge assets reporting (i.e., whether it includes only NHS assets or assets located on other portions of the system). In some states, the DOT does not maintain a portion of NHS pavement and bridge assets. Conversely, North Carolina DOT maintains nearly all roadways in the state. According to the National Bridge Inventory (NBI), most states define culverts spanning longer than 20 feet along the centerline of the highway as bridges and therefore include them in the plan. Several other states including Alabama, Louisiana, Michigan, North Carolina, and Tennessee include culverts that do not meet NBI characteristics but that are still important for handling flood events. North Carolina's Pipe Inventory Program for non-NBI structures (culverts and pipes over 48 inches) and crossline pipes (48 inches and below) "supports the department's life-cycle approach to asset management." California state law mandates that the California DOT (Caltrans) TAMP include drainage, transportation systems management, and other supplementary assets (e.g., lighting, overhead sign structures, and complete streets) (California Department of Transportation 2022).
- Each of the reviewed TAMPS included a separate section on risk management. Approximately half of the reviewed TAMPs defined risk using FHWA's definition as "the positive or negative effects of uncertainty or variability upon agency objectives."
- Across the reviewed TAMPs, states reported a diverse set of risks that included cyberattacks, state finances, changes in security costs, supply chain issues, and inadequate or unreliable data for decision-making. The reviewed TAMPS identified various environmental risks, each mentioning extreme weather events. More specifically, depending on the location, the TAMPs identified climate change and associated events such as flooding, hurricanes, drought, and sea level rise. Several states also mentioned earthquakes, sinkholes, tornadoes, wildfires, and seismic activity, as well as ice/snowstorms, rockfalls, and coastal erosion/subsidence.
- Discussions of resilience in the 2022 TAMPs varied considerably by state, possibly because of the limited time available to consider and document resilience. In most cases, states incorporated resilience by adding a Resilience subsection to the TAMP's existing Risk Management section. Six states did not explicitly define the concept of resilience, while eight states adopted FHWA's standard definition as "the ability to anticipate, prepare for, or adapt to changing conditions or withstand, respond to, or recover rapidly from disruptions." Two States—Florida and North Carolina—established their own resilience policy that set the direction for resilience of the state's transportation infrastructure. All states emphasized the importance of risk management in their resilience approaches (i.e., approaches for identifying hazards, threats, and mitigation strategies). Approximately half of the reviewed states created a separate section under Risk Management that discussed how they considered resilience in the risk management process; however, the details varied. Alabama, Louisiana, Mississippi, New Mexico, and Texas provided general statements about how they consider resilience in their risk

management processes. Many states, including California, Florida, and Michigan, explicitly mentioned climate change policies and actions, such as addressing sea level rise and increasing flood resilience.

- Six states—Florida, Georgia, Michigan, New Mexico, Oklahoma, and Tennessee—have separate sections describing their approaches for incorporating resilience into life-cycle planning. For example, Oklahoma already has methods in place to incorporate the consequences of any external event into life-cycle planning; in other sections of their TAMP, external events are defined as those events not under the control of the DOT, such as extreme weather and wildfires.
- The reviewed TAMPS often highlighted different technological tools that the states were using to support their resilience efforts. For example, Arkansas and Oklahoma use data and advanced technologies, such as LIDAR (Arkansas) and the U.S. Geological Survey's ShakeCast System for earthquake effects (Oklahoma), to inform and improve their resilience strategies. Similarly, North Carolina is developing a Flood Inundation Mapping Alert Network for Transportation.

PROJECT SCOPE REFINEMENT

Following a review of peer state TAMPs and the literature, the research team refined the scope and workplan of this project. The first major decision was to choose flooding as the primary disturbance agent and the focus of risk assessment and resilience efforts. The reasons for choosing flood risk are as follows:

- **Importance:** Flooding presents the largest climate-related risk to transportation and other infrastructure (e.g., homes, utility infrastructure) in Texas.
- **Quantifiable flood effects:** The research team identified multiple ways in which flooding damages infrastructure, including acute and chronic damages and outcomes. Acute damages include the effects of high-pressure water flows over or under transportation infrastructure leading to sudden failure of culverts, bridge components, or roadways. Chronic damages included the long-term effects of repeated flooding on pavement substructures, erosion of materials from embankments or other supporting structures, and scour on bridges.
- **Availability of models and data:** The research team identified and proposed several datasets and models capable of describing flooding. The research team also identified models and datasets that could be used to predict damage to infrastructure following flood events.
- **Potential for risk mitigation and adaptation:** The research team identified a broad range of adaptation strategies that could be used to reduce the likelihood of flooding near transportation infrastructure or the damage caused by such flooding.

- **Statewide assessments:** The research team conceptualized a flood-based risk assessment approach that is applicable and relevant to every area of the state and that can be scaled up to a statewide assessment depending on the availability of data and models.

The remainder of this report discusses methods for conducting statewide assessments of flooding risks to transportation infrastructure. Its organization is as follows:

- Section 2 describes the statewide flood risk dataset used by the research team throughout the project as a foundation for in-depth risk assessment methods.
- Section 3 describes methods to model the chronic effects of flooding on pavement infrastructure and discusses how these models could be used to reduce pavement life-cycle costs (LCCs).
- Section 4 describes two methodologies that can be used to assess flooding risks for bridges.
- Section 5 describes adaptation methods useful for offsetting flooding risks for infrastructure.
- Section 6 introduces a detailed risk assessment and resilience planning methodology that incorporates elements of each preceding chapter.
- Section 7 discusses proxy measures that can be used to improve risk assessment.
- Section 8 explores how elements of this project could be incorporated into TxDOT's next TAMP.
- Section 9 provides conclusions and recommendations for further work.

2. FLOOD EXPOSURE AND RISK

This section of the report describes a flood exposure dataset developed by the Texas Water Development Board (TWDB). The research team used this dataset extensively throughout the project to model the likelihood of a transportation asset becoming flooded.

TWDB'S STATE FLOOD PLAN

TWDB was founded in 1957 to lead the state's efforts in ensuring a secure water future for Texas. While TWDB is involved in a broad range of water management activities, flood management and prediction are its core activities.

According to TWDB's website (Texas Water Development Board 2025b), "The 2019 Texas Legislature and Governor Abbott greatly expanded TWDB's role in flood planning and financing." The referenced legislation—Senate Bill 8—directed TWDB to create a State Flood Plan to unify regional flood planning with a goal of making recommendations to guide state, regional, and local flood control policy.

The State Flood Plan represents a bottom-up approach to managing and predicting flood risk across the state. The term *bottom-up* refers to an approach that uses existing knowledge of the factors that cause flooding, such as rainfall, topography, and land use, to predict floods using a mechanistic modeling approach. In contrast, a statistical, top-down approach would seek to infer the underlying causes of flooding using past flood history.

The State Flood Plan also includes sections that deal with flooding risks for assets throughout the state. Due to TWDB's broad remit, these assets include residential and commercial buildings and populations, as well as transportation assets (see Figure 3 and Table 1).

Flood Frequency, Extent, and Depth Layers

In 2021 as part of the State Flood Plan, TWDB began to develop Geographic Information System (GIS) datasets describing current flood risk across Texas in map form showing flood depth, extent, and frequency. These layers represent the following three different flood types:

1. Coastal (i.e., from tropical storms or hurricane storm surges).
2. Fluvial (i.e., caused by overtopping of river channels).
3. Pluvial (i.e., when rainfall intensities and/or durations exceed the water holding capacity of the soil or drainage systems).

For each of these flood types, TWDB provides risk maps—in the form of water depth above normal ground surface—for annual flood return intervals or annual expected probabilities (AEP) of 5 percent (1 event in 5 years), 10 percent (1 event in 10 years), 1 percent (1 event in 100 years), and 0.2 percent (1 event in 500 years).

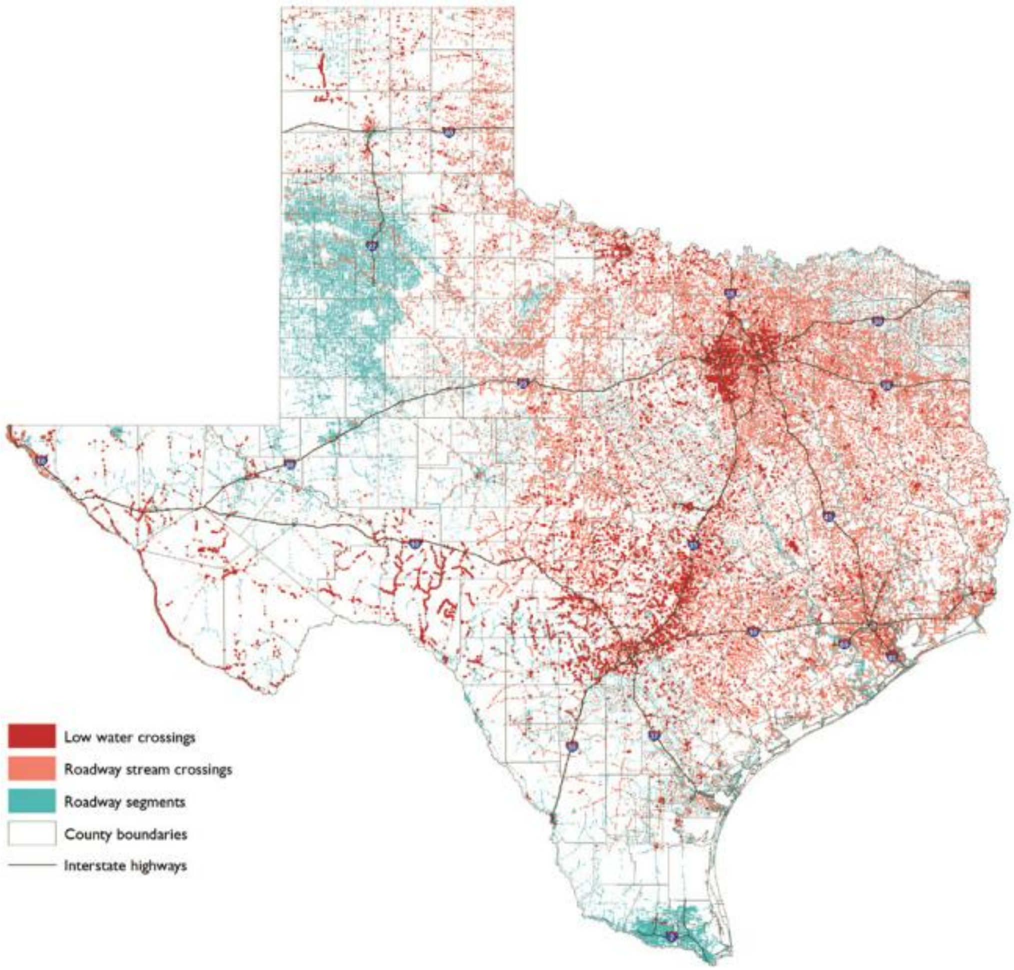

Figure 3. Roadways/Transportation Structures within Existing Flood Hazard Areas (Texas Water Development Board 2024).

Table 1. Roadway Flood Risks across the 15 Regions in the State Flood Plan.(Texas Water Development Board 2024).

Region	Roadway miles within 1 percent (100-year) annual chance floodplain	Roadway miles within 0.2 percent (500-year) annual chance floodplain	Flood prone (unknown annual chance) roadway miles	Total
1	2,299	1,042	8	**3,350**
2	1,924	139		**2,063**
3	3,945	1,936		**5,881**
4	1,518	378		**1,897**
5	1,505	949	615	**3,069**
6	4,350	3,635	13	**7,998**
7	5,944	3,597		**9,541**
8	3,302	1,130	850	**5,281**
9	4,338	1,177		**5,516**
10	2,374	911		**3,285**
11	935	438	6	**1,379**
12	753	214	1	**969**
13	3,215	1,579	90	**4,883**
14	3,047	746	178	**3,970**
15	3,995	2,596	94	**6,686**
Total	**43,444**	**20,468**	**1,856**	**65,768**

Note: Blank cells do not always signify the absence of roadways within flood hazard areas; they may indicate that such roadways were not identified or reported by the regional flood planning groups.

In May 2025, TWDB updated its flood risk data with a new present-day scenario (2024), as well as four future flood risk scenarios focusing on 2060 conditions. The four future scenarios differ according to assumptions concerning future climate, land use change, sea level rise, and subsidence (lowering of land surfaces) as follows:

- **Scenario 1:** Minimal future climate forcing (17th percentile change factors applied) with future subsidence and land use change.
- **Scenario 2:** Moderate future climate forcing (50th percentile change factors applied) with future subsidence and land use change.
- **Scenario 3:** Significant future climate forcing (83rd percentile change factors applied) with future subsidence and land use change.
- **Scenario 4:** Moderate future climate forcing (50th percentile change factors applied) without future subsidence and land use change.

All of TWDB's current flood depth maps are available as GIS-compatible GeoTIFF raster files with a spatial resolution of approximately 3 meters (approximation is necessary because they are projected in a geographic coordinate system such that the actual land area covered by each cell varies with latitude). Future flood risk data was developed in collaboration with a company called Fathom. TWDB's executive summary report (Texas Water Development Board 2025a). associated with flood risk layers states the following:

> The core of Fathom's flood modeling framework is the LISFLOOD-FP 1D-2D hydrodynamic model, which solves the shallow water equations of flow over representations of rivers and floodplains to produce estimates of floodplain depth and extent. Over the state of Texas, inputs used for this model include:
>
> - A gridded digital elevation model (DEM) for terrain elevations.
> - Rainfall, flow, and sea level boundary conditions derived for the flood type under consideration (fluvial, pluvial, and coastal) using flood frequency analysis.
> - River hydrography and bathymetry.
> - River/floodplain friction parameters (Manning's n).
>
> Utilizing the inputs summarized above, LISFLOOD-FP simulates events associated with the five return periods, calculates flood depths and flow per pixel for each timestep of the simulation. Whilst final maps are produced at 3-meter resolution, flood simulations are run at 30-meter resolution since this is more computationally tractable than execution at 3 meters. The 30-meter flood maps are then downscaled to 3-meter resolution raster files allowing higher resolution mapping to be achieved.

The executive summary report (Texas Water Development Board 2025a) also contains a description of the methodology used to model future change scenarios as follows:

> Fathom's approach to modeling future hazard is based on the generation of riverine (fluvial) flooding, local (pluvial) flooding, and coastal flooding “change factors” from ensembles of global climate models, known as general circulation models (GCMs). Riverine (fluvial) flooding, local (pluvial) flooding, and coastal flooding are referred to as the three perils in the document. The climate in 2060 is represented by a 2°C global mean temperature increase relative to the estimated temperature of the 1850–1900 preindustrial period, after which systematic increases in global CO_2 emissions commenced. This future climate scenario was selected in consultation with State Climatologist Dr. John Nielsen-Gammon. Based on the strong relationship between temperature change and precipitation change, the 2°C benchmark is used to select output from an ensemble of GCMs for pluvial modeling and ensembles of GCMs linked to ensembles of hydrological models for fluvial modeling. For simulation of coastal inundation, ensembles of predictions of sea level from the Intergovernmental Panel on Climate Change (IPCC) *Sixth Assessment Report* are used. Comparison of present-day mean indices of precipitation, flow, and sea level to 2060 climate future values are used to generate fluvial (riverine), pluvial (local), and coastal change factors.

Figure 4 and Figure 5 provide examples of TWDB’s flood depth data. Figure 4 illustrates the 1 percent or 1-in-100-year flood depth risk map for an area centered on Houston, Texas. The upper map in this figure shows flood depth caused by coastal surge, while the lower map shows the flood risk of coastal surge and river channel overtopping (again expressed as flood depth). Figure 5 illustrates flood risk centered on a smaller area of southeast Houston. The upper map in this figure shows the 1-in-100-year flood risk for coastal and fluvial floods, while the lower map shows additional pluvial flood risk.

TWDB’s DEM that was used for the flood analysis enables the flood depth data to be converted to flood elevation data (i.e., height of the flooded surface above sea level). The release of TWDB’s flood risk maps presents several new opportunities for assessing flood risk as follows:

- The new flood maps use three descriptors of flood risk including extent (area flooded), depth (depth of water in a flooded area), and recurrence (time or annual probability of a flood condition). The addition of flood depth supports more sophisticated models of flood damage. Other flood mapping endeavors, such as the Federal Emergency Management Agency’s (FEMA’s) flood risk maps, use only two descriptors (extent and frequency), generally with a lower flood frequency resolution (see Figure 6). These maps are often available in GIS formats but are not available in some locations.
- The new data provide statewide flood risk with no gaps in coverage. The data are also packaged in convenient GIS files, thus improving the efficiency of analyses.

Figure 4. One-in-100-Year Flood Depth Risks for Southeast Houston Associated with Storm Surge/Coastal Flooding (Upper) and Storm Surge/River Channel Overtopping (Lower).

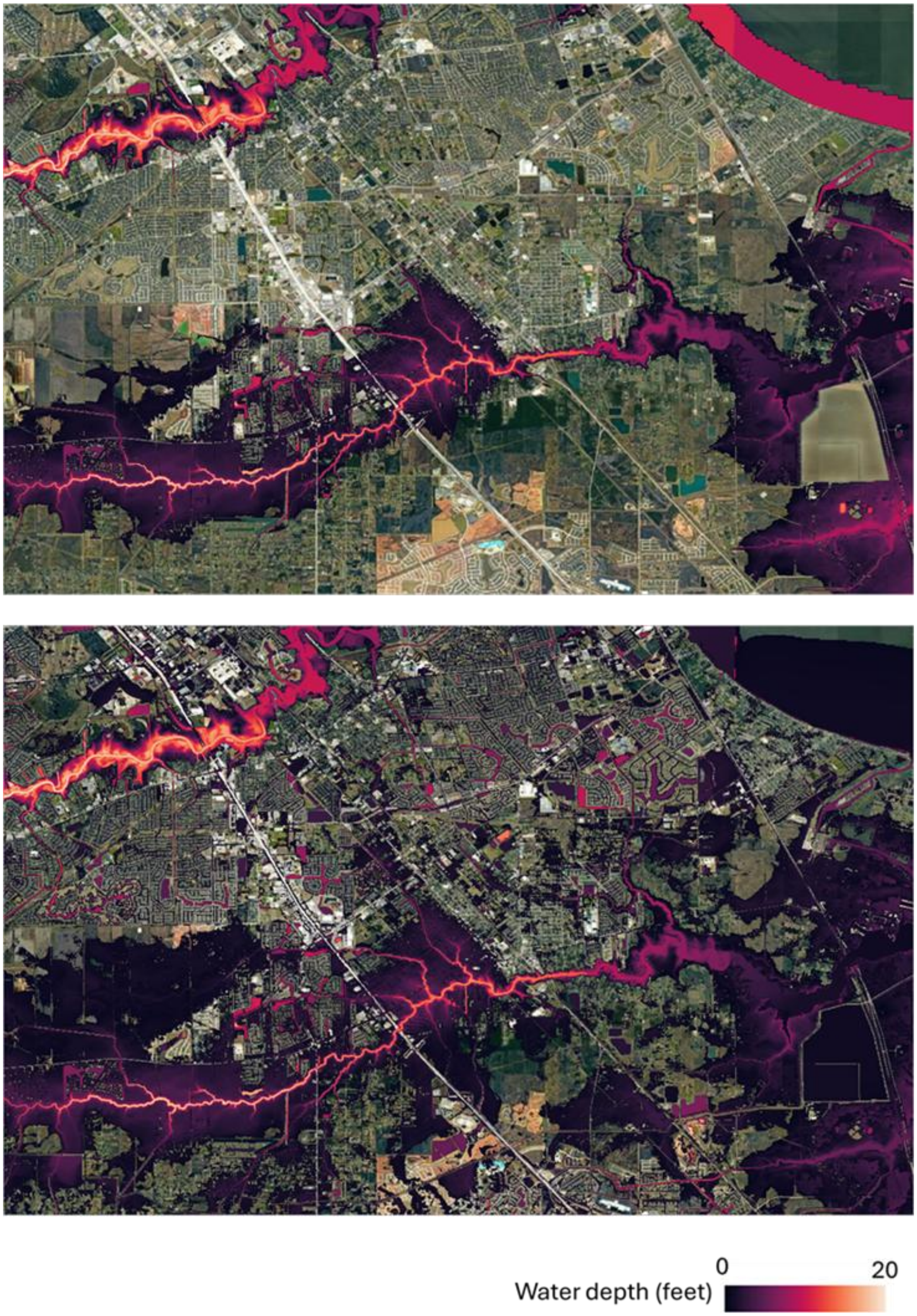

Figure 5. One-in-100-Year Flood Risks for Southeast Houston Shown as Flood Water Depth for Coastal Surge/River Overtopping (Upper) and Additional Pluvial Flooding Caused by Rainfall Intensities/Durations Exceeding Hydraulic Holding or Drainage Capacities (Lower).

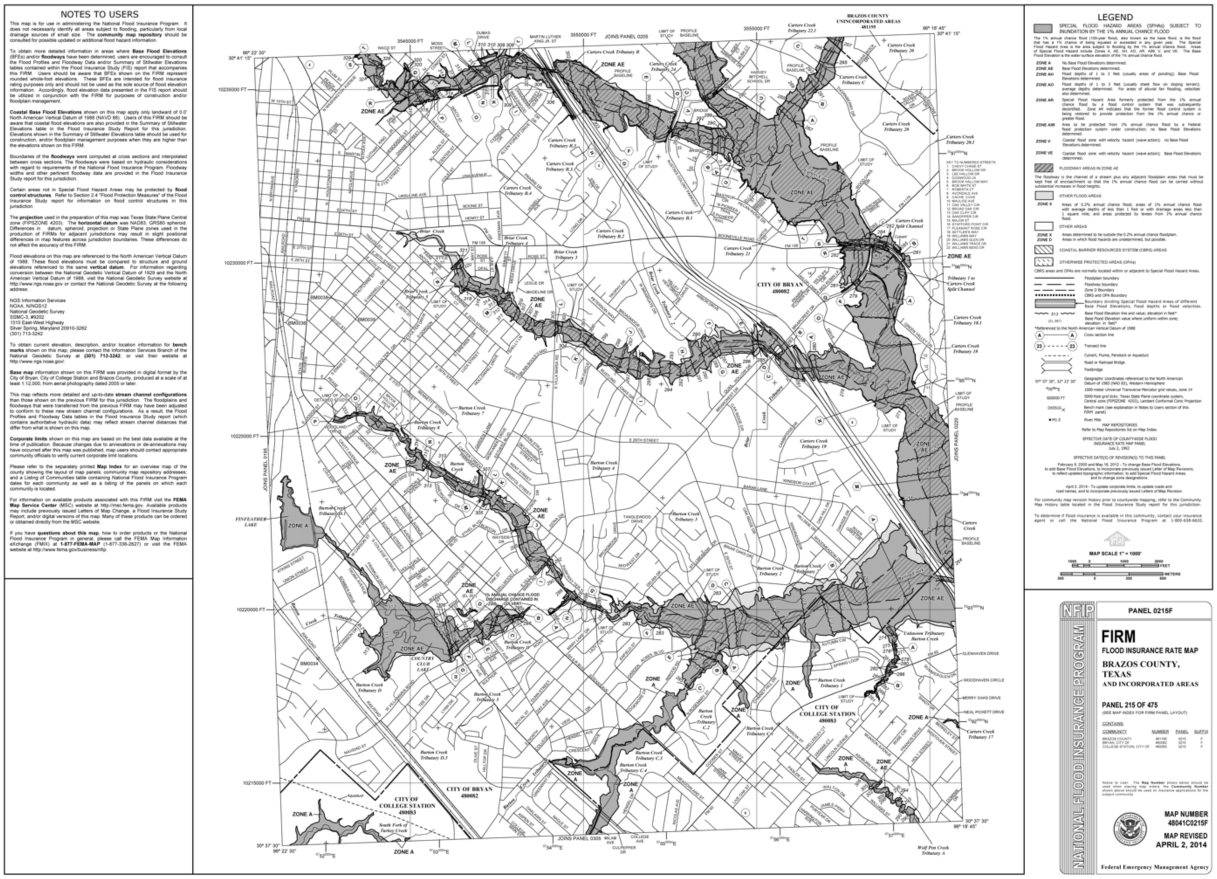

Figure 6. Example Paper-Based FEMA Flood Map Showing Different Flood Zone Boundaries (Shaded Areas).

ROAD, BRIDGE, AND OTHER INFRASTRUCTURE ELEVATIONS

While the availability of flood depth in TWDB's data offers potential advantages for risk assessment, its full potential can only be achieved if the elevation of transportation infrastructure is also known.

TWDB's data describes flood depth (at a 3-meter × 3-meter resolution) above a reference DEM. This reference DEM *does not* represent the elevation of bridge decks, but it does show elevations of raised roadway sections (see Figure 7). As such, TWDB's data can be directly used to identify flooded roadway sections by determining whether the geometry of a road section intersects any areas of flooding delineated by TWDB's data using GIS. For sections of the network that are bridges, this method will yield inaccurate results because neither the DEM nor TWDB's flood data account for the grade change of the bridge deck.

In the case of bridges that span permanent water, the omission of accurate bridge location data can result in false positives for flooding. Due to the nature of TWDB's data, the GIS methodology will falsely assume that the road traverses a flooded area (e.g., a river channel) when, in fact, the elevation of the bridge prevents flooding. However, under flood conditions it is also possible that the water level at a channel becomes deep enough to inundate a bridge (depending on the elevation of the bridge relative to the flood water level).

The same inaccuracies are also relevant to bridges that do not cross water channels. Without knowing the location and elevation of bridges, it is possible that they will falsely be labeled as flooded when real world conditions show they are minimally affected by floods (i.e., at grade roads are flooded, but bridges are not).

In most cases, culverts are not affected by this issue because their elevation is generally included in the underlying DEM. However, given the number of culverts in Texas, it is highly likely that exceptions exist to this generality. Nonetheless, accurate spatial representations of culverts are still useful for risk assessment because they would enable GIS systems to compare the elevation of culverts to the specific watershed elevations that the culvert serves.

It follows that an accurate intersection between TWDB's data and GIS representations of infrastructure requires associated data that accurately describes the three-dimensional geometry of roads and bridges. The most immediate needs are more accurate data describing where bridges occur on the network and preferably elevation data describing the height of bridge decks.

Another useful addition to TWDB's data would be a water depth layer that provides the depth and location of water in a nonflooded state. The rationale is that in both technical (i.e., GIS analysis) and colloquial terms, a flood is defined relative to a nonflooded case. In other words, permanent river channels are not usually considered to be flooded even if they contain water. Instead, they become flooded when water levels rise to an abnormal state. One could make the technical argument that, without the normal state condition, TWDB's data are indicators of water depth under different return intervals rather than explicitly defined flood layers.

In previous resilience studies (Texas Department of Transportation 2019a), the research team used LIDAR data collected from an aircraft to estimate the height of roadway surfaces relative to surrounding land areas. LIDAR-derived height maps differ from traditional DEMs; DEMs were developed to model the height of a base land surface (i.e., a surface without trees, buildings, or other human-made structures), and therefore do not show bridge deck elevations in detail. Figure 8 shows four different views of an intersection in Houston using combinations of LIDAR, road geometry, DEM, and aerial imagery data. The LIDAR (Figure 8[a]) and DEM (Figure 8[c]) data illustrate differences regarding infrastructure elevations, while the road geometry data Figure 8(b) illustrates accuracy relative to elevated roadways.

Figure 9, Figure 10, and Figure 11 illustrate the process of estimating road surface elevation using LIDAR data for a case study region in Bay City, Texas. The use of LIDAR and other elevation data for risk assessments is revisited in future sections of this report dealing with bridge assessments (Section 4) and proxy indicators (Section 7).

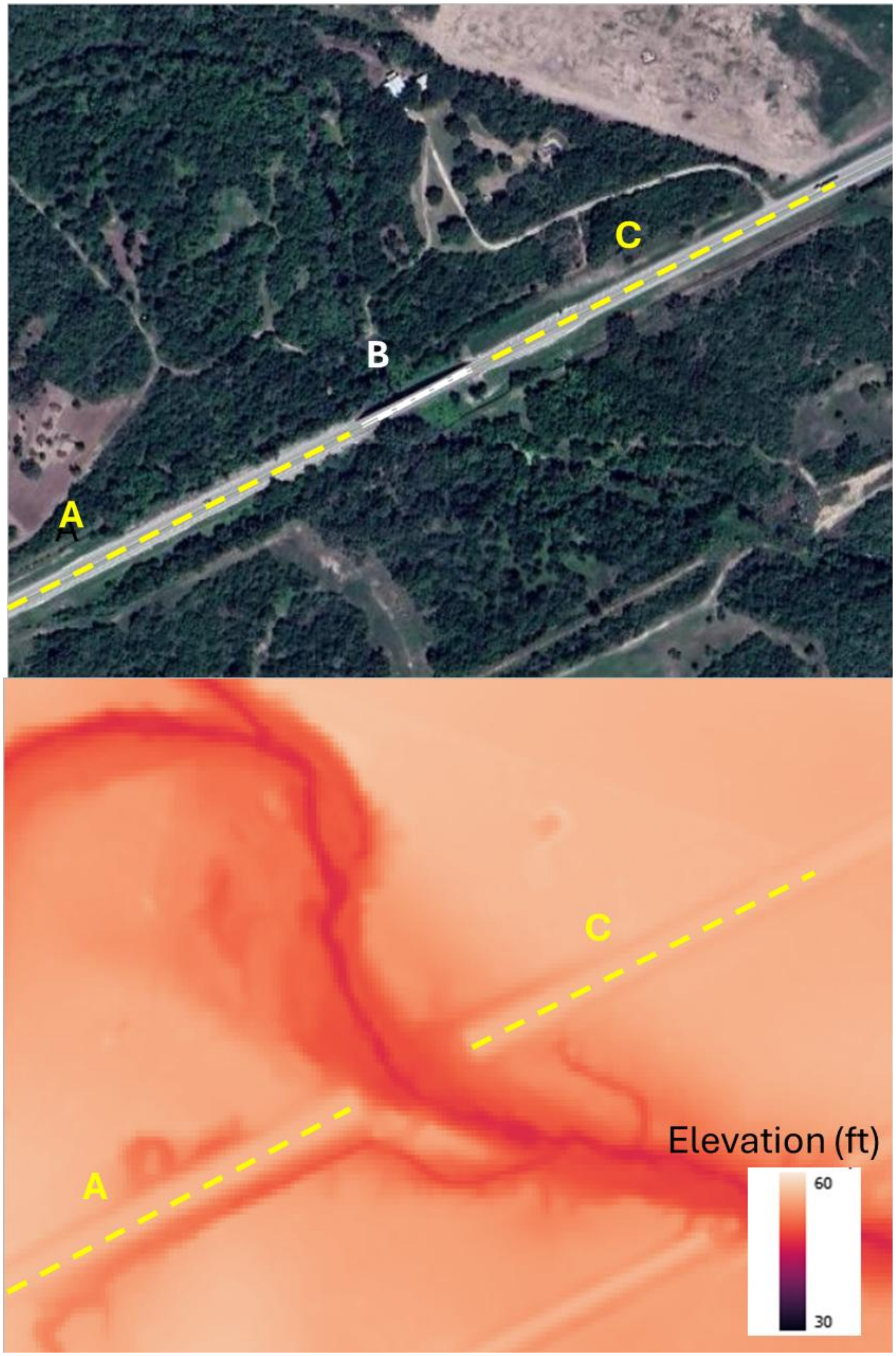

Figure 7. Example DEM Bridge Representation in TWDB Flood Data Comparing an Aerial Image of a Corridor Comprising Road Section A, Bridge Section B, and Road Section C (Upper) with the Same Corridor Represented by a DEM (Lower).

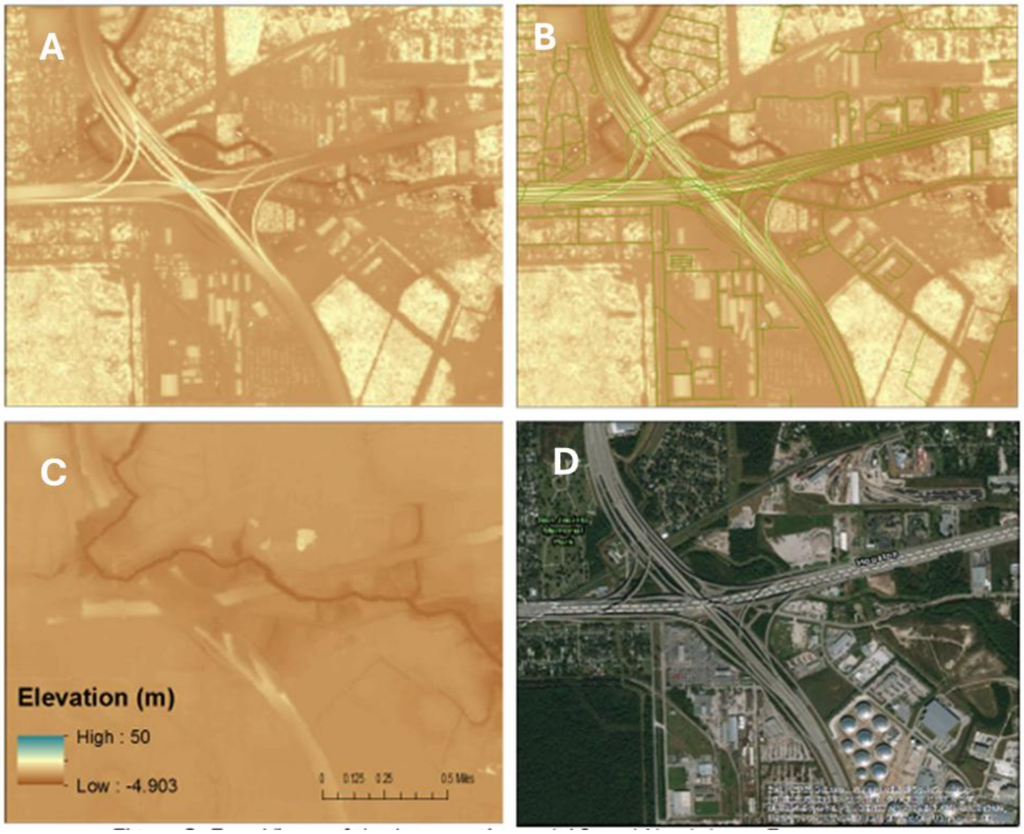

Figure 8. Four Views of the I-10 and North Loop Freeway Intersection Based on Data Source: (a) LIDAR, (b) Road Geometry, (c) DEM, and (d) Aerial Imagery (Texas Department of Transportation 2019a).

Figure 9. Aerial Image of Bay City, Texas.

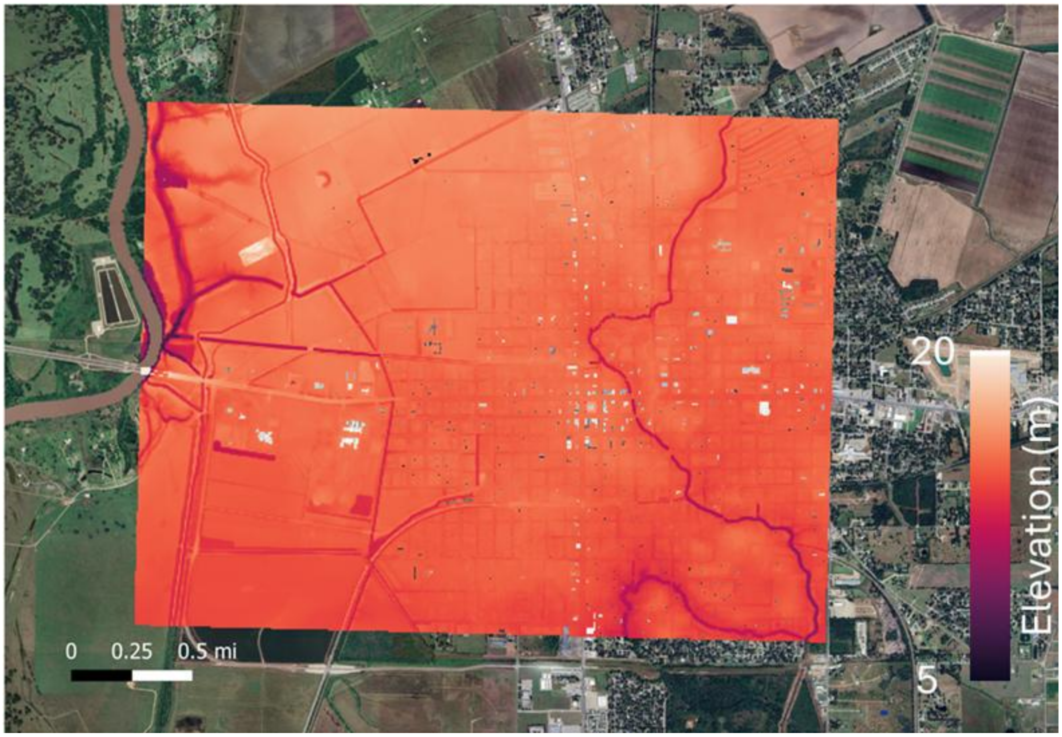

Figure 10. LIDAR-Derived Height Map of Land Surfaces in Bay City, Texas; Highest Surfaces include Trees and Human-Made Structures such as Roads, Buildings, and Utilities.

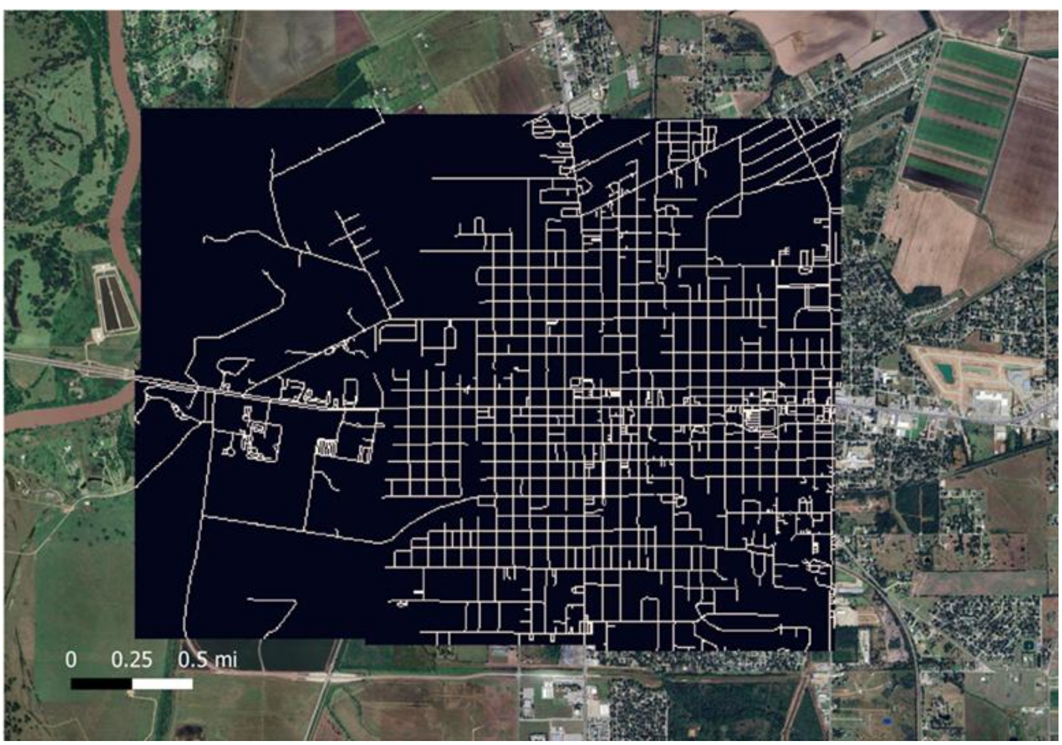

Figure 11. Height Map of Roads in Bay City, Texas, Derived Using LIDAR Height Measurements and OpenStreetMap Road Geometry GIS Layers.

QUANTITATIVE RISK ANALYSIS

The research team conducted three simple analyses (risk assessment 1–3) to illustrate how TWDB's data could be used to conduct relatively simple risk assessments of roadway flooding. Each risk assessment uses TxDOT's roadway data and TWDB's data.

Risk Assessment 1

Risk assessment 1 was designed to assess risk using the simplest assumptions or models of roadway flooding. The research team resampled TWDB's flood depth layers to a resolution of approximately 10,000-foot (3000-meter) cells and then counted the number of original cells (10-foot [3-meter] resolution) in the resampled area that were predicted to be flooded based on TWDB's data. The research team then aggregated this measure of flood risk by TxDOT district and plotted the results as the total flooded acreage, the total flooded acreage as a proportion of district area, and the total flooded area relative to the total number of centerline miles in each district. Figure 12 illustrates the risk assessment for flooding with 1-in 25, 1-in 100, and 1-in-500 year return intervals.

Risk Assessment 2

Risk assessment 2 was designed to explore changes in infrastructure risk as predicted by TWDB's data. This assessment used the same methodology as risk assessment 1 but calculated the *change* in flood extent predicted by TWDB's scenario 3 and scenario 1 models (with significant and minimal future climate forcing with future subsidence and land use change, respectively) compared to current day flood risk. Figure 13 shows the difference in risk for scenario 3 versus present day conditions. The maps illustrate the difference in expected risk in each 10,000-foot (3000-meter) cell of the state. The charts show the change in risk (in million-acres of land area) and the proportional increase in flooded area at the district level. Figure 14 shows these same outputs for scenario 1 versus present day conditions.

Risk Assessment 3

Risk assessment 3 differed from the previous assessments by explicitly estimating the current flood risk to roads (rather than the total land area in the district). For this analysis, the research team overlayed TxDOT's highway GIS data over TWDB's flood exposure data (the 2024 existing conditions dataset). TxDOT's highway data was preprocessed in two ways. First, highway links were aggregated into distinct and unique routes defined by the roadway name or official route number (e.g., US0006) and by the roadbed type. Split roadbeds were used in the analysis (i.e., the centerline roadbeds were removed from the analysis for routes that have distinct individual roadbeds such as major highways or interstates that have separate mainline roadbeds as well as frontage road roadbeds). A routing algorithm was used to ensure that all links that contributed to a unique route were correctly aligned into continuous paths.

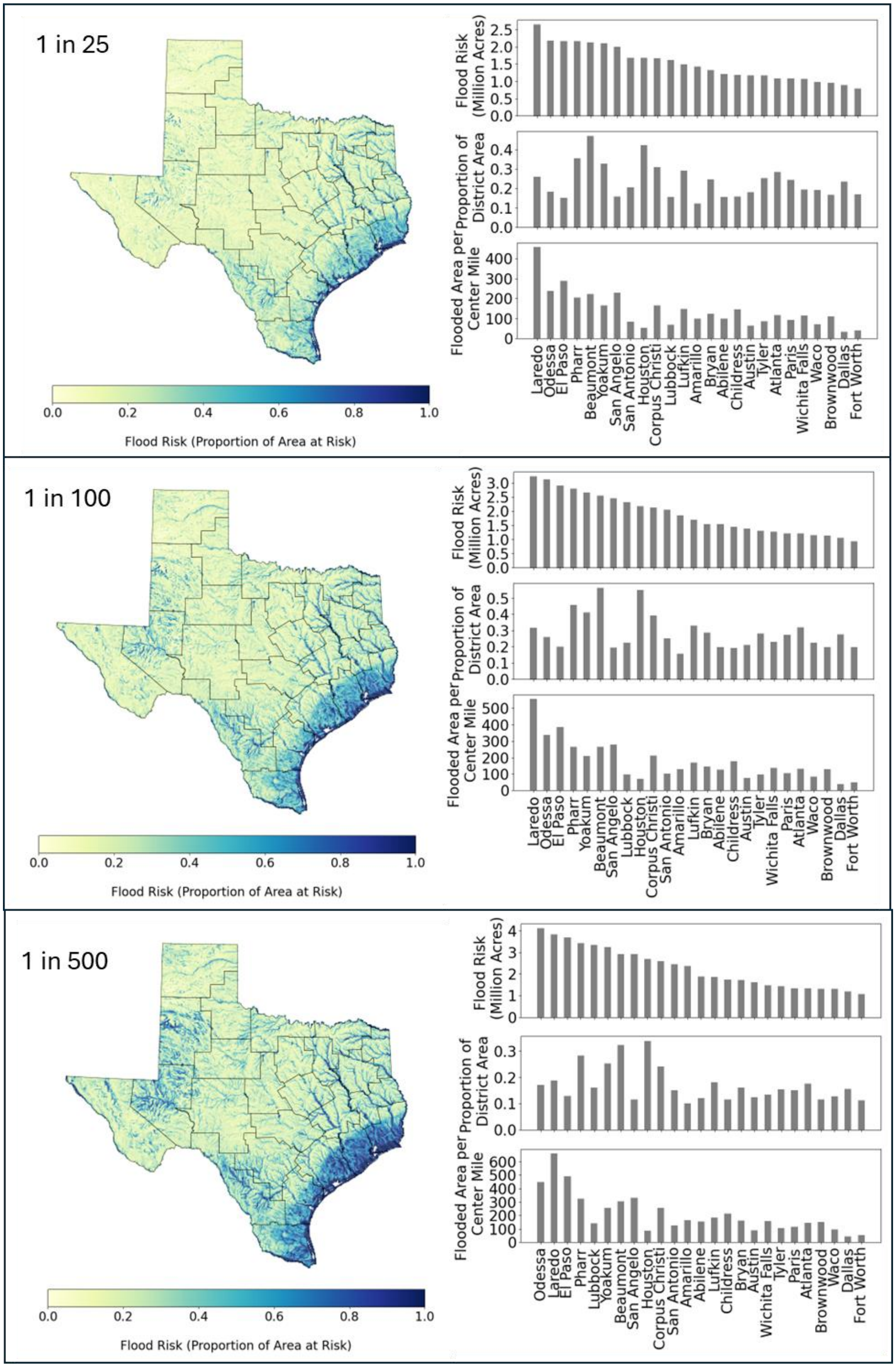

Figure 12. Flood Risk Analysis for Each TxDOT District.

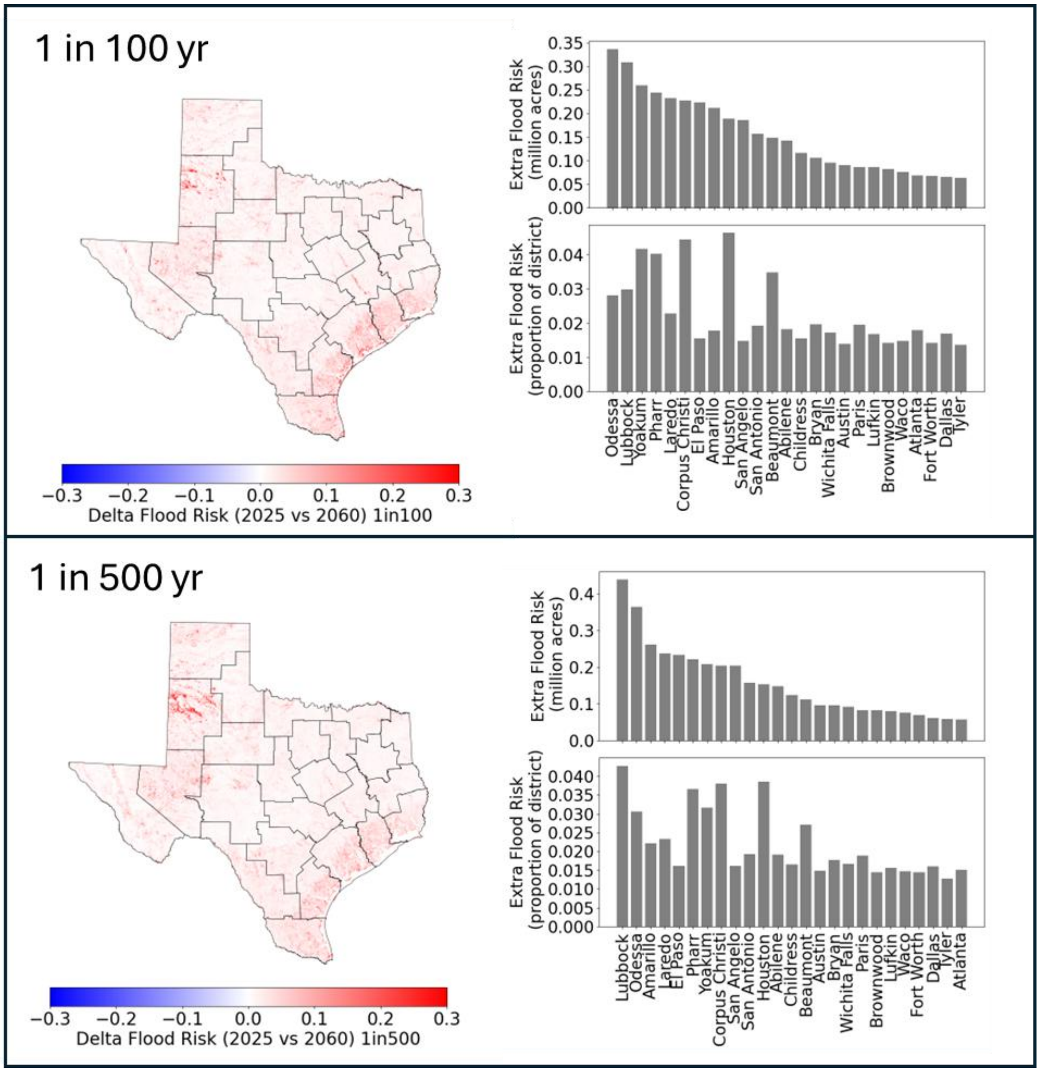

Figure 13. Current and Future Flood Risks for Each TxDOT District Using TWDB Future Risk Scenario 3 Versus Existing Flood Risk Data.

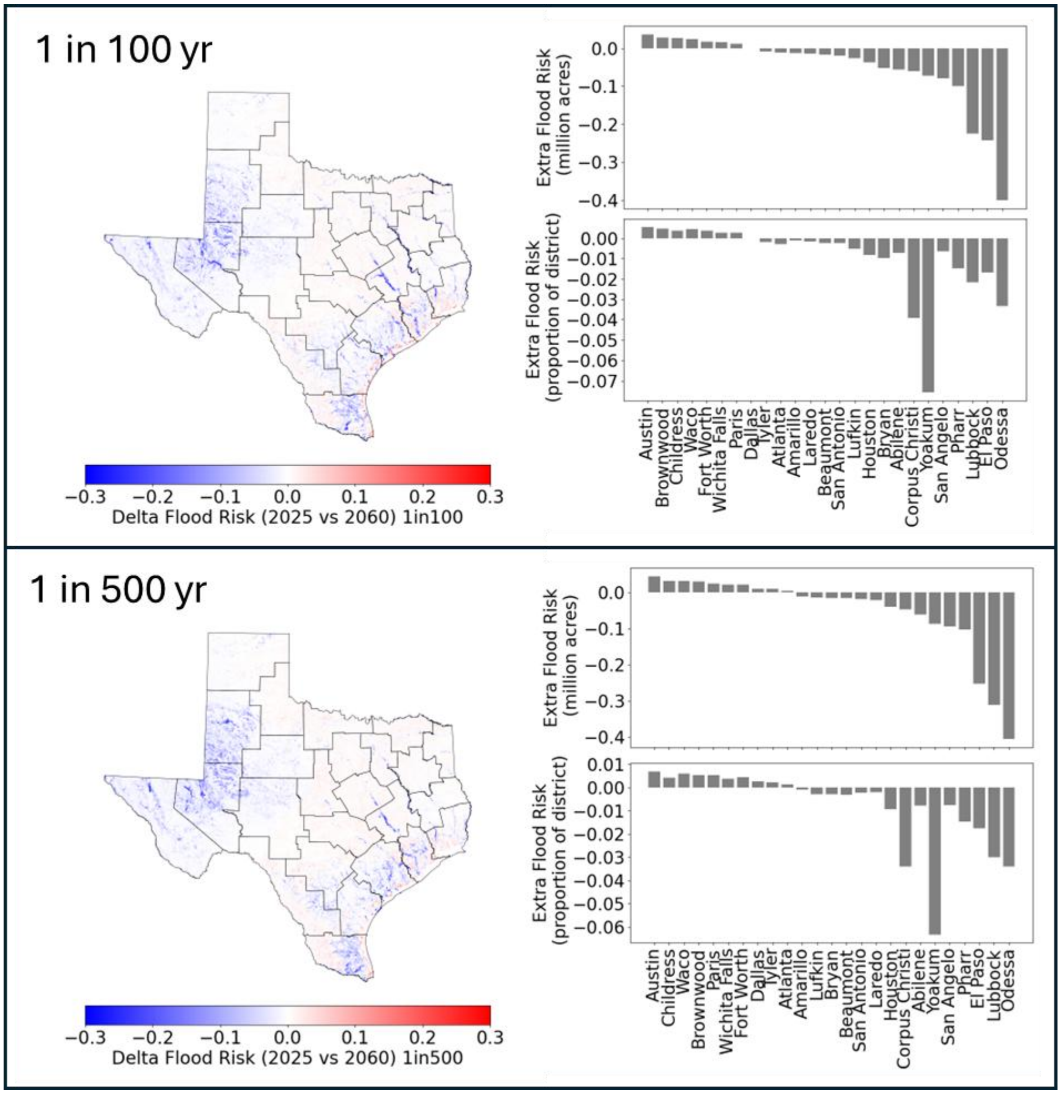

Figure 14. Current and Future Flood Risks for Each TxDOT District Using TWDB Future Risk Scenario 1 Versus Existing Flood Risk Data.

Next, the research team split each of the unique route paths into approximately 10-foot (3-meter) segments to align with the resolution of TWDB's data. Each route section was then overlayed onto a TWDB flood depth raster defined by flood return interval (e.g., 1-in-20-, 1-in-100 year return interval) and the water depth was recorded alongside the segment. A GIS layer of Texas permanent waterbodies was used to remove all segments that cross permanent water (excluding rivers). Figure 15 illustrates one of the outputs of this analysis. The maps show all roads that meet a specified flood depth criteria (2 feet in this case) for each flood return interval. The right-hand maps in each panel show a more detailed regional view of the outputs focused on TxDOT's Houston District.

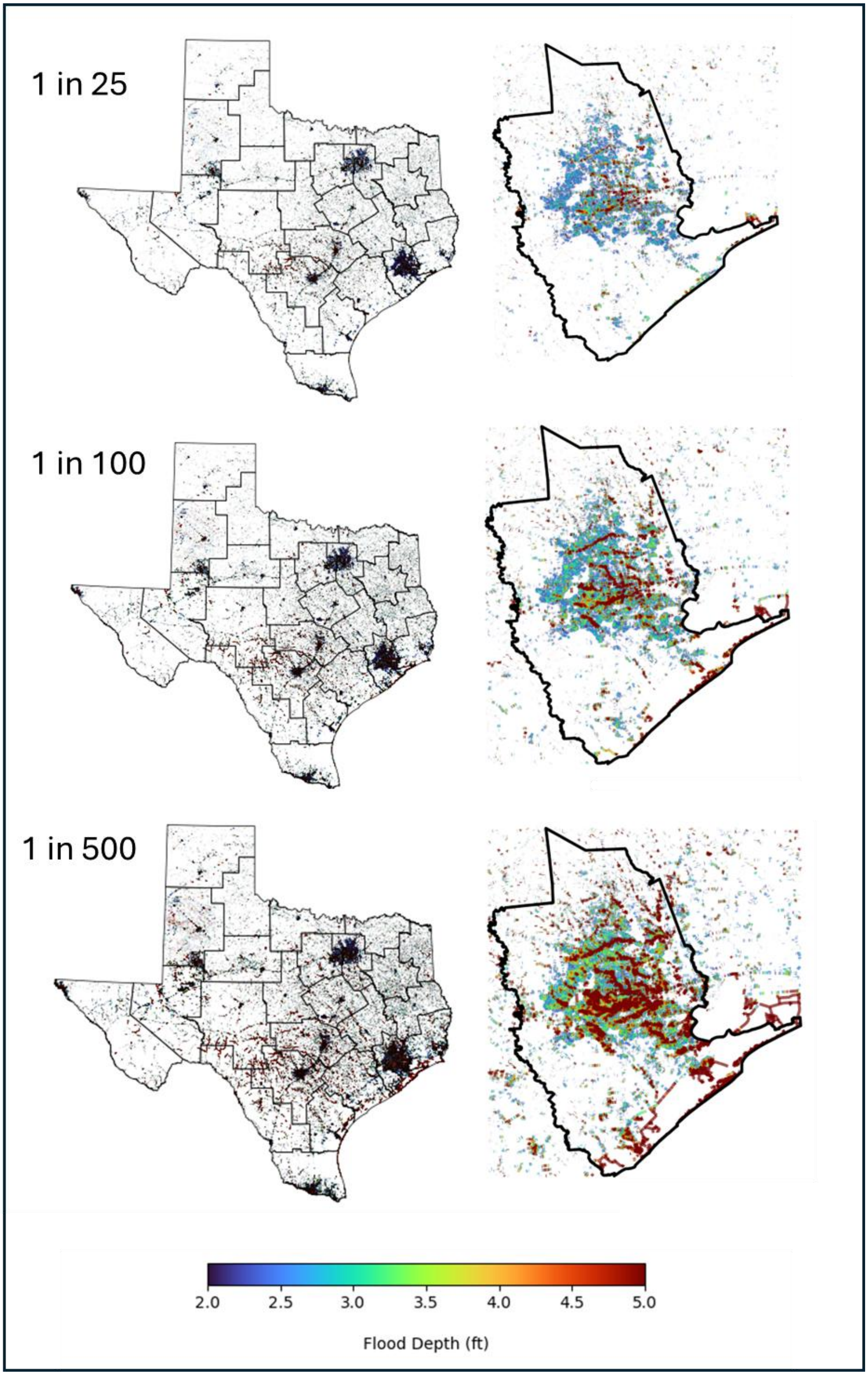

Figure 15. Flood Risks for Texas and TxDOT's Houston District Roads.

Risk Assessment Interpretation and Refinement

While each risk assessment example quantified risk, each targeted a different risk assessment output and used different assumptions or models of risk. None of these assessments were intended to be definitive; instead, they were conducted to illustrate the potential of TWDB's data for quantifying risk, to identify potential issues with data and its effect on the accuracy of assessments, and to explore how such risk assessments could be used institutionally. The research team noted the following:

- Risk analyses 1 and 2 provided quantitative risk estimates without explicitly considering the location of flooding relative to transportation infrastructure. Considerable flooding may occur within an area that does not affect roadway infrastructure. These methods are simple and communicable; simple maps, figures, or tables can portray areas of risk relatively clearly. Such risk assessments could be used as a basis to allocate funding (emergency, maintenance, etc.) to a district for example.
- Risk analysis 3 explicitly includes the location of transportation infrastructure relative to flooded areas, refining the risk assessment and potentially increasing its utility. Total risk aggregated at the district level could again be used as a basis to allocate funding. Alternatively, risk assigned to transportation infrastructure by location could be used to dynamically map at-risk infrastructure and identify high risk assets.
- Risk assessment utility is clearly related to issues of accuracy and communication of results. Ideally, the process of making a risk assessment more explicit should improve risk assessment accuracy and the ability to communicate risk. However, the introduction of more explicit risk models can also lead to greater inaccuracy if the quality of assumptions or data is insufficient. Similarly, the addition of greater detail can detract from the ability to communicate risk and its subsequent utility for decision-making.
- Referring to the underlying formula for risk ($Risk = P_{event} \times P_{damage}$), these three simple risk assessments deal mostly with the likelihood of a flood occurring on a section of roadway, P_{event}; the damage component, P_{damage}, is only implied (i.e., the risk assessments simply and conveniently assume that any road that becomes flooded *could be* damaged, but do not explicitly model the mechanism of damage in any way). Therefore, these assessments do not fully utilize one of the potential useful variables in TWDB's flood data—flood depth. They also ignore a great many other variables in the infrastructure dataset (e.g., pavement type, bridge characteristics) that could potentially be useful for developing and incorporating more explicit damage models for risk assessment.

These three types of risk assessments illustrated the great potential for using TWDB's data and transportation infrastructure data for assessing risk. Figure 12 through Figure 15 also illustrated the myriad of ways in which risk assessment outputs could be presented (i.e., as simple tables or dynamic maps). Considering only these three examples, one could image infinite ways in which the data could be disaggregated, aggregated, overlaid, or modeled.

However, the goal of this project was to develop a high utility risk assessment methodology for the TAMP. To this end, the research team found it prudent to *invert* the problem of developing a risk assessment—instead of focusing on methodologies, the research team focused on questions that helped to explicitly identify the utility of a risk assessment output. Such questions included the following:

- What will the risk assessment be used for?
- What decision-making activities will it support?
- Who will use the risk assessment results?
- How will the risk assessment endpoints be stored, communicated, or retrieved?

FLOOD EXPOSURE MODELING SUMMARY

TWDB's flood depth data have many novel applications for quantifying the flooding risk for transportation infrastructure. These data are particularly compelling for infrastructure risk assessment for the following reasons:

- It is available in a consistent and easily used format for the entire state.
- It has been developed by a state agency with a well-defined mission that includes flood risk modeling. This adds to the credibility of the data and any risk assessment that uses it and provides opportunities for collaboration between state agencies.
- It is part of a broader research program that deals with flood risk modeling. This broader program includes Texas' State Flood Plan and all the knowledge and expertise of TWDB's hydrologists. In turn, the existence of this broader research program suggests that the flood depth data will be regularly produced and likely improved over time.
- It presents flood depth layers instead of the traditional flood extent boundaries historically provided in FEMA maps. This alternative data may enable a broader range of and more accurate damage models to be used in risk assessments.

Despite its potential utility, TWDB's data also presents the following challenges for risk assessments:

- The detail and spatial resolution of the data can only be realized if associated data describing transportation assets is of a similar resolution, quality, and consistency.
- An operational risk exists from assuming that increased detail in the flood data equates to improved accuracy. TWDB goes to considerable lengths to qualify the methods used to develop these layers and the guidelines describing how they should be used. TWDB's executive summary report (Texas Water Development Board 2025a) states the following regarding data usage:

    > Proper representations of flood defenses like levees and dams remain a key challenge in any flood model. Many of these features are not well-represented in

DEMs unless the survey resolution is smaller than 1 or 2 feet. Dams are always a problem for large-scale hydrologic-hydraulic modeling as the dam operating procedures are typically not readily available. Indeed, the operating procedures of many dams depend on the judgments of the operators, who incorporate lessons from history and knowledge of predicted rainfall, antecedent soil moisture, and risks associated with overtopping.

If the Fathom-Texas data product is made publicly available, a statement should be made to the effect that the data product is not equivalent to those of conventional engineering flood modeling studies and should not be solely relied on for capital investment or quantified risk assessment projects.

- Using simple risk assessments, the research team explicitly identified the following data challenges when assessing transportation risk:
    - Inadequate spatial accuracy of the transportation asset data.
    - Inadequate elevation data for exposure analysis, especially for bridges. TWDB's State Flood Plan team noted the same issues while conducting their flood exposure analyses as follows:

        > "… the number of buildings within flood hazard areas identified by the flood planning groups using two-dimensional analyses may be higher than the number of buildings identified using flood elevation (three-dimensional analyses). Therefore, the number of buildings at risk of flooding during a particular storm event is lower than the number of buildings located in the flood hazard area.

    - The inability to accurately identify bridge locations (i.e., roadway and bridge data should be integrated).
    - The need for a GIS layer that can be used to compare the extent of floods to normal nonflooded conditions.
- Overall, the research team suggested that the greatest value in the new TWDB data lies in the effective, mutually beneficial, and long-term collaboration between TxDOT and TWDB.

3. EFFECTS OF FLOODING ON PAVEMENT LIFE CYCLES AND MAINTENANCE

This section describes methods to predict damage that may occur to pavements following flooding events. Flooding can cause both acute and chronic damage to pavements and associated infrastructure. During extreme floods, acute damage can occur when the force of flood water causes pavements or associated structures (e.g., culverts, embankments) to weaken or collapse. Floods also cause long-term, chronic damage to pavements, caused by the presence of moisture in different layers of the pavement structure.

Motivated by the availability of data and models, the research team focused on chronic damage caused by flooding (i.e., the long-term, gradual damage to pavements from a single or repeated exposure to flood events). TWDB's flood risk data include flood extent and depth, which are useful for modeling chronic pavement effects and formed the basis of this project's exposure modeling. Additionally, models and modeling methodologies exist that can be used to predict pavement damage given different assumptions about pavement design (including the moisture content of pavement layers). In contrast, accurate modeling of acute effects requires more detailed estimates of flow and water pressures that are currently unscalable to statewide risk assessments.

The rationale for this work lies in its potential for improving the longevity of a pavement asset and/or the costs involved with maintaining or replacing such assets if they become damaged. Currently, TxDOT and most other state DOTs already implement proactive pavement management-based models that link traffic volumes and time to pavement deterioration and LCCs. The methods presented in this section are designed to explicitly incorporate flooding into the management of pavement assets.

Flood risk is currently incorporated into TxDOT's processes at the design phase of projects (in TxDOT's *Hydraulic Design Manual* [Thomason 2019]). However, no processes are currently in place to assess how flood events affect pavement structures. In the context of asset management and resilience, models that can usefully predict the chronic deterioration of pavements following flooding would enable planners to explore and identify mitigation or adaptation strategies designed to improve pavement performance and life-cycle management.

RESEARCH APPROACH

The research team conducted a mechanistic-empirical (ME) analysis to quantify the relative damage caused by flooding for different pavement types including rigid pavements, thin asphalt concrete pavements (ACP), thick ACP, and seal coats (Appendix A contains detailed descriptions of the pavement types).

The objectives of the analysis were to:

4. Develop *fragility curves* that summarize and describe the probability of a particular pavement design failing under different scenarios of repeated floods.
5. Explore new maintenance and rehabilitation (M&R) decision-making models for the different pavement types based on different exposures to flooding.
6. Evaluate the costs associated with each pavement type under different flood exposures to project future asset management costs under different flood risk scenarios.

The research was completed through a five-step process:

1. The research team viewed pavement damage in a recently flooded corridor (FM521) to collect empirical evidence of chronic flood damage on different pavement types.
2. Mechanistic models were developed to simulate the effects of flooding on the moduli of different types of pavement subsurfaces (based on American Association of State Highway and Transportation Officials' [AASHTO's] classifications). The resulting relationships between soil saturations and moduli were used as inputs to subsequent modeling steps.
3. Pavement design software was used to simulate pavement damage for the five pavement types assuming different saturation levels of the pavement subsurface. In line with the different ways in which water affects different structures, slightly different methods were used to simulate damage for rigid versus flexible pavements as follows:

    a. **Flexible pavements:** The primary damaging effect of flooding on flexible pavements is the loss of interparticle friction within unbound granular layers, leading to a reduction in their structural support capacity. To capture this behavior, flooding effects were simulated by reducing the resilient moduli of the unbound layers due to moisture infiltration. The AASHTOWare Pavement ME Design software was used for all flexible pavement simulations, including surface treatments.
    b. **Rigid pavements:** For continuously reinforced concrete pavement (CRCP), the TxCRCP-ME software was used to model damage to rigid pavement types. This software accounts for the effects of location, traffic loading, and material properties of both the concrete slab and the underlying support layers (Ha et al. 2011). Based on these inputs, the model computes a composite k-value that characterizes the structural support provided to the slab. The increased moisture content decreases the k-value, which in turn decreases pavement life. The number of punchouts expected over the design life is then estimated as a function of this composite k. In this study, a failure threshold was defined as the occurrence of 10 punchouts. A Monte Carlo simulation is used to estimate the probability of failure under flooding conditions.

4. Next, damage factors were normalized using a seal coat standard.
5. Finally, fragility curves were developed.

RESULTS

The results of this research related to pavement types and moisture vulnerability, case study observations, quantified flooding impacts on Texas pavements, flexible and rigid pavement analyses, fragility curves, M&R decisions, and LCC analysis.

Pavement Types and Moisture Vulnerability

The research team conducted a literature review was to establish a theoretical basis for moisture vulnerability across different pavement types, including surface-treated, hot-mix asphalt (HMA), Portland cement concrete (PCC), and composite pavements. The research team examined the impacts of increased moisture levels on each pavement type. Appendix A details the literature review results.

Surface-treated pavements—usually comprising a chip seal or thin bituminous surface treatment over an unbound base—are the most vulnerable to flooding. Their thin surfacing provides minimal structural strength and limited resistance to water infiltration. Under saturated or moving-water conditions, rapid deterioration can occur, manifesting as severe rutting, localized shear failures, or complete washouts. For HMA pavements, excess subgrade moisture accelerates both rutting and fatigue cracking, with the severity of these effects diminishing as the overall structural layer thickness increases. PCC pavements are generally less sensitive to short-term reductions in subgrade bearing capacity due to their ability to distribute loads over a broader area compared with flexible pavements. However, moisture in the subgrade and subbase layers plays a critical role in the long-term durability of rigid pavements by contributing to pumping, faulting, and slab cracking. Composite pavements—typically consisting of an HMA overlay on an older concrete pavement—exhibit moisture behaviors that mimic both flexible and rigid pavement characteristics. The asphalt surface reduces direct subgrade exposure to moisture; however, the system remains susceptible to moisture-induced failure modes of the underlying pavement type. As noted in Caltrans' *Highway Design Manual* (California Department of Transportation 2025), current design procedures do not fully account for the reduced moisture gradient benefits in composite pavement design. Nevertheless, with proper maintenance, these structures can effectively shed water and extend subgrade protection over time. Infiltrating water can deteriorate the concrete and erode the underlying support near joints and cracks, which are common distress locations in both rigid and composite pavements.

Overall, a pavement type's relative vulnerability to moisture can be ranked as follows:

$$\text{Surface Treatment} > \text{Thin HMA} > \text{Thick HMA} > \text{Composite Pavement} > \text{PCC} \qquad (2)$$

This hierarchy shows that flexible pavement performance increases as surface thickness increases, and that rigid pavements generally perform better under wet conditions but are susceptible to moisture-related erosion.

Case Study Observations

To confirm the literature review results regarding the effects of moisture on different pavement types, the research team conducted a case study along FM521 (in TxDOT's Yoakum and Houstin Districts). This corridor was selected due to its variety of pavement surface types and proximity to the coast, which increases its exposure to flooding. This combination of diverse pavement conditions and coastal vulnerability provided a representative scenario for evaluating pavement resilience under extreme moisture conditions. Table 2 summarizes the pavement surface types along the selected roadway corridor, including their corresponding distance from origin (DFO) ranges, retrieved from TxDOT's Pavement Management Information System (PMIS), Pavement Analyst (PA). Pavement type information from fiscal year (FY) 2017 was used because Hurricane Harvey was the focal event of the case study.

Figure 16 shows a representative moisture profile of soil layers along FM521 during and after Hurricane Harvey. Data were obtained from the Langley Research Center's Prediction of Worldwide Energy Resources project funded through the National Aeronautics and Space Administration's Earth Science/Applied Science Program.

Table 2. Pavement Type and Corresponding DFO Ranges.

From DFO	To DFO	Detailed Pavement Type
0	18	Surface treatment pavement
18	26	Medium asphaltic concrete, 2.5–5.5 inches
26	43	Surface treatment pavement
43	47.1	Medium asphaltic concrete, 2.5–5.5 inches
47.1	51.2	Overlaid and widened asphaltic concrete pavement
51.2	52.8	Medium asphaltic concrete, 2.5–5.5 inches
52.8	58.6	Overlaid and widened asphaltic concrete pavement
58.6	66.4	Surface treatment pavement
66.4	78.5	Overlaid and widened asphaltic concrete pavement
78.5	83.6	Widened composite pavement
83.6	84.6	Overlaid and widened asphaltic concrete pavement
84.6	86	Widened composite pavement
86	87.5	Overlaid and widened asphaltic concrete pavement
87.5	90	Widened composite pavement
90	90.5	Medium asphaltic concrete, 2.5–5.5 inches
90.5	92	Continuously reinforced concrete
92	98.3	Medium asphaltic concrete, 2.5–5.5 inches

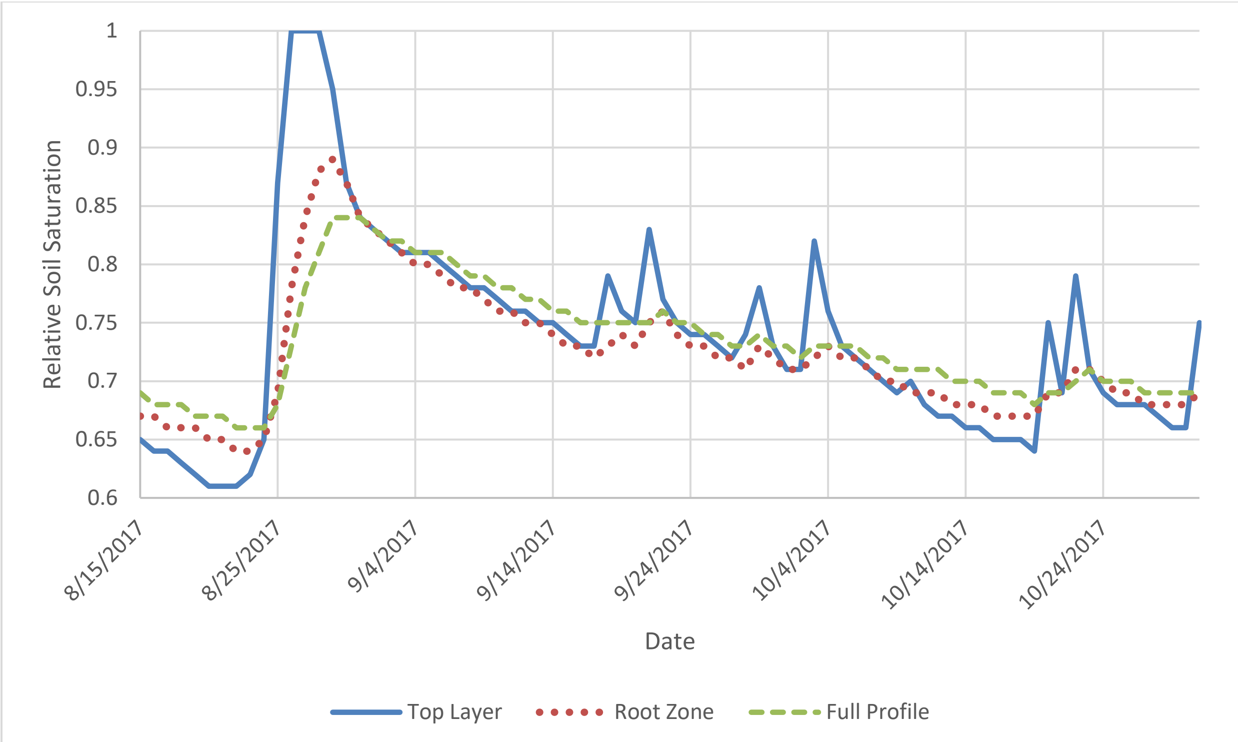

Figure 16. Moisture Profile along FM521 during and after Hurricane Harvey.

The case study examined 31.8 miles of the 98.3-mile FM521 corridor. Three segments with distinct pavement types were selected for analysis. A paired t-test was conducted to evaluate changes in cracked percentages for each 0.5-mile data-collection section between FY 2016–2017 and FY 2017–2018, reflecting the occurrence of Hurricane Harvey. Only the surface-treated segment near the beginning of the corridor exhibited a statistically significant increase in annual deterioration compared to the medium asphaltic concrete and widened composite pavement segments. This finding confirms the higher vulnerability of surface-treated pavements, consistent with the literature review findings.

The case study also highlighted the difficulty of assessing flood-related pavement damage from short-term field observations, particularly over a two-year period. Nevertheless, both theoretical and empirical analyses indicated that flooding could cause chronic pavement damage at levels significant enough to be incorporated into asset management models, and the differing sensitivities of pavement types to flood damage should be accounted for. Based on these findings, the research team concluded:

- A controlled ME approach should be used to evaluate the effects of repeated flooding on pavement damage (as described in later subsections).
- A long-term program of continual in situ research and pavement condition data collection related to flood events is recommended.

Quantified Flooding Impacts on Texas Pavements

To quantify flood-associated impacts on Texas pavement, the research team developed an equivalent damage approach. Based on flood recurrence times and guidelines from TxDOT's *Hydraulic Design Manual* (Thomason 2019), the research team developed fragility curves to estimate the probability of failure. Based on the probability of failure, the research team proposed specific M&R decisions and calculated the increased costs due to flooding. Unit costs were obtained from TxDOT's TAMP.

The research team conducted an ME analysis to quantify the equivalent damage for flexible and rigid pavements using the AASHTOWare Pavement ME Design software and TxCRCP-ME software, respectively. To assess the sensitivity to moisture, the research team conducted a series of sensitivity analyses for each pavement type.

Flexible Pavement Analysis

The primary damaging effect of flooding on flexible pavements is the loss of interparticle friction within the unbound granular layers. To capture this effect, flooding was simulated as a reduction in the resilient moduli of the unbound layers due to moisture infiltration. These effects were incorporated into the analysis to calculate the reduction on rutting and fatigue life. A modulus reduction curve was defined for each material type based on AASHTO's classifications. Drawing from the literature on optimum moduli and moisture-dependent stiffness behavior, reduction curves were developed to account for individual AASHTO soil classes (see Figure 17).

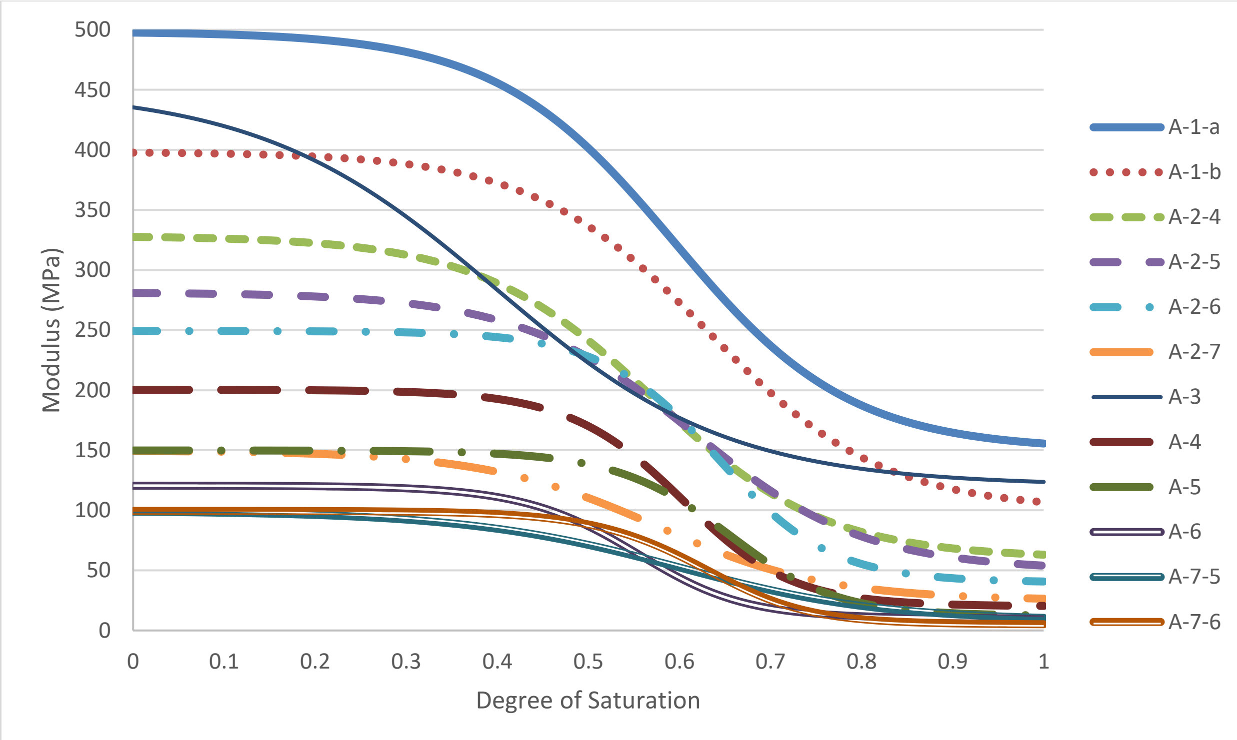

Figure 17. Resilient Modulus Versus Saturation for Different Soil Classes.

To quantify the damage caused by axle loads of varying magnitudes and configurations, the equivalent single axle load (ESAL) concept was used. Under traffic loading, the pavement experiences stress and strain responses at different depths. Critical compressive strains typically develop at the top of the subgrade, which is associated with rutting. Simultaneously, critical tensile strains develop at the bottom of the asphalt surface layer, serving as the primary factor controlling fatigue cracking.

The critical strain responses within the pavement structure are strongly influenced by the stiffness of the supporting material layers. When moisture infiltrates the system, it reduces interparticle friction within the unbound granular materials, leading to a decrease in their resilient moduli, which in turn results in elevated strain responses. Figure 18 illustrates how these strains vary with surface thickness under both optimum and saturated moisture conditions.

Rigid Pavement Analysis

For rigid pavement analysis, the research team used the TxCRCP-ME software, which accounts for the effects of location, traffic loading, and material properties of both the concrete slab and the underlying support layers. The number of punchouts expected over the design life was then estimated as a function of this composite k. In this study, a failure threshold was defined as the occurrence of 10 punchouts. By running the model multiple times with varying input parameters, the proportion of simulations exceeding the failure threshold provided an estimate of site-specific failure probability.

The research team computed the number of load repetitions until failure for each pavement type by incorporating material properties drawn from the relationship between the resilient modulus and moisture content. Figure 19 shows the resulting distributions of allowable repetitions for both flexible and rigid pavements.

To enable comparative evaluation, the research team normalized the values with respect to the seal coat performance, yielding an equivalent or relative damage factor. Table 3 summarizes these factors.

Fragility Curves

Based on the results of the ME analysis and the design flood levels specified in TxDOT's *Hydraulic Design Manual* (Thomason 2019) for each pavement type, the research team developed fragility curves. These curves defined the probability of a pavement section surviving a given flood event as a function of the storm recurrence. Figure 20 illustrates the resulting fragility curves for each pavement type.

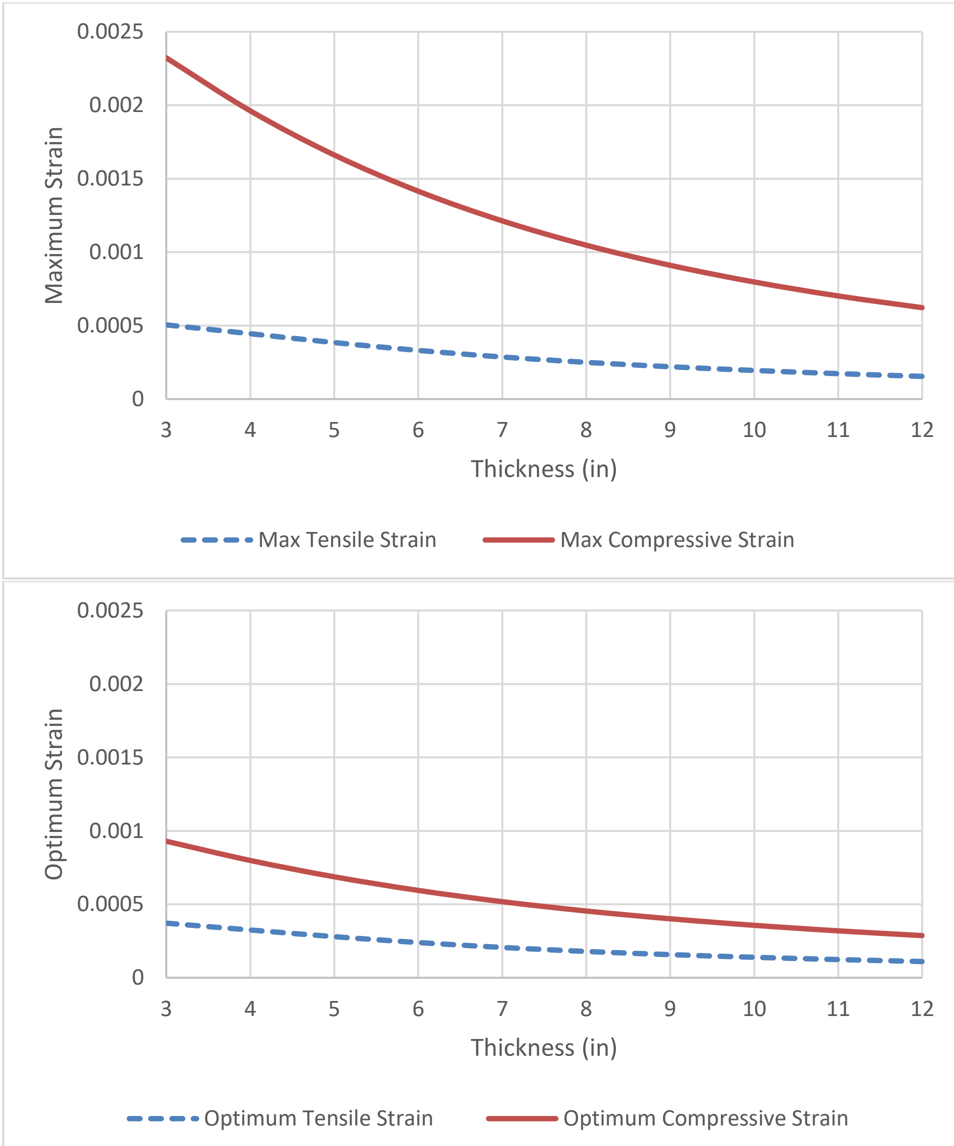

Figure 18. Thickness Effects on Strain under Optimum and Saturated Moisture Conditions.

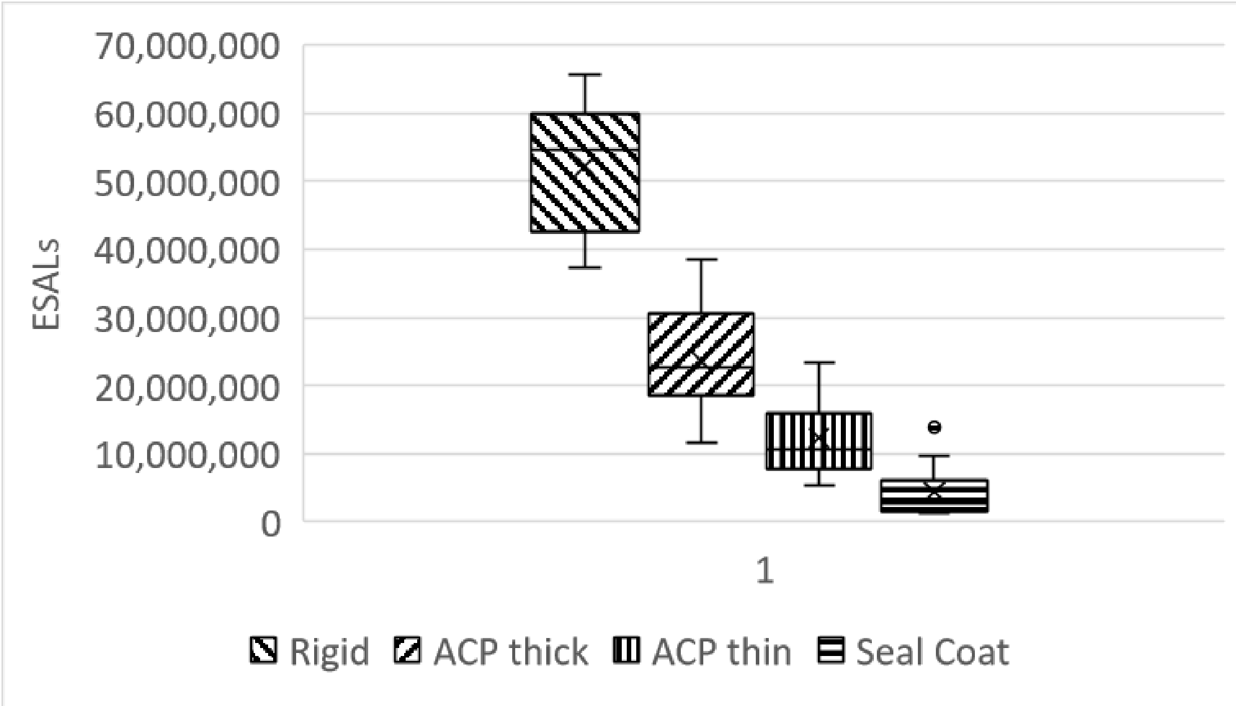

Figure 19. Distribution of Pavement Performance by Pavement Type.

Table 3. Relative Damage Factor by Pavement Type.

Pavement Type	Rigid Pavement	Thick ACP	Thin ACP	Seal Coat
Relative resiliency	11.6	5.23	2.76	1.00
Standard deviation	2.15	1.81	1.22	0.86
Coefficient of variation	18.5%	34.6%	44.2%	86.4%

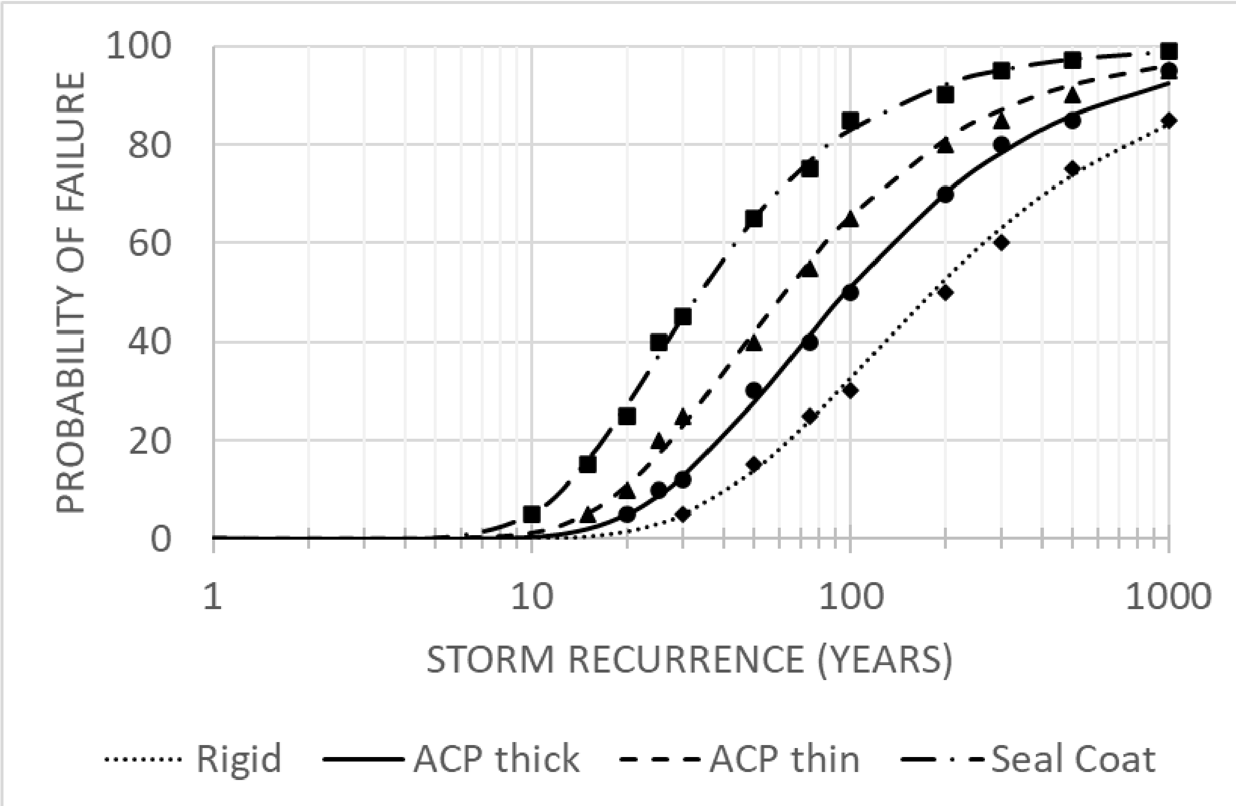

Figure 20. Fragility Curves by Pavement Type and Storm Recurrence.

M&R Decisions

M&R decisions are triggered following each extreme flood event, based on the associated probability of failure (P_f) as determined by the fragility curves in Figure 20. Table 4 summarizes the complete set of decision criteria, and Figure 21 illustrates the proposed decision framework.

Table 4. M&R Decisions based on Probability of Failure.

Probability of Failure (P_f)	Treatment Type Triggered
$P_f \leq 5\%$	Preventive maintenance
$5\% < P_f \leq 15\%$	Light rehabilitation
$15\% < P_f \leq 50\%$	Medium rehabilitation
$P_f > 50\%$	Heavy rehabilitation

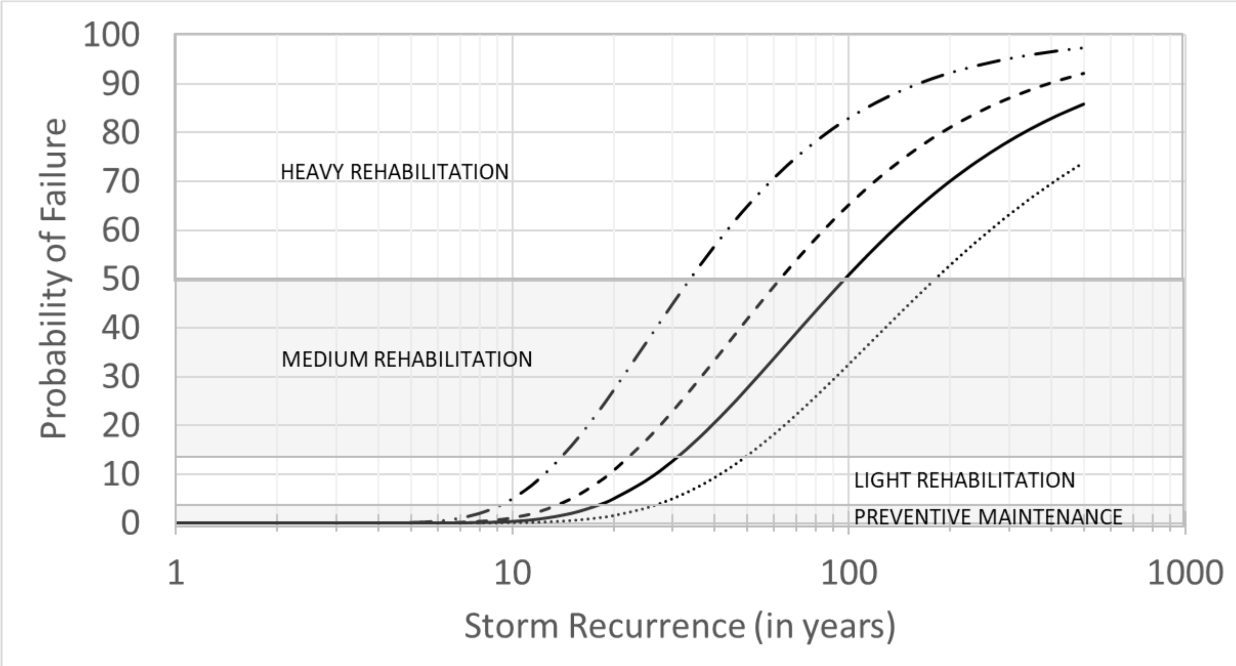

Figure 21. M&R Decision Framework.

The probability thresholds delineate zones of M&R activity as follows:

- If the probability of failure is < 5 percent, apply preventive maintenance.
- If the probability of failure is between 5 and 15 percent, apply light rehabilitation.
- If the probability of failure is between 15 and 50 percent, apply medium rehabilitation.
- If the probability of failure is > 50 percent, apply heavy rehabilitation.

This tiered system allows for scalable response plans that can be matched to both the pavement type and the severity of anticipated flood exposure.

LCC Analysis

Obtained from TxDOT's TAMP, Table 5 lists the M&R unit costs of each treatment type applied to different pavements.

Table 5. M&R Unit Costs by Treatment and Pavement Type.

Treatment Type	Flexible Pavements	Rigid Pavements
Preventive maintenance	$53,462	$81,703
Light rehabilitation	$221,186	$172,041
Medium rehabilitation	$296,023	$210,144
Heavy rehabilitation	$470,988	$971,516

Based on the fragility curves, the proposed M&R decision framework, and the unit cost assumptions, an LCC analysis was performed for each pavement type under varying flood scenarios characterized by different storm recurrences. For each case, both the net present value (NPV) and equivalent uniform annual cost (EUAC) were calculated under baseline conditions (no flood event) and under the various flooding scenarios. Table 6 summarizes these results, with monetary results expressed in thousands of U.S. dollars ($K). NPV_0 and $EUAC_0$ represent the cost metrics when no flood event occurs, and NPV_1 and $EUAC_1$ represent the cost metrics when one flood event occurs for different storm recurrences.

Table 6. LCC Analysis by Pavement Type and Storm Recurrence.

Cost Metric	Seal Coat			ACP			Rigid Pavement		
	10-Yr	20-Yr	50-Yr	20-Yr	50-Yr	100-Yr	30-Yr	100-Yr	200-Yr
NPV_0	$243K			$470K			$908K		
NPV_1	$278K	$311K	$377K	$586K	$637K	$741K	$987K	$1,158K	$1,481K
$EUAC_0$	$19K			$36K			$70K		
$EUAC_1$	$21K	$24K	$29K	$45K	$49K	$57K	$76K	$89K	$114K
Relative	114%	128%	155%	125%	135%	158%	109%	128%	163%

Under baseline (no flood) conditions, rigid pavements exhibited the highest NPV and EUAC due to higher initial construction costs. However, when exposed to flooding, seal coat pavements showed a sharp increase in LCC. In contrast, rigid pavements demonstrated greater flood resilience. Despite higher baseline costs, their relative increase in LCCs under flood conditions is more modest. Regarding the relative costs (see Table 6), the cost sensitivity to flooding was highest for flexible pavements with thinner asphalt concrete. These findings illustrate the concept of *relative resiliency*, whereby pavements with higher initial structural capacity (such as rigid pavements) exhibit more stable long-term cost performance under increasing flood risk.

SUMMARY

In this section the research team outlined a methodology to estimate chronic pavement damage caused by floods. The methodology was useful in the context of risk and resilience because it provides a meaningful way to estimate overall risk (Equation 1) if the exposure of an asset to flooding is known (i.e., using TWDB's flood risk data). This methodology also provides information useful for adapting the M&R of roads to locations that have high exposure to risk.

4. FLOODING RISKS FOR BRIDGES

This section describes two bridge resiliency rating (BRR) frameworks useful for ranking candidate projects for resilience improvements.

Federal law requires that most bridges in the United States be regularly inspected by state DOTs for functionality and structural condition, generating a wealth of annual data stored in the NBI database. TxDOT describes these inspection data in their *Coding Guide* (Texas Department of Transportation 2020) and reports these data annually for inclusion in the NBI. During the inspections, structures (culverts and bridges) receive general appraisal ratings from 0 to 9 (new). The following NBI data are especially worthy of investigation to develop a BRR for network-level ranking of candidate projects:

- Item 19: Detour lengths.
- Item 29: Average daily traffic (ADT).
- Item 61: Channel condition.
- Item 71: Channel appraisal.
- Item 113: Scour.

CASE STUDY STRUCTURE STATISTICS

The research team identified an initial case study corridor (FM521) to evaluate and develop the analytical tools for evaluating methods to assess risk and improve the resiliency of bridges and pavements. Figure 22 depicts the road segment selected for the FM521 corridor. The following statistics for this corridor were retrieved and calculated from the latest TxDOT bridge inventory:

- Number of bridges: 22 bridges.
- Number of culverts: 9 culverts.
- Area of bridges: 347,000 square feet.
- Area of culverts: 12,370 square feet.
- Slight chance of overtopping (Item 71: Channel appraisal): 11 bridges.
- Slight change of overtopping (Item 71: Channel appraisal): 8 culverts.
- Repairs needed (Item 61: Channel condition): 20 bridges.
- Repairs needed (Item 61: Channel condition): 8 culverts.
- Load ratings possibly substandard: A couple of structures.

DATA DESCRIPTION AND AVAILABILITY

Several publicly available data sources were investigated to determine flood levels for different return periods (e.g., 100- and 500-years), and LIDAR data were used to determine structure deck elevations. These data were spatially combined with TxDOT's inventory data for the 31 structures shown in Figure 22, allowing for a detailed analysis of vulnerability to flooding.

Note: Red dots are the bridges and culverts in the case study.

Figure 22. FM521 Case Study Road Segment.

Figure 23 and Figure 24 show examples of the flood and LIDAR spatial data used in this study, respectively. Publicly available spatial data were retrieved from two sources and processed to determine the case study's analytical resiliency. Figure 23 shows a screenshot of the FEMA website, where GeoTIFF files can be downloaded that include flood level data suitable for analytically associating flood water levels with specific structures along FM521. The green-shaded areas indicate available flood levels from extensive flood modeling. These green-shaded areas cover almost the entire length of the FM521 case study, including 27 of the structures.

The researcher team obtained LIDAR data from the U.S. Interagency Elevation Inventory (National Oceanic and Atmospheric Administration 2025b). Figure 24 shows the LIDAR tiles (red squares) used in the analytical geoprocessing to determine structure deck elevations for the FM521 case study. Each tile had a specific uniform resource locator (URL) that sped up retrieval of the pertinent LIDAR data for each structure in the FM521 case study.

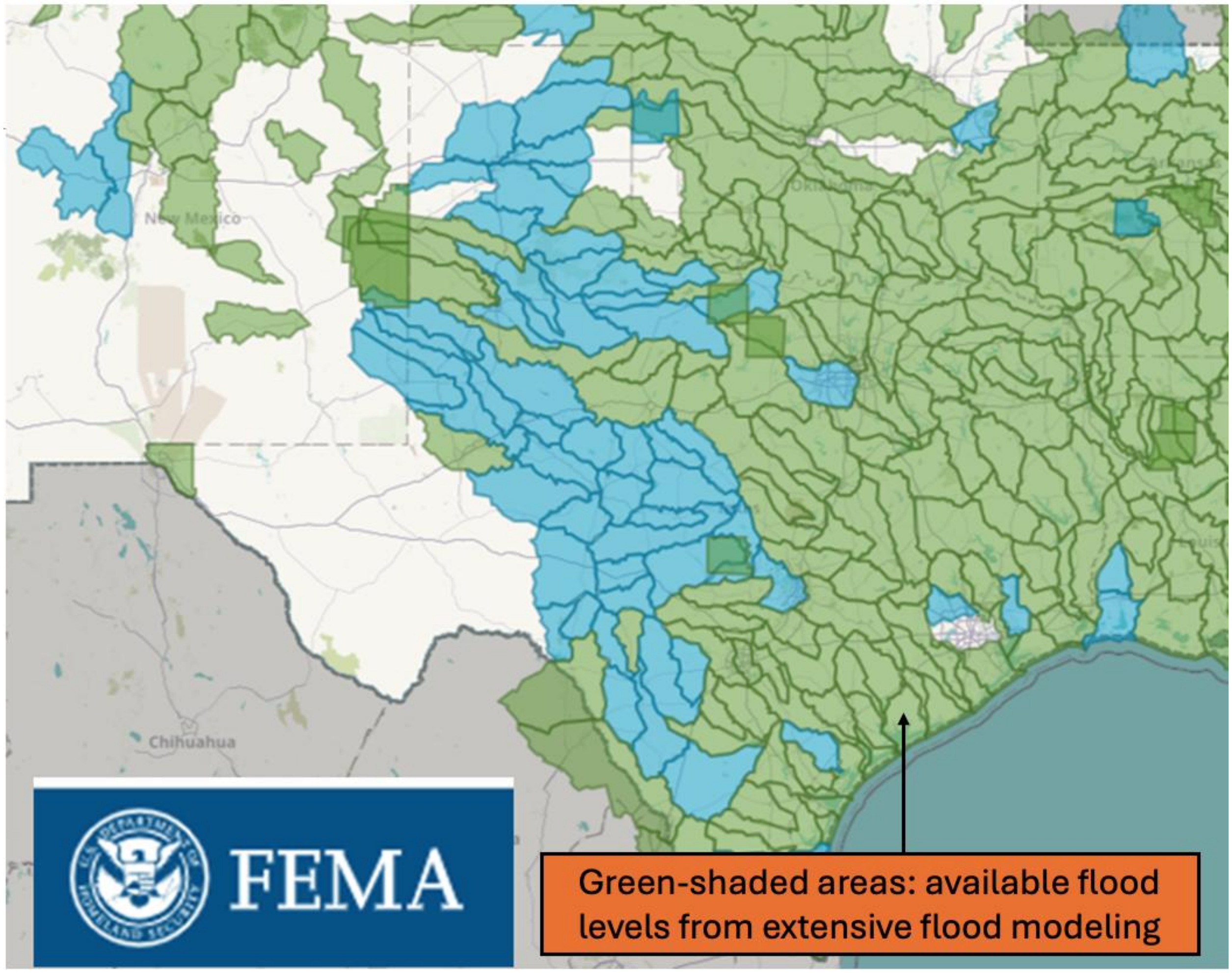

Figure 23. FEMA Flood Level Data (Federal Emergency Management Agency 2025).

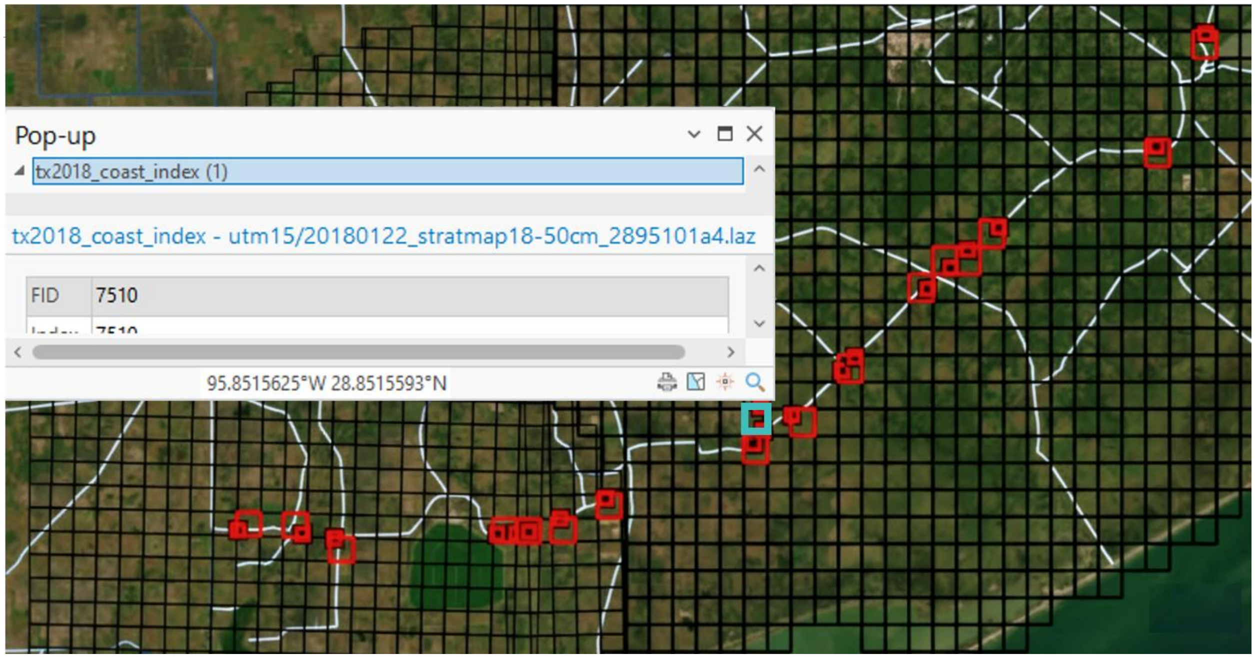

Figure 24. LIDAR Tiles for the FM521 Case Study (National Oceanic and Atmospheric Administration 2025b).

Geoprocessed Spatial Data

All spatial data were combined using Esri's ArcGIS Pro. Figure 25 shows the bridge deck elevation for a specific LIDAR tile after geoprocessing , determined by cross-referencing the LIDAR and structure inventory data. This process was automated in ArcGIS Pro for each of the structures in the FM521 case study, and the elevations were standardized in meters above a common datum. The lower-right box in Figure 25 shows the LIDAR elevation data for the structure before geoprocessing. The upper-left box shows the bridge ID from TxDOT's inventory data correctly matched to the respective LIDAR tile after geoprocessing.

Similarly, Figure 26 shows the flood elevation for a specific LIDAR tile after geoprocessing using the available FEMA flood data. FEMA flood elevations, provided in feet, were converted to meters for compatibility with the LIDAR data. In addition, several consistency checks between the different sources of elevation data were performed to confirm datum references and other aspects of spatial data reliability. Figure 26 also depicts an important calculation derived from data processing. The variable, DeltaElev1, reflects the difference between the top level of the deck for a specific structure and the 100-year flood event. For this specific structure, the difference was 0.9 meters. If the average height distance from the deck to the bottom of the girders is around 2 meters, this specific structure would be vulnerable to the 100-year flood and would need to be raised and consequently extended to improve its resiliency. The same geoprocessing procedure was applied to all 21 structures in the FM521 case study using the 500-year flood events in the FEMA GeoTIFF files that included flood level data.

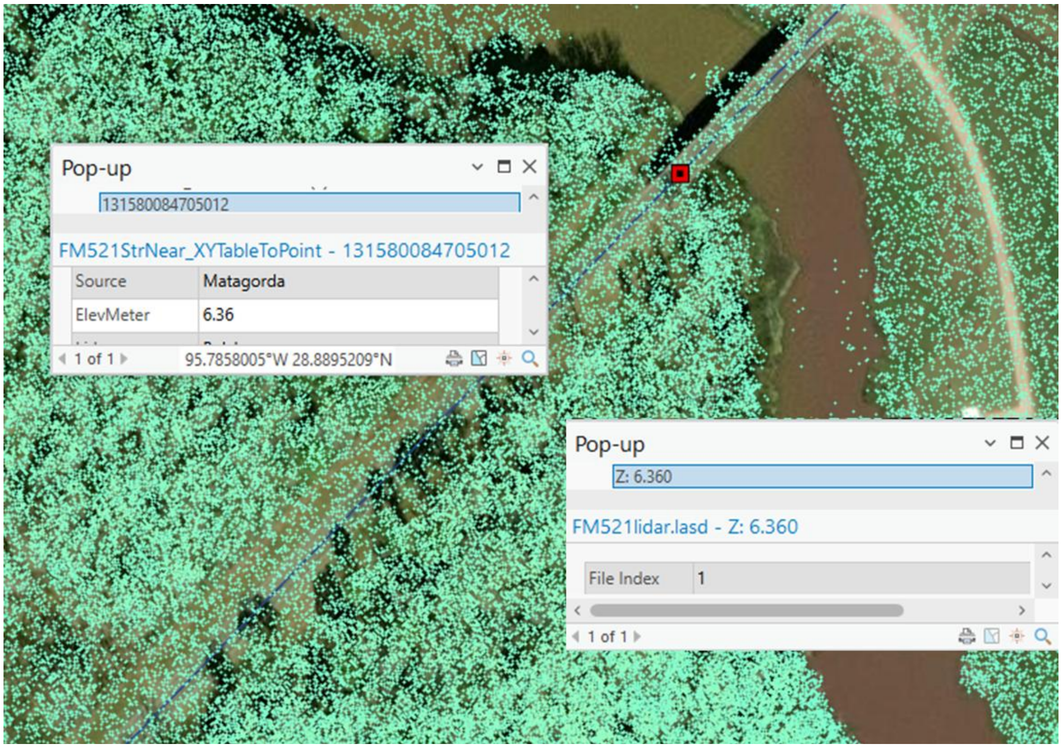

Figure 25. Bridge Deck Elevation for a Specific LIDAR Tile after Geoprocessing.

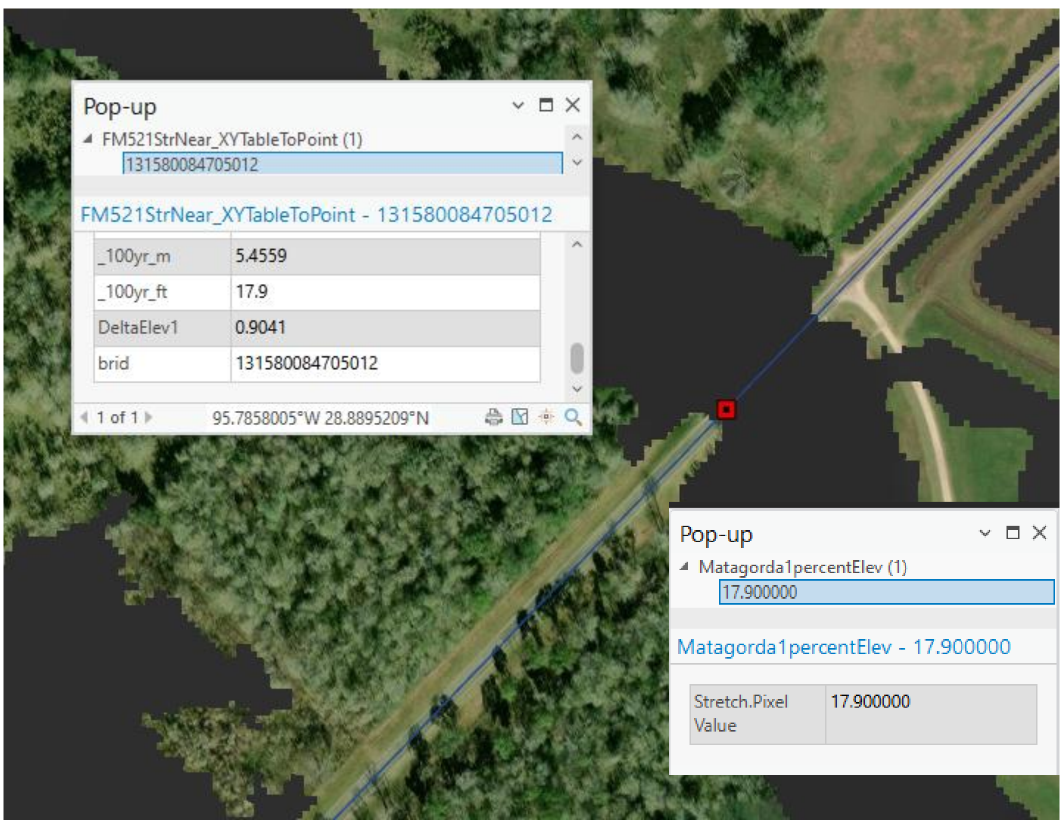

Figure 26. Flood Elevation (100-Year Flood) for a Specific LIDAR Tile after Geoprocessing.

Project-Level Case Study Resiliency Investment Results

The difference in elevations between the structure deck and the flood level is important for supporting decisions to improve the resiliency of structures. Figure 27 illustrates the conceptual approach for cost calculation, using the structure depicted in Figure 25 (bridge ID 131580084705012) as an example. These calculations were developed for every structure in the FM521 case study.

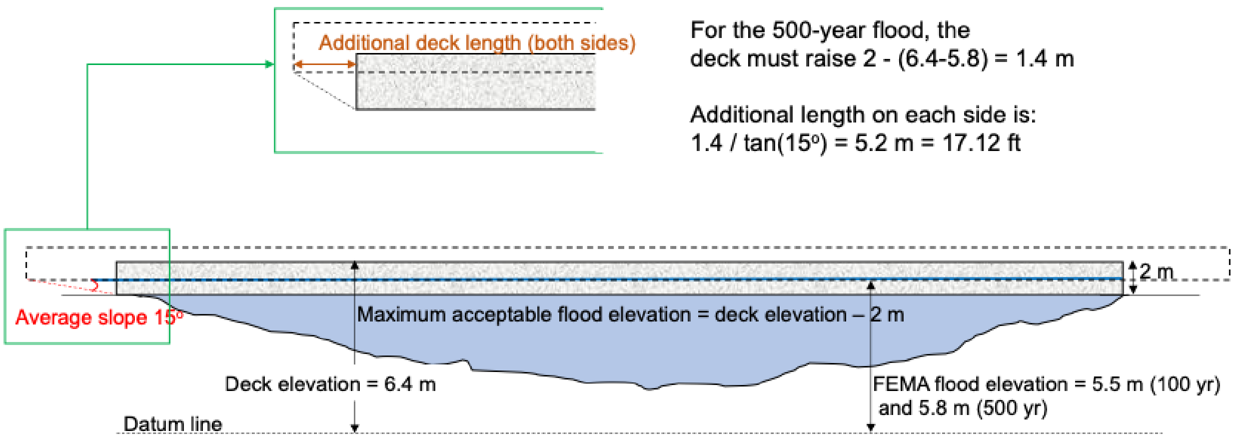

Figure 27. Conceptual Additional Deck Length Calculations for Flood Resilience.

Because this information is not found in any available bridge database, the following assumptions were necessary to calculate the additional deck length for flood resilience:

- The average/typical slope angle of the channel is 15º.
- The average/typical distance between the deck top and the bottom of the girders is 2 meters.

For bridge ID 131580084705012 on FM521, both the 100-year and the 500-year flood events reached above the bottom of the girders (the differences between the top of the deck elevation and the flood event elevations were 0.9 meters and 0.6 meters for the 100-year and 500-year flood events, respectively). Unacceptable from a resiliency standpoint, this specific structure would have to be raised, consequently increasing its length.

The total length of the new raised structure necessary to improve resiliency can be calculated as follows:

$$NewDeckLength = OldDeckLength + 2 \times [2 - (DeckElev - FloodElev)/\tan(15^{\circ})] \qquad (3)$$

where:

- DeckElev - FloodElev ≤ 2 meters; if DeckElev - FloodElev > 2 meters, no improvement is needed (see Figure 27).

- DeckElev is the deck elevation in meters, obtained from the LIDAR data.
- FloodElev is the flood elevation in meters, obtained from the FEMA data.
- DeckElev - FloodElev = Delta for a flood return.

This calculation was performed for all 21 bridges in the FM521 case study for which flood modeling was available. Resilience improvement was necessary only when the difference between the deck elevation and the flood elevation was ≤ 2 meters—the assumed typical distance between the deck top and the girders' bottom.

Table 7 depicts the results from the FM521 case study. The structures highlighted in yellow could potentially be completely overtopped because the difference in deck levels and flood levels were negative values. The results included the costs for reconstruction of the structures considering the expansion factor summarized by Equation 3. Reconstruction costs summarized in Table 7 were estimated using a cost per square foot of deck of $150 and $200 for culverts and bridges, respectively. The total cost to improve resiliency of the FM521 structures for 100- and 500-year floods was estimated to be $40.1 and $41.6 million, respectively. These costs are referred to in the infrastructure resiliency literature as *adaptation costs*.

Table 7. Cost Summaries for the FM521 Case Study.

Bridge ID	Struct. Length(ft)	DECK WIDTH (ft)	Culvert	500yr meters	Deck Elev meters	100yr meters	Delta100 meters	Delta500 meters	Deck Area sqft	Resiliency Cost 100	Resiliency Cost 500
120200084703011	91	46	N	8.0	8.0	8.0	0.00	0.00	4,186	965,778	965,778
120200084706015	243	31	N	10.0	11.2	9.5	1.70	1.20	7,533	1,164,105	1,221,030
120200100401006	881	46	N	6.5	11.7	6.0	5.70	5.20	40,526		
120800011103024	31	45	Y	19.1	18.8	18.9	-0.10	-0.30	1,395	741,745	785,816
120800011103025	50	42	N	20.5	21.6	20.5	1.10	1.10	2,100	453,824	453,824
120800011103026	38	45	Y	21.0	21.3	20.7	0.60	0.30	1,710	650,497	716,603
120800011103027	80	42	N	18.6	19.4	18.5	0.90	0.80	3,360	673,673	689,098
120800011103028	80	42	N	17.0	18.9	16.8	2.10	1.90	3,360		519,425
120800011103069	52	43	N	19.3	19.6	18.9	0.70	0.30	2,236	540,697	603,866
120800011103076	33	48	Y	19.1	18.8	18.6	0.20	-0.30	1,584	739,881	857,404
131580084603004	334	28	N	4.9	4.5	4.2	0.30	-0.40	9,352	1,577,615	1,649,598
131580084603010	23	46	Y	5.9	6.1	5.6	0.50	0.20	1,058	549,478	617,053
131580084603013	121	31	N	5.4	4.3	4.8	-0.50	-1.10	3,751	847,275	915,585
131580084603014	2,360	46	N	7.0	8.4	7.0	1.40	1.40	108,560	16,385,363	16,385,363
131580084603015	80	56	N	6.2	7.6	6.1	1.50	1.40	4,480	774,832	795,399
131580084603016	170	56	N	6.4	7.3	6.3	1.00	0.90	9,520	1,633,665	1,654,231
131580084603017	490	56	N	7.2	7.7	7.2	0.50	0.50	27,440	4,424,497	4,424,497
131580084603018	80	56	N	8.1	9.2	7.9	1.30	1.10	4,480	815,965	857,098
131580084701014	121	31	N	6.2	6.6	5.9	0.70	0.40	3,751	710,655	744,810
131580084701016	152	31	N	7.4	8.3	7.3	1.00	0.90	4,712	820,650	832,035
131580084701022	115	47	N	7.0	7.9	6.9	1.00	0.90	5,405	983,361	1,000,622
131580084705008	27	33	Y	4.1	4.4	3.9	0.50	0.30	891	420,590	452,909
131580084705009	27	41	Y	3.9	3.6	3.6	0.00	-0.30	1,107	622,936	683,166
131580084705010	27	30	Y	5.7	5.9	5.4	0.50	0.20	810	382,355	426,426
131580084705012	210	28	N	5.8	6.4	5.5	0.90	0.60	5,880	995,116	1,025,965
131580084705013	90	28	N	6.3	6.9	6.2	0.70	0.60	2,520	511,682	521,965
131580084705019	214	42	N	5.0	3.8	4.4	-0.60	-1.20	8,988	1,749,246	1,841,795
									Total	40,135,481	41,641,362

BRR FOR NETWORK-LEVEL RANKING

The previously discussed project-level, detailed flood modeling method using LIDAR and FEMA data to compare structure deck elevations to flood levels is accurate. However, this method could not be implemented statewide for every bridge and culvert because it would require a significant statewide data collection and processing effort that was beyond this project's schedule and resources. Moreover, implementing this method at TxDOT would require the same data collection and processing effort, rendering this method impractical.

Thus, the research team developed a simpler BRR that can easily be scaled for statewide assessment. This rating is based on statistics retrieved from TxDOT's structure inventory and uses scaling factors based on theoretical concepts from decision theory, such as utility curves.

Analysis Dataset

TxDOT's structures inventory and inspection database contains several variables that are conducive to measuring structure resiliency and strategic importance. All data are described in TxDOT's *Coding Guide* (Texas Department of Transportation 2020), and inspection data are reported annually for inclusion in the NBI. The following NBI data were deemed useful for developing a BRR for network-level ranking of candidate projects:

- Item 19: Bypass detour length.
- Item 29: ADT.
- Item 61: Channel and channel protection.
- Item 71: Waterway adequacy.
- Item 113: Scour critical bridges (coded separately as Item 113c for culverts and Item 113b for bridges).

The analysis dataset used in this study was a subset of TxDOT's latest structure inventory and inspection database. It comprises 26,272 on-system structures over waterways, as well as appraisal ratings for Items 61, 71, and 113. Item 113: Scour critical bridges was recently revised to address the differences in ratings for bridges and culverts. Item 19: Bypass detour length and Item 29: ADT were also included to capture the strategic importance of the structure.

ATTRIBUTE UTILITIES

The conceptual basis underlying the BRR is decision theory—a well-known methodology often used to rank alternatives. Decision theory requires developing a common, consistent scale to measure decision attributes, which are later combined into a ranking index (the BRR in this case). In decision theory, the scale values are termed *utility values* and measured, in nearly all cases, using a scale from 0 to 100, where utility = 100 is the highest priority. For the BRR, a higher utility value reflects a higher priority for resilience improvements.

The cumulative distribution of an attribute has the same shape and scale as a typical utility curve. Therefore, cumulative percentiles have been successfully used to measure attributes' utilities in a variety of applications, including bridge management and rail crossing management. Figure 28 shows the cumulative ADT (Item 29) distribution of 26,272 structures in the current analysis dataset. The ADT values were rounded to the next 100. Higher traffic levels reflect a structure's strategic importance and result in higher associated utilities and higher improvement priorities. For example, a structure with an ADT of 5,000 vehicles per day would be assigned a utility of 60.4, meaning that—based solely on ADT—this structure's priority is higher than 60.4 percent of the other structures in the analysis dataset. Analogous reasoning is applicable to detour length (Item 19) (see Figure 29).

Items 61, 71, 113c, and 113b were stored as ratings ranging from 0 (structure must be closed) to 9 (new condition). Higher ratings reflect higher condition levels and lower improvement priorities for resilience. Cumulative percentiles increase as variable values increase, representing the inverse of utilities. Therefore, utilities are calculated as 100 - cumulative percentiles. Figure 30 helps visualize this concept using channel and channel protection (Item 61). In this figure, the attribute's cumulative distribution is superimposed on the utility curve. As the rating increases, its cumulative percentile increases, but its utility decreases. This behavior is consistent with the concept of utility—as structure condition decreases, its improvement priority increases. Table 8 summarizes the utility values—derived from the current inventory and inspection data—for Items 61, 71, 113c, and 113b.

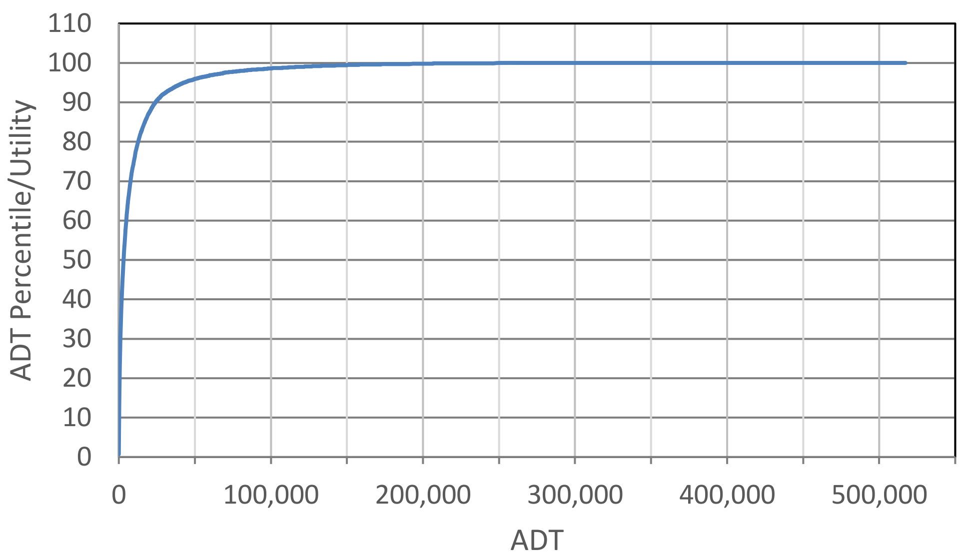

Figure 28. ADT (Item 29) Utility Values.

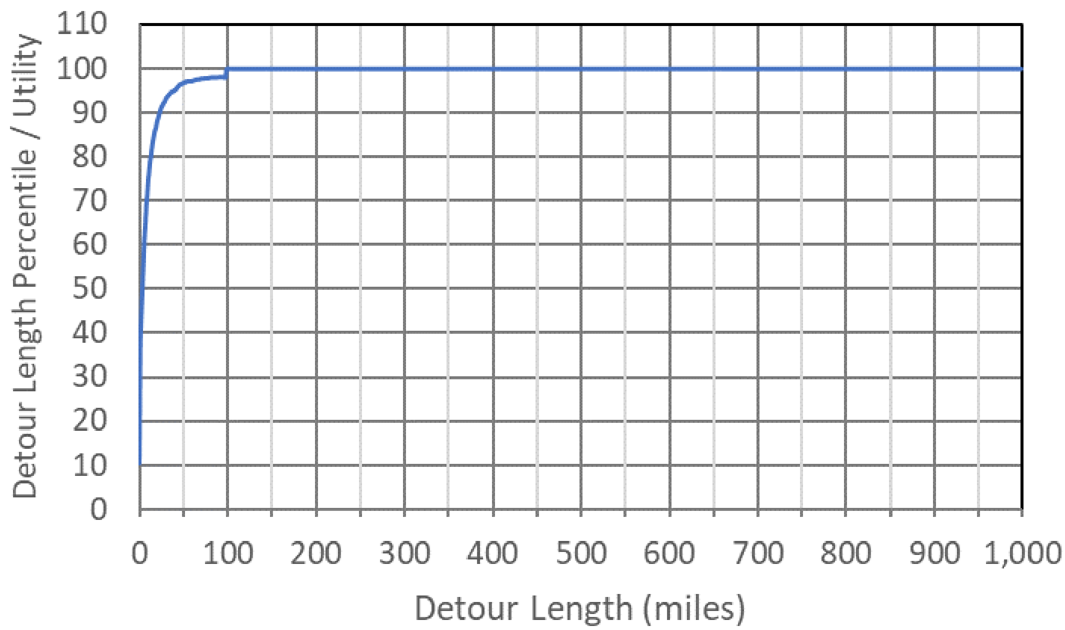

Figure 29. Bypass Detour Length (Item 19) Utility Values.

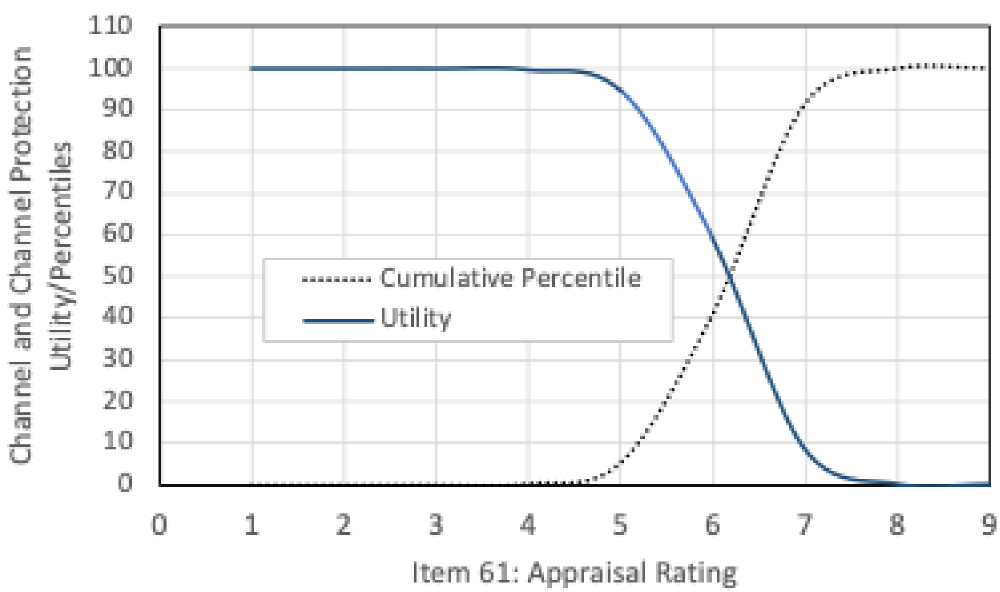

Figure 30. Channel and Channel Protection (Item 61) Utility/Percentile Values.

Table 8. Utility Values for Items 61, 71, 113b, and 113c.

Rating	Utility Values			
	Item 61: Channel and Channel Protection	**Item 71: Waterway Adequacy**	**Item 113b: Scour Critical Bridges**	**Item 113c: Scour Critical Culverts**
0	100.0	100.0	100.0	100.0
1	100.0	100.0	100.0	100.0
2	100.0	99.9	99.9	100.0
3	100.0	98.9	98.2	99.9
4	99.7	98.1	97.2	95.2
5	94.7	97.9	85.2	95.1
6	59.1	41.7	67.8	79.5
7	8.6	28.9	65.1	76.5
8	0.1	25.6	0.2	0.1
9	0.0	0	0	0

The utility values of each attribute are dynamic, reflecting the current condition of each structure over waterways in the network. As new inspection data become available, the utility values of these attributes should be updated, preferably via computer software that reads the data and recalculates the utilities and BRR on an annual basis.

Similar to the previous ADT example in which an ADT value of 5,000 vehicles per day (rounded to the next 100) was assigned a utility/percentile value of 60.4, Table 8 indicates that a structure with a waterway adequacy (Item 71) rating of 4 would be assigned a utility/percentile values of 98.1. These utility/percentile figures were derived internally using SAS coding execution and stored as tables allowing for the significant numbers after the decimal point to be included easily in the calculations.

BRR FORMULA AND RESULTS

After the utility values were determined, they were combined in a weighted formula to determine a BRR utility score, ranging from 0 to 100. The following generic BRR formulation includes weighting factors (*W*) that measure the importance of different attributes to the decision-maker and must sum to one:

$$BRR = W_{61} \times U_{61} + W_{71} \times U_{71} + W_{113} \times U_{113} + W_{Detour} \times U_{Detour} + W_{ADT} \times U_{ADT} \quad (4)$$

where:

- W_{61} is the weight assigned to Item 61: Channel and channel protection.
- W_{71} is the weight assigned to Item 71: Waterway adequacy.
- W_{113} is the weight assigned to Item 113: Scour critical bridges or scour critical culverts, depending on structure type.
- W_{Detour} is the weight assigned to Item 19: Bypass detour length.
- W_{ADT} is the weight assigned to Item 29: ADT.
- U is the attribute utility; the subscript reflects the item number in the inventory database.

Each of the 26,272 on-system bridges and culverts in the current dataset was assigned its own BRR, calculated from the utility values for each of its attributes using Equation 4. The research team sorted all bridge IDs in the dataset by BRR, which ranked them in terms of improvement priorities. Table 9 shows the attribute values, utilities, and calculated BRRs for the top 15 improvement priorities, ranked according to the BRR. The weights used in these calculations were as follows:

- $W_{ADT} = 0.05$.
- $W_{Detour} = 0.20$.
- $W_{61} = 0.25$.
- $W_{71} = 0.25$.
- $W_{113} = 0.25$.

These weights can be changed to reflect the relative importance of each attribute for the decision-maker at TxDOT.

Table 9. BRR Results for Top 15 Priority Bridge Structures Using Calculation Weights of W_{ADT} = 0.05, W_{Detour} = 0.20, W_{61} = 0.25, W_{71} = 0.25, and W_{113} = 0.25.

Bridge ID	ADT		Item 61		Item 71		Item 113b		Item 113c		BRR
	Value	Utility	Value	Utility	Value	Utility	Value	Utility	Value	Utility	
132410042010010	400	16.7	5	94.7	3	98.9	4	97.2			91.7
171450067503131	200	9.8	5	94.7	4	98.1			4	95.2	89.7
032440012404012	800	25.8	5	94.7	5	97.9	5	85.2			89.3
071930083002001	100	6	5	94.7	3	98.9	5	85.2			89
010750017404044	300	13.5	5	94.7	5	97.9	5	85.2			88.6
150950244202001	800	25.8	5	94.7	4	98.1	3	98.2			87.8
011130146603002	300	13.5	4	99.7	3	98.9	5	85.2			87.6
171450067504120	400	16.7	5	94.7	4	98.1			4	95.2	87.1
222540087805007	200	9.8	5	94.7	3	98.9	3	98.2			86.5
151630059503005	200	9.8	5	94.7	5	97.9			6	79.5	85.8
022130025903047	17,800	85.6	6	59.1	4	98.1	3	98.2			85.8
150150225501001	1600	37.3	4	99.7	3	98.9	3	98.2			85.6
022200109802003	6,600	66.6	5	94.7	4	98.1			7	76.5	83.1
021820073601016	400	16.7	6	59.1	3	98.9	3	98.2			82.6
112020006406059	5,000	60.4	4	99.7	6	41.7	2	99.9			82.0

The top priority (highest BRR) structure in the dataset was bridge ID 132410042010010 with a BRR score of 91.7, using the assigned weights provided previously. The weights are important inputs because they reflect TxDOT decision-makers' measure of the importance of a specific attribute used in the calculation of the BRR. In the example summarized in Table 9, the assigned weights clearly emphasize lower-traffic-volume structures because of the low 0.05 weighting factor for ADT (Item 29).

Blank cells under Item 113b and 113c in Table 9 suggest missing data in the inventory database (e.g., missing deck widths or missing structure lengths that prevent calculation of deck area). Similarly to the project-level approach discussed in previous paragraphs, the deck area could be converted to adaptation costs using a cost per square foot of deck to estimate structure improvements.

Table 10 summarizes replacement costs without expansion for the top-ranked structures based on deck area. Table 11 lists the URL links for the top-ranked structure locations in Google Maps.

Table 10. Improvement Cost Estimates for the Top 15 Priority Bridge Structures.

Bridge ID	BRR	Deck Area (SF)	Improvement Cost	
			Bridges	Culverts
132410042010010	91.7	2,247.7	$449,540	
171450067503131	89.7	N/A		
032440012404012	89.3	2,639.1	$527,820	
071930083002001	89.0	20,650	$4,130,000	
010750017404044	88.6	10,880	$2,176,000	
150950244202001	87.8	3,250	$ 650,000	
011130146603002	87.6	7,224	$1,444,800	
171450067504120	87.1	986		$147,900
222540087805007	86.5	2,898	$579,600	
151630059503005	85.8	666		$99,900
022130025903047	85.8	11,100	$2,220,000	
150150225501001	85.6	2,930	$586,000	
022200109802003	83.1	1,997.6		$299,640
021820073601016	82.6	1,145.5	$229,100	
112020006406059	82.0	13,877.4	$2,775,480	

Table 11. Top 15 Priority Bridge Structure Locations.

Bridge ID	BRR	Google Maps Link
132410042010010	91.7	https://maps.google.com/?q=29.22774810,-96.60679520
171450067503131	89.7	https://maps.google.com/?q=31.31070870,-96.00325980
032440012404012	89.3	https://maps.google.com/?q=34.01475290,-99.24276190
071930083002001	89.0	https://maps.google.com/?q=29.81046990,-100.01735920
010750017404044	88.6	https://maps.google.com/?q=33.82361170,-95.86103330
150950244202001	87.8	https://maps.google.com/?q=29.45322990,-98.12453360
011130146603002	87.6	https://maps.google.com/?q=33.24998320,-95.79089340
171450067504120	87.1	https://maps.google.com/?q=31.18919190,-95.99281320
222540087805007	86.5	https://maps.google.com/?q=28.69451680,-99.79985600
151630059503005	85.8	https://maps.google.com/?q=29.26407530,-99.26886600
022130025903047	85.8	https://maps.google.com/?q=32.24456460,-97.74360480
150150225501001	85.6	https://maps.google.com/?q=29.23883070,-98.45283340
022200109802003	83.1	https://maps.google.com/?q=32.97724750,-97.43247970
021820073601016	82.6	https://maps.google.com/?q=32.76902020,-98.29549010
112020006406059	82.0	https://maps.google.com/?q=31.16674000,-93.97168780

SUMMARY AND IMPLEMENTATION RECOMMENDATIONS

Key findings and recommendations regarding flooding risk assessment for bridges and the development of a BRR for network-level ranking include the following:

- The results of the project-level flood resiliency analysis reported in this section highlight the importance of including each structure's deck elevation as a TxDOT data collection item for bridges over waterways. Availability of these data would expedite corridor level evaluations and eliminate the need for external LIDAR data analysis, which is labor intensive.
- The road alignment inventory could also benefit significantly with the addition of road surface elevations for the purpose of flood resiliency analysis. The research team recommends adding georeferenced coordinates with elevations for every 10 meters of road alignment length, for example.
- Available flood level information for structures and road alignments with different return periods should also be retrieved from FEMA and incorporated/spatially referenced to TxDOT's structure and road inventory.

Each of these recommendations would improve road infrastructure resiliency tremendously and allow for more accurate road infrastructure investment planning, as required by the TAMP, which is maintained and updated by TxDOT.

5. ADAPTATION STRATEGIES

According to FHWA, *adaptation* is defined as "the adjustment in natural or human systems in anticipation or response to a changing environment in a way that effectively uses beneficial opportunities or reduces negative effects" (Federal Highway Administration 2017). Furthermore, FHWA defines *adaptation capacity* as "the ability of a transportation asset or system to adjust, repair, or flexibly respond to damage caused by climate variability or extreme weather" (Federal Highway Administration 2017). A plethora of adaptation strategies exist in practice for transportation assets, such as pavements and bridges. These adaptation strategies involve various phases of an asset's life cycle, covering planning, design, construction, maintenance, rehabilitation, monitoring, and operation. In this section, a list of adaptation strategies is presented and discussed, corresponding to each individual life cycle phase (see Figure 31). Next, a decision-making framework is proposed regarding whether the relevant adaptation strategies should be implemented. Finally, a case study is presented in the life-cycle context.

Figure 31. Adaptive Strategy Flow in the Infrastructure Life Cycle.

Planning strategies for resilient transportation infrastructure start with dedicated funding to support investments in strengthening infrastructure and ensuring certain redundancy such as alternative roads. Specifically, these planning strategies can include the following six *R*s:

- **Resilience funding:** The IIJA has dedicated funding to ensure surface transportation resilience to natural hazards through its Promoting Resilience Operations for Transformative, Efficient, and Cost-saving Transportation (PROTECT) grant program. The hazards mainly include climate change, sea level rise, flooding, extreme weather events, and other natural disasters. According to TxDOT's Transportation Planning and Programming Division, $729 million was allocated to Texas for FY 2022–2026, with an average of $145 million per year (Texas Department of Transportation 2023). The recent Unified Transportation Program indicated that TxDOT received federal transportation funding through multiple apportionment programs, including PROTECT, which is to be used in 11 out of the 12 program categories (Texas Department of Transportation 2024a). TxDOT's Transportation Planning and Programming Division leads the effort to allocate the PROTECT funds and recommends project selection criteria.
- **Redundancy**: Roadway redundancy means that multiple alternative routes exist between two points in a transportation network to address roadway closures due to natural or manmade incidents. It is important to consider redundancy for critical routes based on their societal and economic consequences. For example, if a high-impact route

connecting an origin and destination is vulnerable to flooding, a redundant or alternative route should be evaluated and planned in transportation planning. This process can include adding new roads/bridges or increasing the capacity of existing roads/bridges.

- **Relocation:** Roadway relocation refers to the process of changing the alignment or route of an existing highway. In the context of resilience improvement, relocation should be evaluated to avoid flood-prone areas, landslides, or areas vulnerable to other natural disasters. An area where a highway passes through can be more prone to natural disasters due to more frequent extreme weather conditions in recent years.
- **Retrofit:** Infrastructure retrofit refers to the process of modifying or upgrading existing structures such as bridges and pavements. In the planning phase, funding should be allocated to vulnerable structures to meet the challenges of varying climatic stressors.
- **Replacement/reconstruction:** Infrastructure replacement means removing and rebuilding an existing asset. In the context of resilience, planning for replacement should be prioritized for pavements or bridges reaching the end of their service life or at a high climatic risk. For example, resilience-improvement pavement reconstruction projects can be included in the four-year pavement management plan.
- **Raise elevation:** Replacement/reconstruction can include raising the elevation of existing or planned structures, such as a highway roadbed or bridge superstructure. Raising elevations serves to mitigate or avoid the detrimental impact of natural stressors such as floods or sea level rise. For example, TxDOT recently initiated a $407 million project to raise a portion of IH10 along White Oak Bayou above the 100-year flood plain (Texas Department of Transportation 2025).

ADAPTIVE DESIGN

Traditionally, transportation infrastructure design has included climatic and environmental factors such as temperature, precipitation, and moisture. For example, the *AASHTO Guide for Design of Pavement Structures* (American Association of State Highway and Transportation Officials 1993) uses drainage coefficients in the calculation of structure numbers to reflect moisture impacts. The updated ME pavement design approach—reflected in either the AASHTOWare Pavement ME Design software at the national level or the TxCRCP-ME software at the state level—incorporates climatic information through enhanced integrated climatic models. However, resilience was not sufficiently and explicitly emphasized in the existing design process. With more frequent occurrences of extreme weather conditions in Texas recently, it is essential to enhance the design process to improve transportation infrastructure resilience. The design-related adaptation strategies involve the following design inputs, processes, and methods:

- **Hydraulic:** TxDOT published and periodically updates its *Hydraulic Design Manual* (Thomason 2019), which provides procedures for analyzing and designing effective highway drainage facilities. This manual includes the following key aspects related to adaptation strategies for hydrology, bridges, and pavements:

- **Hydrology:** Estimates of flood magnitude due to precipitation are used to estimate the (maximum) flow rate for the drainage design of a facility of interest. The estimation method includes the following steps:

  - Adjust the design storm criterion or AEP. In the hydrology analysis process, a critical input is the AEP, expressed as a percentage. For a critical facility, recent observed weather data should be used to check the reasonableness of the design AEP. Specifically, the binomial distribution can be used to check if the design AEP is too low or too high (Texas Department of Transportation 2019b).

    $$P = \frac{n!}{y!(n-y)!} p^y (1-p)^{n-y} \tag{5}$$

    where:

    - P is the probability of y exceedances in n years for design level p.
    - y is the number of design exceedances.
    - n is the number of years.
    - p is the design AEP.

    If the design AEP is too high, reflecting more frequent extreme weather situations, a lower AEP must be used. For example, in a 30-year observation period, if a 10 percent design AEP flow was exceeded in three years, the probability of this event is 23.6 percent. This outcome means the 10 percent design AEP is too high, and a lower percentage is thus recommended. The research team also recommends proactively using an updated climatic prediction model for flooding so that the extreme weather trend is better reflected when adjusting the AEP.

  - Update the rainfall intensity-duration-frequency coefficients (*e*, *b*, *d*) in the following rainfall intensity formula:

    $$I = \frac{b}{(t_c + d)^e} \tag{6}$$

    where:

    - t_c is the time of concentration (in minutes).
    - *e*, *b*, and *d* are coefficients based on rainfall intensity-duration-frequency data from the National Oceanic and Atmospheric Administration's (2025a) Atlas 14 via its Precipitation Frequency Data Server.

When the rational model is used to estimate the maximum or peak rate of runoff, the average rainfall intensity, I, should be carefully examined to better reflect the flood flow from extreme weather events. Currently, TxDOT uses the EBDLKUP-2019 model (Texas Department of Transportation 2019b) to calculate I.

The updated e, b, d coefficients can be used to better reflect recent observations of climate conditions. In addition, an adjusted AEP can be used to better accommodate drainage resilience design. For example, changing from a 10 to 4 percent AEP will change the rainfall intensity from 7.13 to 8.68 inches/hour—a 22 percent increase. This change will in turn result in a 22 percent increase in the maximum rate of runoff (Q) in the hydraulic drainage design. Consequently, the facility designed under the adjusted Q will be more resilient to flood impacts.

- **Bridges:** Bridges overpassing a waterway can be affected by water flow or flood. Per TxDOT's *Hydraulic Design Manual* (Thomason 2019), adaptive strategies to adjust or respond to the relevant stressor include the following:
  - Measures to minimize scour or erosion include the following:
    - Reducing the number of piers by increasing span lengths.
    - Using bullet-nosed or circular-shaped piers.
    - Using drilled shaft foundations.
    - Using deeper foundations.
    - Aligning bends with flood flow to the degree practicable.
    - Increasing bridge length to reduce through-bridge velocities.
    - Using stone protection for embankment.
    - Using stable vegetation on embankment.
    - Using riprap.
    - Using dikes or timbers to impede flow along the embankment.
    - Using riprap header slopes and deep toe walls to protect the abutment.
    - Using vertical abutment walls.
    - Using guide banks.
  - Measures to minimize hydraulic forces and debris impact on the superstructure include the following:
    - Making the superstructure as shallow as possible.
    - Providing a roadway approach profile that will be overtopped prior to the submergence of the bridge superstructure.
    - Using longer spans and high freeboards where large volumes of debris are likely to occur.
- **Pavements:** Pavement materials, particularly unbound materials such as base/subbase and subgrade are susceptible to moisture damage. Sufficient drainage is warranted to ensure the pavement structure is adaptive to the moisture impact, which includes:

  - Longitudinal gutter slopes.
  - Sufficient transverse (cross) slopes.
  - Pavement underdrains (see Item 556 in TxDOT's *2024 Standard Specification*s [Texas Department of Transportation 2024b])

- **Structure:** Both bridge and pavement structures are designed to sustain external loading involving traffic and environmental loads. The adaptive strategies related to structure design are considered separately for bridges and pavements as follows:

  - **Bridges:** Adaptive strategies related to bridge design include the following (Texas Department of Transportation 2024b):

    - Adjusting design criteria to accommodate extreme event limit states.
    - Providing system redundancy.
    - Protecting bridges from vehicle and vessel collision.
    - Including lateral restraint of superstructures on substructure.

  - **Pavements:** Adaptive strategies related to pavement design include the following:

    - Adjusting pavement design using enhanced models in ME pavement design to accommodate future extreme weather impacts.
    - Updating design inputs using predicted temperature and moisture data from the climate models instead of historical weather data in the design.
    - Considering concrete pavement versus asphalt pavement. Continuously reinforced concrete pavement can be more resilient to moisture damage (Mack 2020).
    - Using thicker pavement structures. Thicker pavement provides higher load-bearing capacity, which is particularly beneficial when the pavement is under the impact of rescue or maintenance traffic after a flood event.
    - Using chemically stabilized bases or subgrades to increase their strength. The stabilized layers have proven to be much less vulnerable to moisture than unbound materials (Texas Department of Transportation 2021).
    - Using geosynthetics to reinforce pavement layer structure capacity.
    - Performing full-depth reclamation for pavement rehabilitation. Incorporating a foamed-asphalt or cement-treated base provides a more robust structure to sustain heavier traffic loading or environmental stress, such as moisture.
    - Using a higher rebar ratio for concrete pavement.

- **Materials:** In addition to structure design, the selection of high-performance materials in the material design process can contribute to the adaptive capacities of the transportation infrastructure. The adaptive strategies related to materials design are considered separately for bridges and pavements as follows:

- **Bridges:** Adaptive strategies related to bridge materials include the following:

  - Using ultrahigh-performance concrete.
  - Using self-healing concrete.
  - Using fiber-reinforced polymers.
  - Using high-strength steel.

- **Pavements:** Adaptive strategies related to pavement materials include the following:

  - Using an adjusted PG binder for asphalt pavement that better resists rutting due to predicted higher temperatures.
  - Using a modified asphalt to resist permanent deformation and/or cracking.
  - Using moisture-resistant materials such as antistripping agents.
  - Using self-healing asphalt.
  - Using high-performance concrete materials.

ADAPTIVE CONSTRUCTION

Major adaptive construction strategies that can be used to improve transportation infrastructure resilience include the following:

- Construction that is scheduled in the low-risk construction season avoids unfavorable construction conditions (e.g., flooding, rain, hurricanes, extreme low of high temperatures).
- Modular and prefabricated construction allows for faster assembly and completion of the construction work in a natural hazard or time-sensitive environment.
- Safety enhancements ensure a safe construction environment under the condition of extreme weather or high climatic variations.

ADAPTIVE MAINTENANCE, REHABILITATION, AND OPERATION

M&R plays a critical role in the life cycle of transportation assets. Timely M&R activities are based on frequent monitoring of asset condition. The proper operation of the assets before, during, and particularly after extreme weather events is closely associated with M&R activities. Adaptation strategies related to M&R and operation include the following:

- Performance monitoring reveals the performance impact related to environmental stressors (e.g., extreme temperature, flood, etc.). For example, long-term pavement rutting monitoring can reveal any impacts from increasing temperatures. Before-and-after flood pavement condition monitoring can facilitate understanding of moisture damage. Both can provide feedback to improve adaptive pavement design.

- Routine or preventive maintenance for pavements, such as crack seal, fog seal, or seal coat, is used to mitigate moisture infiltration into pavement (Texas Department of Transportation 2024b).
- Routine or preventive maintenance for bridge components, such as joints, bearings, decks, and drainage, as well as other measures including using the Texas Bridge Deck Protection System, using penetrating concrete surface treatments, washing bridge decks, repairing concrete spall repair, etc. have the potential to improve resilience (Texas Department of Transportation 2024b).
- Shoulder maintenance provides support to the main lanes.
- Slope/vegetation maintenance reduces erosion effects on the pavement structure.
- Roadside drainage appurtenances, such as ditches, gutters, side drains, outlets, etc., control normal runoff.
- Debris removal mitigates impacts on structures such as bridges.
- Clearing clogged culverts prevents localized flooding.
- Imposing a load zone on weak pavements or bridges immediately after hazardous events, such as floods, mitigates the impact of heavy traffic loads.

IMPLEMENTATION FRAMEWORK

Without doubt, the aforementioned adaptation strategies can be utilized to improve transportation infrastructure resilience. However, from an investment perspective, the implementation of these strategies bears costs. For example, a thicker pavement structure is more resilient than a weaker one but is more expensive to build. A balance should be reached practically from both economic and social impact perspectives in a life-cycle context. This subsection presents a framework for implementing the adaptation strategies in the individual life-cycle phases. The framework is composed of the following four steps (see Figure 32):

1. **Input:** Includes two types of variables—asset-related physical variables and climatic/environmental factors affecting infrastructure resilience.
2. **Assessment:** Serves to assess asset vulnerability under circumstances described by various factors.
3. **Adaptation strategies:** Supports decision-making on whether proactive or mitigation measures are necessary based on the assessment results.
4. **LCC analysis:** Used for evaluation and adjustment of the adaptation strategies if needed in a life-cycle context.

Figure 32. Multistep Implementation of Adaptation Strategies.

Figure 33 illustrates the implementation framework involving adaptive *planning* strategies. First, the input variables are prepared and include planning factors such as pavement/bridge inventories, traffic, historical conditions, and funding at the network level, and climatic/environmental stressors such as temperature, flood, and sea level rise. Second, an asset's criticality and vulnerability are assessed based on these variables. For vulnerability analysis, use of the U.S. DOT's Vulnerability Assessment Scoring Tool (U.S. Department of Transportation 2017) is highly recommended. This tool offers a macro-enabled spreadsheet that evaluates an asset's vulnerability according to three interrelated aspects including exposure to climate effects, sensitivity to climate effects, and adaptive capacity. In the third step, the assessment results in two possible outputs—critical/vulnerable or not critical/vulnerable. If an asset is not critical/vulnerable, no action is recommended. If an asset is critical/vulnerable, a series of adaptive planning strategies are evaluated based on LCC analysis. The analysis results determine whether the recommended adaptive strategy is economically or socially more viable than no action.

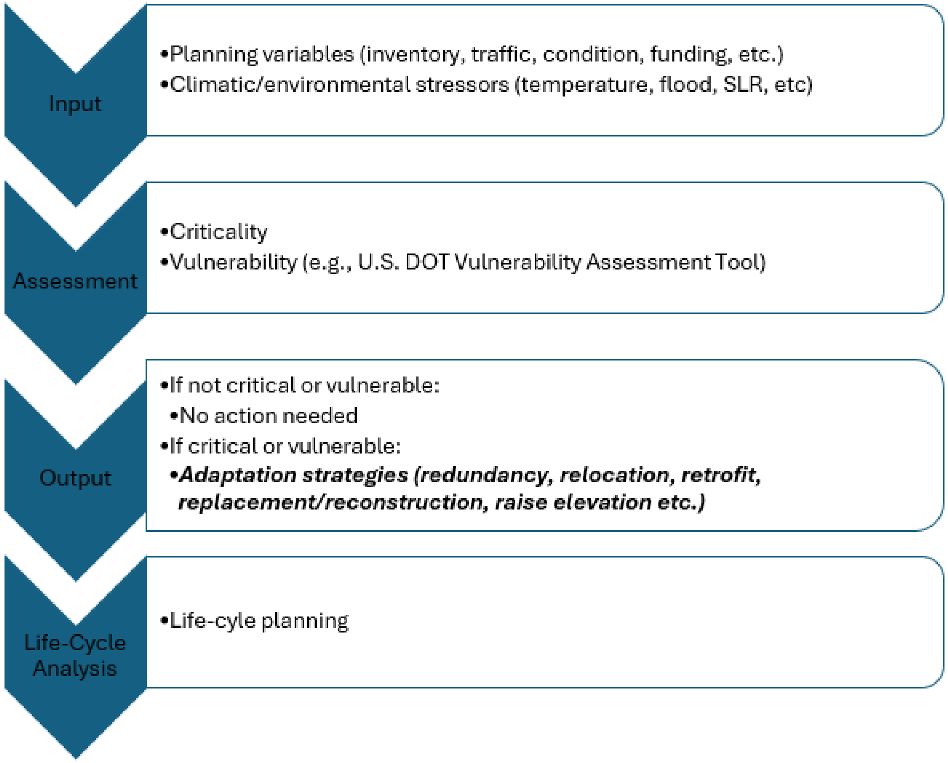

Figure 33. Implementation Framework for Adaptive Planning.

Similarly, Figure 34 illustrates the implementation framework involving adaptive *design* strategies. First, the input variables are prepared and include design factors such as traffic/loads, materials, structures, design lives, reliabilities, and safety factors and climatic/environmental stressors such as temperature, moisture, and flood. Second, the asset's distress and load-bearing capacity is predicted based on these variables. In the pavement example, the AASHTOWare Pavement ME Design software or the TxCRCP-ME software can be used to predict distresses such as cracking, rutting, punchouts, etc., as well as layer moduli, which represent the pavement's load-bearing capacity. These predictions are based on the climatic/environmental stressor inputs such as extreme weather or high levels of climate variations, which differ from pavement design under normal environmental conditions. In addition, the risk is evaluated based on selected reliability. Third, the predicted conditions are used to determine if the assets are sensitive to the climatic/environmental stressors. If the assets are not sensitive, no adaptive action is needed. If the assets are sensitive, a series of adaptive design strategies are evaluated based on LCC analysis. The analysis results determine whether the recommended adaptive strategy is economically or socially more viable than no action.

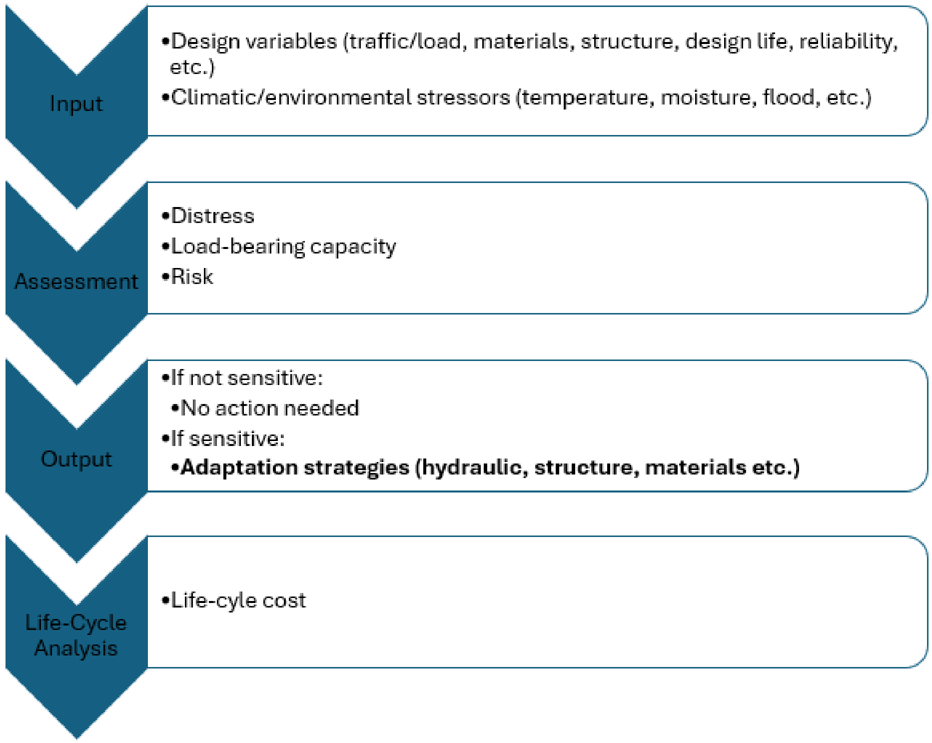

Figure 34. Implementation Framework for Adaptive Design.

Figure 35 illustrates the implementation framework involving adaptive *construction* strategies. First, the input variables are prepared and include construction variables such as scheduling and labor/material/equipment utilization and climatic/environmental stressors such as temperature, flood, and hurricane, tornado, wildfire, winter storm, etc. Second, the construction performance including constructability, compaction (e.g., subgrade or hot-mix asphalt density), curing (e.g., cement concrete curing time), etc. is assessed based on these variables. Risk is also evaluated based on likelihood and consequence information. Third, if the assessment shows a significant impact, a series of adaptation strategies are recommended related to scheduling, modular/prefabricated panel, and safety enhancements. Otherwise, no action is recommended. Lastly, the benefits and cost of these strategies are quantified in an LCC context.

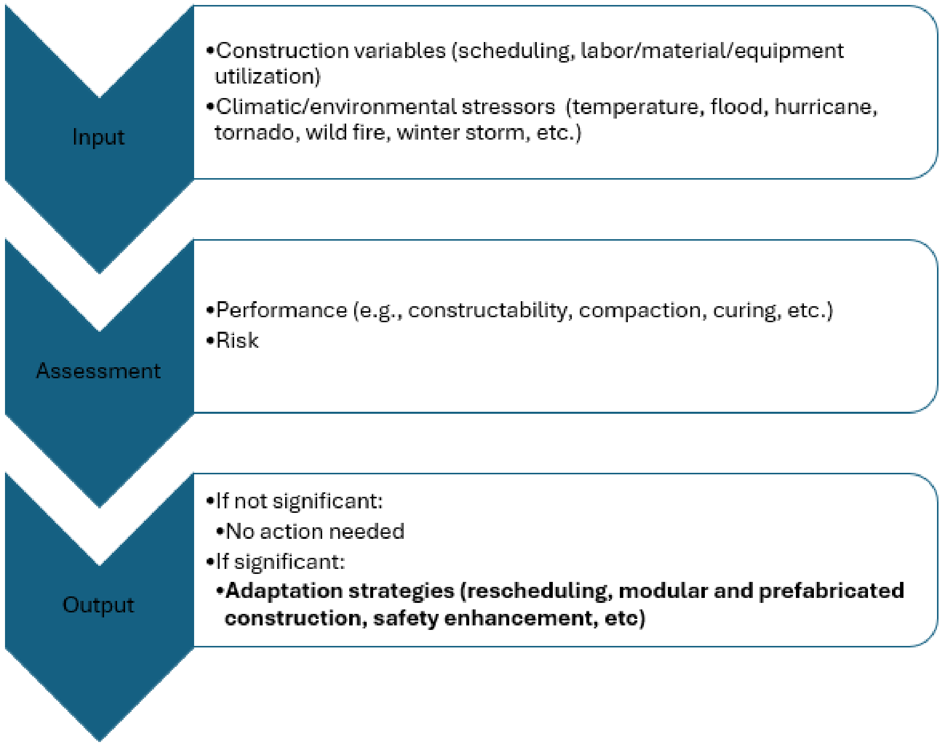

Figure 35. Implementation Framework for Adaptive Construction.

Finally, Figure 36 illustrates the implementation framework involving adaptive *maintenance, rehabilitation, and operation* strategies. First, the input variables are prepared and include monitoring variables such as bridge conditions from the Bridge Management System or PMIS and climatic/environmental stressors such as temperature, flood, hurricane, etc. Second, the asset's performance—including long-term performance due to climatic variation or short-term performance due to extreme weather events—is assessed based on these variables. In addition, M&R effectiveness is monitored and evaluated. Third, if the assessment shows the performance is insensitive to the climatic/environmental stressors, no action is recommended. Otherwise, a series of adaptation strategies are recommended, such as preventive maintenance, shoulder maintenance, slope maintenance, drainage maintenance, load zones for pavements or bridges, etc. Lastly, the benefits and cost of these strategies are quantified in an LCC context.

CASE STUDY

This subsection describes a case study that used quantitative LCC analysis to assess the effectiveness of upgrading pavement types to improve corridor resilience. The case study included a segment of FM521 in the coastal area of Matagorda County in TxDOT's Yoakum District (see Figure 37). This area is frequently subjected to extreme weather conditions such as hurricanes. Per the Hurricane Harvey Water Content GIS map (https://www.arcgis.com/apps/View/index.html?appid=8350c2f309bb49f8865a44cb972024c2), this segment of FM521was covered by water (see Figure 38). This segment is a two-lane highway, 37.6 miles long, with a seal coat surface (see Figure 39).

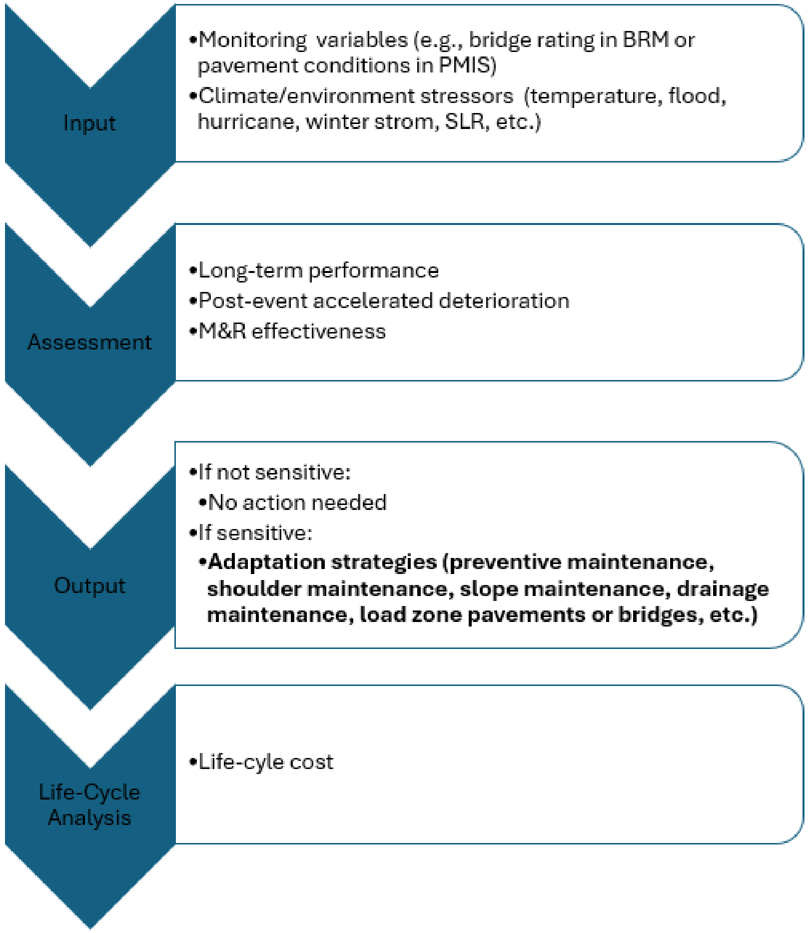

Figure 36. Implementation Framework for Adaptive Maintenance, Rehabilitation, and Operation.

Figure 37. FM521 Case Study Location.

Figure 38. FM521 Segment in Hurricane Harvey Water Content Range.

Figure 39. Typical Pavement Surface View along FM521.

Pavement Structures

To assess adaptive strategies (i.e., replacing pavements), two pavement structures were compared—a regular pavement structure with a flexible base that served as a reference and a pavement structure with a stabilized base that served as an adaptive strategy. Figure 40 details these two structures. The stabilized base strategy can be included in the planning phase (incorporated in the four-year pavement management plan) and in the design phase.

The regular/typical pavement structure is vulnerable to flooding because the flexible base material is sensitive to moisture. The pavement with stabilized base is flood-resilient because the enhanced base material is insensitive to moisture. The pros and cons of these two structure alternatives can be assessed using readiness, response, and repair (three *R*s) perspectives. The regular pavement structure is not prepared for flooding, particularly severe flooding, and thus requires repair after flooding. The pavement with stabilized base is *ready* or prepared to respond to flooding, although it bears more cost to build up front.

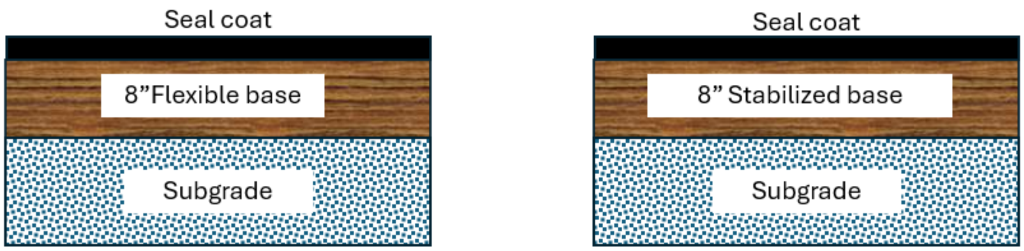

Figure 40. Two Pavement Structure Alternatives in the FM 521 Case Study.

LCC Analysis Scenarios

To evaluate the performance of these two pavement structures under different flood impacts, the research team used the following three scenarios in the analysis:

- **Scenario 1: Reference**: The first scenario was characterized as follows:
    - The pavement is designed to meet basic requirements (i.e., a 20-year flood per design standards in TxDOT's *Hydraulic Design Manual* [Thomason 2019]). No flood with a higher annual exceedance interval is considered.
    - The structure includes a seal coat pavement with a flexible base.
    - M&R includes routine maintenance annually and preventative maintenance (PM) with a seal coat in a 10-year cycle per engineering practice (see upper panel in Figure 41).

- **Scenario 2: Rehabilitation and readiness:** The second scenario was characterized as follows:
    - The pavement is the same as Scenario 1; however, rehabilitation will be needed if a higher-than-expected annual exceedance interval (50-year flood) occurs.
    - The structure includes a seal coat pavement with a flexible base.
    - M&R includes routine maintenance annually, rehabilitation with a stabilized base plus seal coat if a 50-year flood occurs (the pavement will be ready to respond to future flooding after rehabilitation following a 50-year flood), and PM with a seal coat in a 10-year cycle per engineering practice (see middle panel in Figure 41).

- **Scenario 3: Readiness:** The third scenario was characterized as follows:
    - The pavement is designed with a resilient structure to respond to a 50-year flood.
    - The structure includes a seal coat pavement with a stabilized base.

- M&R includes no required rehabilitation under flood impact, routine maintenance annually, and PM with a seal coat in a 10-year cycle per engineering practice (see lower panel in Figure 41).

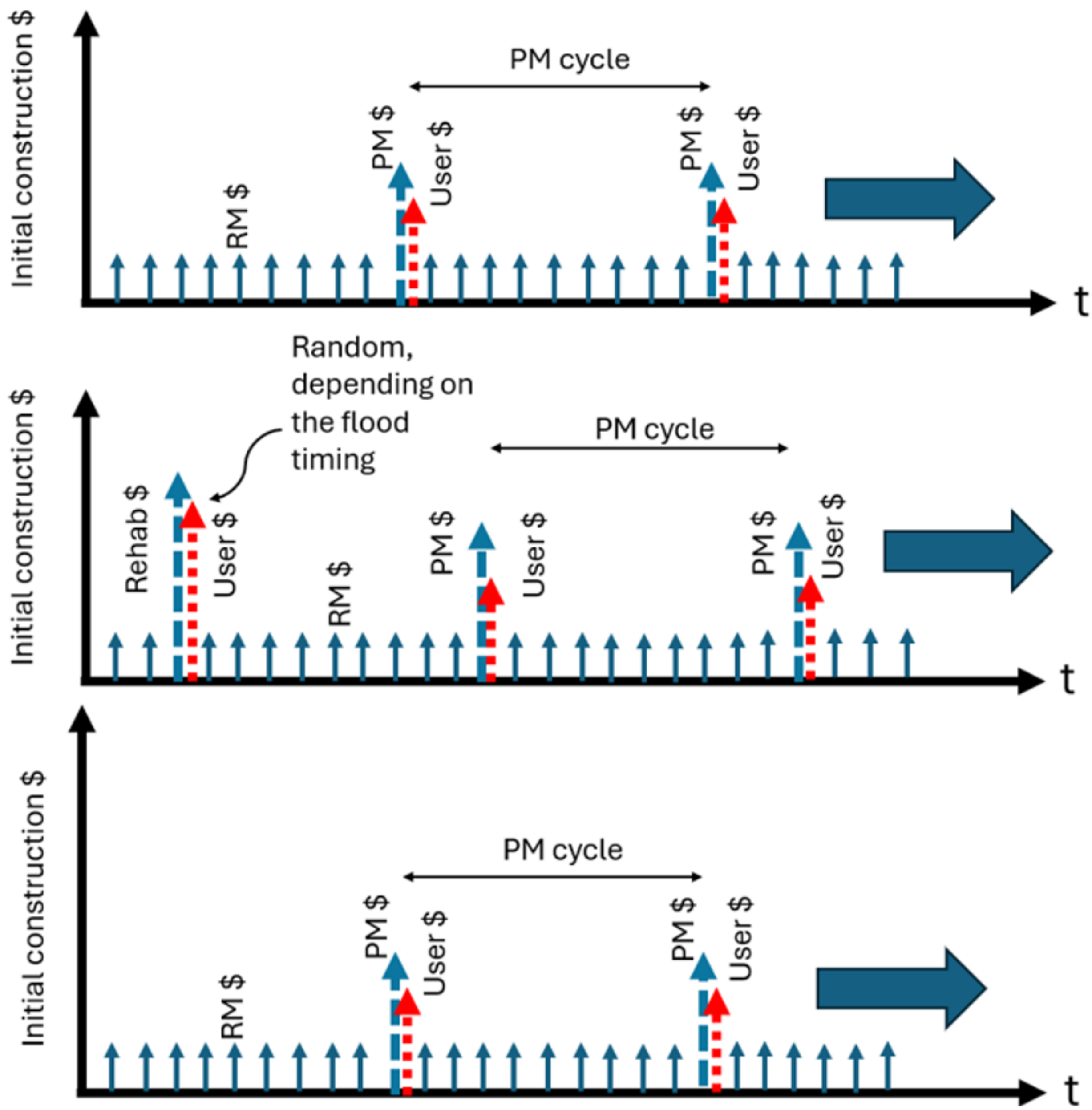

Figure 41. Maintenance Cycles for Different Pavement Types and Flood Scenarios: Flexible Base under a 20-Year Flood (Scenario 1, Upper); Flexible Base under a 50-Year Flood (Scenario 2, Middle); and Stabilized Base under a 50-Year Flood (Scenario 3, Lower).

Cost Components

Cost components considered in this analysis included construction costs, maintenance costs, and user costs.

Construction Costs

Construction costs in this case study included initial construction costs, PM costs, and rehabilitation costs. To obtain these costs, the unit costs per lane-mile for the breakdowns were needed. These unit costs were obtained from the average bid costs over the last 12 months in TxDOT's Yoakum District where FM521 is located. Table 12 summarizes the most recent 12-month average unit costs as of January 2025.

Table 12. Most Recent 12-Month Construction Unit Costs for FM521 Case Study.

Item No.	Material/Work	Unit	Cost/ Unit	Cost/ Lane-Mile	Note
316	Grade 3 aggregate	CY	$101	$9,876	0.5-inch layer
316	Asphalt	Gal	$2.65	$7,462	Apply 0.4 Gal/SY
247	Grade 1–2 flexible base	CY	$115	$179,911	8-inch layer
275	Stabilized base (cement treatment)	SY	$4.41	$31,046	Treat flexible base material
105	Removal/rework	SY	$3.73	$26,259	Remove seal coat and convert existing flexible base to stabilized base

Maintenance Costs

Maintenance costs include costs for routine maintenance including crack seal, patching, edge repair, etc., which are relatively less costly but more frequent than PM and rehabilitation. Routine maintenance cost data were extracted for the last 5 years from TxDOT's PMIS, Pavement Analyst. As a result, an average of $12,693 per lane-mile per year was used in this case study. It was assumed that routine maintenance is applied annually.

User Costs

In addition to the agency costs incurred to TxDOT, the research team estimated work zone road user costs. These costs are part of the additional project-specific liquidated damages required by Texas Transportation Code §223.012. The Work Zone Road Users Cost Calculator tool was used to obtain user costs. In this case study, user costs accrue because of reduced speeds during construction, PM, or rehabilitation. Table 13 details the average delay costs per day. To calculate the total delay costs for this 37.6-mile stretch of highway work zone, the construction duration was also needed. A duration of 3 months and 24 months was assumed for the PM work (i.e., seal coat) and the rehabilitation work, respectively.

Table 13. Average Delay Cost per Day Due to Reduced Speeds at Work Zones.

Project Information		
Control section job		
Highway/roadway	FM521	
County	Matagorda	
District	Yoakum	
Project letting year	2024	
Inputs	**Car**	**Truck**
AADT of section	1437	183
Length of the work zone (miles)	37.6	
Original posted speed (mph)	65	65
Work zone speed (mph)	40	40
Duration of work zone (days)	365	
Calculations	**Car**	**Truck**
Hourly value of time	$37.20	$52.75
Travel time posted speed (seconds)	2,082.46	2,082.46
Travel time work zone speed (seconds)	3,384.00	3,384.00
Additional travel time (seconds)	1,301.54	1,301.54
Additional travel time (hours)	0.362	0.362
Delay cost per vehicle	$13.45	$19.07
Delay cost per day	$19,327	$3,490
Delay cost for work zone duration	$7,054,189	$1,273,858
Total delay cost for work zone duration	$8,328,047	
Results		
Average delay cost per day	$22,817	

LCCs

In the LCC analysis, a 50-year analysis period was selected, representing a relatively long cycle. All future costs were converted to 2024 present values with a typical discount rate of 4 percent. For each scenario, the total LCC was calculated by summing all present values as follows:

$$LCC = ICCost + \sum_{m=1}^{M} MNTCost_m \left(\frac{1}{(1+r)^{m_t}}\right) + \sum_{n=1}^{N} (PMCost_n + PMWZCost_n) \left(\frac{1}{(1+r)^{n_t}}\right) + (RHBCost + RHBWZCost) \left(\frac{1}{(1+r)^{k}}\right) \quad (7)$$

where:

- *LCC* is the life-cycle cost.
- *ICCost* is the initial construction cost.
- *MNTCost* is the routine maintenance cost.
- *PMCost* is the cost of the PM work.
- *PMWZCost* is the workzone delay cost due to PM work.
- *RHBCost* is the cost of rehabilitation work.
- *RHBWZCost* is the workzone delay cost due to rehabilitation work.
- m is the m^{th} routine maintenance, 1, 2, … M = 50.
- m_t is the time corresponding to each routine maintenance, in years.
- *n* is the n^{th} PM work, 1, 2, … N, which follows a cycle of 10 years.
- n_t is the time corresponding to each PM work, in years (e.g., year 10, 20, 30 ,40, 50 if no rehabilitation is needed).
- *k* is the time corresponding to the rehabilitation work, in years, depending on the randomly occurring 50-year flood.
- *r* is the discount rate, assumed to be 4 percent.

For Scenarios 1 and 3, no rehabilitation costs were involved (see Figure 41). For Scenario 2, the rehabilitation timing was randomly determined by the occurrence of the flood (see Figure 41). Consequently, the subsequent PM timing was dependent upon the rehabilitation timing, although it still followed a 10-year cycle pattern after the rehabilitation.

Analysis and Results

Scenarios 1 and 3

For Scenarios 1 and 3, the LCC calculations were straightforward. By plugging in the relevant values in Equation 7 without considering the rehabilitation-related cost, the LCCs per lane-mile were $613,574 for Scenario 1 and $644,200 for Scenario 3. The latter was higher than the former mainly because of the higher initial construction cost of adopting a stabilized base instead of a flexible base. The initial construction cost with the stabilized base was 16 percent higher than the cost with the flexible base.

Scenario 2

Unlike Scenarios 1 and 3, the LCCs for Scenario 2 were related to flood timing. For example, if a 50-year flood occurred in year 3 or 13, rehabilitation was needed to restore the pavement’s structural capacity. Thus, the present values incurred by the rehabilitation were different due to different time lengths (i.e., 3 versus 13 years). In addition, the PM patterns between these alternatives were different, which resulted in different present values. Figure 42 shows the relationship between LCC and flood timing for Scenario 2—the LCC decreased as the flood timing increased. The closer a 50-year flood occurrence is to the initial construction, the higher the LCCs. For comparison, Figure 42 also includes the LCC for Scenario 3. The LCC for the pavement with a flexible base was higher than the pavement with the stabilized base if the flood occurs within 30 years of the initial construction. If the flood occurs during the remaining part of the analysis period, the relationship is reversed.

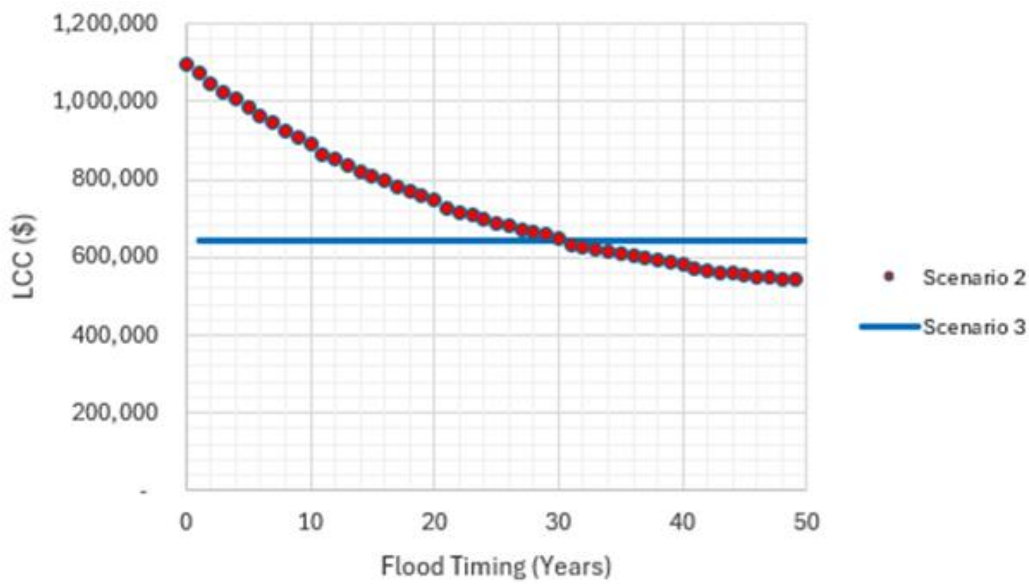

Figure 42. LCC per Lane-Mile Versus Flood Timing for a 50-Year Flood.

Figure 42 showed LCC estimates when a flood occurs in a given year; however, floods occur in a probabilistic manner. Figure 43 illustrates an example of the 50-year flood timing in a random manner. A relatively large number of simulation realizations were generated to mimic a 0.02 AEP or 50-year flood. For each random realization, the flood timing varied between 0 and 50 years, with a probability of 0.02 in any given year.

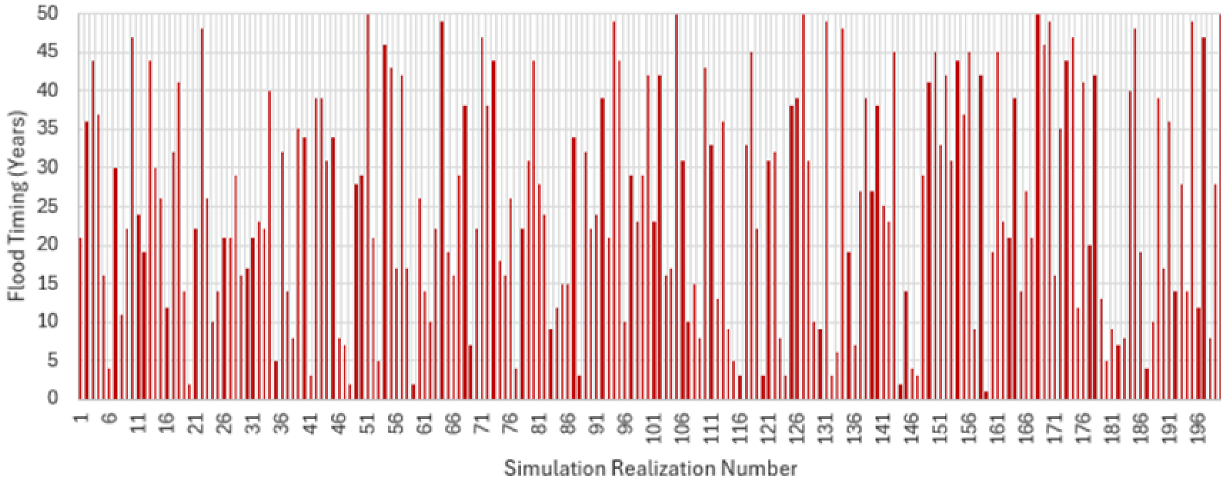

Figure 43. Simulation of Flood Timing for a 50-Year Flood.

Due to the randomness of flood timing, the LCC is characterized by randomness. To effectively capture this process in the LCC calculation, a Monte Carlo simulation was applied. In each simulation representing one occurrence of a 50-year flood, the following steps were followed to estimate the LCCs:

- Generate a random number to represent a flood timing year for a 50-year flood (i.e., flood timing for one of the simulation realizations in Figure 43).
- Calculate the rehabilitation cost and the associated road user cost due to the construction work, and convert them to present values.
- Exclude routine maintenance costs during the two years of rehabilitation work.
- Calculate the PM cost and the associated road user cost due to the construction work under a 10-year PM cycle pattern, and convert them to present values.
- Convert the annual routine maintenance cost to present values.
- Sum all present values to obtain the LCC for the underlying flood timing.
- Repeat these steps to obtain LCCs for different randomly generated flood timings.

Figure 44 shows the results of this LCC analysis for Scenarios 1–3. The columns reflect the average LCCs from 200 simulations. The error bar shown for Scenario 2 reflects the maximum and minimum values of these simulations. A large variation in LCCs was observed. Depending on when a flood occurs, the Scenario 2 LCCs ranged from around $550,000 to $1,100,000. From an economic perspective, higher variation means higher risk. Scenario 1 (pavement with a flexible base under a 20-year flood) had the lowest average LLC because of its 20-year flood assumption. The average LLC for Scenario 3 (pavement with a stabilized base under a 50-year flood) was only slightly lower than the average Scenario 2 LLC.

Using Scenario 1 as the reference, Figure 45 shows the LCC ratios for Scenarios 2 and 3. If one 50-year flood occurs, the LCC of the pavement with a flexible base (Scenario 2) was about 120 percent of Scenario 1, with a variation between 90 and175 percent. Comparatively, the LCC of the pavement with a stabilized base (Scenario 3) was 105 percent of Scenario 1, without any variation.

Multiple floods could occur in a given analysis period. For a flood with a given AEP, the number of occurrences during an analysis period follows a binomial distribution. Figure 46 shows the probability distribution of a 50-year flood (or AEP of 0.02) in a 50-year analysis period. The probability that a 50-year flood will not occur in a 50-year period was around 36 percent. The probability that a 50-year flood will occur once or twice in a 50-year period was 37 and 19 percent, respectively. The probability that a 50-year flood will occur five or six times in a 50-year period was almost zero and zero.

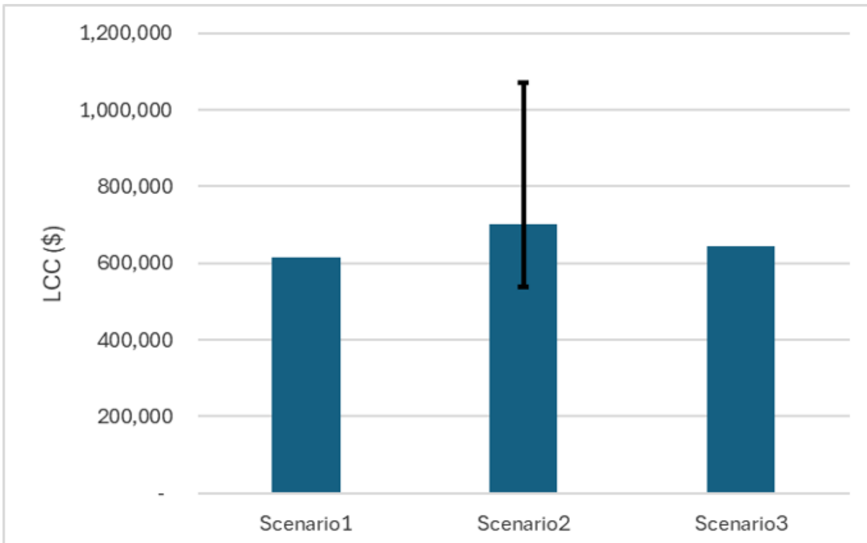

Figure 44. LCCs for Scenario 2 (Pavement with Flexible Base under One Occurrence of 50-Year Flood) Compared with Scenarios 1 and 3.

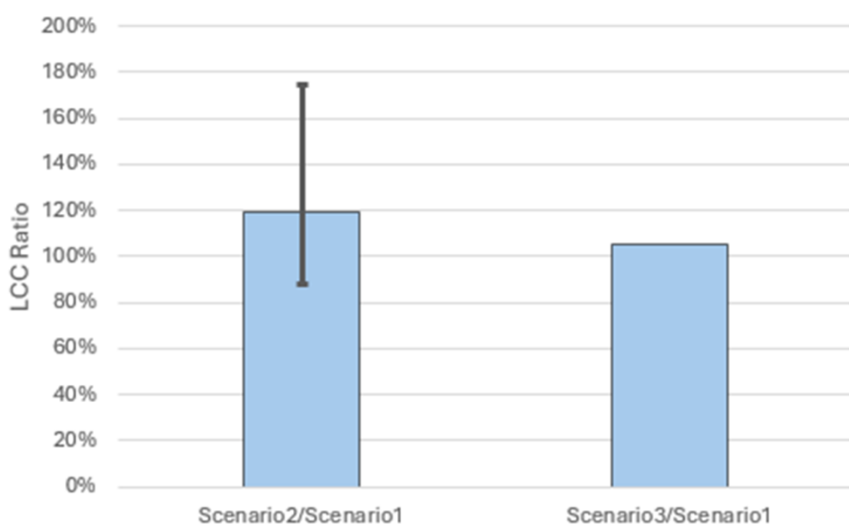

Figure 45. LCC Ratios of Scenarios 2 and 3 under One 50-Year Flood to Scenario 1 under a 20-Year Flood.

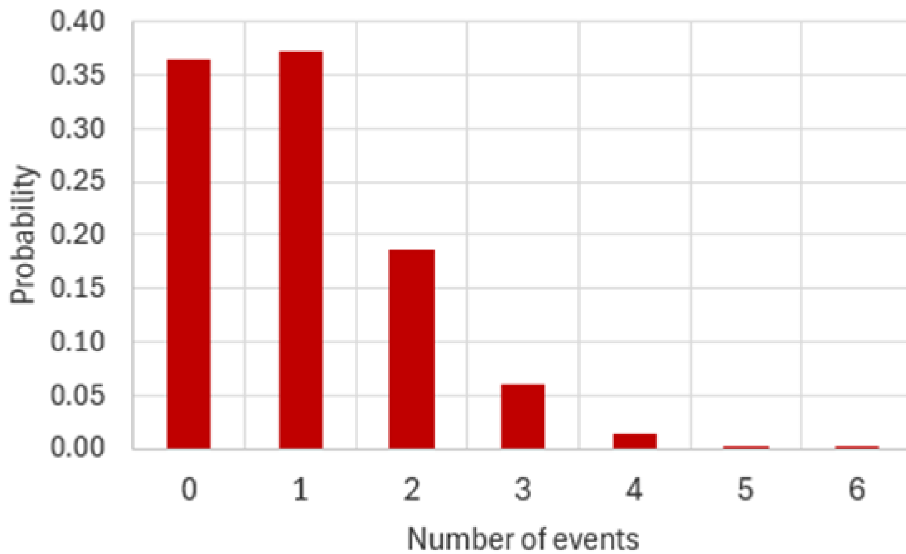

Figure 46. Probability Distribution of a 50-Year Flood in a 50-Year Analysis Period.

The LCCs will vary based on these probabilities. For example, if no flood events occur, no rehabilitation is needed, leading to an LCC of $613,567. If one flood event occurs, one rehabilitation is needed, which results in an average LCC of $729,112, with a standard deviation of $159,117. If two or more flood events occur, the LCC will be the same as if at least one flood event occurred because the first rehabilitation with a stabilized base will make the pavement resilient or ready to survive subsequent floods. Thus, an expected LCC can be calculated as follows:

$$E(LCC) = \sum_i P_i LCC_i \quad (8)$$

where:

- P_i is the probability for the i^{th} flood event, $i = 0, 1, 2, 3, \ldots$
- LCC_i is the life-cycle cost corresponding to the i^{th} flood event.

By plugging in the values of P_i and LCC_i, the expected LCC for the pavement with a flexible base under a 50-year flood (Scenario 2) is $686,917.

Using Scenario 1 as the reference, the ratio of the expected LCC in Scenario 2—considering all possible numbers of flood events—to Scenario 1 was about 112 percent; the ratio of the expected LCC in Scenario 3 to Scenario 1 was 105 percent (see Figure 47). This finding implies that using a stabilized base in the initial construction is more economically efficient than using a flexible base followed by a stabilized base rehabilitation if a 50-year flood occurs.

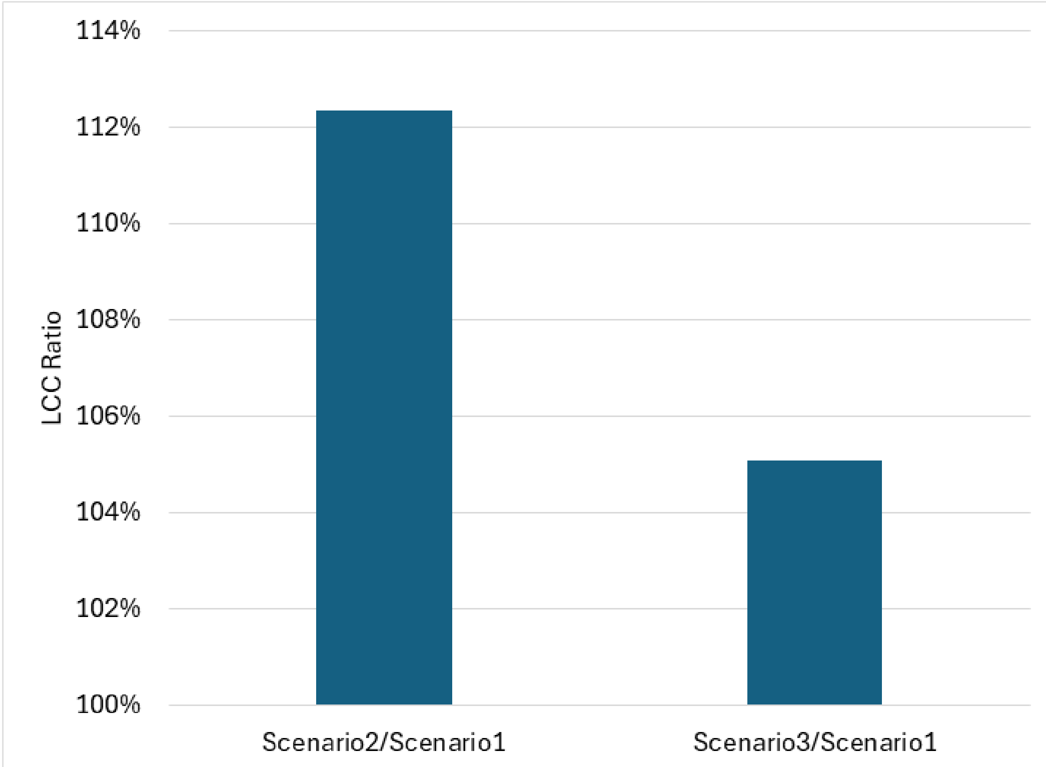

Figure 47. Expected LCC Ratios of Scenarios 2 and 3 under a 50-Year Flood to Scenario 1.

SUMMARY

This section discussed adaptation strategies for roads and bridges. These strategies covered the different phases of an asset's life cycle, including planning, design, construction, and maintenance/rehabilitation/operation. The research team proposed an implementation framework for these adaptation strategies, which was composed of four steps: input, assessment, adaptive strategies, and LCC analysis. Specifically, if an asset is vulnerable or sensitive to climatic/environmental stressors, adaptation strategies were recommended. A case study was provided to demonstrate the effectiveness of a typical pavement adaptive strategy with a stabilized base under the effect of flooding. Both the agency costs (initial construction costs and M&R costs) and user costs attributable to work zone delays were calculated over the asset's life cycle.

6. ASSET RISK AND RESILIENCE ASSESSMENT FRAMEWORK

This section describes the development and implementation of a robust analytical decision-making framework to prioritize assets for maintenance and retrofitting based on climate stressors and asset criticality. Recognizing the growing threats to transportation infrastructure from extreme weather, this risk and resilience (R&R) framework provides a systematic, quantitative, and repeatable methodology for assessing TxDOT's highway assets. It is designed to be directly applicable to TxDOT's planning processes, moving beyond conceptual discussions of risk to provide tangible, data-driven inputs for the 2026 TAMP. This section details the components, methods, and guiding principles of the R&R framework as successfully applied in the 10 corridor case studies in Section 7. Appendix B provide a detailed literature review and description of the R&R framework.

The R&R framework was built on the following core principles designed to make risk management practical, objective, defensible, and directly useful for asset management decisions:

- **Converting risk into a single economic currency:** A central tenet of the R&R framework is to translate abstract, complex risks like flooding into a single, understandable economic metric—annual average loss (AAL). This conversion into a common currency of dollars per year allows for a direct *like-for-like* comparison of risk across different assets, corridors, and geographic regions. It accounts for both the probability and the financial consequence of potential damage, providing a holistic measure of an asset's financial exposure to a given hazard.
- **Cost-benefit analysis as the bottom-line metric:** The R&R framework culminates in a clear, bottom-line selection metric for decision-making—the benefit-cost (B/C) ratio. By comparing the total expected benefits (in the form of avoided AAL) to the costs of a proposed adaptation strategy, the B/C ratio provides an objective, economic justification for investments. This moves resilience planning from a qualitative goal to a financially optimized strategy, ensuring that every dollar spent on adaptation is expected to yield a positive return in future savings.
- **Systematic identification of vulnerable assets:** The R&R framework provides a structured and data-driven process to identify specific assets within a corridor or regional network that are most vulnerable to damage. By integrating high-resolution hazard data with engineering-based fragility functions, the R&R framework can pinpoint which segments are most likely to sustain minor, moderate, major, or severe damage under various scenarios, allowing for the surgical targeting of interventions.
- **Across corridors:** Because the R&R framework produces standardized output metrics (AALs and B/C ratios), it enables TxDOT to compare both the relative risk and the relative cost-effectiveness of adaptation strategies across different corridors. This capability is essential for statewide planning and the efficient allocation of limited resources to the projects that offer the highest risk reduction and return on investment.

- **Extensibility to other risks and assets:** While the methods detailed here focus specifically on flood risk to pavement assets, the R&R framework itself is extendable. The core principles of quantifying hazard exposure, assessing criticality and vulnerability, calculating the AAL, and performing a B/C analysis can be adapted for other critical assets, such as bridges, and for other climate stressors, such as extreme heat, wildfire, or subsidence.

R&R FRAMEWORK COMPONENTS

The R&R framework consists of five interconnected components that translate individual components of risk into a clear, economic-based metric (B/C ratio) for decision-making. The process moves logically from identifying and quantifying hazards to evaluating the economic viability of proactive adaptation measures. This integrated approach ensures that decisions are informed by a holistic understanding of not only where a hazard might occur, but also how critical the affected asset is, how vulnerable it is to damage, what the financial consequences of that damage are, and whether investing in mitigation is economically justified. Figure 48 illustrates the relationship between these components.

Figure 48. Five Components of the R&R Framework.

Hazard Exposure Quantification

A foundational step in the R&R framework is to quantify the likelihood and magnitude of a specific hazard exposure (i.e., flooding) for each road asset. An accurate understanding of hazard exposure is essential for all subsequent analysis because it provides the primary input for determining potential physical damage. The primary data source for this component was the Texas Water Development Board's flood depth data (Texas Water Development Board 2025a), previously described in Section 2. This high-resolution, statewide dataset was a critical resource, providing projected flood likelihoods and inundation depths for various return periods, including 5-, 10-, 25-, 100-, and 500-year flood events. A key strength of this dataset is that it includes projections for both current (2020) and future (2060) climate and land use scenarios, allowing the R&R framework to account for the potential impacts of changing environmental conditions on flood risk over the planning horizon of the TAMP or asset life cycles.

The methodology involves a geospatial analysis where TxDOT road segments are overlaid with TWDB's flood maps using GIS software. Through this process, each discrete road segment in a given corridor is assigned a specific flood likelihood (e.g., a 1 percent annual chance for a 100-year event) and a corresponding potential inundation depth for each return period and climate scenario. This granular, segment-level data provides the foundational input for assessing potential physical damage in the vulnerability assessment.

Criticality Assessment

The criticality assessment was designed to determine the importance of each road segment, independent of its exposure to hazards. This step is crucial for ensuring that adaptation investments are prioritized not just on any vulnerable asset, but on those assets that are most critical to the functioning of the transportation network and the communities it serves.

The methodology assigns a criticality level from L1 (most critical) to L4 (least critical) to each road segment. This assignment is not based on a single variable like traffic volume but rather a weighted synthesis of the following three key metrics that capture different dimensions of importance:

- **Network connectivity:** This metric evaluates the role of the segment in maintaining the overall connectivity and redundancy of the road network. Segments that, if closed, would cause significant detours or isolate communities are rated as more critical.
- **Proximity to essential facilities:** This metric assesses the importance of the segment for providing access to vital community services like hospitals, schools, fire stations, and other emergency response centers.
- **Cascading impact:** This metric considers the potential for the segment's failure to disrupt other critical infrastructure networks, such as power grids, communication lines, or pipelines that may be colocated or dependent upon the transportation corridor.

The output is a map of the corridor where each segment is rated for criticality, providing a key input for the final adaptation evaluation.

Vulnerability Assessment

The vulnerability assessment assesses the susceptibility of a road segment to physical damage when exposed to the specific flood hazards quantified in the first framework component. It answers the question, "If a flood of a certain depth occurs at this location, how much damage is likely to result?"

The primary analytical tool in this component is the fragility curve function. This function establishes a probabilistic relationship between a given flood depth (the hazard magnitude) and the likelihood of an asset sustaining a certain level of damage. The fragility curves used in this framework were taken largely from Section 3 that dealt with the physical response of different pavement structures to flood events. They essentially provide a *dose-response* model for infrastructure, where the flood depth is the *dose* and the resulting damage is the *response*.

The output of this analysis is a categorization of the potential damage to each road segment into one of four distinct levels—minor, moderate, major, or severe. This process generates a detailed, scenario-based map of potential damage across the corridor for each flood return period, clearly identifying the segments that are most physically vulnerable to failure.

Risk Assessment

The risk assessment component translates the physical damage state from the vulnerability assessment into a quantifiable financial risk. This critical step creates a metric that can be used directly in asset management and financial planning.

The core metric used is the AAL. The AAL is calculated for each road segment by multiplying the estimated repair cost for each potential damage state (minor, moderate, major, severe) by the annual probability of that flood event occurring. These values are then summed across all possible flood events to produce a single, annualized financial risk value for that segment. The AAL represents the expected average monetary loss per year for a given asset due to flooding. It provides a powerful, data-driven metric to identify the segments that pose the greatest financial risk to TxDOT and allows for direct, apples-to-apples comparison of risk levels across different corridors and regions of the state.

Adaptation Evaluation

The final component of the R&R framework evaluates the economic viability of a proposed adaptation strategy by comparing its costs to its benefits, which are measured in the form of reduced risk. The methodology follows a three-step process:

1. **Define the adaptation strategy:** A specific, feasible adaptation measure is defined (e.g., the enhancement of the road pavement structure from a standard flexible base to a more resilient stabilized base). This strategy was targeted specifically at segments identified in the preceding steps as being both highly critical (L1 or L2) and susceptible to severe damage, ensuring an efficient use of resources.
2. **Calculate the benefits:** The AAL is recalculated for the targeted segments assuming the adaptation measure is in place. The improved pavement structure alters the fragility curve, reducing the likelihood of severe damage at a given flood depth. The benefit of the strategy is the avoided AAL (the difference in AAL with and without the adaptation), which represents the tangible, long-term financial savings achieved by the investment.
3. **Calculate the B/C ratio:** To provide a comprehensive, and easily communicable measure of economic viability, a B/C ratio is calculated. This metric is calculated by dividing the benefits of a strategy (the avoided AAL) by the adaptation costs.

The output of this final component is a clear, bottom-line metric for decision-making. A B/C ratio > 1 indicates that the long-term financial benefits of the adaptation outweigh the initial costs, making it a sound and defensible investment of public funds.

ASSET RISK AND RESILIENCE ASSESSMENT CASE STUDIES

To demonstrate and validate the proposed R&R framework, detailed analyses were conducted on 10 corridors across Texas (see Table 14). These case studies were carefully selected to represent the diverse geography, climate, and operational contexts of the state's vast transportation network. The selection includes major urban and coastal arteries critical to the state's economy, vital rural connectors, and inland routes, providing a comprehensive test of the framework's applicability. The primary goal of these case studies is to illustrate how the R&R framework can be applied as a systematic, repeatable process to generate actionable, data-driven insights that directly support the strategic goals of TxDOT's TAMP.

Table 14. Selected Case Studies.

No.	Corridor
1	FM521
2	SH0006—N. Houston to Bayou Vista
3	SH0006—Bryan/College Station to Hempstead US0290
4	SH0006—Waco to Bryan/College Station
5	US0290—Austin to Houston
6	SH0288—Port Freeport to Houston
7	US0087—Victoria to Port Lavaca
8	SH0359—Laredo to San Diego US0044
9	SH0124—High Island to Beaumont
10	US0027/US0039—Kerr County

This section summarizes the key, high-level findings and their direct implications for the 2026 TAMP. Appendix C provides the complete, detailed analysis of all 10 case studies, including all methodologies, data, tables, and figures.

Case Study Key Findings

Across the 10 corridors, three overarching findings emerged related to flood risk, proactive adaptation, investment decision-making that are critical for future asset management and resilience planning. These findings provide a clear, evidence-based foundation for enhancing TxDOT's approach to risk and resilience management.

Flood Risk is a Widespread, Growing, and Quantifiable Threat

The analysis confirmed that significant flood risk is not confined to the Texas coastline. While corridors near the Gulf Coast, such as SH0288—Port Freeport to Houston, face the highest financial risks, inland corridors also show significant and growing vulnerability (see Figure 49). The 2025 July flooding event in Kerr County that severely damaged US0027/SH0039 serves as a stark reminder of the effect flooding can have on infrastructure. Even corridors with less extensive exposures can suffer from high-consequence, acute events that cause major disruptions and require costly emergency repairs, reinforcing that risk is a function of both probability and consequence. In all 10 cases, the projected AALs increased between the 2020 and 2060 scenarios. This consistent upward trend provides a clear, quantitative signal that the financial impact of flooding on TxDOT's assets will grow without proactive intervention, increasing the strain on maintenance and repair budgets and threatening long-term asset condition goals.

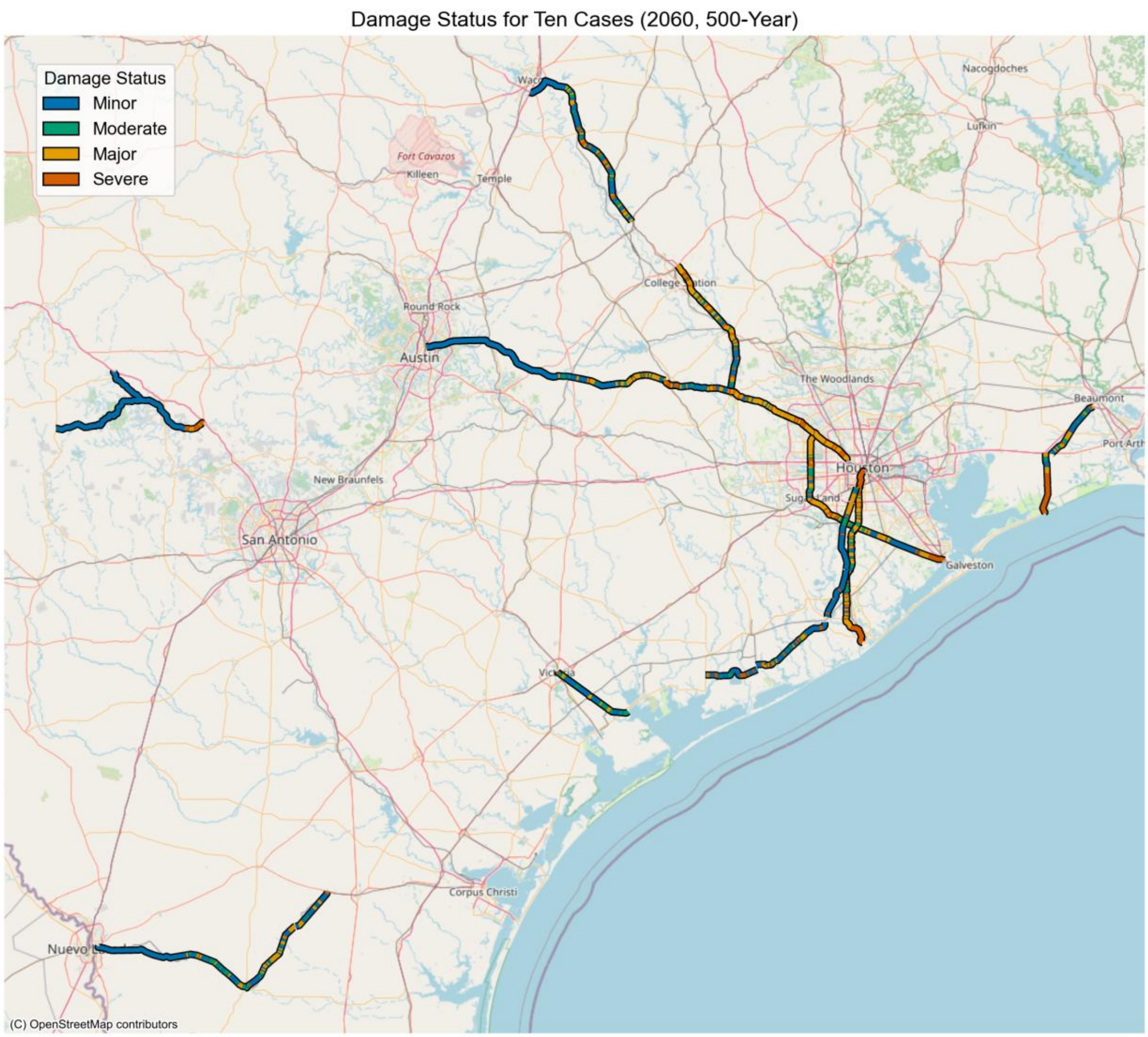

Figure 49. Flooding Damage Status for the 10 Case Studies in 2060 (500-Year Return Period).

Proactive Adaptation is a Highly Cost-Effective Strategy

A critical outcome of this analysis is the powerful economic case for investing in resilience. By translating risk into the economic currency of AAL, the framework moves beyond abstract risk registers to allow for a clear-eyed, quantitative evaluation of adaptation strategies. The proposed strategy—upgrading pavement structures on the most critical and vulnerable segments—was found to be highly cost-effective across the board. The B/C ratios were consistently positive and, in many cases, exceptionally high (see Table 15). Other key findings include the following:

- **Major coastal corridors:** For the SH0288 corridor, the overall B/C ratio exceeded 116.0, indicating an overwhelming return on investment where the benefits are more than 100 times the cost.
- **Major urban connectors:** For the US0290 corridor, the B/C ratio was over 9.0, meaning every $1 invested was projected to save $9 in future flood damage.
- **Rural and inland corridors:** Even for lower-risk inland corridors like SH0359, the B/C ratio was a solid 1.48, confirming the economic wisdom of proactive maintenance.

This finding directly supports the TAMP's core objective of efficient spending and demonstrates that investing in resilience is a fiscally sound strategy to preserve assets, maintain a state of good repair, and reduce long-term costs.

Table 15. B/C Ratios across the 10 Case Studies.

Case	2020 Scenario	2060 Scenario
FM521	1.76	1.84
SH0006—N. Houston to Bayou Vista	5.98	5.64
SH0006—Bryan/College Station to Hempstead US0290	4.16	4.41
SH0006—Waco to Bryan/College Station	1.66	1.66
US0290—Austin to Houston	9.07	9.06
SH0288—Port Freeport to Houston	116.04	116.04
US0087—Victoria to Port Lavaca	6.08	6.08
SH0359—Laredo to San Diego US0044	1.48	1.48
SH0124—High Island to Beaumont	2.05	2.05
US0027/US0039—Kerr County	1.61	1.61

R&R Framework Enables Tailored, Risk-Informed Investment

The R&R framework provides the data needed to tailor strategies to the specific risk profile of a corridor. For example, a high-criticality, high-risk corridor like US0290—Austin to Houston justifies a significant, corridor-level investment strategy to protect a major economic artery that connects two of the nation's largest metropolitan areas. In contrast, a corridor like US0087—Victoria to Port Lavaca, with lower overall risk but specific vulnerabilities to more frequent, less severe events, might warrant more targeted, localized treatments like drainage improvements at specific problem spots rather than a full-scale pavement hardening program. By identifying the specific segments that contribute most to a corridor's AAL, the R&R framework allows TxDOT to surgically allocate resources for the greatest impact, maximizing the efficiency of every dollar spent on asset preservation and ensuring that the right treatment is applied at the right time and in the right place.

R&R FRAMEWORK SUMMARY

The proposed asset risk and resilience assessment framework provides TxDOT with a systematic, data-driven, and economically grounded process for managing flood risk to its road assets. By converting abstract risks into quantifiable financial metrics like AALs and B/C ratios, the R&R framework enables a proactive, risk-informed approach to asset management that aligns directly with the strategic goals of the TAMP. It is a feasible and scalable tool that can be used to prioritize investments, justify expenditures, and build a more resilient transportation network for Texas.

Implications for 2026 TAMP

This work provided a feasible and scalable R&R framework that can be integrated into TxDOT's existing asset management systems. The metrics developed here—particularly the criticality level and AAL—can be incorporated into project prioritization processes. By treating AAL as a quantifiable performance metric, resilience projects can be evaluated and ranked alongside traditional preservation and mobility projects, ensuring that funding is directed toward the most important and vulnerable corridors. By applying this R&R framework, TxDOT can continue to lead in building a robust, reliable, and resilient transportation system for the future, ensuring the long-term preservation of its vital assets.

7. PROXY INDICATORS

This section describes the adoption of proxy indicators that could be used to help measure flood risk. As discussed in the introductory Section 1, a proxy indicator is a metric that can be measured relatively easily and that can be used in place of a *direct* measurement of infrastructure risk or damage.

DAMAGE PROXY INDICATORS

TxDOT's Maintenance Division-Pavement Preservation Branch routinely publishes the *Condition of Texas Pavements: Pavement Management Information Systems Annual Report* that summarizes network-level pavement conditions. These reports are available for download at https://ftp.txdot.gov/pub/txdot/mnt/crossroads/pmis/annual%20reports/ (Texas Department of Transportation n.d.). Each report includes a list of indices that can be used as proxy indicators of a network's vulnerability to deterioration or failure due to future risks such as climatic factors. These indicators include, but are not limited to, the following:

- **Condition score**. The condition score reflects the overall condition of a pavement. TxDOT uses the *percentage of lane-miles in good or better condition* (equivalent to a condition score ≥ 70) as the performance measure of the roadway network.
- **Distress**. Distress refers to various types of pavement deterioration, such as ruts, cracks, potholes/failures, and patches. A pavement with higher distress means it is closer to its end of service life. Some distresses (e.g., cracks) make the pavement more susceptible to future climatic stressors like flooding because of easy moisture infiltration into the pavement structure and damage to unbound materials. The distress trend—the year-to-year change in distress as published in the pavement condition annual reports—can serve as an indicator of the network's vulnerability to future deterioration or failure.
- **Maintenance level of service**. Only defined for asphalt pavements, the maintenance level of service is based on rutting, alligator cracking, ride quality, and/or a combination of these three indices. For each index, the maintenance level of service is defined as desirable, acceptable, tolerable, or intolerable per *TxDOT Administrative Circular No. 5-92* (Texas Department of Transportation 1992). The pavement condition annual reports report the maintenance level of service trends in desirable and acceptable categories. A decreasing maintenance level of service trend could serve as an indicator that the network is more vulnerable to future risks.

These indicators were already included in the 2022 TAMP, mostly under the Life-Cycle Planning section. However, the predive models outlined in Section 3 (effects of flooding on pavement life cycles and maintenance) suggest that the correlation between these proxy indicators and pavement damage may change if flooding is considered in pavement life-cycle models. Long-term in situ observations of the relationships among pavement damage, flood, and observable pavement characteristics could also yield new proxy indicators.

EXPOSURE AND RISK PROXY INDICATORS

The most significant initiative that could be used to understand and mitigate asset risk is the development of a fully integrated risk modeling system. In the context of proxy indicators, the research team purport the following:

- Bottom-up, mechanistic models of flooding, pavement damage, and associated user and maintenance costs are the best and most cost-effective way to assess infrastructure risk.
- Arguably, risk models *are* proxy indicators for pavement damage. They are indirect, relatively cost-effective measures of long-term risk compared to direct measurement techniques such as ground penetrating radar, destructive sampling, flood data collection, etc. These initiatives are still important, but a bottom-up risk modeling framework is more cost-effective and can provide immediate risk assessments.
- In the context of exposure and the typical life cycles of infrastructure and the humans that manage infrastructure, direct measurement of flooding (i.e., directly recording when and where flooding has occurred) is unlikely to yield accurate insights into current or future flood risk. Probabilistically, an asset with a 100-year flood risk could flood several times during its life cycle or it may never flood over its serviceable lifetime. This problem of direct measurement arises because flooding is a rare event (relative to nonflooding) but clearly a common and significant event relative to other threats and when magnified by the effects of space and time. Furthermore, flooding is driven by local conditions (e.g., weather, topography, land use, drainage infrastructure) that change dynamically across a very large state. While it remains important to collect historical flood data, these characteristics of flood disturbances make it difficult to directly measure risk from historical measurement alone.
- The conceptual bottom-up model of risk ($Risk = P_{event} \times P_{damage}$) is an efficient way to compartmentalize risk and risk assessment procedures. This paradigm provides a unifying model of risk, but at the same time enables each element to be considered somewhat independently. For example, flood exposure can be disaggregated into two components—flood modeling and asset inventories. Both can be refined continuously to provide increasingly accurate risk estimates. A similar statement can be made concerning damage assessments. For example, this report touches on chronic pavement damage, but similar exposure data could also be used to introduce acute damage models. The $Risk = P_{event} \times P_{damage}$ paradigm essentially provides a plan that helps bind independent and often specialized risk models and expertise together.
- Substantial data are now available to improve transportation risk assessments, including data that were traditionally outside of the knowledge zone of transportation engineers. Nontraditional data sources include the U.S. Department of Agriculture's Soil Survey Geographic Database, the U.S. Geological Survey's digital elevation models, TWDB's flood depth data, LIDAR data, and the National Oceanic and Atmospheric Administration's Atlas 14 rainfall data. In line with these novel data sources, many new

models and techniques can be used to improve estimates of flood depth or improve the accuracy and detail of transportation data. Many of these datasets are large and unwieldly unless integrated into an enterprise system.

In the remainder of this section, the research team provides examples of how existing data and knowledge could be used to refine asset management risk assessments.

Road and Bridge Geometry Refinement

As mentioned in previous sections of this report, the development of statewide flood depth data provides several opportunities to refine risk assessments. However, these opportunities can only be exploited with refined data on the location and geometric representation of critical infrastructure.

The most pressing risk assessment refinement would be to match or unify the geometry of TxDOT's roadway inventory data to its bridge inventory data. Currently, a field exists within the GIS roadway data that should contain a unique TxDOT bridge identification number if that section of the roadway is part of a bridge or culvert. Using data obtained in April 2025, Table 16 compares entries in TxDOT's roadway and bridge inventory databases. On average, 76 percent of bridges in TxDOT's bridge inventory database had matching entries in TxDOT's roadway inventory database. For bridges that traverse water, the percentage of matched bridges was lower (~50 percent). Moreover, match rates varies quite considerably across TxDOT districts.

The ability to distinguish bridge sections from road sections would help refine risk assessments. When dealing with any flood data and risk metrics such as miles of roadway affected by flooding, logically it is important to deal with bridges and culverts explicitly. For example, if mapped in a two-dimensional plane, a bridge may cross a flooded zone and be incorrectly considered impacted by flooding. However, if mapped correctly in a three-dimensional plane (including elevation), the same structure could be considered unaffected by the same flood pattern (i.e., considered at low risk).

Other roadway geometry endeavors could include adjustments of geometric accuracy in the two-dimensional plane. Two-dimensional accuracy is important when matching roadway geometry to flood layers. In some cases, raised roads behave like small levees that impound upstream water (both under real-world conditions and as represented in TWDB's maps). If roadway geometry does not match the actual location of the road, inaccurate risk metrics will likely result. This phenomenon also raises an important issue in the context of collaborations with TWDB. Roadway culverts are designed to allow water to flow continuously through or under the roadway. If, or to the extent that, they are not included in the flood models used by TWDB, they could result in inaccurate flood exposure data. Thus, developing new and improved infrastructure inventories has the potential to benefit both agencies.

Table 16. Number of Bridges/Culverts in TxDOT's Bridge Inventory and Percentage of Matching Bridges/Culverts in TxDOT's Roadway Inventory.

District	Total Culverts	Total Bridges	Culverts over Water	Bridges over Water
Abilene	824 (79.7%)	948 (61.1%)	824 (79.7%)	655 (58.6%)
Amarillo	280 (83.6%)	557 (62.3%)	280 (83.6%)	252 (68.7%)
Atlanta	670 (80.7%)	673 (71%)	670 (80.7%)	455 (74.5%)
Austin	1,854 (33.3%)	2,325 (47.7%)	1,851 (33.3%)	1,574 (47.8%)
Beaumont	561 (66%)	1,116 (54.8%)	557 (66.1%)	861 (52.7%)
Brownwood	642 (70.7%)	676 (59.9%)	641 (70.8%)	621 (59.9%)
Bryan	614 (68.6%)	1,356 (48.2%)	614 (68.6%)	1,147 (46.8%)
Childress	486 (85.4%)	419 (61.3%)	486 (85.4%)	382 (59.4%)
Corpus Christi	735 (65.2%)	1,092 (62.1%)	735 (65.2%)	761 (62.9%)
Dallas	2,267 (30.9%)	4,931 (37.5%)	2,265 (30.9%)	2,925 (40.1%)
El Paso	550 (77.8%)	830 (46%)	550 (77.8%)	451 (50.8%)
Fort Worth	1,564 (33.1%)	2,928 (38.6%)	1,563 (33.1%)	1,634 (35.4%)
Houston	1,309 (26.9%)	5,544 (24.6%)	1,308 (26.9%)	3,538 (21.1%)
Laredo	642 (80.4%)	433 (67.7%)	642 (80.4%)	309 (69.9%)
Lubbock	194 (80.9%)	324 (67.6%)	194 (80.9%)	73 (80.8%)
Lufkin	359 (73.3%)	985 (48.1%)	359 (73.3%)	891 (46.2%)
Odessa	797 (85.6%)	378 (79.1%)	796 (85.6%)	157 (89.8%)
Paris	604 (81.5%)	1,647 (44.6%)	604 (81.5%)	1,428 (43.2%)
Pharr	252 (58.3%)	856 (38.8%)	252 (58.3%)	543 (34.6%)
San Angelo	821 (85.1%)	542 (78.6%)	819 (85.2%)	423 (83%)
San Antonio	1825 (49%)	2,322 (50.1%)	1,821 (49.1%)	1,304 (50.8%)
Tyler	743 (68.9%)	1,220 (49.4%)	742 (69%)	1,006 (49.2%)
Waco	1,010 (62.6%)	1,809 (41.8%)	1,010 (62.6%)	1,396 (41%)
Wichita Falls	659 (71.3%)	895 (55.6%)	659 (71.3%)	655 (45.6%)
Yoakum	1,082 (67.2%)	1,839 (40%)	1,082 (67.2%)	1,630 (37.5%)
Total/Average	21,344 (58%)	21,324 (76.8%)	36,645 (30.2%)	25,071 (49.4%)

Motivated by the tragic floods that occurred in and around Kerrville in early July 2025, Figure 50 illustrates what an integrated data system could look like in its early stages. The upper panel shows TWDB's flood depth layer for a 1-in-100-year flood at the Johnson Creek crossing on SH00039 outside Kerrville. The lower image shows a section of LIDAR data collected for this bridge, processed using TWDB's DEM to estimate the corresponding bridge deck height. The 100-year TWDB flood data showed a water elevation of ~33 feet compared to the bridge elevation of ~ 30 feet. The research team is unaware of the actual flood water levels that occurred or whether the bridge was fully overtopped, but the integration of such data would enable performance of risk assessments to improve current and future decision-making.

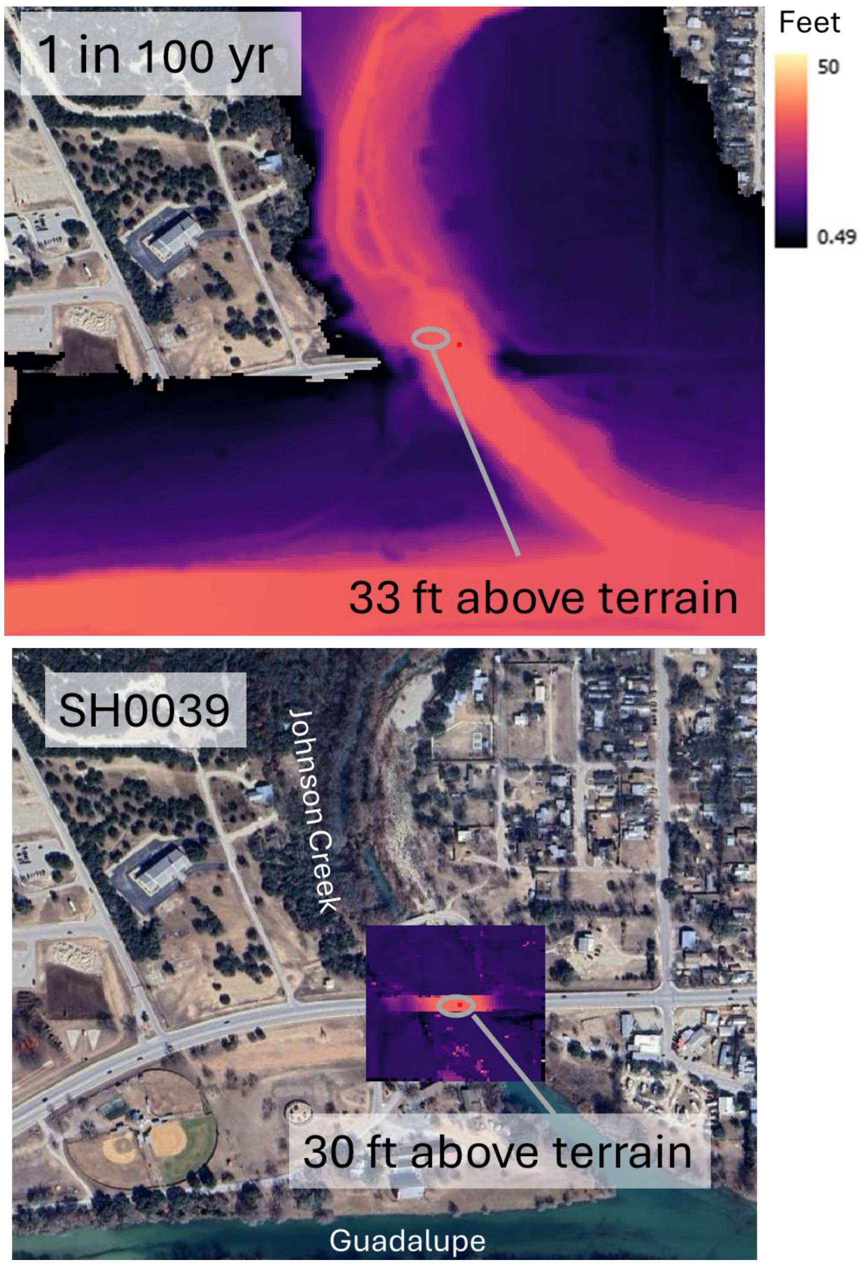

Figure 50. Example Flood Depth and LIDAR Data Integration Used to Assess Risk.

The barrier to such a system is complexity and the availability of data to some extent. During this project, the research team downloaded bridge-sized LIDAR boundaries to derive bridge elevations for approximately 20,000 overwater bridges but ran out of time and resources to process them. LIDAR data is not universally available for Texas and may be older than the structures they illuminate in some cases. Nonetheless, LIDAR data could be used to screen risk. Obvious missing data could prompt alternate data collection methods so that risk assessments could be completed.

While data coverage is limited, the biggest problems are the perceived cost of analysis and the size of datasets. For example, the LIDAR datasets are approximately 300 GB in size. TWDB's DEM data and flood data are over 1 TB in size. Neither are portable or easy to analyze and manage. However, an enterprise system could be used to integrate these data. A very straightforward option for making TWDB's data more accessible would be for TWDB or TxDOT to convert them into dynamic web mapping base maps of the kind that seamlessly and dynamically show aerial imagery in Google Maps, etc. This conversion would involve preprocessing the DEM's into tiles representing different *zoom levels*, which would then be stored on a server using a specific structure and naming convention. This process is easily achieved using off-the-shelf software or programming libraries. Then, a web page would be developed that integrates a standard web map (many options are available), automatically enabling TWDB's data to be overlayed on top of other web mapping layers (street maps, aerial imagery) or even GIS software.

The LIDAR data presented in Figure 50 could also be preprocessed to enable elevation data to be attached to the bridge deck (previously discussed in Section 3). The objective would be to *estimate* the height of the deck and possibly other elements of the bridge structure. This outcome could also be achieved using a simpler method—by sampling the route with accurate global positioning systems or adjusting bridge monitoring methods. In any case, LIDAR data may still be useful for identifying features in proximity to the bridge deck such as embankments. A similar argument on the versatility of LIDAR data could be made for roads. Here LIDAR data could be used to identify swales or drainage zones that are technically an important component of roads (i.e., an asset) but that are currently not included in risk estimates.

The development of such a system could require time and resources. Due to the dynamics of new roadway projects and new flood data, the system may never become complete. However, it is better to have some idea or estimate of risk, even if not fully accurate, and then develop ways to refine it.

One method that would encourage the continual refinement of risk would be to explicitly build into the system a way of quantifying uncertainty in the accuracy of roadway geometry (or other data) and use this information in the P_{event} component of the risk assessment, as well as data such as TWDB's flood data. In this way, locations with inaccurate information on infrastructure could be classified as *higher risk*, independent of flood patterns. This classification could help prioritize data collection, increase the institutional knowledge of assets, and result in better risk assessments. Given the size of Texas and the number of new projects across the state, this approach could be used to enable logically sound, objective risk assessments even if important risk assessment data are missing.

Proxy Indicator Expansion

The ideas presented previously would help ensure that the highest quality datasets are being collected for the purposes of statewide risk assessments and the decision-making processes they serve. The concept of adding uncertainty about infrastructure into the risk assessment highlights that risk assessment is a pragmatic endeavor and that ultimately a risk assessment is useful depending upon the type of decision-making it supports. Other extensions to this proposed risk management system could include the following:

- The addition of other essential infrastructure that is not currently required by the TAMP, such as traffic barriers and traffic signals.
- The development of additional hydraulic layers such as watersheds associated with culverts that would enable culvert flows to be calculated, thus providing a means to assess the risk of culvert failure.
- The development of a suite of *standard* damage models, such as the pavement model developed in Section 3, that would enable more complete risk assessments.
- The incorporation of formal project designs into GIS layers to help engineers more formally screen for risk.
- The incorporation of datasets depicting known historical flood locations like the information provided through the Drive Texas program.
- The incorporation of a unified asset criticality layer (as discussed in Section 6).
- The incorporation of official TxDOT routable network layers that would enable researchers and TxDOT employees to examine alternative routes and identify/link critical assets based on routing through the network (the current TxDOT roadway inventory data were not designed to be routable).

8. PROJECT OUTCOME INCORPORATION INTO 2026 TAMP

A central goal of this project was to develop risk assessment methods that TxDOT can use to incorporate extreme weather-based risk assessments in their next (2026) TAMP.

The requirement for the new extreme weather risk assessment stems from the signing of the IIJA in November 2022, just prior to the publication of TxDOT's 2022 TAMP. As a result, the current TAMP included only minimal content covering extreme weather risk. Nevertheless, the 2022 TAMP provides a template for the content that could be included in the 2026 TAMP.

Figure 51 shows the table of contents for TxDOT's 2022 TAMP. The contents include an entire chapter on risk assessment. In the 2022 TAMP, most of the content related to extreme weather appears in Risk Management (Section 5) and describes studies that TxDOT has funded to improve the resilience of infrastructure or to improve risk assessment methods. As discussed in the introductory Section 1 of this report, other state TAMP's follow a similar plan structure. The 2022 TAMP also addresses Life-Cycle Planning (Section 3), which may serve as a potential location for some of the work presented on pavement life-cycle planning in Section 3 of this report.

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Figure 51. Contents and Organization of TxDOT's 2022 TAMP.

This project yielded the following three types of content that could be included in TxDOT's 2026 TAMP:

- **Summaries of research projects and activities:** Consistent with the 2022 TAMP, TxDOT could summarize all recently funded projects that deal with extreme weather or resilience in this content category.
- **Detailed adopted activities and institutional programs:** This content category would *explicitly* state one or more risk and resilience methodologies that TxDOT is adopting at an institutional level to assess risk and resilience of assets to extreme weather.
- **Quantitative risk assessments:** This content category would provide an explicit, extreme weather-related risk assessment (for bridges and roads) that describes methodology, results, and implications for asset management. In other words, an analysis that follows the outline of the formal quantitative asset management summaries that occur in other sections of the TAMP (e.g., Inventory and Condition [Section 2], Financial Plan and Investment Strategies [Section 6]).

For each of these three content categories, the following subsections present ideas for 2026 TAMP content (from this study). A mix of these content types could be included in the next TAMP, but ideally, the 2026 TAMP should progress from a summary of research plans toward some adopted practices and explicit risk assessments.

RESEARCH PROJECT SUMMARY CONTENT

The following text is an example of potential 2026 TAMP content based on a nontechnical summary of the work undertaken during this project:

- **Content idea 1:** In FY 2025, TxDOT sponsored Research Project 0-7191: Develop Systematic and Quantitative Approaches to Assess the Probability of Extreme Weather and Resilience Risks for TxDOT Highways and Bridges. This study focused on flooding as a disturbance or potential cause of damage to Texas roads and bridges and identified flood risk layers from TWDB as a source of statewide data useful for assessing flood risk to TxDOT-maintained pavements and bridges. The research team developed methods to predict the chronic damage that occurs to pavements because of repeated flooding and highlights methods to incorporate flood damage effects into TxDOT's existing M&R and project selection (planning) processes.

  TxDOT Research Project 0-7191 also developed two methods to assess the vulnerability and resilience of bridge infrastructure. The first method proposes the use of fixed-wing LIDAR, NBI, and roadway inventory data to add elevation details to bridges and associated infrastructure. The method proceeds by identifying vulnerable bridge infrastructure and adaptation plans by comparing bridge elevations to TWDB's flood depth data. The research team also proposed a method that can be scaled for statewide analysis. In the statewide analysis, the research team identified key variables in the NBI that can be used to screen or identify bridges and culverts in the state that are the most vulnerable to flood damage.

The final methodology proposed in TxDOT Research Project 0-7191 was a corridor level analysis that expresses the risk of infrastructure damage in units of economic cost. The proposed framework, initially developed as part of TxDOT Research Project 0-7079, incorporates measures of criticality to the risk assessment process (i.e., it measures of the importance of road and bridge sections relative to the function of the regional transportation system). The method then proceeds to use TWDB flood risk data to assess the likelihood of flooding and fragility curves (developed in other project tasks) to predict life-cycle infrastructure damage and cost. Finally, using data on adaptation strategies (i.e., potential changes to infrastructure), the framework compares the costs of different no-build and build scenarios using a B/C analysis. The framework proposes the use of the AAL metric—a single, economic metric that objectively describes the opportunity costs of not improving the resilience of a specific infrastructure component. This metric encapsulates all the known hazards, damages, and maintenance expectations for an infrastructure component, enabling planners to identify assets with the highest AALs. Once identified, the framework will also enable planners to explore adaptation strategies that reduce LCCs and improve the resilience of corridors or regional networks that rely upon these assets.

Adopted Activities and Institutional Programs Content

Although the precise content language would depend on details of any institutional adoption, the following passages present ideas for 2026 TAMP content if TxDOT is able to adopt some of the methods and ideas proposed in this report:

- **Content idea 1**: TxDOT is currently developing new, flood driven pavement distress models to be incorporated into its PMIS, PA. These new deterioration models will update current models that use relatively simple climate and subgrade zones as inputs to deterioration and damage predictions. The new models will incorporate state-of-the-art inputs on pavement saturation and dry down based on the precise location of a pavement section and current and future flood risk data provided by TWDB. The PA system will use the new flood exposure data as inputs to models of chronic pavement damage developed using AASHTO-approved simulations. These additions to the PA software will enable TxDOT to make more effective M&R decisions following flood events and will especially help to prioritize maintenance operations during extreme regional flood events. During regional flood events, these changes to PA will help TxDOT maintain and recover local transportation services during flood events and maintain the most cost-effective road design and maintenance strategies in flood prone areas across the state over the long-term.

- **Content idea 2:** TxDOT has joined forces with TWDB to create a working group responsible for coordinating flood specific data and knowledge sharing between the two agencies. The working group will help TxDOT identify and develop the data and knowledge useful for maintaining a cost-effective, efficient, and resilient transportation system. Over the short term, such data will include current and future flood hazard data, hydraulically consistent DEMs useful for hydraulic modeling, and access to the expertise and knowledge of regional flood plain managers and hydraulic engineers. In return, TxDOT will provide TWDB with knowledge and data on the location and design of transportation infrastructure. This data and knowledge will help TWDB perform their own infrastructure risk assessments and in turn help guide cost-effective flood prevention and mitigation strategies. Detailed data on the design of structures such as culverts will also help TWDB and its partners refine flood risk data layers useful for both organizations and for a great many other agencies around the state. Over the long term, the TxDOT-TWDB working group will be tasked with developing the next generation of hydraulic modeling and simulation systems that integrates TxDOT infrastructure with climate, weather, topography, soil, and land use data capable of providing dynamic, real-time information on the risk and consequences of flooding to TxDOT infrastructure for both asset management and safety purposes.
- **Content idea 3:** TxDOT is currently working with academic partners to design and develop a next generation GIS system for asset management and other research purposes. The new GIS system will map assets in three dimensions (x and y ground surface location and elevation), provide routable network data, combine pavement and bridge data, and integrate new infrastructure such as drainage ditches, embankments, and other transportation assets. This GIS expansion will enable TxDOT's research partners to explore state-of-the-art resilience models and methods. At the same time, by standardizing and documenting a greater range of useful variables, the system will make it easier for TxDOT sponsored research to be translated into enterprise models that can be rapidly deployed within the agency.
- **Content idea 4:** TxDOT has deployed a risk and resilience project screening tool to prioritize project selection based on flood risk, infrastructure vulnerability, and infrastructure criticality to the transportation network. The R&R framework identifies infrastructure that will make the greatest and most cost-effective difference to the functioning and recovery of transportation networks during and following flood events. The tool estimates resilience benefits using AAL, which reflects the cost savings that could be made if infrastructure were to be upgraded to improve network resilience. The AAL is a single economic metric that can be fairly compared between competing infrastructure projects. This provides a path forward for TxDOT to integrate the resilience benefits of projects into existing project selection processes.

Quantitative Risk Assessment Content

In the 2022 TAMP, quantitative content (e.g., pavement performance projections and targets, investments, etc.) typically includes a factual measure (e.g., a performance measure) followed by a statement of future plans in place to improve or maintain performance. Because the TAMP is a high-level document, its existing quantitative content is presented using simple text, tables, and graphs. The research team recommends this same approach for any risk assessment content.

The following passages present ideas for quantitative risk assessment content that could be incorporated into the 2026 TAMP; these ideas are dependent upon TxDOT's internal processes:

- **Content idea 1**: Finalize a simple, statewide inventory of flood risk using the examples presented in Section 2. Ideally, this effort should take place after some preliminary work matching bridges to roadway data. The research team identified the following three key components of risk assessment:
    - Descriptions of methodologies or activities that TxDOT has integrated to enable risk assessment (e.g., TxDOT collaborates with TWDB to develop and assess statewide flood risk). TxDOT has established a new GIS system that fully integrates bridge and roadway assets allowing roads, bridges, and other transportation assets to be mapped at high resolution and enabling TxDOT engineers to visually and programmatically identify at-risk assets.
    - Simple, factual results based on a clear but simple method. Many specific risk assessment results could be reported. Based on this project's findings, the research team suggests focusing on pavement types vulnerable to chronic flood events. This determination could be derived from a simple summary of damage or vulnerable pavement types (e.g., a simple ranking of at-risk pavement types using data from Section 3). The result could be an overlay of the number of at-risk road sections, aggregated by district or by major route and presented as a simple table. For bridges, the focus could be a simple metric such as the risk of overtopping (subject to the appropriate organization of data).
    - A simple description of how TxDOT is using the data to inform decision-making or set future performance targets (e.g., TxDOT's goal is to reduce the miles of pavement types vulnerable to flooding by 10 percent and prioritize funding to routes that link critical infrastructure or communities, TxDOT is using this risk analysis to allocate emergency maintenance funding to districts and prioritize pavement maintenance schedules for vulnerable roads).

- **Content idea 2**: More ambitious content would address scaling the R&R framework to a statewide level. Again, the added complexity of the risk assessment methodology should not get in the way of focusing on simple content that is appropriate for the TAMP. The three key components of risk assessment in this context are as follows:

- Descriptions of methodologies or activities that TxDOT has integrated to enable risk assessment (e.g., TxDOT has developed a risk and resilience project screening tool that identifies vulnerable transportation assets [bridges and pavements] according to asset criticality (their importance for linking communities, emergency infrastructure, and facilities such as ports, border entries); flooding risk; and asset vulnerability to flood damage. The purpose of the tool is to identify those assets that have the highest benefits and lowest costs for maintaining or increasing the resilience of the statewide network in response to flooding.
- Simple, factual results based on a clear but simple method. Many specific results could be reported. For example, a table listing 20 of the most vulnerable assets on the network, along with their AALs (to provide insight into the potential cost savings of investments in these assets) and associated criticality and vulnerability scores.
- A simple description of how TxDOT is using the data to inform decision-making or set future performance targets. This may include a statement describing that the next step is for the at-risk assets to be assessed using project-level engineering models or a statement that the R&R framework is used to assign all assets with a risk and resilience score that is then used in TxDOT's project selection process (e.g., long range transportation plan).

9. CONCLUSIONS AND RECOMMENDATIONS

This study provided several risk assessment models and approaches that could be used for quantitative risk assessments in TxDOT's upcoming 2026 TAMP. The risk assessment methods are bound together by a simple model of risk and risk assessment, Risk = $P_{event} \times P_{damage}$.

Some of the methods presented in this report deal only with the P_{event} risk component (related to flood data and bridge risk). Section 3 deals explicitly with the P_{damage} risk component that repeated flooding can cause to pavements.

Risk assessment is a foundational step for developing resilience. The risk assessment process enables *high risk* assets to be identified or screened. The Adaptation Strategies section (Section 5) addressed the next step in the process of building resilience and explored methods to assess the benefits of considering alternate pavement designs that could be used to mitigate risk.

Finally, the R&R framework was developed using a holistic view of risk (exposure and damage assessment) and adaptation. The R&R framework also explicitly includes the concept of asset *criticality* (i.e., bridges and pavements that are especially important to the functioning of corridors or networks).

RECOMMENDATIONS

Based on the research team's experiences during this project and on the project outcomes, the research team offers the following recommendations:

- **Maintain a strong collaborative partnership with TWDB:** TWDB currently has the expertise and models to develop statewide risk assessments for flooding. Due to the importance of flooding as a hazard (both to assets [per the relevance of this report] and to safety), TWDB has a long-term role in developing the State Flood Plan and maintaining data useful for flood risk assessments. In the near term, TWDB can play an important role in standardizing data and providing advice and expertise useful to TxDOT. In the long term, mutually beneficial collaborations are likely to result in the sharing of data (assuming transportation assets play a role in flood patterns), the development of refined flood risk models, and potentially the development of models to provide additional flood data such as peak flow models that could be used to develop novel models of asset damage.
- **Develop or refine GIS-based asset inventories:** Development and refinement of GIS-based asset inventories will greatly improve the accuracy and efficiency of TxDOT risk assessments included in the TAMP and for other purposes.
- **Include simple, accurate risk assessments in the 2026 TAMP:** At this stage, a simple quantitative analysis may be most suitable for the 2026 TAMP. Such an analysis might follow the methods suggested in Section 2 (i.e., a GIS overlay of roads and bridges

relative to flood data provided by TWDB). Further, in the context of the TAMP, the risk assessment will be more impactful if bridges and roads can both be dealt with accurately. Other sections of the TAMP could then allude to activities currently taking place (inspired by the contents of this report and other activities) that will be used to refine future risk assessments.

- **Include a purpose-driven risk assessment statement in the 2026 TAMP:** A strong statement of purpose and intent concerning how the risk assessment results will be used is important for incorporating risk assessment in the 2026 TAMP. This statement recommendation followed the research team's review of existing TAMP content and factual presentation (factual information such as asset inventories were simply presented). The feature that makes the TAMPs most compelling is that simply presented asset inventories are linked to outcomes or actions that the DOT is undertaking to improve transportation function. The research team proposes that—before deciding upon a specific risk assessment methodology—TxDOT should brainstorm feasible ideas for how the results of a risk assessment could be practically used to improve the transportation network or TxDOT processes.

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APPENDIX A: MOISTURE EFFECTS ON PAVEMENT LIFE CYCLES LITERATURE REVIEW

This appendix contains a literature review on the moisture effects on pavement life cycles. The literature review was originally submitted as a Technical Memorandum during the project.

INTRODUCTION

Understanding the response and performance of pavement structures is critical for maintaining an efficient and safe transportation network, which is subjected to a variety of environmental stressors. As highlighted by Zapata et al. (2007), key environmental factors including precipitation, temperature fluctuations, freeze-thaw cycles, and the water table depth interact with internal characteristics of the pavement, such as the materials' susceptibility to moisture and freeze-thaw damage, the drainage capabilities of paving layers, and the pavement's potential for water infiltration. Among the external factors, moisture and temperature stand out as the two most significant environmentally driven variables affecting the properties of pavement layers and subgrade, ultimately impacting the pavement's load-carrying capacity. Meyer et al. (2013) emphasized that extreme weather events disrupt operations, damage infrastructure, and demand more frequent maintenance, compelling transportation agencies to balance the rising costs of recovery with public expectations for rapid system restoration. Qiao et al. (2020) further highlighted pavement sensitivity to climatic conditions by identifying their significant influence on deterioration rates, maintenance requirements, and LCCs.

Recent hurricanes in Texas, such as Harvey and Beryl, highlighted the significant effect of flooding on pavements. As climate projections indicate an increased likelihood of intense precipitation events in many regions (Intergovernmental Panel on Climate Change 2023), a better understanding of pavement flooding and quantification of its impacts is crucial for developing more resilient pavement designs, implementing effective maintenance strategies, and ensuring the long-term well-being of road infrastructure in flood-prone areas (Pregnolato et al. 2017). Mndawe et al. (2015) associated 80 percent of road distresses and pavement damages with the presence of excess water, emphasizing that moisture fluctuations significantly weaken flexible pavements and increase their susceptibility to damage from heavy vehicle loads, ultimately shortening their service life. Flood events can significantly compromise the structural integrity and functional performance of pavements, leading to accelerated deterioration, reduced service life, and increased maintenance costs (Mallick et al. 2017). Hedayati and Hossain (2015) found that variations in subgrade moisture content significantly altered the material properties such as resilient modulus and shear strength, leading to premature pavement failure. Immediate physical damage to pavements occurs through reduced structural capacity with the saturation of the subgrade, subbase, and base layers, differential swelling in expansive subgrade soils, and stripping of asphalt binders (Rokade, Agarwal, and Shrivastava 2012). Moreover, prolonged exposure to water can lead to long-term deterioration of pavement materials, reducing their service life and performance, as residual moisture in pavement layers continues to affect pavement response long after floodwaters have receded (Elshaher, Ghayoomi, and Daniel 2019). Khan et al. (2019) conducted a case study investigating pavement deterioration caused by extreme moisture intrusion in untreated pavement layers, framing an approach to quantify the detrimental structural impacts of flooding events. It is easy to observe how rapidly a pavement deteriorates after a long period of rain as water penetrates the underlying layers and cracks and potholes quickly develop.

Flexible pavements, constituting the majority of road surfaces in the United States, are particularly vulnerable to climate-induced stresses. Almeida and Picado-Santos (2022) emphasized asphalt pavements' vulnerability to water, demonstrating the weakening effect on flexible pavement structures by moisture intrusion. Qiao et al. (2023) acknowledged the risk of increased LCCs due to cumulative damage from repeated flood inundation, which can occur when the pavement is inadequately designed. By understanding potential moisture-related risks, engineers can proactively incorporate drainage systems, select appropriate materials, and implement structural adjustments that mitigate moisture-induced damage.

Despite the critical nature of this issue, a gap remains in the understanding of how flood exposure affects pavement performance over time, particularly in the context of uncertain climate patterns. Existing methodologies for predicting pavement deterioration often do not adequately incorporate detailed hydraulic and moisture-mechanical interactions under extreme precipitation conditions. This knowledge gap hinders the development of effective strategies for enhancing the resilience of road infrastructure in flood-prone areas (Douglas et al. 2010), highlighting the need for improved integrated modeling approaches that couple hydrologic processes, pavement mechanical responses, and performance deterioration mechanisms. Lu et al. (2017) applied the AASHTOWare Pavement ME Design software to evaluate pavement performance on sections in Canada under extreme climate scenarios, including flood conditions. They concluded that the software lacks the capability to fully model pavement behavior during and after subgrade saturation caused by severe moisture events. Khan (2017) also found through a review of road deterioration models that many existing prediction models were developed under normal functioning conditions, with limited information for flooding conditions. The lagging effects following the flooding event are also not adequately accounted for.

As such, comprehensive research is required to quantify the impacts of increased flood frequency on road infrastructure and inform adaptive design and maintenance practices. To fully understand the often-overlooked structural weakening caused by extreme weather events like flooding—dependent upon its duration, intensity, and quantified impacts on pavement response and performance—it is essential to consider the pavement structure, the water movement mechanisms within it, and the damage development over time. This research project sought to address this critical gap by developing a comprehensive framework to evaluate the impact of extreme precipitation events like hurricanes on pavement structures, with a focus on moisture-induced modulus reductions, resulting structural responses, and long-term pavement resilience.

SCOPE DEFINITION

Nationwide performance data collected for both asphalt concrete and PCC pavements indicated that sections where moisture was effectively managed through the use of permeable bases exhibited significantly improved resistance to pumping, faulting, and surface cracking (Mathis 1989).

Moisture affects all pavement layers, including the surface materials, granular bases, subbases, and subgrades, leading to progressive deterioration. Elsayed and Lindly (1996) emphasized that excess water significantly contributes to premature roadway failures by reducing the shear strength of pavement layers and foundation materials. Additionally, the accumulation of excess pore water pressure under repeated wheel loads can induce large hydrostatic forces within the pavement structure, leading to the pumping of material from beneath the surface layers. Either or both of these mechanisms can result in excessive deflection, cracking, reduced load-carrying capacity, and eventual disintegration of the pavement structure.

In particular, natural subgrades are highly susceptible to increases in moisture content. As an example, the Washington Asphalt Pavement Association (2025) indicated that "moisture in the subgrade and aggregate base layer can weaken these materials by increasing pore pressure and reducing the materials' resistance to shear." Inadequate removal of water from unbound layers has been identified as a major cause of pavement problems (Schaefer et al. 2008). When water infiltrates the pavement structure and reaches the subgrade, it can dramatically weaken the soil foundation and result in premature failure.

Different types of pavement surfaces (flexible asphalt, rigid concrete, composite, and thin surface-treated pavements) may manifest moisture-induced subgrade problems in distinct ways. Understanding these moisture-related mechanisms across different surface types is essential for designing resilient pavement structures in Texas.

PAVEMENT STRUCTURE GENERAL OVERVIEW

Dawson (2009) described modern pavement structures as "one or more bound layers overlying one or more unbound aggregate layers which, in turn, rest on the subgrade." Typically, the layers observed from bottom to top include the subgrade, followed by the subbase layer, the pavement base, and the surface course (see Figure A-1) (Huang 2004).

Each layer has a distinct role and responds differently to moisture. Flooding and prolonged saturation can affect each layer. Damage and failure often propagate from one layer to another if the moisture problem is not mitigated. Considering these layers from the bottom upwards, the typical configuration consists of the unbound granular layers, the subgrade, and the base and subbase layers.

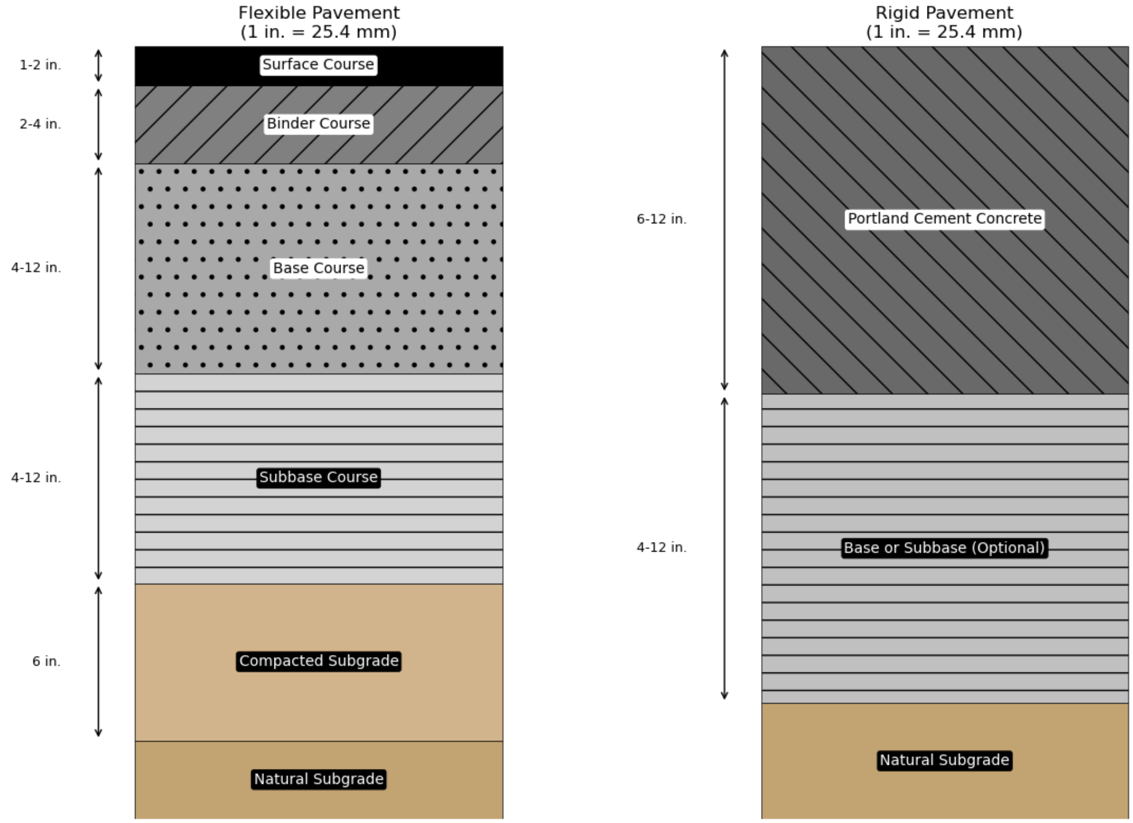

Figure A-1. Typical Sections for Flexible and Rigid Pavements (Huang 2004).

Unbound Granular Layers

The subgrade serves as the foundation soil upon which the pavement is constructed. It may consist of natural soil or compacted fill. The base layer is typically placed directly on the subgrade or, in many designs, on an intermediate unbound aggregate subbase. For low-volume roads, the base layer commonly comprises untreated materials such as unbound crushed stone or gravel. In contrast, high-traffic pavements often utilize treated base layers, such as asphalt-treated or cement-treated base materials, to enhance structural durability.

The principal mechanisms of moisture-induced damage include soil softening (strength loss), stiffness reduction, permanent deformation under load, erosion and pumping of support materials, and volume instability (such as heaving or collapse).

Dawson (2002) explained that the mechanical properties of unbound granular materials are governed by three primary factors—the condition of particle contacts, the pore network, and the water contained within the pores. The condition of particle contacts significantly influences the material's strength, stiffness, and resistance to permanent deformation under repeated traffic loading (Thorn and Brown 1989). Strong interparticle interactions enhance these properties, contributing to the overall performance of the material. Meanwhile, pore water plays a critical role by affecting suction within the pore network, effectively adding confining stress between particles. This phenomenon makes granular materials highly sensitive to water conditions, particularly when small pore sizes are involved. Lekarp, Isacsson, and Dawson (2000) observed that excess moisture decreases stiffness and strength and increases susceptibility to permanent deformation, indicating the detrimental effects of moisture intrusion into unbound layers. Under the action of repeated loads, unbound granular materials exhibit two types of deformation under cyclic traffic loading—recoverable or resilient deformation and plastic or permanent deformation (Lekarp, Isacsson, and Dawson 2000; Rahman and Erlingsson 2016). While resilient deformation in the unbound granular materials layers, especially the base layer, is associated with fatigue cracking in the asphalt concrete layer, permanent deformation contributes to the development of rutting in the pavement structure.

Subgrade

The subgrade serves as the foundation for the pavement structure, and its mechanical properties play a crucial role in overall pavement performance. The subgrade layer is directly affected by the presence of the water table; raising the water table into the subgrade reduces effective stress and shear strength (Terzaghi 1943). Under dry conditions, the subgrade might have adequate strength to support a pavement, but under flooding conditions, its bearing capacity can reduce dramatically (Ghayoomi et al. 2021). A pavement that is perfectly sound in dry weather might experience subgrade shear failure (collapse) if the subgrade is fully saturated and heavy trucks drive on it (Golalipour et al. 2024). Though immediate failure is not usually the case, the margin of safety is greatly reduced. Saturated subgrades will deform more (causing rutting or differential settlement) and are much more susceptible to repetitive load damage. If the subgrade is erodible (such as silty sand), moving water can actually scour it out from under the pavement, creating voids and sinkholes. If an expansive clay is present, sudden wetting can cause the soil to swell, lifting parts of the pavement, causing localized heaving or bumps. Later as it dries, it might shrink and leave cracks or depressions. Moreover, a weakened subgrade often leads to failure in the layers above—once the subgrade deforms or softens, the base layer on top will also deform and even break apart, and the surface will be prone to crack or collapse. Thus, protecting the subgrade from saturation is key to pavement resilience.

Wang et al. (2015) identified stiffness as a key engineering property of subgrade soils, directly influencing load-induced responses and distress mechanisms such as plastic deformation. Laboratory tests demonstrated that a high moisture content, simulated through flooding scenarios, significantly reduced subgrade stiffness. Following inundation, significant increases in tensile strain at the bottom of asphalt concrete layers and compressive strain at the top of subgrade layers were observed. These critical strains reached excessive levels shortly after flooding, underscoring the importance of timely evaluation and intervention to mitigate long-term impacts on pavement performance.

Chu et al. (2023) emphasized the importance of the subgrade in supporting upper pavement structures under repeated traffic loads. The reliability of subgrade performance is particularly challenged by its sensitivity to moisture variation. For unsaturated soils, increased moisture content diminishes matric suction, leading to reduced effective stress and subsequent degradation of mechanical properties. Saturated soils experience positive pore water pressure under traffic loading, which reduces effective stress as the load the soil particles are able to carry decreases.

When a subgrade becomes wet or saturated, several deleterious processes can occur. Loss of strength and stiffness is a primary concern; as pore water pressure increases in saturated soils under load, the effective stress is reduced, leading to softening of the subgrade. Particularly, in saturated fine-grained soils, traffic loading generates excess pore pressures that cannot dissipate quickly, causing a temporary loss of bearing capacity (Schaefer et al. 2008). Studies have shown that higher subgrade moisture contents correlate to lower resilient moduli and greater accumulation of plastic strain under cyclic loading (Rahman, Gassman, and Islam 2023; Neupane and Wu 2025). In other words, a wet subgrade will deform more under the same traffic, accelerating failure in the form of rutting or depressions.

Another mechanism is the pumping and erosion of fines. Water moving within or out of the pavement under traffic can carry fine soil particles from the subgrade into overlying layers or out through joints and cracks. If the subgrade is saturated, repeated wheel loads can pump fine material upwards into the base or out of the pavement, leaving voids behind (Schaefer et al. 2008). This erosion process, known as pumping, undermines pavement support and is especially notorious under rigid pavements (at the slab joints) but can also occur under flexible pavements with cracks or at the edges. Pumping was observed as a major cause of early pavement failures in historical road tests, prompting the inclusion of subbase layers and drainage features in design (Transportation Research Board-Pavement Management Section 2007).

Moisture can also cause volume changes in certain subgrade soils. Expansive clays swell upon wetting and shrink upon drying. This cyclic swelling and shrinking process can induce pavement upheaval or settlement and associated cracking. Highly plastic clay subgrades often lead to longitudinal and random cracking in the pavement that is not directly load-related. Cracks tend to meander near pavement edges in regions with expansive subgrades, reflecting differential volume changes as the soil wets and dries (Sebesta, Scullion, and Estakhri 2004). Repeated cycles of swelling and shrinkage create roughness and undermine the pavement integrity over time. Similarly, in cold climates, water in the subgrade can freeze causing heave and then thaw to leave a supersaturated, weakened soil. The spring-thaw period often produces severe subgrade softening and loss of support, which has been documented as a cause of seasonal pavement distress in northern regions (Neupane and Wu 2025).

Base and Subbase Layers

Bilodeau and Doré (2012) demonstrated the critical role of granular base layers in ensuring adequate pavement performance. Serving as a foundation for overlying asphalt concrete layers, unbound granular layers distribute loads and mitigate stresses on the subgrade by dissipating stresses through particle contacts and interlock (Dawson 2002; Bilodeau and Doré 2012). To ensure stability and durability under repeated high stresses, granular base materials are typically composed of high-quality, crushed, or partially crushed aggregates. However, as Thom and Brown (1987) first suggested, water at particle contacts acts as a lubricant, reducing the stiffness of the granular base layer. The degree of saturation influences the stiffness and deformation resistance of granular base layers via this lubrication effect (Dawson 2021; Lekarp, Isacsson, and Dawson 2000; Thom and Brown 1987; Korkiala-Tanttu and Dawson 2007).

SURFACE (WEARING COURSE) LAYER

The surface course—sometimes laid over a binder course—forms the topmost layer, directly exposed to traffic and environmental conditions. It must resist traffic wear and protect the structural layers below, especially against water infiltration.

Asphalt Surfaces

When new and intact, asphalt is somewhat water-resistant, but over time oxidation and traffic cause small cracks and increased permeability. Water can infiltrate through open-graded surfaces or cracks, especially during a flood where water may actually submerge the pavement. Asphalt is also susceptible to surface damage from water pressure. For instance, fast-moving floodwater can strip away poorly bonded aggregate or cause debris impacts. If water gets into the asphalt mix, it can cause stripping of the binder as discussed and lead to surface raveling.

The rate of moisture-induced damage in asphalt mixtures is influenced by water diffusion into the mastic and the amount of water retained by the asphalt, as demonstrated by Cheng et al. (2002). Utilizing the concept of surface energy—defined as the energy required to create a new surface area in a vacuum—the authors described how moisture facilitates de-bonding at the asphalt-aggregate interface and crack formation within the mastic. Mixtures retaining more water exhibit accelerated damage accumulation due to the reduction in both adhesive and cohesive strengths.

Cheng et al. (2002) defined moisture damage in hot-mix asphalt pavements as “the loss of strength and durability in asphalt mixtures due to the effects of moisture.” This damage manifests either as adhesive failure (stripping)—de-bonding at the asphalt-aggregate interface—or cohesive failure within the mastic, involving the fracture of asphalt-cement films binding aggregate particles. Further insights highlighted the critical role of asphalt or mastic coating thickness in determining failure mechanisms. Thin asphalt films are prone to adhesive bond rupture, while thicker films predominantly fail cohesively within the mastic. Moreover, moisture intrusion into thicker mastic films significantly affects their rheological properties and damage resistance, emphasizing the need to evaluate mastic moisture retention when addressing moisture-induced damage.

The mechanisms contributing to stripping in asphalt mixtures include detachment, displacement, spontaneous emulsification, pore pressure development, and hydraulic scour (Taylor and Khosla 1983). These processes collectively weaken the asphalt-aggregate bond, increasing vulnerability to cyclic loading. Additionally, Kiggundu and Roberts (1988) identified factors such as pH instability and environmental conditions as contributing to moisture damage, while Terrel and Shute (1989) emphasized the roles of temperature, air, and water in affecting asphalt concrete durability.

Ultimately, moisture weakens adhesive bonds at the asphalt-aggregate interface and reduces the cohesive strength within the mastic, accelerating fracture damage and limiting microcrack healing. These findings highlight the importance of moisture management strategies to enhance the durability and longevity of asphalt mixtures.

Concrete Surfaces

Concrete is less permeable, but it has joints (in jointed plain concrete pavement) or intended cracks (in CRCP) that allow water entry. The concrete surface can also suffer scaling or spalling if water freezes in its pores, but in most of Texas, especially around Houston, Fort Worth, Dallas, and Beaumont where many of CRCP sections are located, this is rarely an issue. However, once water penetrates to the steel reinforcement (in CRCP or doweled joints), it can cause corrosion or other long-term issues. In all cases, any surface cracks or construction joints become critical points; they must be sealed or designed with drainage, otherwise they become direct conduits for water into lower layers.

FLEXIBLE PAVEMENT MOISTURE EFFECTS

In HMA pavements, a wet subgrade typically leads to loss of support and increased pavement deflections under traffic. The flexible asphalt layers distribute the traffic load but rely heavily on the unbound layers (including the base, subbase, and subgrade) for support; thus, subgrade softening quickly translates into surface distress. Wide rutting is a common symptom of moisture-weakened subgrades in asphalt pavements. As the subgrade saturates and its shear strength drops, the repeated wheel loads cause the pavement to permanently deform downward in the affected areas (Neupane and Wu 2025). Research has confirmed that subgrade stiffness (resilient modulus) can decrease dramatically with higher moisture content, leading to greater strain levels under each load and a rapid accumulation of rut depth (Rahman, Gassman, and Islam 2023). Heavy rainfall events or the rise in the water table can reduce subgrade strength so much that rutting and even general shear failure may occur in a short time (Neupane and Wu 2025). Excess subgrade moisture can accelerate fatigue cracking as well; the softer support leads to larger bending deflections in the asphalt, increasing the critical tensile strain at the bottom of the asphalt layer, hastening crack initiation.

Historically, engineers recognized the danger of water to flexible pavement subgrades early on. The California Bearing Ratio test for subgrades, for example, is often performed on soaked samples to ensure the pavement is designed for the worst-case moisture condition. Field observations from as far back as the 1950s–1960s (American Association of State Highway Officials [AASHO] Road Test) indicated that flexible pavement sections could suffer rapid deterioration during wet or thaw periods even if they performed adequately when dry. As a result, empirical design methods incorporated safety factors or drainage coefficients to account for adverse moisture conditions. One outcome of the AASHO Road Test was the realization that seasonal changes (freeze-thaw, wetting) in a clay subgrade significantly affected performance; however, the test's limited two-year duration and single climate meant further research was needed to generalize those findings (Transportation Research Board-Pavement Management Section 2007).

More recently, the advent of ME design formalized the incorporation of moisture in subgrade strength and pavement performance; the original *AASHTO Mechanistic-Empirical Pavement Design Guide* (2008) (currently commercialized as the AASHTOWare Pavement ME Design software) explicitly modeled how subgrade moisture changes over a year affect pavement damage accumulation. The Enhanced Integrated Climate Model simulates moisture variation and adjusts the subgrade's resilient modulus accordingly (Gaspard et al. 2020). This model reflects a significant advancement. Older design methods would use a single conservative subgrade modulus value, whereas now the design can consider, for example, a weakening during wet seasons and recovery during dry seasons. Researchers have also pursued unsaturated soil mechanics approaches to better capture the relationship between matric suction and resilient modulus. For instance, Cary and Zapata (2010) developed improved models for how the degree of saturation influences the subgrade modulus, refining the environmental adjustment factors used in design. All these efforts aim to predict flexible pavement performance more accurately under real moisture fluctuations.

In terms of distress manifestations, a saturated subgrade under an asphalt pavement often leads to a combination of rutting and fatigue cracking (alligator cracking) in the surface. If the subgrade soil is expansive, differential heave can cause longitudinal cracking that runs along the roadway (often near the shoulder or centerline). Such cracks are non-load-related and stem from the subgrade lifting the pavement as it swells with moisture; they tend to appear irregular or meandering in plan view (Sebesta, Scullion, and Estakhri 2004). During dry periods, those cracks may partially close but then reopen or new ones form upon rewetting, leading to a maintenance challenge. Field manuals have documented that on pavements underlaid by highly plastic clays, longitudinal cracking and even slight faulting (vertical displacement) along those cracks can occur due to the wet/dry cycles in the subgrade.

For flexible pavements, the overall consensus in the literature indicates that keeping the subgrade as close as possible to its optimum moisture content is key to longevity. Excessive wetting inevitably brings a sharp reduction in supporting capacity (Rahman, Gassman, and Islam 2023) and an increase in distresses like rutting and fatigue cracking (Neupane and Wu 2025).

RIGID PAVEMENT MOISTURE EFFECTS

For PCC pavements, the subgrade's immediate bearing capacity is less commonly the controlling factor for load support. Rigid pavements have a much broader area of the subgrade over which applied loads are distributed compared to flexible pavements with asphalt concrete surfaces. As such, rigid pavements can typically be constructed with thinner base layers than their flexible counterparts (Hein et al. 2017).

Nevertheless, moisture in the subgrade (and subbase) of rigid pavements plays a critical role in durability by contributing to pumping, faulting, and slab cracking. Pumping is the ejection of water and fine material from beneath the slab through joints or cracks under the impact of traffic loads. It was identified as a major failure mechanism for concrete pavements in early highway research. Notably, during the AASHO Road Test, many rigid pavement sections without adequate subbases exhibited pumping of subgrade fines under heavy truck traffic and wet conditions, leading to voids under slabs and early failures (Transportation Research Board-Pavement Management Section 2007). The presence of free water at slab interfaces, combined with repeated slab deflections, causes a slurry of soil particles to be sucked and pushed along the slab edges. This results in loss of subgrade support over time. Subsequent slabs bridging over the voided area can crack (corner breaks) or settle unevenly, causing joint faulting (steps at the joints). Over time, multiple joints faulting will lead to significant roughness.

The AASHO Road Test proved that simply adding a granular subbase under the concrete slabs greatly improved performance by reducing pumping, compared to slabs placed directly on clay subgrade. In fact, sections with a gravel subbase had much less faulting and slab damage than those without it, regardless of subbase thickness. However, the AASHO Road Test also showed that a granular layer alone was not a panacea under severe conditions—under very heavy loads and substantial rainfall, even the gravel subbase became saturated and experienced pumping, leading to slab failure. In response, highway agencies began adopting stabilized subbases (cement- or asphalt-treated layers) in the 1970s to create a firmer, erosion-resistant platform under concrete slabs. These measures, combined with better joint load transfer (dowel bars), drastically reduced pumping-related distress in modern PCC pavements as compared to mid-century designs.

Despite these improvements, moisture can still cause issues in rigid pavements if not properly managed. A classic manifestation is corner cracking of slabs when the support underneath is eroded by water. If water infiltrates through joints or cracks and saturates a pocket of subgrade, repeated wheel loads on the slab corner can cause that corner to deflect and eventually crack off (a corner break), especially if load transfer is inadequate.

For PCC pavements, the emphasis in the literature was on preventing water accumulation at slab-subgrade interfaces. Water entering the pavement can lead to concrete deterioration and loss of support near joints/cracks, which is exactly where distress in composite or concrete pavements is frequently observed (McDaniel 2020). Thus, while rigid pavements are less sensitive to subgrade softening, they are quite sensitive to subgrade erosion caused by water movement.

COMPOSITE PAVEMENT MOISTURE EFFECTS

Composite pavements generally refer to structures combining HMA and PCC layers—typically an asphalt overlay on top of an older concrete pavement. These systems inherit some characteristics of both flexible and rigid pavements in terms of moisture response. A well-bonded asphalt overlay can act as a relatively impermeable *moisture blanket* over a concrete layer (California Department of Transportation 2023). In new composite construction, designers note that the asphalt top can reduce the ingress of water and reduce moisture gradients in the underlying concrete, thereby reducing concrete curling and warping stresses. A fresh asphalt layer initially helps seal the pavement, preventing rainwater from reaching the subgrade or the concrete-subgrade interface. This asphalt layer can be especially beneficial over an exposed jointed concrete surface, where water can directly enter through joints.

However, with time, reflective cracking often develops in the asphalt overlay above the concrete joints or cracks. Research and field experience have shown that composite pavements tend to experience concentrated distress at the locations of underlying concrete joints and cracks. The cracks in the asphalt overlay coincide with the old joints, and water can enter the pavement structure at these locations, leading to concrete deterioration and loss of subgrade support (McDaniel 2020). Essentially, the pumping and erosion mechanism can occur in composite pavements much as in a concrete pavement if water gets underneath the overlay. The overlay itself may begin to exhibit depressions or cracks above these voids. Many times, the first sign of distress in an asphalt-over-concrete composite pavement is the appearance of a dip or a crack over a joint after heavy rains, indicating pumping or loss of support at that joint.

Another scenario is that the asphalt overlay, especially if relatively thick, might rut or deform if the support is compromised by moisture. Consider an old concrete pavement that had voids under some slabs from past pumping; if it is overlaid without correcting those voids (via undersealing or patching), the composite pavement will have *hidden* support deficiencies. When the subgrade gets wet, those deficiencies combined with the load on a somewhat flexible overlay can cause the asphalt to bend and rut over the voided areas.

Historically, many composite pavement practices arose from the need to rehabilitate aging concrete pavements by overlaying them with asphalt, although composite pavements can also include cases like asphalt over a heavily cement-stabilized base. In the latter case, if cracking in the cement stabilized layer occurs (due to shrinkage or fatigue), moisture can infiltrate and soften the underlying subgrade or cause stripping in the asphalt above the cracks. Thus, managing cracks and keeping them sealed is important in composite structures.

Recent studies on patching composite pavements emphasized that the durability of repairs around joints depends on preventing water ingress at those critical spots (McDaniel 2020). The overlay will generally protect the concrete from rapid moisture changes if intact, but once breaches occur, maintenance of seals becomes as important as it is on flexible pavements.

Composite pavements have the potential advantage of reduced direct subgrade moisture exposure thanks to the asphalt top but remain susceptible to the classic moisture-induced failure modes of the underlying pavement type. They require a blending of strategies that include good waterproofing of the asphalt layer (through materials and timely crack sealing) and good drainage of the old pavement's joints. As Caltrans' *Highway Design Manual* (2025) notes, current design methods do not yet fully credit the reduced moisture gradient benefit in concrete thickness design, but it is recognized qualitatively. With good maintenance, it can effectively shed water and protect the subgrade for a longer period.

SURFACE-TREATED PAVEMENT MOISTURE EFFECTS

Surface-treated roads—usually thin-surfaced flexible pavements consisting of a chip seal or bituminous surface treatment over an unbound base—are extremely vulnerable to flooding. In some Texas coastal counties, which use surface treatments, heavy rain events have caused widespread damage, prompting studies to quantify how flood frequency correlates with accelerated failure in these thin pavements (Hong and Prozzi 2024). Unlike a thick asphalt or concrete layer, a chip seal provides only a modest barrier to water; any slight opening or aging of the seal can permit significant moisture ingress. Recent experiments coupled with simulations have shown how moisture can migrate upward from a high water table into an unbound base under a chip seal, and conversely how evaporation in dry periods can pull moisture out, indicating that thin-surfaced pavements can have large moisture fluctuations in the base and subgrade compared to thicker pavements (Madakalapuge et al. 2022). Water infiltration through the thin surface (via cracks, porous texture, or edges) can quickly saturate the base and subgrade, leading to rapid deterioration. The loss of support leads to rapid deterioration; the road may develop severe rutting, localized shear failures, or complete washouts under moving water.

Surface-treated pavements are also particularly vulnerable to subgrade moisture due to their minimal structural thickness. These pavements (common on low-volume roads) rely almost entirely on the aggregate base and subgrade for strength. When the layers under a surface-treated road become saturated, the pavement often exhibits large deflections and rapid deformation under traffic. Excessive rutting can develop not only in the underlying layers but even reflect at the surface after heavy rain events (Transport for NSW 2023). To prevent such outcomes, agencies often apply multiple treatments or a prime coat on the base to improve waterproofing. Still, these treatments remain the most moisture-sensitive pavement type. As a result, design guidelines for surface-treated roads usually assume a worst-case strength for the subgrade (because it will often get wet), and emphasize drainage and maintenance to keep the road serviceable.

APPENDIX B: R&R FRAMEWORK DETAILS

This appendix contains additional details of the R&R framework presented in Section 5 of the main report. Specifically, this appendix presents additional literature review findings and definitions relevant to the R&R framework.

INTRODUCTION

Transportation assets (e.g., bridges and highways) are critical for the functioning of communities—connecting people and freight flow. The growing threats associated with various natural, human-made, and technological hazards, coupled with the aging transportation infrastructure, have made transportation assets highly vulnerable with significant societal and economic impacts (U.S. Department of Homeland Security 2006; American Association of State Highway and Transportation Officials 2013; Federal Highway Administration 2013; American Water Works Association 2014; The Polis Center 2015). As such, it is essential to conduct regular assessments of the risk and resilience of transportation assets to minimize these losses and ensure continuity of vital transportation services. In fact, integrating risk and resilience assessment into transportation infrastructure asset management is also a national imperative (Alder et al. 2020; Federal Highway Administration 2017; Parkany and Ogunye 2016).

Recognizing this important challenge, various federal programs have focused on incorporating risk and resilience assessments into various transportation planning, infrastructure prioritization, project selection and screening, and project scoping processes (U.S. Department of Transportation 2017; Flannery, Pena, and Manns 2018; Weilant, Strong, and Miller 2019). FHWA statutes and regulations require state DOTs and metropolitan planning organizations (MPOs) to include resilience considerations in asset management plans (Dix et al. 2024; Federal Highway Administration 2019). The Biden Administration announced the PROTECT formula program to help states and communities better prepare for and respond to extreme weather events like wildfires, flooding, and extreme heat (Federal Highway Administration 2022). Adherence to these federal mandates and the ability to take a full advantage of the PROTECT formula program requires transportation agencies to have quantitative tools, methods, and measures to identify and prioritize highly critical transportation assets, examine the extent of vulnerability of critical assets, implement risk and resilience assessments on the highly critical assets, evaluate and select cost-effective hazard mitigation alternatives, and continuously reduce the systemic risks and vulnerability in their transportation systems.

Over the past few years, multiple research projects have been implemented by the National Cooperative Highway Research Program, FHWA, and AASHTO to conceptualize transportation asset resiliency and make a business case for the significance of integrating resiliency into various transportation planning, infrastructure prioritization, project selection and screening, and project scoping processes (National Academies of Sciences, Engineering, and Medicine 2021; Sun, Bocchini, and Davison 2018; Proctor, Varma, and Roorda 2016; O'Har, Senesi, and

Molenaar 2016; Filosa et al. 2017). While these efforts have been successful in bringing resiliency into the mainstream discussion of transportation agencies and conceptualizing it for making the business cases and establishing research roadmaps, the critical missing element is an assessment framework with quantitative methods, procedures, and measures that could be used by diverse transportation agencies with varying threat types for different transportation asset classes.

FHWA's *Vulnerability Assessment and Adaptation Framework* is one of only a few available resources (Filosa et al. 2017). However, it provides an overall framework for vulnerability assessment on transportation assets and does not provide quantitative methods, measures, and procedures for such assessment. Recently, the U.S. DOT released its Resilience and Disaster Recovery Tool Suite that enables transportation agencies to assess transportation resilience return on investment for specific transportation assets over a range of potential future conditions and hazard scenarios, which can then be used as a consideration in existing project prioritization processes. This tool is still new; its effectiveness and ease of adoption has not been extensively evaluated by state DOTs. Some state DOTs have also implemented state-specific risk and resilience assessments on their transportation assets (see Table B-1).

Table B-1. State-Specific Risk and Resilience Assessments on Their Transportation Assets.

No.	DOT	Content
1	Texas	Specified network-level criticality and vulnerability of transportation assets in Texas using various quantitative methods and measures.
2	Delaware	Prioritized road infrastructure improvement considering communities' access to critical facilities through network analyses and stakeholder interviews.
3	Colorado	Conducted a pilot risk and resilience assessment on the I-70 corridor to identify critical assets and examine risks and resilience of each asset facing different threats.
4	Michigan	Worked on a statewide resilience plan; started a climate and resilience team to coordinate efforts across the department; and worked with other organizations to develop a resilience assessment tool and completed a vulnerability assessment on their assets.
5	Maryland	Established an office of climate change, resilience, and adaptation; worked on competency training, stakeholder engagement, and staffing/funding resource identification for resilience efforts; and conducted vulnerability assessments for its transportation, bridge, transit system, and port assets.
6	Minnesota	Updated its transportation plan to include resilience and climate, and established a climate and resiliency work group with local partners.
7	Florida	Per a state legislative requirement, developed a resilience action plan that included a full vulnerability assessment of the state transportation system, identification of priorities, and prioritization of projects.

However, the methods and measures were not consistent and uniform across different states and the level of analyses varied widely from state to state. Existing frameworks have either been highly specific—developed independently by individual agencies or in detailed studies focusing on certain asset classes or hazards, such as the Colorado DOT's 2020 Risk and Resilience Analysis Procedure (Colorado Department of Transportation 2020)—or they have proposed a general process-oriented framework without accompanying analytical tools to support decision-making. Agencies are, more than ever, in need of clear, concise methodology and guidance for risk and resilience assessment, formulation of potential interventions, and investment decision-making in the face of potential trade-offs between risk, LCC, and life-cycle performance at the scale of the asset, network, and broader region.

Hence, the goal of this task was to develop an asset risk and resilience assessment framework to enable TxDOT to systemically, quantitatively, uniformly, and consistently integrate resilience into transportation planning, asset management, infrastructure prioritization, project selection and screening, project scoping, and strategic performance assessments. In pursuit of this goal, the specific objectives of this task were threefold:

1. **Identify and screen assets:** The first step was to agree on a limited scope of assets to include in the risk and resilience analysis. This limited number of assets could be identified from the ongoing Statewide Resiliency Plan and the network-level resilience analysis completed in TxDOT Research Project 0-7079. Other information could include historical asset-level damage and disruption data (to identify locations that have experienced multiple events in the past), input from maintenance and operations staff who have on-the-ground experience with assets, and input from community members who have been affected by past events or have insight into conditions that might lead to future damage and disruption.
2. **Pair assets and threats and analyze event likelihood and failure extent:** Risk assessment begins with the identification of hazards (risk sources) and events that may impact assets in the scope of the assessment. TxDOT identified various risk registers during development of its 2022 TAMP. The research team identified additional resources related to climate hazards and other threats as part of this study's tasks and as reported by federal agencies and other organizations so that TxDOT could use them for updating risk registers based on the most recent threat information. Next, the research team developed an analytical framework to assess identified risks based on event probability and the likelihood of asset failure across all potential failure modes given predicted exposure and sensitivity to hazards associated with the event.
3. **Identify and evaluate consequences of events:** The research team developed the R&R framework and delivered guidance for quantifying event consequences. Consequences may include costs associated with damage and disruption and other quantifiable and nonquantifiable measures describing the extent to which an event impacts an asset's ability to deliver its intended performance. The research team captured agency impacts

(i.e., physical damages and costs of repairs) and assessed the likelihood of consequences to adjust potential consequences to the asset's operating context and other factors that are known or can be predicted or modelled. Accordingly, the analytical tool was designed to determine the AAL for the selected assets in their remaining life cycle; the AAL values included agency costs (e.g., costs of repair). The present AAL values were used to prioritize the assets and enabled quantifying the averted losses due to hazard mitigation treatments to determine the B/C ratios.

LITERATURE REVIEW

Risk and Resilience Assessment Definition

Risk/resilience-informed transportation asset management has received much attention and has become mainstream in recent years. Order 5520, published by FHWA in 2014, aimed to improve the preparedness and resilience of transportation infrastructure during climate change and extreme weather events. In 2015, the FAST Act was signed to provide long-term funding for surface transportation to improve transportation resilience. FHWA published a guide to incorporate risk management into transportation asset management plans (TAMPs) in 2017. In the same year, FHWA published the *Vulnerability Assessment and Adaptation Framework* (Filosa et al. 2017) to provide resources for state DOTs and MPOs to analyze the impacts of climate change and extreme weather and integrate vulnerability consideration into decision-making on transportation infrastructure. In 2021, the IIJA required the U.S. DOT to develop a process for quantifying risk to increase transportation system resilience.

The concepts of risk and resilience are sometimes used interchangeably by state DOTs and MPOs. Although they are related, differences between them exist. The National Academies defines resilience as "the ability to prepare and plan for, absorb, recover from, or more successfully adapt to actual or potential adverse events" (National Research Council 2012). According to FEMA, risk is defined as "the potential for an unwanted outcome resulting from an incident, event, or occurrence, as determined by the probability of the occurrence and the severity of the consequences" (Federal Emergency Management Agency n.d.). That is, risk management emphasizes mitigating unwanted outcomes, including but not limited to reducing hazard impacts, mitigating vulnerabilities, and allocating preparedness resources. In contrast, resilience management focuses on the capabilities of rapid recovery and adaptations to adverse events. Although state DOTs and MPOs incorporate risk assessments into transportation planning regularly, a recent study indicated that only a few agencies conducted resilience assessments, and the understanding of the relationship between risk and resilience was inadequate (National Academies of Sciences, Engineering, and Medicine 2018).

Transportation Resilience Assessment

Transportation infrastructure is the backbone of a society, empowering the movement of people and goods safely and efficiently. The 2009 AASHTO-Transportation Research Board Transportation Hazards and Security Summit proposed a comprehensive definition of resilience as "the ability of a system to provide and maintain an acceptable level of service or functionality in the face of major shocks or disruptions to normal operations" (American Association of State Highway and Transportation Officials 2017). Order 5520 (Federal Highway Administration 2014) defines resilience as "the ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions."

State-level transportation agencies have developed different definitions to improve transportation resilience. For example, The Minnesota DOT (2019) includes "reducing vulnerability and ensuring redundancy and reliability to meet essential travel needs" in its resilience definition. The Wisconsin DOT (2009) emphasizes that a resilient transportation system needs "to quickly respond to unexpected conditions and return to its usual operational state." To achieve rapid recovery, Oregon DOT (2009) noted in its *Seismic Vulnerability of Oregon State Highway Bridges: Mitigation Strategies to Reduce Major Mobility Risks* report that "it requires government continuity, resilient physical infrastructure, and business continuity." The Arkansas DOT (2016) stated plans for "improving statewide safety by funding projects reducing fatal and serious injury crashes, reducing vulnerability (the magnitude of impact on the system due to events such as major traffic incidents, flooding, lane closures, bridge failures, and seismic activity), and improving resiliency of the system (the ability of the system to recover from these events). The Colorado DOT (2020) aimed to "improve the resiliency and redundancy of the transportation system to address the potential effects of extreme weather and economic adversity, emergency management, and security." The Hawaii DOT (2014) sought to promote "long-term resiliency, relative to hazard mitigation, namely global climate change, with considerations to reducing contributions to climate change from transportation facilities and reducing the future impacts of climate change on the transportation system" and to "improve the resiliency of the state through the transportation system."

The American Society of Mechanical Engineers (2009) published a framework for critical infrastructure assessment, including transportation. The framework comprised a seven-step process to analyze and mitigate risks from potential terrorist attacks on critical infrastructure assets. The National Academies of Sciences, Engineering, and Medicine (2021) developed a guide to "provide transportation officials with a practical, self-assessment tool to gauge their agency's efforts to improve the resilience of the transportation system by mainstreaming resilience concepts into agency decision-making and procedures." When developing this guide, researchers reviewed current practices by transportation agencies for evaluating resilience and conducting investment analysis for the purpose of restoring and adding resilience. They found that although there had been significant progress in integration of resilience criteria into transportation decision-making, much inconsistency existed in how resilience was measured and assessed. In a previous report, the National Academies of Sciences, Engineering, and Medicine (2016) documented available LCC analysis tools by application level (e.g., asset, project, program, or network) and the challenges involved with such tools.

Risk-Based Asset Management

Per 23 USC §119(e), "A State shall develop a risk-based asset management plan for the National Highway System to improve or preserve the condition of the assets and the performance of the system," where asset management is defined in 23 USC §101(a)(2) as "a strategic and systematic process of operating, maintaining, and improving physical assets, with a focus on both engineering and economic analysis based upon quality information, to identify a structured sequence of maintenance, preservation, repair, rehabilitation, and replacement actions that will achieve and sustain a desired state of good repair over the life cycle of the assets at minimum practicable cost."

FHWA statutes and regulations require state DOTs and MPOs to consider resilience in the transportation planning process and in asset management plans. State DOTs make risk-based decisions from a long-term assessment of the NHS and other public roads included in the plan. The state DOTs have some discretion in this process because it relates to managing physical assets and laying out a set of investment strategies to address the condition and system performance gaps. This process also addresses how the highway network system will be managed to achieve state DOTs targets for asset condition and system performance effectiveness while managing the risks, in a financially responsible manner, at a minimum practicable cost over the life cycle of its assets. In 2017, 23 CFR §515 (i.e., the asset management rule) was put in place, stating that state DOTs shall "develop a risk-based asset management plan that describes how the National Highway System (NHS) will be managed." This requirement included establishing a process for conducting performance gap analysis and life-cycle planning, as well as developing a risk management plan, a financial plan, and investment strategies at minimum. Due to complex nature of risk management, a study of national and international efforts to integrate performance, risk, and asset management was conducted (National Academies of Sciences, Engineering, and Medicine, 2022). This study sought to develop guidance for a process framework that any agency—regardless of current maturity level—could continuously apply to identify how the evolving management practices intersect and how effective integration can be incorporated. This same study also identified the investments needed to drive these changes and the expected benefits and value added for state DOTs. In a previous study, researchers found that only 13 state DOTs had formalized enterprise risk management programs, and even fewer had comprehensive approaches encompassing risk management at the enterprise, program, and project levels National Academies of Sciences, Engineering, and Medicine, 2010). The results of this latter study provided a systematic approach to apply risk analysis tools and management policies to aid state DOTs in controlling project cost growth.

Risk and Resilience Assessment Components

The proposed R&R framework involves the following six components (see Figure 1):

1. **Hazard exposure quantification:** Specifies the magnitude and likelihood of climate hazards and the transportation assets' exposure to these hazards.
2. **Vulnerability assessment:** Examines the susceptibility of transportation infrastructure assets to different hazard magnitudes and specifies the extent of damage/disruption caused by certain hazard magnitudes.
3. **Risk assessment:** Estimates the impacts (in terms of costs) of disruptions and damages in transportation infrastructure assets.
4. **Criticality assessment:** Determines transportation assets that are critical for regional connectivity and functionality of systems for the purpose of prioritizing infrastructure assets for adaptation/mitigation measures and investments.
5. **Adaptation evaluation:** Evaluates adaptation measures to reduce the vulnerability of transportation infrastructure to hazards.
6. **Economic assessment:** Examines the LCCs (including physical damages) that hazards exert on regional transportation networks and the adaptation measure benefits (in terms of avoided losses) to specify the economic feasibility of resilience investments.

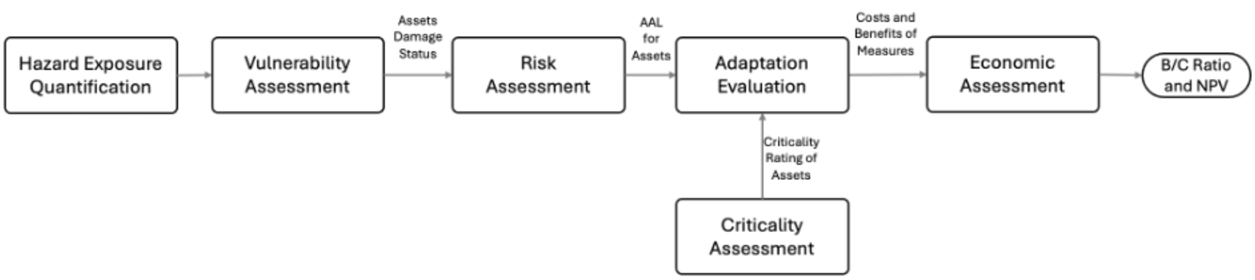

Figure B-1. R&R Framework Components.

Hazard Exposure Quantification

The first step in the R&R framework is to quantify the extent and likelihood of hazard exposure for different transportation assets (see Figure B-2). Depending on the hazard type (e.g., floods, wildfires, earthquakes, landslides), hazard exposure maps could be the primary source of data for matching transportation assets with relevant hazard types (see Table B-2).

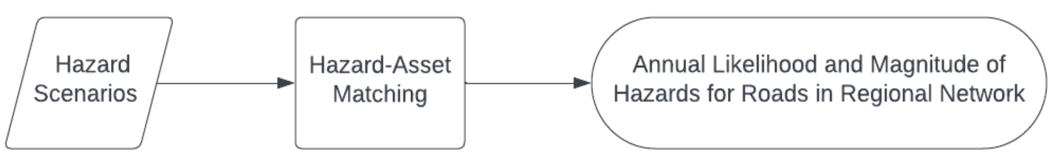

Figure B-2. Hazard Exposure Quantification Process.

Table B-2. Summary of Data, Methods, and Output for Hazard Exposure Quantification.

Data	Methods	Output
• Detailed hazard data products and models • Regional road network topology • Hazard return periods and intensity under climate projection scenarios	• Hazard-asset matching • Annual hazard likelihood estimation • Hazard magnitude estimation at asset level	• Annual likelihood of hazards for different climate projection scenarios • Hazard magnitude for different scenarios

To quantify hazard exposure for transportation assets, the relevant hazard types are first matched to individual transportation assets. Next, the hazard likelihood and magnitude for each asset are determined. A hazard's extent/magnitude can be reflected as flood depths, earthquake ground motion intensities, etc. The magnitude of hazard is used to determine the hazard damage/impact in the vulnerability assessment step. The hazard likelihood is used to determine the annual likelihood of hazards for assets, which is subsequently used to determine the AAL in the risk assessment step.

In this study, the research team focused on floods as the prominent hazard type, which are among the hazards that cause the highest annual losses on road networks worldwide. Next, the research team performed hazard-asset matching using standard hazard maps, such as 5-, 25-, and 100-year floodplain maps. Here, flood maps are used to illustrate hazard exposure quantification assessment, but a similar approach could be implemented for other hazard types. In the first step, GIS shapefiles of hazard maps are overlaid on the regional road network. Accordingly, the overall annual chance of a road asset being flooded can be calculated based on a road segment's percentage of length located in 5-, 25-, and 100-year floodplains. The portion of road segments intersecting with each floodplain was determined, the length percentage of each road segment in each floodplain was calculated, and an overall annual likelihood of inundation was calculated using Equation B-1 as follows:

$$P_F = 0.2 \times L_5 + 0.04 \times L_{25} + 0.01 \times L_{100} \qquad \text{B-1}$$

where L_5, L_{25}, and L_{100} represent the length percentage of each road segment in 5-, 25-, and 100-year floodplains, and P_F is the overall annual chance of inundation (between 0 and 0.2).

The hazard-asset matching step can also be performed using high-resolution hazard models from Fathom or other vendors. High-resolution hazard models provide different return periods for different hazard magnitudes and include different future climate scenarios affecting the return periods of hazards with different magnitudes. For example, flood maps for 2-, 5-, 10-, 25-, 50-, and 100-year return periods under different climate scenarios can be used to quantify the likelihood and magnitude of hazards. Such models provide the most comprehensive data for implementing hazard exposure quantification. These models also enable detailed vulnerability and risk assessments in subsequent steps and ultimately support a probabilistic economic analysis of resilience investments.

Vulnerability Assessment

The second step in the R&R framework is vulnerability assessment, in which the extent of physical damages to transportation infrastructure assets due to the hazards identified and quantified in the previous step are determined (see Figure B-3 and Table B-3). The main task in vulnerability assessment is specifying the extent of physical damage to each asset given the exposed hazard magnitude (identified in the previous step).

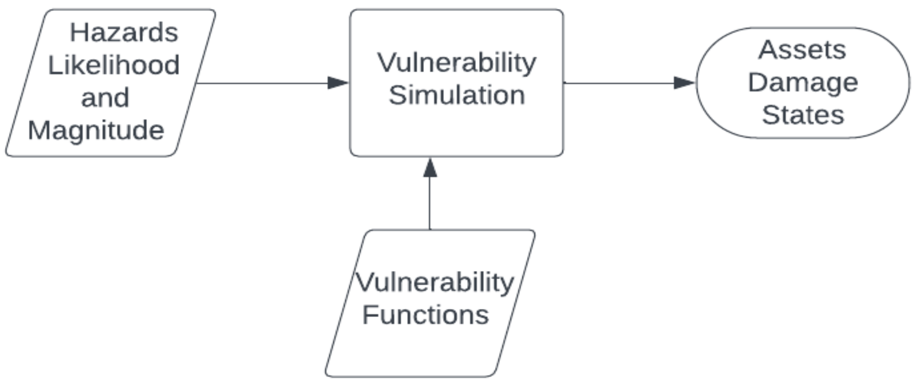

Figure B-3. Vulnerability Assessment Process.

Table B-3. Summary of Data, Methods, and Output for Vulnerability Assessment.

Data	Methods	Output
• Asset-level hazard likelihoods and magnitude • Regional road network topology • Fragility functions/curves	• Probabilistic simulation of annual hazard occurrence during the analysis period (e.g., Monte Carlo simulation)	• Annual damage state for each road and each simulation iteration

In this study, vulnerability assessment involves using fragility curves that specify the extent of damage to an asset given the magnitude of the hazard. For this purpose, empirical fragility curves suggested in the literature could be used. For illustration purposes, the use of empirical fragility curves for road assets exposed to flood hazards is presented here. Fragility functions for roads are available from empirical and computational studies (Gehl and D'Ayala 2015; Williams et al. 2019). While select factors that contribute to the damage state estimation of roads may not be considered, these functions can provide a reliable estimation of damage states given the intensity of the hazard. The development of fragility functions is challenged by soil structure interaction and deterioration, model uncertainties, the modeling of multiple hazard effects, and climate change effects. In this study, the research team adopted an existing mudflow-blocking fragility function to estimate the damage state of each road segment. For each simulation run, the output was the estimated length of the road in each damage state (i.e., no damage, minor damage, moderate damage, major damage), which is further used as a basis for estimating the cost of the hazard. Based on the estimated annual likelihood of inundation, the following steps can be implemented to obtain the annual damage state of roads for vulnerability assessment through Monte-Carlo simulation:

1. **Assign an inundation status to each road segment:** For each road segment, a random number is generated using a uniform distribution, U[0,1]. The inundation probability is considered as the threshold to determine the inundation status. The road segment is considered as inundated if the random number is less than the threshold. Otherwise, no repair cost is associated with the road segment.
2. **Assign a flow volume to each inundated road:** The mud flow can be calculated based on the inundation depth of roads. If high-resolution inundation maps are not available for inundated roads, damage can be estimated using the mudflow-blocking fragility function. The flood flow in each road segment is estimated based on its proximity to the closest river's centerline. Due to the lack of specific data to model flood flow on roads, the research team assumed that the road segment would not encounter floods if its distance is 5,000 meters from the river's centerline, and the flood flow volume decreases linearly with its distance from the river's centerline.
3. **Assign a damage state to each road:** The mudflow-blocking fragility function for local roads at 50 percent (Lam et al. 2018) was used for damage state estimation. This function gives the relationship between the damage state exceedance probability and the flood flow volume. With the flood flow volume calculated, the range of exceedance probability for each damage state could be obtained using the mudflow-blocking fragility function. For each simulation step, a random number is generated using a uniform distribution, U[0,1]. The probability interval that contains this random number determines the damage state of this road segment. For example, if the random number falls in the probability interval for extensive damage, then the damage state of this road segment will be determined as extensive in the current simulation step. Based on Lam et al. (2018), the parameters of μ and β can be derived for a road segment's damage state estimations given the flood flow volume.

Similar fragility curves and equations are available for other hazard types and could be used for vulnerability assessment in the context of other hazard types. The key step in vulnerability assessment is the implementation of probabilistic simulations (e.g., Monte Carlo simulation) to specify the damage state of each road asset in a given year for each iteration of the simulation. When implemented over multiple simulation iterations (e.g., 100 iterations), the distribution of annual damage states for each asset can be obtained and then used in the calculation of the AAL in the risk assessment step.

Risk Assessment

The third step in the R&R framework is risk assessment. Risk assessment involves associating physical costs to road asset damages due to hazard events determined in the vulnerability assessment (see Figure B-4 and Table B-4). In this study, the research team examined agency costs, which included the costs to repair/replace the damaged road segments to restore functionality. Using fragility functions, estimated damage states can be considered as a basis for converting losses due to the cost of repairing damages. Agency costs are estimated based on the length of roads in different damage states and the weighted unit damage cost. Weighted unit repair costs associated with each damage state are calculated based on the characteristics of the road segment.

Figure B-4. Risk Assessment Process.

Table B-4. Summary of Data, Methods, and Output for Risk Assessment.

Data	Methods	Output
• Annual damage state for each road for each simulation iteration • Repair costs for each damage state	• Construction engineering economic analysis	• AAL for each road • Ranking of at-risk assets based on AAL values

The risk assessment in this study involved using the simulated road damages from the vulnerability assessment based on different hazard scenarios. The procedure for estimating agency costs (i.e., repair cost) involved two steps. First, the research team calculated repair costs for each length of damaged road. Using the output of the vulnerability assessment step (i.e., the length of damaged roads in each damage state for different road types), repair costs were estimated based on the length of roads in different damage states and the weighted unit damage costs. Table B-5 lists relative repair costs by damage state. Second, to capture the uncertainty associated with repair cost, the values in Table B-5 were specified using probability distributions estimated based on historical data and expert judgment.

Table B-5. Relative Repair Costs by Damage State.

Damage Status	**Concrete Pavements**			**Asphalt Pavements**		
	Minor Damage	**Moderate Damage**	**Major Damage**	**Minor Damage**	**Moderate Damage**	**Major Damage**
Repair cost	$	$$	$$$$	$	$$	$$

Criticality Assessment

The fourth step in the R&R framework is criticality assessment. Criticality assessment considers the importance of each road asset for the resilience of the regional network when prioritizing investments (see Figure B-5 and Table B-6). Criticality assessments specify which assets—among various road assets in a regional network—should be prioritized for retrofit to maximize the resilience of the overall regional network. Because resilience investment funding is limited, criticality assessment plays a crucial step in informing the allocation of limited funding resources to the most critical road assets in a regional network. Criticality assessment should be performed independently from the previous hazard, vulnerability, and risk assessments. The criticality of a road should be determined based on its importance to the overall connectivity of the regional network, access to critical facility, importance to vulnerable populations, and other criteria. If a road is identified as highly critical and also determined to be at-risk from the previous steps of the assessment, the road should be prioritized for resilience investments. The criticality assessment outcome is a criticality rating or ranking of road assets.

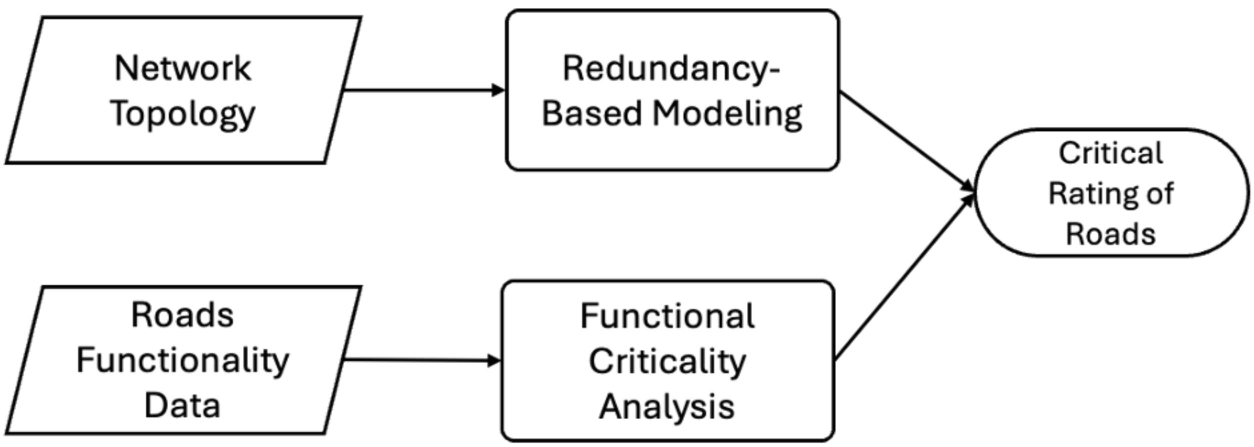

Figure B-5. Criticality Assessment Process.

Table B-6. Summary of Data, Methods, and Output for Criticality Assessment.

Data	Methods	Output
• Regional road network topology • Functionality metrics of each road (e.g., importance for access to critical facilities)	• Redundancy-based analysis (using methods such as the NetworkX Python package) • Multicriteria analysis methods	• Criticality rating of roads and ranking of roads based on their criticality

In this study, the criticality assessment involved capturing multiple criticality metrics for road assets to specify their criticality. The criticality is a measure of transportation assets crucial to the region's routine functions and economic activities (e.g., access to critical facilities). The four criticality metrics adopted in this study included the following:

1. **Connectivity of road segments:** This metric evaluates the vulnerability of road segments to flooding, determining how likely a road is to be impacted by flood events. The metric is based on road elevation, slope, and proximity to flood-prone areas. The flood vulnerability of each road segment is calculated using topographical data and flood hazard maps to assess the exposure of road segments to potential flooding. The data sources include Fathom data to capture elevation and slope, and flood hazard maps obtained from federal or local agencies that delineate flood-prone areas.
2. **Vulnerability to flooding:** This metric measures the centrality of road segments within a transportation network, focusing on how crucial each segment is to overall connectivity. The centrality is calculated by assessing the road segment's role in connecting different parts of the network, its betweenness, and its alternative routes. This task involves analyzing the road network topology and identifying the most critical paths that, if disrupted, would affect a large portion of the network. The required data include road network geometries, which are simplified for computational efficiency and typically sourced from national or regional transportation databases such as OpenStreetMap or local transportation agencies.
3. **Proximity to critical facilities:** This metric assesses the importance of road segments based on their proximity to critical facilities, which are essential during and after flood events for transporting resources and providing services. The criticality of each road segment is calculated by creating a 2,000-meter buffer around the road and counting the number of critical facilities (e.g., hospitals, fire stations, power plants, etc.) within that buffer. Road segments that provide access to a higher number of critical facilities receive higher criticality scores.
4. **Cascading impact of critical infrastructure networks:** This metric evaluates the criticality of road segments based on their proximity to critical infrastructure networks (e.g., electric grids, railroads, oil pipelines, etc.), which can experience cascading failures when a link in the network is disrupted by flood events. Instead of focusing solely on proximity, this metric considers how failure in one part of an infrastructure network can propagate and affect other systems. The criticality score is calculated by analyzing the road segment's closeness to nodes within critical infrastructure networks. Data for this metric include network geometries of critical infrastructures (e.g., transmission lines, railroads, pipelines, etc.) and are sourced from Spectus and the ArcGIS Open Data Portal. The infrastructure networks are simplified into node-and-link models to facilitate the calculation of interdependencies and cascading impacts.

Criticality of road assets can be determined based on their importance in the overall connectivity of the regional network. Such topology-based evaluation of criticality also captures the extent of redundancy in the network. Critical roads are roads with no redundancy; if they experience disruptions, alternative routes would not be available to connect certain origins and destinations. Such topology-based evaluation of road criticality is implemented independent of the hazard exposure and vulnerability of assets. If a critical road is determined to be also highly at risk, then it should be prioritized for resilience investments.

Adaptation Evaluation

The fifth step in the R&R framework is adaptation evaluation. Adaptation evaluation involves specifying proper adaptation measures for improving the resilience of road assets and determining the costs and benefits of implementing the identified adaptation measures (see Figure B-6 and Table B-7). In this step, proper adaptation measures are specified for the critical and at-risk road assets. Based on the adaptation measures, the costs and benefits of implementing the adaptation measures are quantified. The quantified costs and benefits are then used in the subsequent step—the B/C analysis. The steps for implementing adaptation evaluation are as follows:

1. For critical and at-risk road assets (obtained from the previous steps of the assessment), identify suitable adaptation measures.
2. Estimate the cost of implementing the adaptation measure for each critical and at-risk road asset.
3. Estimate the benefits of implementing in terms of reduction in vulnerability and risk (measured based on avoided AAL).

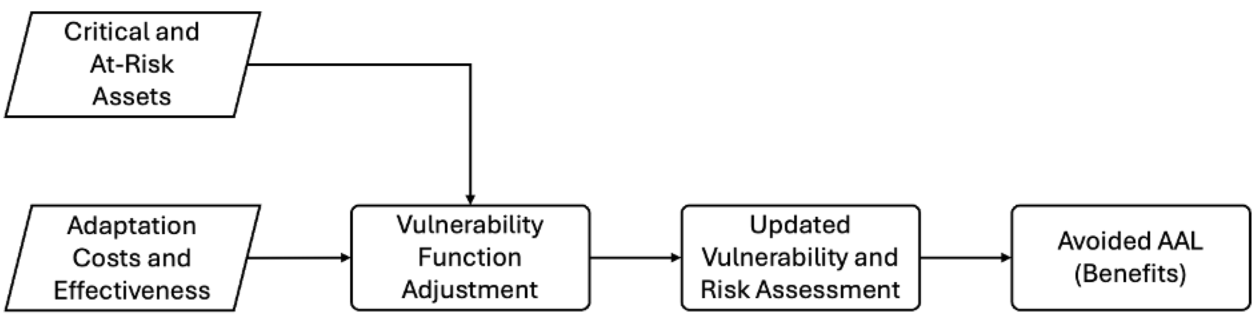

Figure B-6. Adaptation Evaluation Process.

Table B-7. Summary of Data, Methods, and Output for Adaptation Evaluation.

Data	Methods	Output
• Critical and at-risk road assets • Adaptation measures for different road types • Adaptation measure costs and effectiveness	• Vulnerability function adjustment based on adaptation measures effectiveness • Re-implementation of vulnerability and risk assessment	• Avoided AAL (i.e., difference in AAL with and without with adaptation)

In this study, adaptation evaluation involved examining specific adaptation measures based on the characteristics of road assets and estimating their costs. The research team considered adaptation costs using probability distributions to capture the uncertainty associated with the costs of adaptation measures. For quantifying the benefits, adaptation evaluation determined the extent to which the selected adaptation measure would reduce the vulnerability of the road asset. Accordingly, the vulnerability function or the fragility curve in the vulnerability assessment was adjusted based on the level of effectiveness of the adaptation measures, and the vulnerability and risk assessments were implemented with the adjusted vulnerability functions/fragility curves and the updated AAL for the road asset after implementation. Consider this example for adjustment of vulnerability functions due to adaptation measures. A road that would have experienced major damage under a 1.5-meter flood exposure would experience minor damage after the implementation of the adaptation measure. Accordingly, the avoided AAL is calculated based on AAL values before and after implementing adaptation measures. The specification of the effectiveness of adaptation measures and the adjustment of vulnerability functions for different adaptation measures is performed based on expert judgment. Hence, proper sensitivity analysis should be done to examine the sensitivity of the calculated avoided AALs and the resulting B/C ratios in subsequent steps based on the adaptation effectiveness assumptions made.

The type of adaptation/mitigation measures would depend on asset type, condition, and hazard type. Some key adaptation and hazard mitigation measures for road infrastructure subjected to floods and other climate hazards include the following:

- **Elevating roads:** Raising the level of roads above the flood line can prevent inundation during floods. This measure is especially effective in areas prone to frequent or severe flooding.
- **Improving drainage systems:** Enhancing the capacity of drainage systems along roads helps to quickly channel away floodwater, reducing water accumulation and the risk of road damage.
- **Use of permeable materials:** Building roads with permeable materials allows water to seep through the surface, reducing runoff and the potential for flooding.
- **Reinforcing road infrastructure:** Strengthening road foundations and surfaces to withstand extreme weather conditions, such as heavy rainfall, strong winds, and temperature fluctuations, can prolong the lifespan of the roads.
- **Slope stabilization:** In hilly or mountainous areas, stabilizing slopes adjacent to roads can prevent landslides and rockfalls, which are often triggered by heavy rain or seismic activity.

Estimation of unit costs for implementing adaptation and hazard mitigation measures on existing roads, particularly against flood and other climate hazards, can be complex and varies significantly based on geographical location, project scale, local labor and material costs, and the specific road conditions.

Economic Assessment

The sixth and final step in the R&R framework is economic assessment. Economic assessment involves establishing the cash flow model associated with the costs and benefits (i.e., avoided AAL) of resilience investments and implementation of adaptation measures (see Table B-8). The steps for implementing resilience economic assessment include the following:

1. Based on the resilience investment budget and costs of adaptation measures, calculate the number of road assets (or length of roads) that could receive adaptation measures in the regional networks.
2. Use the total costs of adaptation measures as the initial resilience investment capital outlay.
3. For the road assets involved in the resilience investment analysis, aggregate their avoided AAL.
4. Discount the avoided AAL (benefits) and adaptation costs (costs) to present values using a specified discount factor.
5. Calculate the B/C ratios (based on the discounted benefits and costs) and the NPV for the total resilience investment.

The specification of a discount rate should consider the social benefits of resilience investments and the extent to which social benefits could be quantified and incorporated into the analysis. The selected analysis period is usually between 20 and 35 years. Usually a discounted rate of 8–12 percent is used in the economic assessment of resilience investments. If the social benefits of resilience investments in transportation infrastructure in a region are difficult to quantify (but the social benefits are known to be significant), a lower discount rate should be used to avoid discounting future social benefits for the communities.

In this study, economic assessment involved incorporating the costs and benefits (i.e., avoided AAL) of resilience investment using probability distributions. Because the costs and benefits were obtained based on probabilistic simulations of hazard exposure likelihoods, probabilistic fragility functions, and risk assessment, the economic analysis could be performed in a probabilistic way to show the range of variation in the expected B/C ratios and NPVs of resilience investments. In addition, the previous steps—from hazard exposure quantification to risk assessment to adaptation evaluation—can be performed for different climate projection scenarios (e.g., shared socioeconomic pathways 4.5 or 8.5), and the associated hazard return periods/magnitudes, B/C ratio, and NPV can be obtained for each climate projection scenario to better understand the economic viability of resilience investments.

Table B-8. Summary of Data, Methods, and Output for Economic Assessment.

Data	Methods	Output
• Costs of adaptation projects • Benefits of adaptation projects (avoided AAL) • Analysis period (20–35 years) • Discount rate (6–12%)	• Discounted cash flow analysis • B/C analysis	• B/C ratio and NPV

SUMMARY

This appendix described work performed in Task 7 of TxDOT Research Project 0-7191: Develop Systematic and Quantitative Approach to Assess the Probability of Extreme Weather and Resilience Risks for TxDOT Highways and Bridges. Task 7 was specifically focused on designing an assets risk and resilience assessment framework. The objective of this task was to create an analytical decision-making framework for probabilistic scenario simulations to prioritize assets for maintenance and retrofit based on climate stressors and the asset's criticality and implement probabilistic resilience economic analysis for adaptation strategies for critical assets.

The proposed R&R framework was not only able to determine the economic metrics of resilience investments but was also able to incorporate various aspects of uncertainty (including hazard exposure, cost estimation, and climate projection). The Task 7 research team applied the proposed framework to an initial case study (FM521) and used outputs from Tasks 4, 6, 7, and 9 to model the medium- and long-term costs of pavement damage caused by flooding. For FM521, the framework assessed long-term pavement repair costs over a series of flood events, assuming the existing infrastructure remained unchanged. It then applied the same models and data to evaluate the damage and costs under strategies that either reduced flood risk or mitigated flood damage. Ultimately, the framework compared the cost differences between the *in-place* infrastructure and *adapted* management strategies. In the future, the framework will be expanded to address bridge damage and acute pavement damage, and will be continually refined and improved through its application in FM521.

APPENDIX C: R&R FRAMEWORK CASE STUDIES

INTRODUCTION

This appendix presents a series of 10 case studies (see Table C-1) conducted as part of TxDOT Research Project 0-7191, which aimed to develop a systematic and quantitative approach for assessing the probability of extreme weather and resilience risks for TxDOT highways and bridges. Each case study evaluated a critical highway corridor in Texas, analyzing its exposure, vulnerability, and risk to flooding hazards under both current (2020) and future (2060) climate scenarios.

The methodology employed across these studies involved several key steps including quantifying hazard exposure using flood depth data, assessing the criticality of road segments based on their role in the transportation network, evaluating vulnerability through damage-state projections, and calculating the financial risk in terms of AAL. Finally, the economic viability of a targeted adaptation strategy (e.g., upgrading pavement structures on high-risk segments) was assessed using a B/C analysis.

The findings from these 10 distinct corridors—ranging from coastal and major metropolitan routes to inland rural highways—provided critical insights into the escalating challenges posed by flooding. The results were intended to equip TxDOT with a data-driven framework to prioritize investments and enhance the long-term resilience of the state's vital transportation infrastructure.

Table C-1. Selected Case Studies.

No.	Case
1	FM521
2	SH0006—N. Houston to Bayou Vista
3	SH0006—Bryan/College Station to Hempstead US0290
4	SH0006—Waco to Bryan/College Station
5	US0290—Austin to Houston
6	SH0288—Port Freeport to Houston
7	US0087—Victoria to Port Lavaca
8	SH0359—Laredo to San Diego US0044
9	SH0124—High Island to Beaumont
10	US0027/US0039—Kerr County

CASE NO. 1: FM521

Background

The FM521 case study is in located in Matagorda County, Texas, in TxDOT's Yoakum District, and spans 94.55 miles (see Figure C-1). It is a two-lane highway with a seal coat surface. This segment was selected due to its exposure to extreme weather conditions, such as hurricanes (i.e., Hurricane Harvey in 2017).

Figure C-1. **FM521 Case Study: (a) Location and (b) Typical Pavement Surface View.**

Hazard Exposure Quantification

To quantify hazard (e.g., flooding) exposure, the research team utilized TWDB's cursory floodplain data (Texas Water Development Board 2025a) using 2020 existing condition and 2060 future condition scenarios. This dataset provides probability frequencies of annual fluvial, pluvial, and coastal flood events across various return periods (e.g., 5-, 10-, 25-, 100-, and 500-year).

The research team segmented the road into discrete management sections based on TxDOT's established divisions. Figure C-2 visually illustrates the annual likelihood of pluvial flooding for both the 100- and 500-year return periods, projected for the 2020 existing scenario and the 2060 future scenario. This study's results revealed a significant increase in pluvial flood exposure over time. The research team observed that in the 2020 scenario, a considerable length of road experienced high (higher than average) exposure to pluvial flooding (19.19 miles for the 100-year return period and 26.42 miles for the 500-year return period). A visual comparison of Figure C-2(c) and Figure C-2(d) to Figure C-2(a) and Figure C-2(b) indicated that the situation becomes more serious in the 2060 scenario flooding with an increased number/wider spread of high-likelihood segments (22.00 miles for the 100-year return period and 30.67 miles for the 500-year return period). This finding underscores the escalating challenges posed by flooding events to Texas transportation infrastructure in the coming decades.

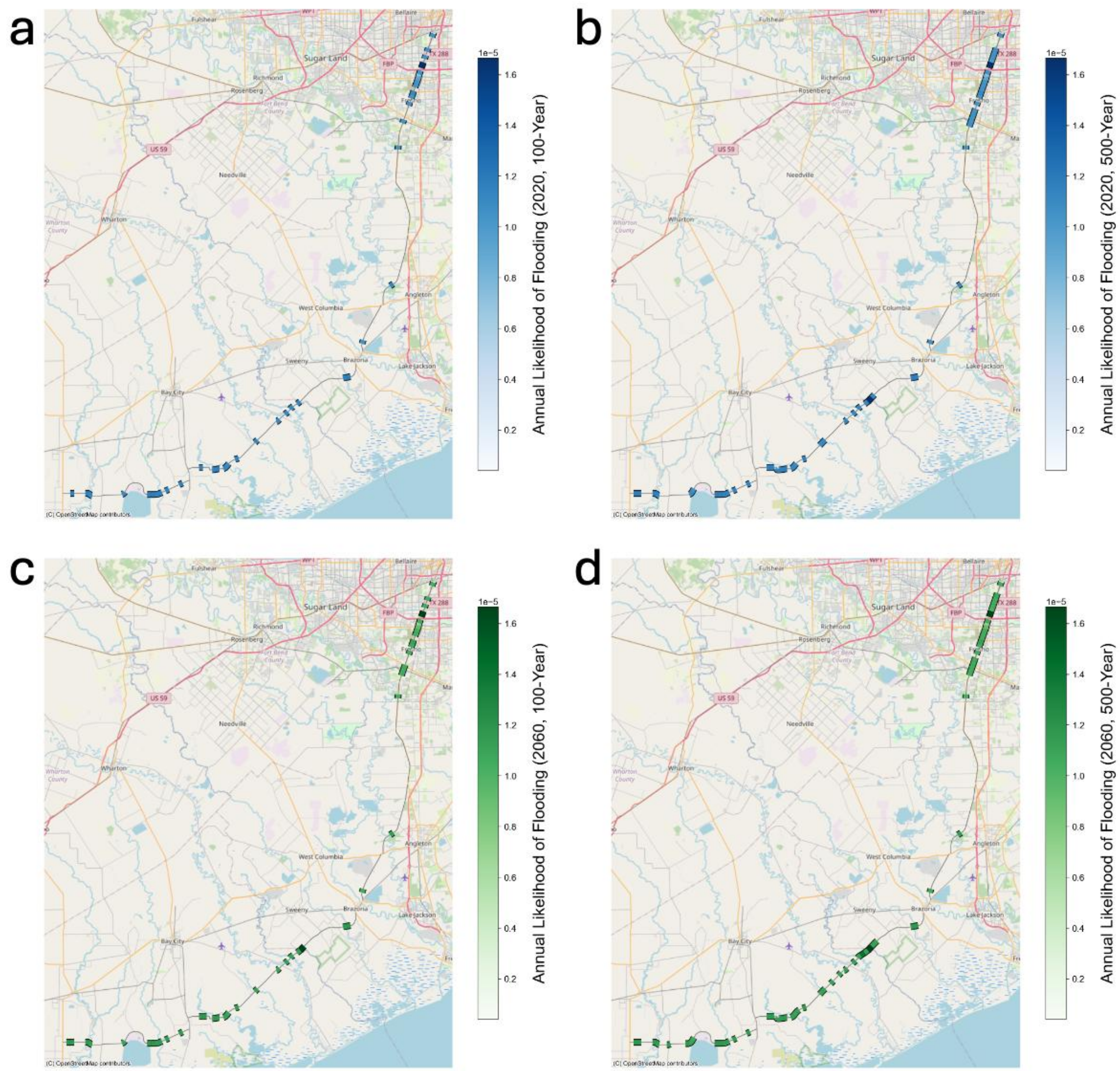

Figure C-2. Annual Likelihood of Pluvial Flooding for the FM521 Case Study: (a) 100-Year Return Period and 2020 Scenario, (b) 500-Year Return Period and 2020 Scenario, (c) 100-Year Return Period and 2060 Scenario, and (d) 500-Year Return Period and 2060 Scenario.

Criticality Assessment

The research team employed multifaceted metrics to evaluate the criticality level of the road segments. Here, *criticality* refers to the intrinsic importance of a road segment based on its role within the transportation network and its connection to essential services and infrastructure. The research team's assessment was based on the following three metrics:

- **Network connectivity:** This metric evaluates the potential for a road segment to become isolated, thereby disrupting connectivity within the broader transportation network.
- **Proximity to essential facilities:** This metric assesses a road segment's importance based on its proximity to vital community facilities such as hospitals, emergency services, schools, and critical infrastructure.
- **Cascading impact on critical facility networks:** This metric evaluates the potential for a road segment's disruption to trigger cascading failures within interconnected critical infrastructure networks, such as gas lines, oil pipelines, and power grids.

Figure C-3 illustrates overall criticality levels for FM521, with L1 representing the most critical segments and L4 indicating the least critical. This spatial distribution synthesizes the contributions of the individual criticality metrics—network connectivity, proximity to essential facilities, and cascading impact on critical facility networks—using an average weighted sum. This visualization pinpoints the most vulnerable and essential road segments along the FM521 corridor. Quantitatively, the most critical segments (L1) comprised 3.55 miles of FM521, while the least critical segments (L4) accounted for 27.40 miles of the road.

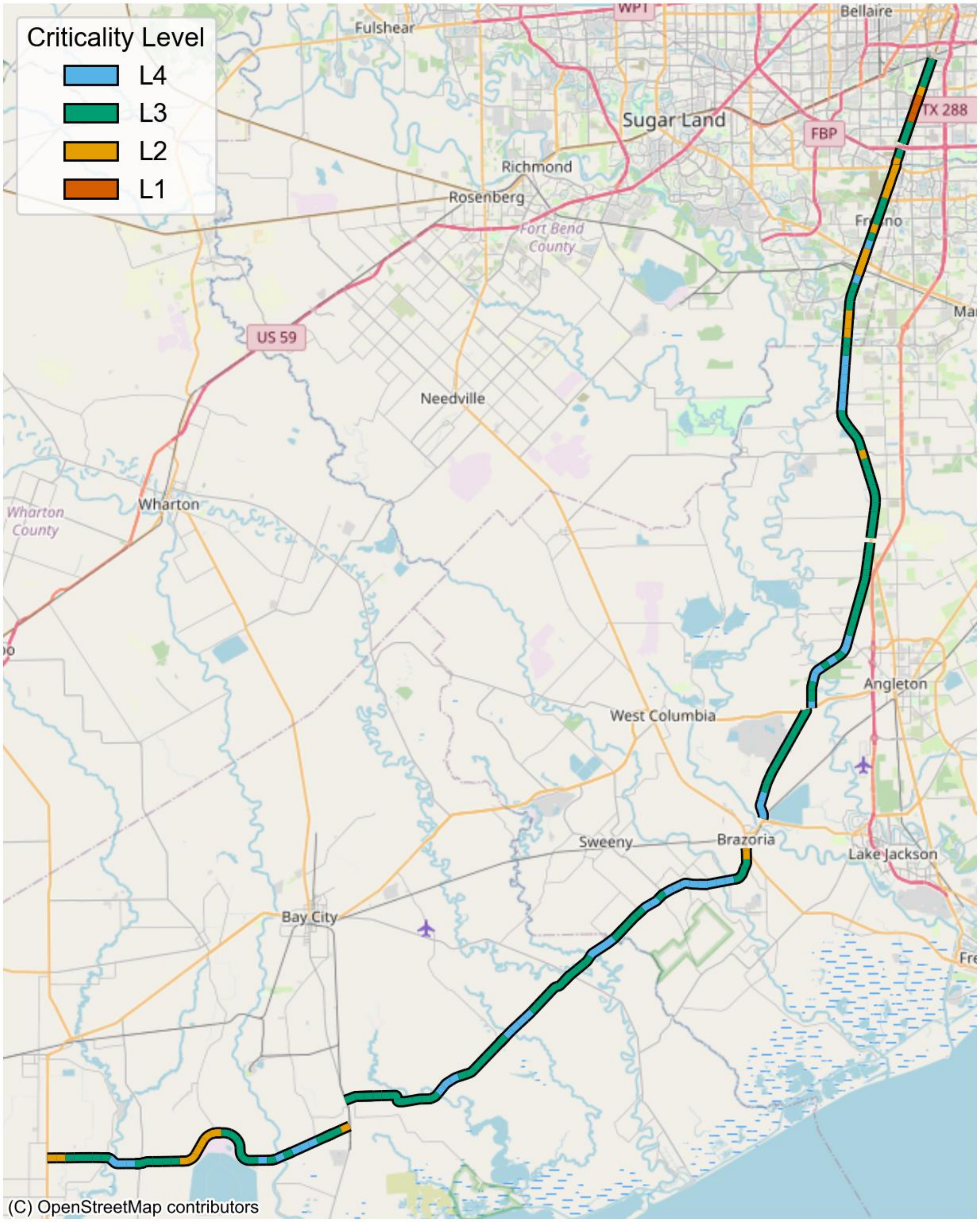

Figure C-3. Criticality Levels for the FM521 Case Study.

Vulnerability Assessment

To assess the vulnerability of FM521, the research team applied the fragility curve function from Task 6. This function establishes a probability distribution that quantifies the likelihood of a road segment sustaining a specific level of damage under varying flood conditions. The research team categorized damage into four distinct levels based on the probability of flooding:

1. **Minor damage:** The probability of flooding is < 5 percent.
2. **Moderate damage:** The probability of flooding is ≥ 5 percent but < 15 percent.
3. **Major damage:** The probability of flooding is ≥ 15 percent but < 50 percent.
4. **Severe damage:** The probability of flooding is ≥ 50 percent.

Table C-2 and Table C-3 and the spatial distribution map in Figure C-4 present the aggregated damage lengths for FM521 under different flood types (i.e., pluvial, fluvial, and coastal) and return periods (i.e., 5-, 10-, 25-, 100-, and 500-year) for both the 2020 existing scenario and 2060 future scenario.

Table C-2. Damage Length by Flood Type and Return Period under the 2020 Scenario for the FM521 Case Study.

Damage Length	Pluvial					Fluvial					Coastal				
	1-in-5	1-in-10	1-in-25	1-in-100	1-in-500	1-in-5	1-in-10	1-in-25	1-in-100	1-in-500	1-in-5	1-in-10	1-in-25	1-in-100	1-in-500
Minor	79.49	77.77	76.20	72.00	64.77	84.84	82.69	82.69	80.38	66.01	91.58	91.04	91.04	90.52	88.38
Moderate	0.77	1.25	2.82	6.04	7.79	0.00	0.00	0.00	1.46	7.67	0.00	0.00	0.00	0.00	0.53
Major	7.21	6.35	5.34	7.31	11.11	1.00	0.00	0.00	2.40	9.01	0.52	0.00	0.00	0.52	0.54
Severe	4.63	6.73	7.74	6.75	8.32	6.26	9.40	9.40	7.85	9.40	0.00	1.06	1.06	1.06	2.65

Table C-3. Damage Length by Flood Type and Return Period under the 2060 Scenario for the FM521 Case Study.

Damage Length	Pluvial					Fluvial					Coastal				
	1-in-5	1-in-10	1-in-25	1-in-100	1-in-500	1-in-5	1-in-10	1-in-25	1-in-100	1-in-500	1-in-5	1-in-10	1-in-25	1-in-100	1-in-500
Minor	76.73	75.69	74.19	69.19	60.5	83.77	82.69	82.36	78.89	64.58	91.04	91.04	90.52	89.44	86.82
Moderate	2.28	3.33	2.99	6.37	8.67	0.00	0.00	0.00	2.47	6.43	0.00	0.00	0.00	0.00	1.55
Major	5.82	5.82	6.12	8.26	11.96	1.01	0.00	0.34	2.89	11.21	0.00	0.00	0.52	1.08	2.66
Severe	7.26	7.26	8.80	8.28	10.96	7.32	9.40	9.40	7.85	9.88	1.06	1.06	1.06	1.58	1.06

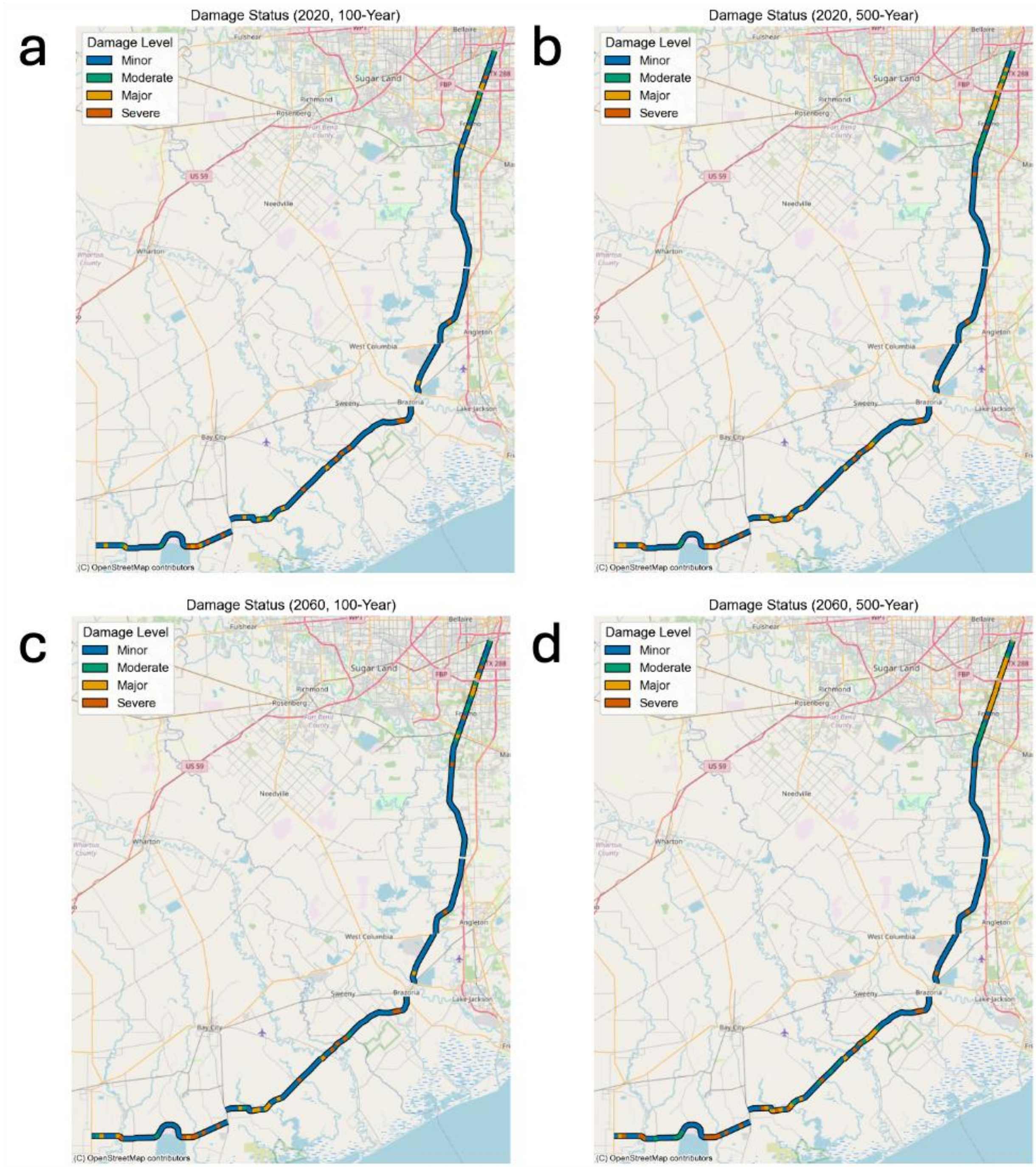

Figure C-4. Damage Status of Pluvial Flooding for the FM521 Case Study: (a) 100-Year Return Period and 2020 Scenario, (b) 500-Year Return Period and 2020 Scenario, (c) 100-Year Return Period and 2060 Scenario, and (d) 500-Year Return Period and 2060 Scenario.

For all flood types, as event intensity increased, the percentage of road segments experiencing minor damage generally decreased, while moderate, major, and severe damage proportions increased. This trend was particularly evident for pluvial and fluvial flooding. Comparative analyses between flood types revealed that pluvial flooding generally affected a larger percentage of the road at major damage levels for lower return periods. However, for extreme events like the 1-in-500-year flood, fluvial and pluvial damage lengths for major and severe categories became comparable to, or even exceeded, the damage lengths from coastal events. Furthermore, the research team anticipated a substantial increase in vulnerability in the future scenario, with significant increases expected in segments categorized with moderate, major, and severe damage across all flood types and return periods.

Risk Assessment

This section quantifies the financial implications of flood damage to road segments by calculating the AAL. The AAL represents the expected average monetary loss per year due to flood events, providing a critical metric for economic risk assessment and the prioritization of mitigation efforts. Table C-4 and Table C-5 present the AALs for the road segments, categorized by flood type (i.e., pluvial, fluvial, and coastal), and return period (i.e., 5-, 10-, 25-, 100-, and 500-year) for both the 2020 existing scenario and 2060 future scenario. All values are expressed in thousands of U.S. dollars ($K).

As the return period increased, the total AAL generally increased. This relationship indicated that despite their less frequent occurrence, more extreme flood events were projected to incur substantially higher costs due to severe damage requiring heavy rehabilitation. For example, the pluvial AAL increased from $50.91K (1-in-5-year) to $107.55K (1-in-500-year) in 2020, and from $62.45K (1-in-5-year) to $128.03K (1-in-500-year) in 2060. Furthermore, for both the 2020 and 2060 scenarios, pluvial and fluvial flooding consistently contributed the largest components to the total AAL, particularly for the higher return periods.

Analysis of damage status contributions revealed that severe damage consistently accounted for the largest proportion of the AAL across most return periods and flood types. This finding highlighted that while minor, moderate, and major damages were more frequent, the economic burden was primarily driven by the high costs associated with repairing severely damaged segments. For example, for the 1-in-500-year pluvial event in 2060, severe damage alone contributed $67.67K to the total $128.03K AAL.

Lastly, a crucial insight from comparisons of the 2020 and 2060 scenarios is the substantial increase observed in the AAL for most categories in the future scenario. For instance, the total AAL for a 1-in-100-year pluvial event increased from $77.84K in 2020 to $94.08K in 2060. Similarly, the 1-in-500-year coastal AAL increased from $17.60K in 2020 to $18.71K in 2060. This projected increase in AAL directly translates to higher long-term maintenance and repair budgets needed to maintain the functionality of FM521 under future climate conditions. These AAL calculations provided a critical economic perspective on flood risk, enabling stakeholders to understand the magnitude of potential financial impacts and to prioritize investments in flood resilience and adaptation measures for FM521.

Table C-4. Annual Average Loss by Flood Type and Return Period under the 2020 Scenario for the FM521 Case Study.

Damage Status	Pluvial					Fluvial					Coastal				
	1-in-5	1-in-10	1-in-25	1-in-100	1-in-500	1-in-5	1-in-10	1-in-25	1-in-100	1-in-500	1-in-5	1-in-10	1-in-25	1-in-100	1-in-500
Minor	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Moderate	2.83	3.69	7.64	13.56	17.45	0.00	0.00	0.00	3.42	19.05	0.00	0.00	0.00	0.00	1.36
Major	22.36	18.10	14.81	23.94	38.34	3.21	0.00	0.00	7.11	28.47	1.73	1.73	0.00	1.73	1.85
Severe	25.72	37.03	42.26	40.35	51.75	41.17	59.33	59.33	49.55	57.75	0.00	0.00	5.72	5.72	14.39
Total	50.91	58.81	64.70	77.84	107.55	44.39	59.33	59.33	60.08	105.28	1.73	1.73	5.72	7.44	17.60

Table C-5. Annual Average Loss by Flood Type and Return Period under the 2060 Scenario for the FM521 Case Study.

Damage Status	Pluvial					Fluvial					Coastal				
	1-in-5	1-in-10	1-in-25	1-in-100	1-in-500	1-in-5	1-in-10	1-in-25	1-in-100	1-in-500	1-in-5	1-in-10	1-in-25	1-in-100	1-in-500
Minor	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Moderate	6.27	8.89	6.93	15.61	20.94	0.00	0.00	0.00	5.86	15.25	0.00	0.00	0.00	0.00	3.87
Major	16.31	16.31	19.44	27.08	39.43	3.03	0.00	0.52	8.61	36.27	0.00	0.00	1.73	3.72	9.13
Severe	39.87	39.87	52.55	51.39	67.67	46.66	59.33	59.33	49.55	60.04	5.72	5.72	5.72	8.47	5.71
Total	62.45	65.07	78.92	94.08	128.03	49.69	59.33	59.85	64.02	111.56	5.72	5.72	7.44	12.19	18.71

Adaptation Evaluation

This section describes the effectiveness of the proposed adaptation strategy by quantifying the avoided AAL. Avoided AAL represents the financial benefit gained from implementing an adaptation strategy, indicating the reduction in expected annual flood-related damages. It is calculated as the difference between the AAL in a baseline scenario (without intervention) and the AAL after implementing a specific adaptation strategy (improvement scenario). The research team then calculated the B/C ratio to assess the economic viability of the adaptation strategy. A B/C ratio > 1 signifies that the benefits (avoided losses) outweighed the costs of adaptation, indicating a favorable investment. A B/C ratio < 1 suggests that the costs exceed the benefits.

The research team designed an example adaptation strategy that enhanced the road pavement structure. The baseline scenario assumed the existing road structure was a seal coat pavement with a *flexible* base. The improvement scenario assumed upgrading the structure to a seal coat pavement with a *stabilized* base. The research team derived the unit costs per lane-mile from average bid costs over the last 12 months (as of January 2025) within TxDOT's Yoakum District. For this evaluation, the research team focused improvement efforts on severely damaged and highly critical road segments.

Table C-6 and Table C-7 present the avoided AALs, adaptation costs, and B/C ratios for pluvial, fluvial, and coastal flooding across various return periods (i.e., 5-, 10-, 25-, 100-, and 500-year) under the 2020 existing scenario and 2060 future scenario. All values are again expressed in thousands of U.S. dollars (K$).

Table C-6. Adaptation Strategy Effectiveness by Flood Type and Return Period under the 2020 Scenario for the FM521 Case Study.

	Pluvial					Fluvial					Coastal				
	1-in-5	1-in-10	1-in-25	1-in-100	1-in-500	1-in-5	1-in-10	1-in-25	1-in-100	1-in-500	1-in-5	1-in-10	1-in-25	1-in-100	1-in-500
AAL-baseline	50.91	58.81	64.70	77.84	107.55	44.39	59.33	59.33	60.08	105.28	1.73	1.73	5.72	7.44	17.60
AAL-improvement	30.99	28.33	29.33	52.61	77.18	4.64	2.34	2.34	12.53	50.06	1.73	1.73	0.38	2.11	4.16
Avoided AAL	19.92	30.48	35.37	25.23	30.37	39.75	56.99	56.99	47.55	55.22	0.00	0.00	5.34	5.33	13.44
Adaptation Cost	12.73	19.26	22.39	16.00	19.22	24.05	26.14	26.14	31.77	69.31	0.00	0.00	3.28	3.28	8.23
B/C	1.56	1.58	1.58	1.58	1.58	3.11	2.73	2.73	2.68	2.45	0.00	0.00	1.63	1.63	1.63

Table C-7. Adaptation Strategy Effectiveness by Flood Type and Return Period under the 2060 Scenario for the FM521 Case Study.

	Pluvial					Fluvial					Coastal				
	1-in-5	1-in-10	1-in-25	1-in-100	1-in-500	1-in-5	1-in-10	1-in-25	1-in-100	1-in-500	1-in-5	1-in-10	1-in-25	1-in-100	1-in-500
AAL-baseline	62.45	65.07	78.92	94.08	128.03	49.69	59.33	59.85	64.02	111.56	5.72	5.72	7.44	12.19	18.71
AAL-improvement	29.44	32.06	43.68	64.16	87.21	4.83	2.34	2.86	16.47	54.21	0.38	0.38	2.11	4.28	13.38
Avoided AAL	33.01	33.01	35.24	29.92	40.82	44.86	56.99	56.99	47.55	57.35	5.34	5.34	5.33	7.91	5.33
Adaptation Cost	22.04	22.04	23.62	20.16	27.18	16.08	20.91	20.91	17.77	54.21	3.28	3.28	3.28	4.89	3.28
B/C	1.50	1.50	1.49	1.48	1.50	2.79	2.73	2.73	2.68	1.06	1.63	1.63	1.63	1.62	1.63

Generally, almost all B/C ratios for both 2020 and 2060 were > 1, which signified that the benefits of implementing the pavement improvement strategy consistently outweighed the costs of adaptation across all analyzed flood types, return periods, and climate change scenarios. The research team also noticed that the avoided AAL generally increased with higher return periods, indicating that the adaptation strategy became more effective in preventing losses from more severe and less frequent flood events. For instance, in 2020, the avoided AAL for pluvial flooding increased from $19.92K (1-in-5-year) to $30.37K (1-in-500-year). A significant increase in avoided AAL was also observed when comparing the 2020 and 2060 scenarios, reflecting an increased baseline flood risk in the future. For the 1-in-500-year pluvial event, the avoided AAL increased from $30.37K in 2020 to $40.82K in 2060. This upward trend in avoided AAL in the future scenario highlighted the growing importance of such adaptation measures. (For this case, the B/C analysis was performed separately for pluvial, fluvial, and coastal flood types. Subsequent cases used a combined flooding approach and presented an overall B/C ratio.)

Summary

This section evaluates FM521 for its risk and resilience to flooding. Using the Cursory Floodplain dataset, flooding exposure for pluvial, fluvial, and coastal events under different return periods (i.e., 5-year, 10-year, 25-year, 100-year, and 500-year) for both the 2020 existing scenario and 2060 future scenario was quantified. Vulnerability assessment categorized damage levels and indicated a general trend of increasing severe damage across flood types and return periods, particularly in the 2060 scenario. Risk was quantified through AAL, which showed an escalation with higher return periods and a projected substantial increase by 2060. An adaptation strategy involving pavement structure improvement was then evaluated for its effectiveness in reducing flood damage costs. This strategy yielded B/C ratios greater than 1 across almost all flood types, return periods, and both 2020 and 2060 scenarios, confirming its economic viability for enhancing FM521's flood resilience. These findings imply the critical need for proactive transportation infrastructure investment to mitigate escalating flood risks and ensure the long-term functionality of FM521.

CASE NO. 2: SH0006—N. HOUSTON TO BAYOU VISTA

Background

SH0006—N. Houston to Bayou Vista is a critical transportation corridor in the Houston District, spanning 123.93 miles (see Figure C-5). The highway was selected for this case study due to its significant exposure to a combination of flood hazards in a major metropolitan and coastal area.

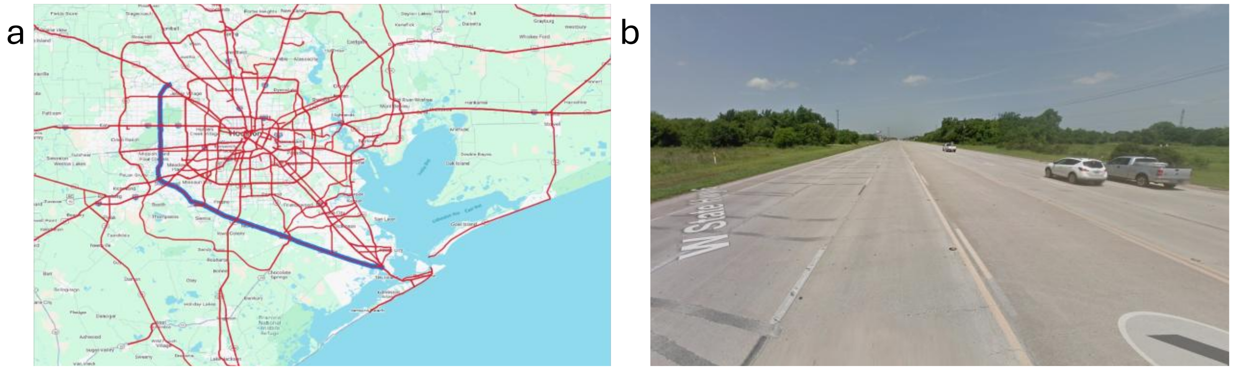

Figure C-5. SH0006—N. Houston to Bayou Vista Case Study: (a) Location and (b) Typical Pavement Surface View.

Hazard Exposure Quantification

To quantify hazard exposure, the research team again utilized the TWDB's cursory floodplain data (Texas Water Development Board 2025a) for both the 2020 existing condition and the 2060 future condition. Unlike Case 1, this analysis considered the combined flooding effects of pluvial, fluvial, and coastal events to provide a holistic view of the flood risk.

Figure C-6 visually illustrates the annual likelihood of combined flooding for both the 100- and 500-year return periods across the 2020 and 2060 scenarios. This study's results revealed a substantial and increasing exposure to flooding over time. In the 2020 scenario, a significant length of the highway experienced high (higher than average) exposure with 74.69 miles affected in a 100-year return period and 86.96 miles affected in a 500-year return period. The situation was projected to worsen by 2060, with the length of highly exposed roadway increasing to 77.24 miles for a 100-year event and 93.25 miles for a 500-year event.

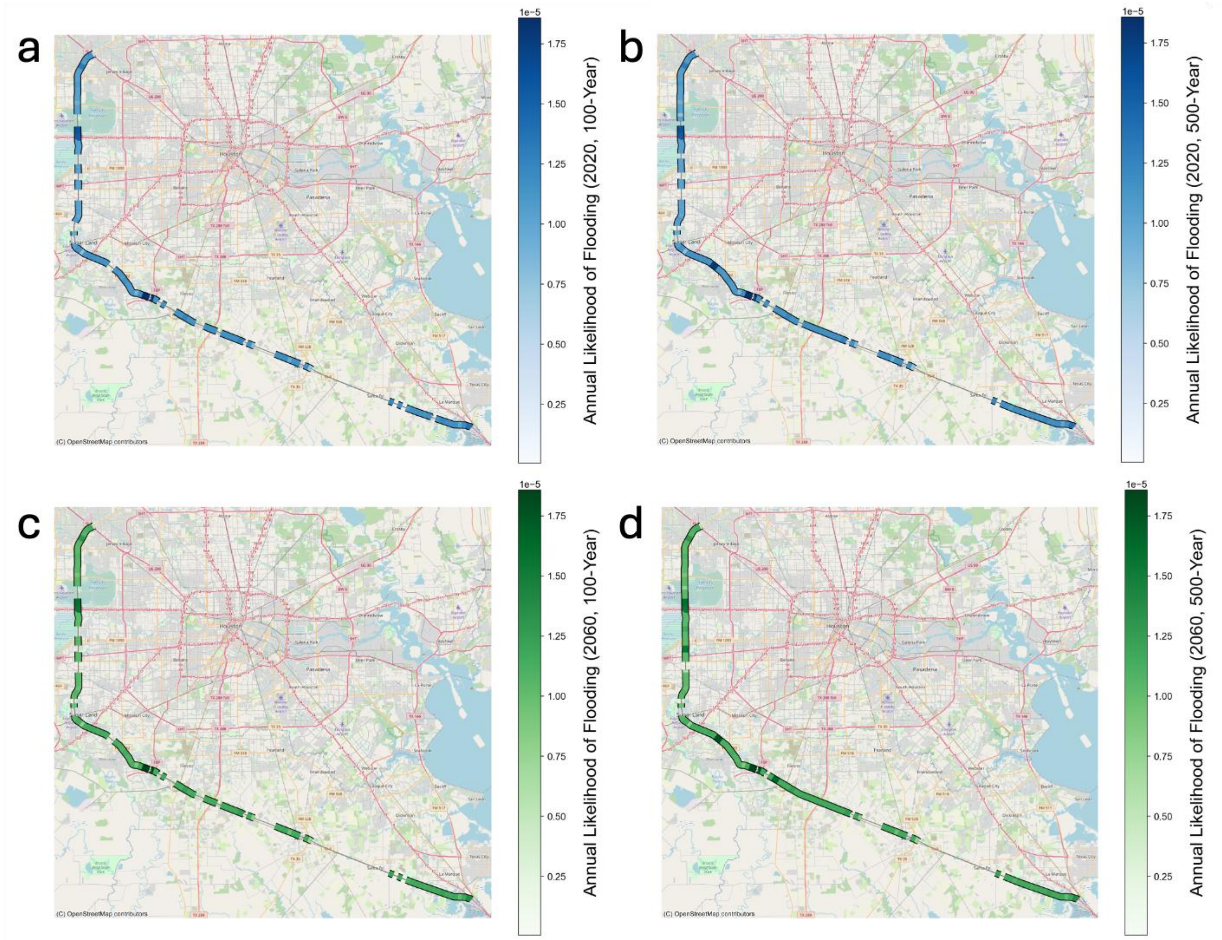

Figure C-6. Annual Likelihood of Flooding for the SH0006—N. Houston to Bayou Vista Case Study: (a) 100-Year Return Period and 2020 Scenario, (b) 500-Year Return Period and 2020 Scenario, (c) 100-Year Return Period and 2060 Scenario, and (d) 500-Year Return Period and 2060 Scenario.

Criticality Assessment

The research team employed the same multifaceted metrics in Case 1 to determine the overall criticality level of SH0006—N. Houston to Bayou Vista (see Figure C-7). Quantitatively, the most critical segments (L1) comprised 10.91 miles of the highway; the remaining segments were classified as L2 (37.46 miles), L3 (51.70 miles), and L4 (23.86 miles).

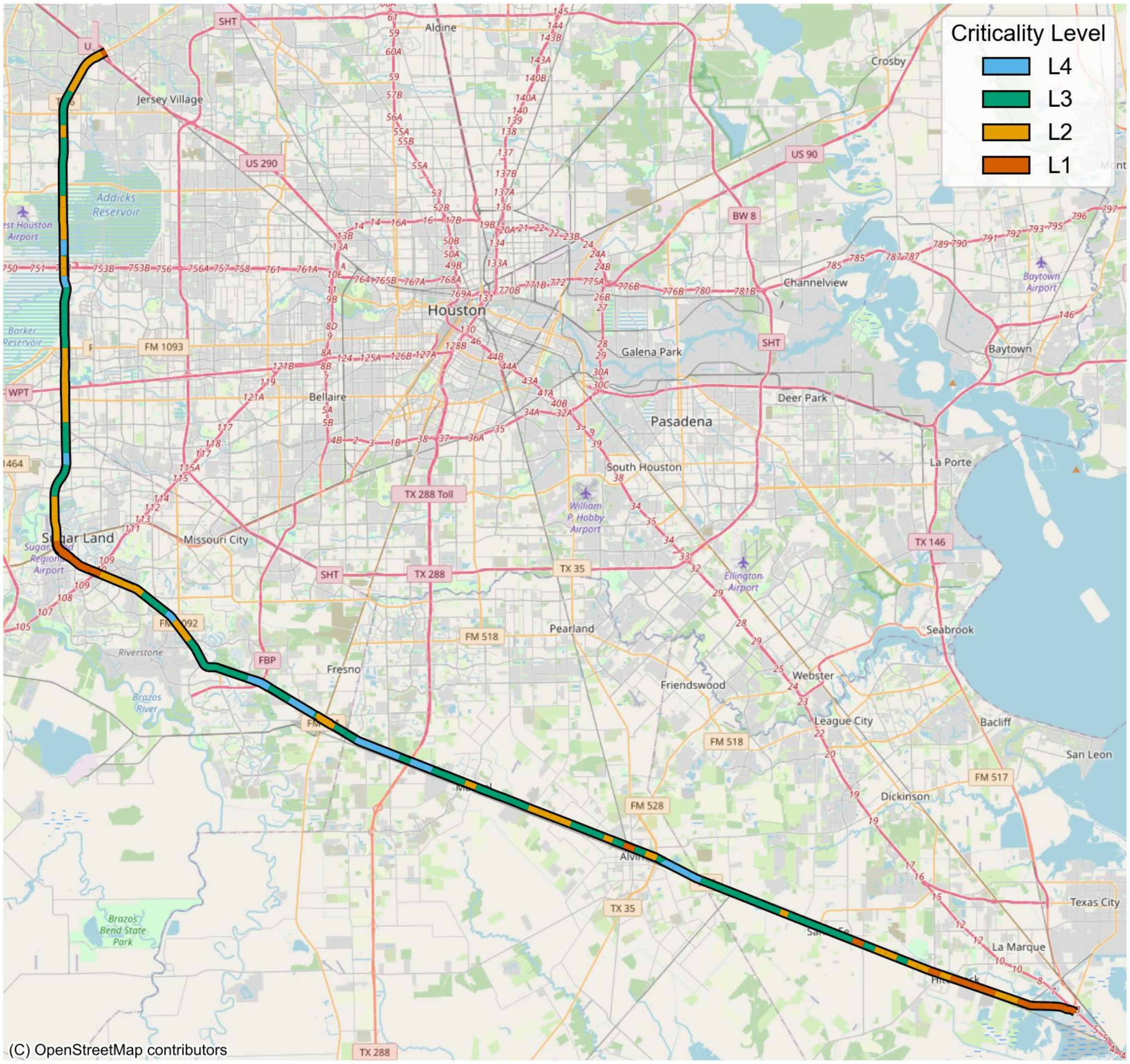

Figure C-7. Criticality Levels for the SH0006—N. Houston to Bayou Vista Case Study.

Vulnerability Assessment

To assess the vulnerability of SH0006—N. Houston to Bayou Vista, the research team applied the fragility curve function to determine the likelihood of a road segment sustaining specific levels of damage under varying combined flood conditions. Damage was categorized into four levels—minor, moderate, major, and severe.

As the intensity of the flood event (i.e., return period) increased, the length of road segments with minor damage decreased, while the length with major and severe damage increased (see Figure C-8 and Table C-8). In the 2020 100-year scenario, 43.78 miles would sustain minor damage, while 43.26 miles would sustain major damage. In the 2060 100-year scenario, the length with major damage increased to 50.01 miles. This trend highlighted a substantial increase in the highway's vulnerability in the future, with a significant increase anticipated in segments categorized with moderate, major, and severe damage across all return periods.

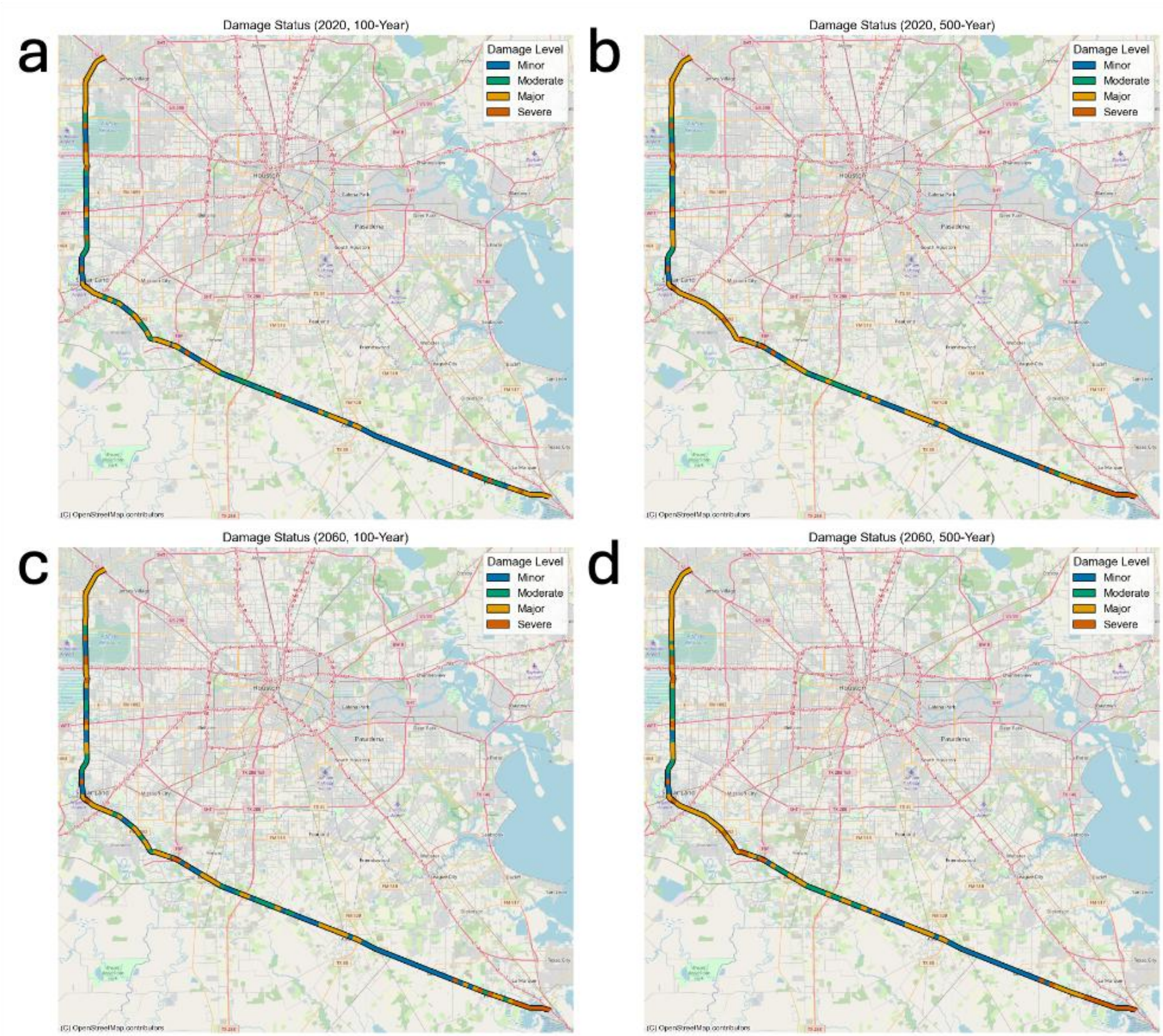

Figure C-8. Damage Status of Flooding for the SH0006—N. Houston to Bayou Vista Case Study: (a) 100-Year Return Period and 2020 Scenario, (b) 500-Year Return Period and 2020 Scenario, (c) 100-Year Return Period and 2060 Scenario, and (d) 500-Year Return Period and 2060 Scenario.

Table C-8. Damage Length by Return Period under the 2020 and 2060 Scenarios for the SH0006—N. Houston to Bayou Vista Case Study.

Damage Length	Combined-2020					Combined-2060				
	1-in-5	1-in-10	1-in-25	1-in-100	1-in-500	1-in-5	1-in-10	1-in-25	1-in-100	1-in-500
Minor	82.32	67.38	56.68	43.78	31.16	71.01	61.66	52.59	41.23	24.59
Moderate	14.80	21.11	24.70	26.48	21.86	17.60	22.12	23.55	22.77	24.98
Major	20.70	25.94	34.76	43.26	58.51	26.85	31.94	39.49	50.01	61.90
Severe	8.66	12.06	10.35	9.98	14.96	11.04	10.77	10.86	12.48	15.03

Risk Assessment

This section quantifies the financial implications of combined flood damage by calculating the AAL. The total AAL increased significantly with the return period, indicating that less frequent, more extreme flood events were projected to cause substantially higher economic losses (see Table C-9). In the 2020 scenario, the total AAL increased from $162.53K for a 1-in-5-year event to $316.45K for a 1-in-500-year event. Analysis of the damage contributions revealed that major and severe damage consistently accounted for the largest proportion of the AAL.

Crucially, a comparison between the 2020 and 2060 scenarios revealed a substantial projected increase in financial risk. For a 1-in-100-year event, the total AAL was expected to increase from $255.38K in 2020 to $273.53K in 2060. For the 1-in-500-year event, the AAL increased from $316.45K to $337.42K. This projected increase in the AAL underscores the increasing long-term maintenance and repair costs required to maintain the functionality of SH0006—N. Houston to Bayou Vista under future climate conditions.

Table C-9. Annual Average Loss by Return Period under the 2020 and 2060 Scenarios for the SH0006—N. Houston to Bayou Vista Case Study.

Damage Status	Combined-2020					Combined-2060				
	1-in-5	1-in-10	1-in-25	1-in-100	1-in-500	1-in-5	1-in-10	1-in-25	1-in-100	1-in-500
Minor	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Moderate	30.17	43.07	50.56	54.66	45.61	35.54	44.67	47.56	46.44	54.87
Major	56.24	67.53	90.06	122.96	153.39	71.23	85.19	105.41	130.82	162.27
Severe	76.12	105.86	83.08	77.76	117.44	96.21	89.47	91.64	96.27	120.28
Total	162.53	216.46	223.70	255.38	316.45	202.98	219.33	244.60	273.53	337.42

Adaptation Evaluation

This section describes the economic viability of a proposed adaptation strategy by quantifying the avoided AAL and calculating the B/C ratio. The strategy involved upgrading the pavement structure on severely damaged and highly criticality road segments.

The results were compelling (see Table C-10). The B/C ratio was significantly > 1 across all analyzed return periods and scenarios, signifying that the financial benefits of implementing the pavement improvement strategy consistently and substantially outweighed the costs. The analysis also showed that the avoided AAL generally increased with higher return periods in the future scenario, indicating the strategy's growing value in preventing losses from more severe flood events. For the 1-in-500-year event, the avoided AAL increased from $114.47K in 2020 to $117.3K in 2060. This finding highlighted the increasing importance and economic justification for implementing such adaptation measures proactively.

To provide a single but comprehensive measure of economic viability, an overall B/C Ratio was then calculated. This metric represents the total expected benefit (avoided AAL) across all flood scenarios divided by the total cost (adaptation costs). This overall B/C ratio provided a single, powerful number that represented the total expected dollars saved for every dollar spent on the adaptation strategy, considering the full spectrum of potential flood events. For the 2020 scenario, the overall B/C ratio was 5.98, indicating that for every dollar invested in adaptation, nearly six dollars in future damage costs were avoided. This ratio remained exceptionally strong in the 2060 scenario at 5.64, confirming the long-term value of the investment.

Table C-10. Adaptation Strategy Effectiveness by Return Period under the 2020 and 2060 Scenarios for the SH0006—N. Houston to Bayou Vista Case Study.

	Combined-2020					Combined-2060				
	1-in-5	1-in-10	1-in-25	1-in-100	1-in-500	1-in-5	1-in-10	1-in-25	1-in-100	1-in-500
AAL-Baseline	162.53	216.46	223.70	255.38	316.45	202.98	219.33	244.60	273.53	337.42
AAL-Improvement	87.26	111.96	142.15	179.30	201.98	108.13	131.22	154.30	179.85	220.12
Avoided AAL	75.27	104.5	81.55	76.08	114.47	94.85	88.11	90.30	93.68	117.3
Adaptation Cost	7.79	12.43	13.97	15.44	25.98	12.43	12.43	12.30	22.65	25.98
B/C	9.66	8.41	5.84	4.93	4.41	7.63	7.09	7.34	4.14	4.52
Overall B/C	5.98					5.64				

Summary

This case study evaluated the risk and resilience of SH0006—N. Houston to Bayou Vista to combined flooding. The analysis quantified a significant and growing flood exposure, with projections indicating that over 93 miles of the highway would be in high-exposure zones during a 500-year event by 2060. The vulnerability assessment revealed a corresponding increase in expected damage, with a growing number of segments facing major and severe impacts. Consequently, the financial risk—quantified as the AAL—was projected to increase substantially, with a 1-in-500-year event potentially costing over $337K annually by 2060. An adaptation strategy involving targeted pavement improvements was evaluated and found to be highly cost-effective, with B/C ratios consistently > 1. These findings underscore the critical need for proactive investment in transportation infrastructure to mitigate the escalating flood risks and ensure the long-term functionality and economic viability of SH0006—N. Houston to Bayou Vista.

CASE NO. 3: SH0006—BRYAN/COLLEGE STATION TO HEMPSTEAD US0290

Background

This segment of SH0006 runs from the Bryan/College Station area to Hempstead at US0290. It is a key corridor within TxDOT's Bryan District, spanning 148.78 miles (see Figure C-9).

Figure C-9. SH0006—Bryan/College Station to Hempstead US0290 Case Study: (a) Location and (b) Typical Pavement Surface View.

Hazard Exposure Quantification

The analysis for this corridor also considered the combined flooding effects of pluvial, fluvial, and coastal events. Figure C-10 shows a clear and growing exposure to flooding over time. In the 2020 scenario, a significant length of the highway experienced high exposure, with 72.19 miles affected in a 100-year return period and 80.65 miles in a 500-year return period. This exposure was projected to increase by 2060, with the length of highly exposed roadway growing to 77.72 miles for a 100-year event and 85.21 miles for a 500-year event.

Criticality Assessment

Figure C-11 shows results of the criticality assessment for this segment of SH0006. Quantitatively, the most critical segments (L1) comprised 10.61 miles of the highway; the remaining segments were classified as L2 (37.52 miles), L3 (49.50 miles), and L4 (51.15 miles).

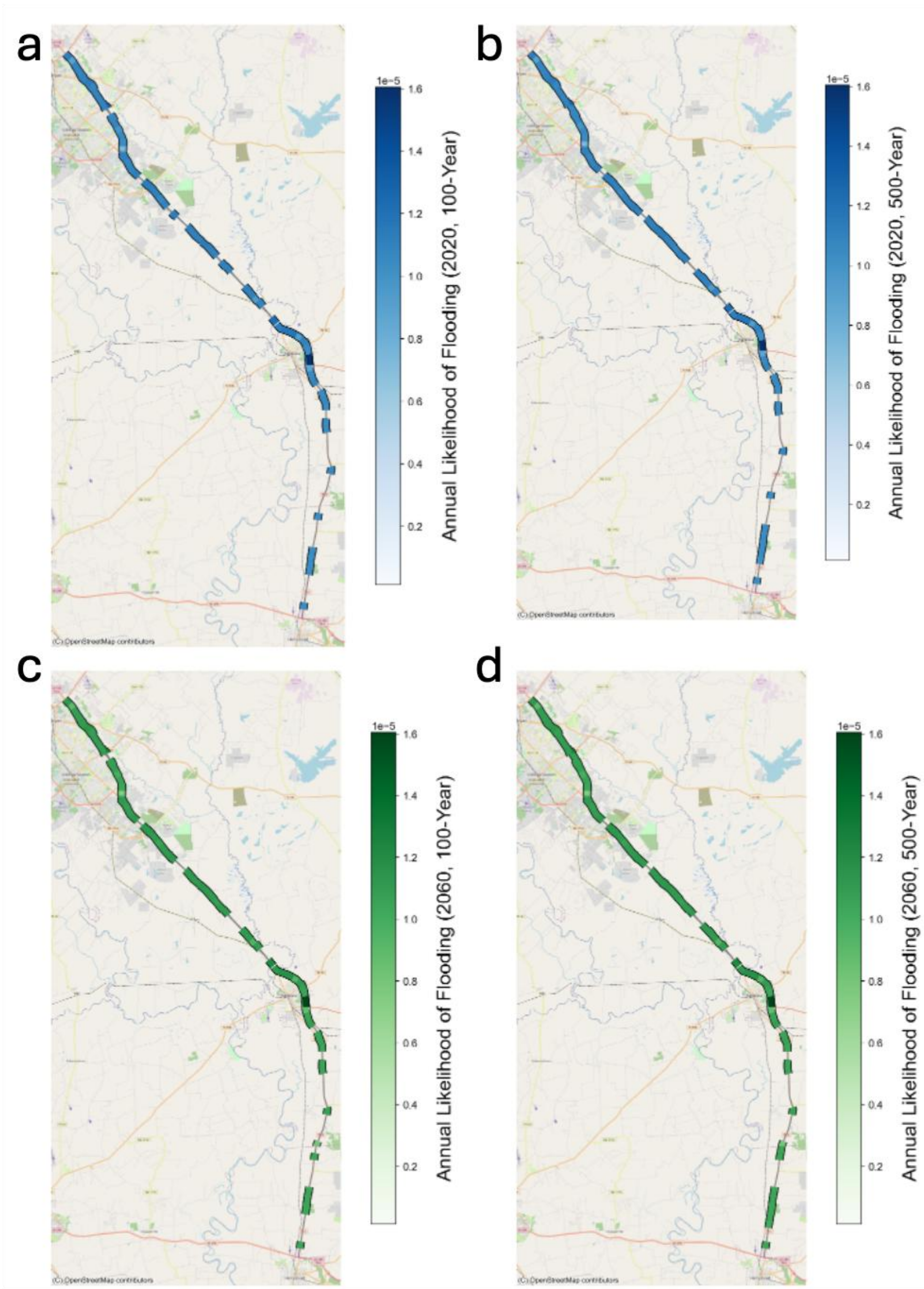

Figure C-10. Annual Likelihood of Flooding for the SH0006—Bryan/College Station to Hempstead US0290 Case Study: (a) 100-Year Return Period and 2020 Scenario, (b) 500-Year Return Period and 2020 Scenario, (c) 100-Year Return Period and 2060 Scenario, and (d) 500-Year Return Period and 2060 Scenario.

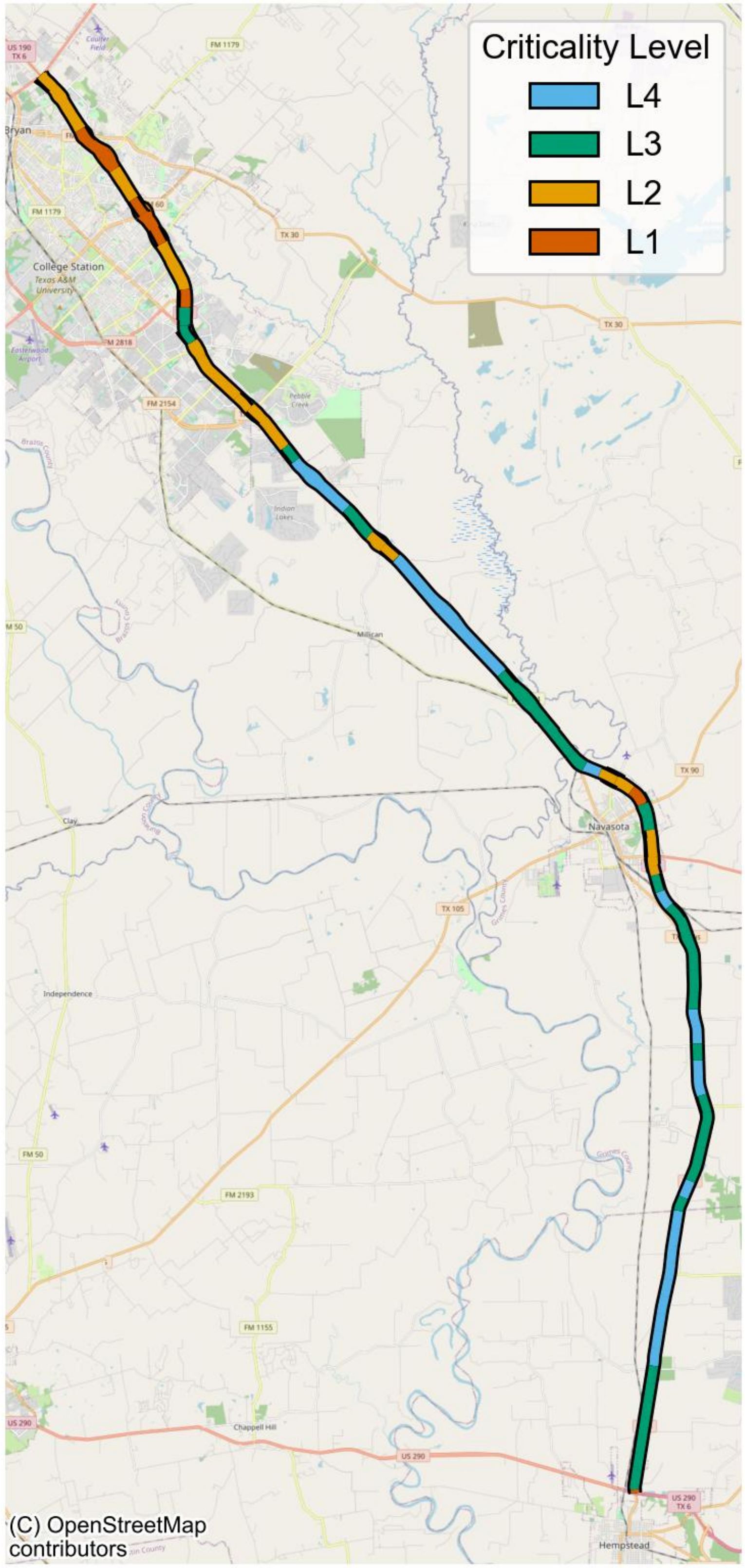

Figure C-11. Criticality Levels for the SH0006—Bryan/College Station to Hempstead US0290 Case Study.

Vulnerability Assessment

This highway's vulnerability to damage increased with the intensity of the flood event (see Figure C-12 and Table C-11). As the return period increased, the length of road segments with minor damage decreased, while segments sustaining major and severe damage increased. For instance, in the 2020 100-year scenario, 40.04 miles were expected to have major damage. By the 2060 100-year scenario, this length increased to 46.59 miles. This trend indicated a substantial increase in this highway's future vulnerability.

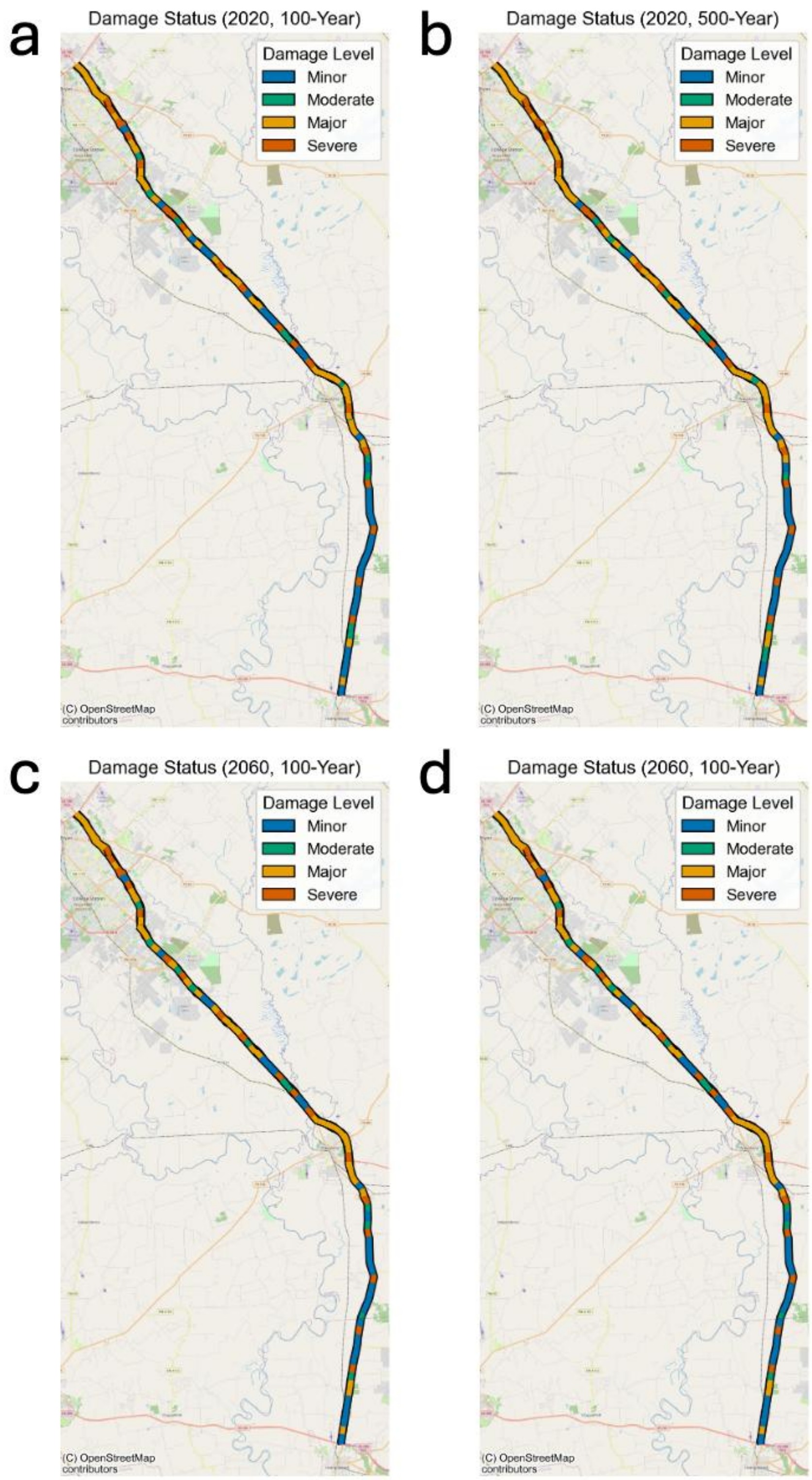

Figure C-12. Damage Status of Flooding for the SH0006—Bryan/College Station to Hempstead US0290 Case Study: (a) 100-Year Return Period and 2020 Scenario, (b) 500-Year Return Period and 2020 Scenario, (c) 100-Year Return Period and 2060 Scenario, and (d) 500-Year Return Period and 2060 Scenario.

Table C-11. Damage Length by Return Period Uding the 2020 and 2060 Scenarios for the SH0006—Bryan/College Station to Hempstead US0290 Case Study.

Damage Length	Combined-2020					Combined-2060				
	1-in-5	1-in-10	1-in-25	1-in-100	1-in-500	1-in-5	1-in-10	1-in-25	1-in-100	1-in-500
Minor	114.05	94.40	83.34	71.60	62.25	103.34	83.55	72.26	65.69	57.31
Moderate	6.43	10.87	11.78	16.71	17.65	10.14	15.89	17.53	18.59	18.07
Major	17.31	28.50	35.16	40.04	51.48	23.33	31.32	39.46	46.59	57.55
Severe	10.38	14.40	17.89	19.82	16.79	11.36	17.41	18.91	17.29	15.24

Risk Assessment

The financial implications of the combined flood damage were quantified using the AAL (see Table C-12). The total AAL increased significantly with the return period, from $148.17K for a 1-in-5-year event to $312.30K for a 1-in-500-year event in the 2020 scenario. A comparison between the 2020 and 2060 scenarios revealed a substantial projected increase in financial risk. For a 1-in-100-year event, the total AAL was expected to increase from $299.02K in 2020 to $305.95K in 2060. For the 1-in-500-year event, the AAL increased to $320.90K.

Table C-12. Annual Average Loss by Return Period under the 2020 and 2060 Scenarios for the SH0006—Bryan/College Station to Hempstead US0290 Case Study.

Damage Status	Combined-2020					Combined-2060				
	1-in-5	1-in-10	1-in-25	1-in-100	1-in-500	1-in-5	1-in-10	1-in-25	1-in-100	1-in-500
Minor	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Moderate	13.63	23.80	25.90	37.87	39.75	22.02	34.58	39.08	41.90	40.56
Major	55.60	89.45	109.72	124.88	158.83	74.37	98.48	122.54	144.97	177.67
Severe	78.94	100.99	121.50	136.27	113.72	85.20	116.47	126.79	119.08	102.67
Total	148.17	214.25	257.13	299.02	312.30	181.58	249.54	288.41	305.95	320.90

Adaptation Evaluation

Table C-13 shows the economic viability of the proposed pavement upgrade strategy. The B/C ratio was significantly > 1 across all analyzed return periods and scenarios, signifying that the financial benefits of the adaptation consistently outweighed the costs. For the 2020 scenario, the B/C ratio ranged from 4.44 for a 1-in-5-year event to 3.37 for a 1-in-500-year event. The analysis also showed that the avoided AAL was substantial, reaching $132.16K for a 100-year event in 2020 and $115.51K for the same event in 2060, highlighting the economic justification for proactive adaptation.

To simplify the economic analysis, an overall B/C ratio was calculated by summing all benefits (avoided AAL) and costs across the different return periods. The analysis yielded an overall B/C ratio of 4.16 for the 2020 scenario. This high ratio demonstrated a very strong return on investment. The economic justification for the project became even stronger in the future, with the overall B/C ratio increasing to 4.41 for the 2060 scenario.

Table C-13. Adaptation Strategy Effectiveness by Return Period under the 2020 and 2060 Scenarios for the SH0006—Bryan/College Station to Hempstead US0290 Case Study.

	Combined-2020					Combined-2060				
	1-in-5	1-in-10	1-in-25	1-in-100	1-in-500	1-in-5	1-in-10	1-in-25	1-in-100	1-in-500
AAL-Baseline	148.17	214.25	257.13	299.02	312.30	181.58	249.54	288.41	305.95	320.90
AAL-Improvement	71.15	116.36	139.58	166.86	202.16	98.46	137.19	165.93	190.44	221.44
Avoided AAL	77.02	97.89	117.55	132.16	110.14	83.12	112.35	122.48	115.51	99.46
Adaptation Cost	17.33	28.26	36.04	37.49	32.73	18.81	37.61	39.20	32.70	29.50
B/C	4.44	3.46	3.26	3.53	3.37	4.42	2.99	3.12	3.53	3.37
Overall B/C	4.16					4.41				

Summary

For the SH0006—Bryan/College Station to Hempstead US0290 case study, the risk and resilience analysis quantified a significant and growing flood exposure. The AAL was projected to increase by 2060. The adaptation strategy involving targeted pavement improvements was found to be highly cost-effective. These findings underscored the need for proactive investment to mitigate escalating flood risks and ensure the long-term functionality of this corridor.

CASE NO. 4: SH0006—WACO TO BRYAN/COLLEGE STATION

Background

This segment of SH0006 provides a key connection between Waco and the Bryan/College Station area. The analyzed corridor spans 133.49 miles (see Figure C-13).

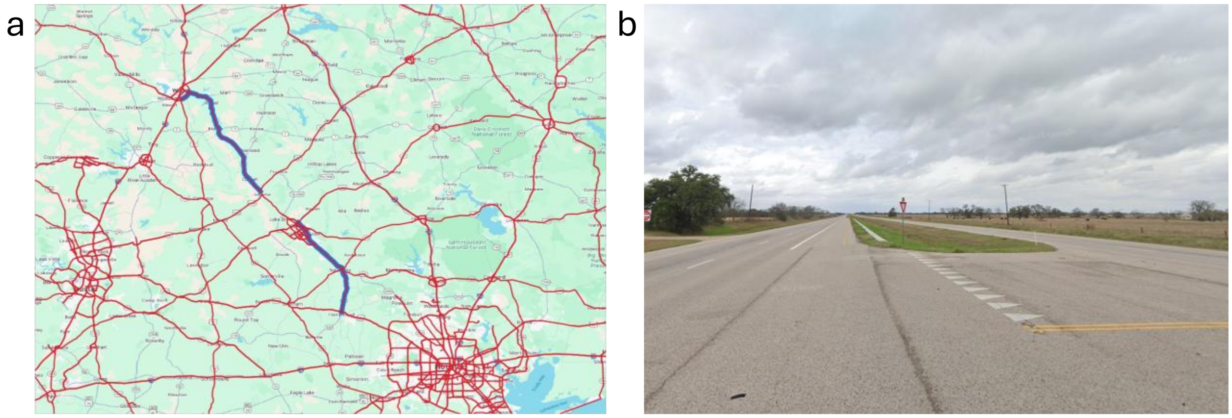

Figure C-13. SH0006—Waco to Bryan/College Station Case Study: (a) Location and (b) Typical Pavement Surface View.

Hazard Exposure Quantification

The analysis for this corridor considered the combined flooding effects. Figure C-14 shows an increasing exposure to flooding over time. In the 2020 scenario, 31.84 miles of the highway experienced high exposure in a 100-year return period, increasing to 38.01 miles in a 500-year event. This exposure was projected to grow by 2060, with the length of highly exposed roadway increasing to 34.51 miles for a 100-year event and 41.97 miles for a 500-year event.

Criticality Assessment

Figure C-15 shows the results of the criticality assessment for this segment. Notably, this corridor had no segments classified as most critical (L1). Instead, the segments were classified as L2 (7.45 miles), L3 (45.10 miles), and L4 (80.94 miles).

Vulnerability Assessment

The highway's vulnerability to damage increased with the intensity of the flood event (see Table C-14 and Figure C-16). As the return period increased, the length of road segments sustaining major and severe damage generally increased. For example, in the 2020 100-year scenario, 10.79 miles were expected to have major damage. By the 2060 100-year scenario, this length increased to 12.91 miles.

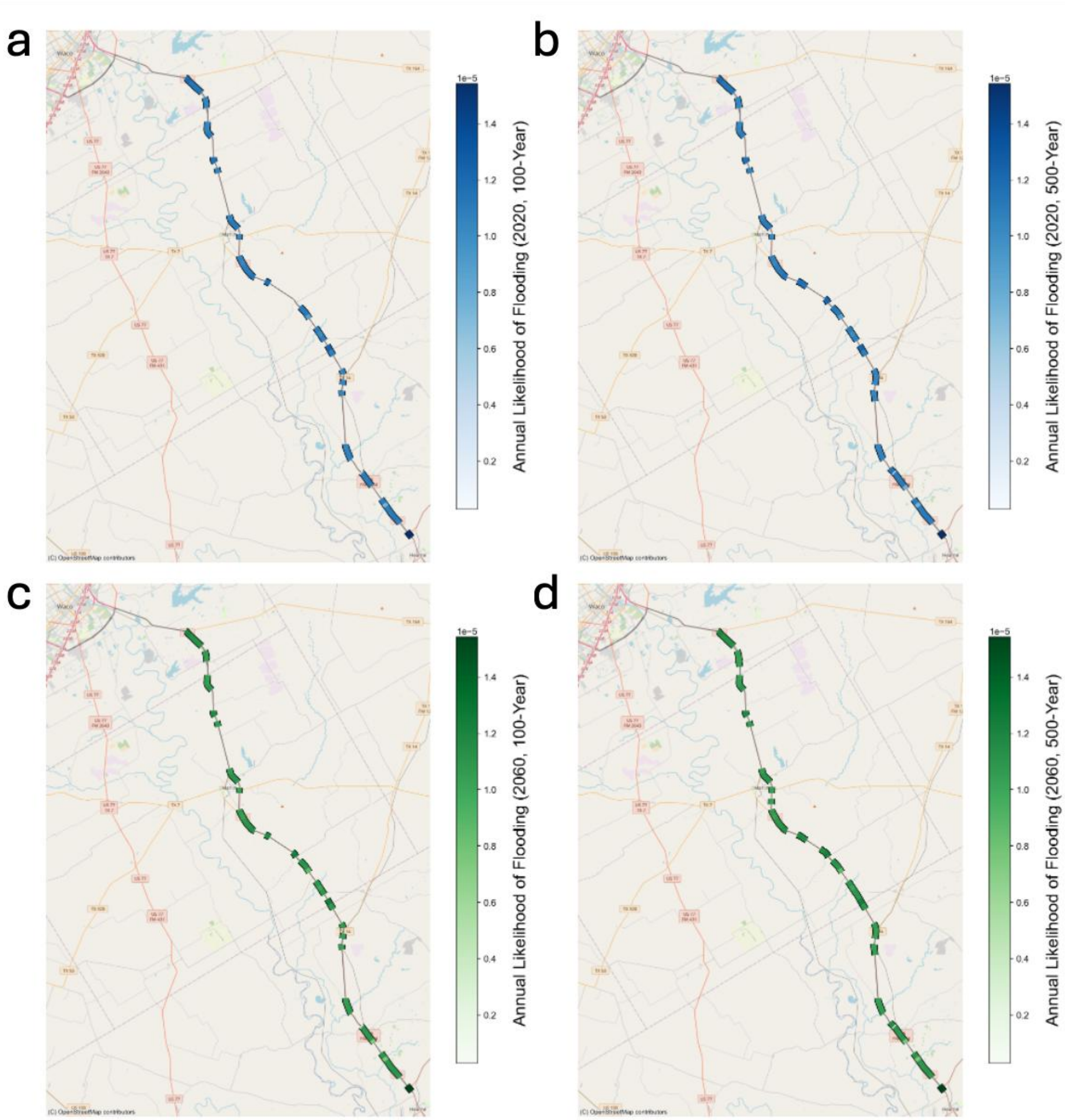

Figure C-14. Annual Likelihood of Flooding for the SH0006—Waco to Bryan/College Station Case Study: (a) 100-Year Return Period and 2020 Scenario, (b) 500-Year Return Period and 2020 Scenario, (c) 100-Year Return Period and 2060 Scenario, and (d) 500-Year Return Period and 2060 Scenario.

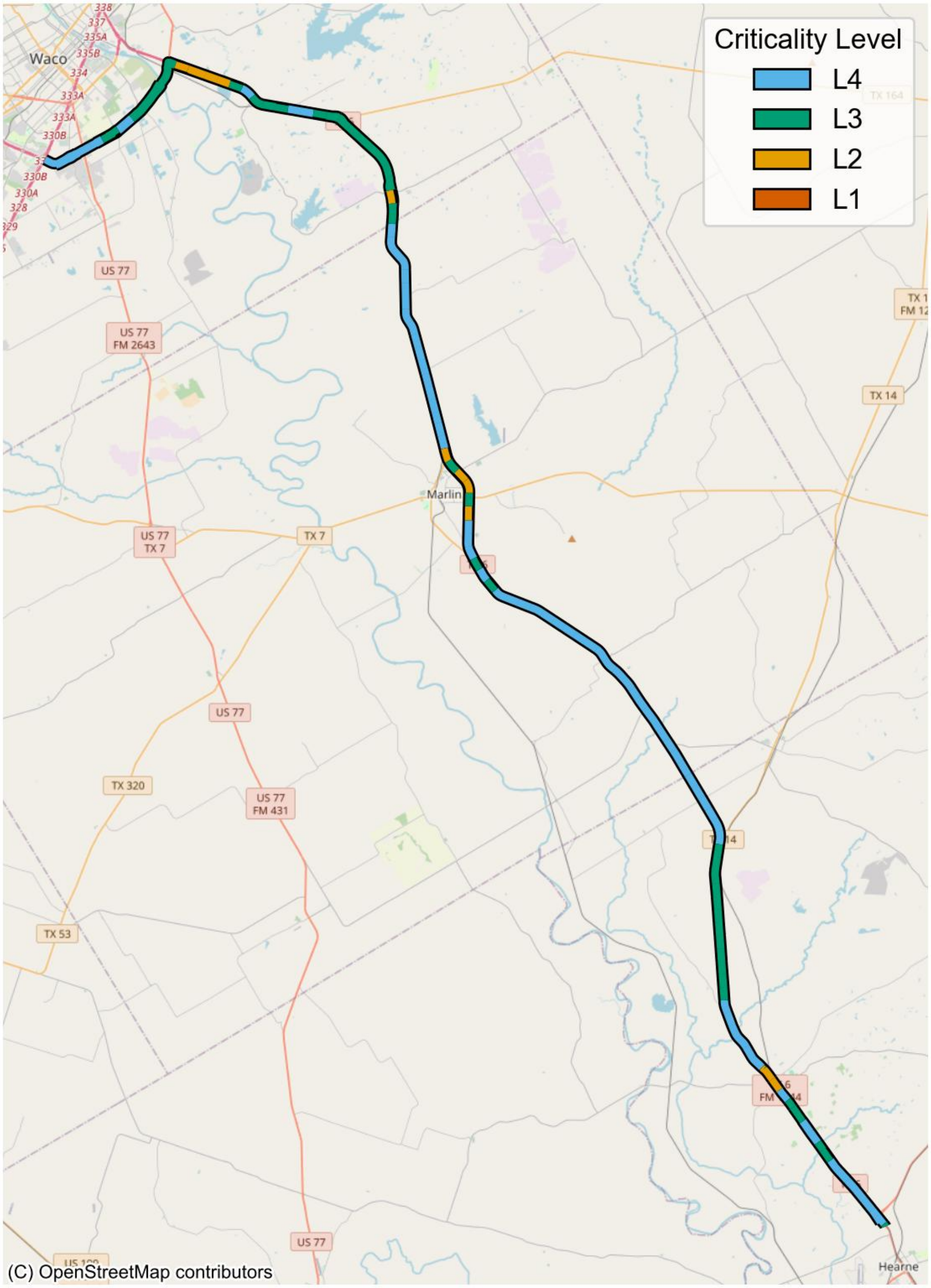

Figure C-15. Criticality Levels for the SH0006—Waco to Bryan/College Station Case Study.

Table C-14. Damage Length by Return Period under the 2020 and 2060 Scenarios for the SH0006—Waco to Bryan/College Station Case Study.

Damage Length	Combined-2020					Combined-2060				
	1-in-5	1-in-10	1-in-25	1-in-100	1-in-500	1-in-5	1-in-10	1-in-25	1-in-100	1-in-500
Minor	107.31	106.71	105.14	101.18	94.21	106.71	103.99	101.57	98.16	90.25
Moderate	8.51	8.61	9.65	12.06	15.04	8.61	9.66	9.53	12.46	16.98
Major	8.02	9.53	9.58	10.79	13.65	8.53	10.23	13.27	12.91	16.61
Severe	10.92	9.92	10.39	10.74	11.87	10.92	10.88	10.39	11.23	10.92

Figure C-16. Damage Status of Flooding for the SH0006—Waco to Bryan/College Station Case Study: (a) 100-Year Return Period and 2020 Scenario, (b) 500-Year Return Period and 2020 Scenario, (c) 100-Year Return Period and 2060 Scenario, and (d) 500-Year Return Period and 2060 Scenario.

Risk Assessment

Table C-15 shows the total AAL for this corridor. The AAL increased with the return period, from $102.42K for a 1-in-5-year event to $142.23K for a 1-in-500-year event in the 2020 scenario. A comparison between the 2020 and 2060 scenarios revealed a projected increase in financial risk. For a 1-in-100-year event, the total AAL was expected to increase from $119.79K in 2020 to $130.39K in 2060. For the 1-in-500-year event, the AAL increased to $151.58K.

Table C-15. Annual Average Loss by Return Period under the 2020 and 2060 Scenario for the SH0006—Waco to Bryan/College Station Case Study.

Damage Status	Combined-2020					Combined-2060				
	1-in-5	**1-in-10**	**1-in-25**	**1-in-100**	**1-in-500**	**1-in-5**	**1-in-10**	**1-in-25**	**1-in-100**	**1-in-500**
Minor	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Moderate	20.58	20.61	23.14	28.35	35.59	20.61	23.22	22.63	29.19	40.14
Major	26.11	31.20	31.53	35.89	44.86	27.98	34.17	44.01	43.18	54.31
Severe	55.73	52.04	54.36	55.54	61.78	57.16	56.73	54.36	58.02	57.13
Total	**102.42**	**103.85**	**109.03**	**119.79**	**142.23**	**105.75**	**114.12**	**121.00**	**130.39**	**151.58**

Adaptation Evaluation

Table C-16 shows the economic viability of the proposed pavement upgrade strategy. The B/C ratio was consistently > 1 across all analyzed return periods and scenarios, signifying that the financial benefits of the adaptation outweighed the costs. For the 2020 scenario, the B/C ratio was stable at approximately 1.64–1.67 for most events. The analysis showed that the strategy was economically justified.

A consolidated overall B/C ratio was calculated to provide a single measure of the adaptation strategy's value. By aggregating the benefits and costs across all flood scenarios, the overall B/C ratio was 1.66 for both the 2020 and 2060 scenarios. This finding indicated a positive and consistent return on investment, confirming the strategy is economically sound.

Table C-16. Adaptation Strategy Effectiveness by Return Period under the 2020 and 2060 Scenarios for the SH0006—Waco to Bryan/College Station Case Study.

	Combined-2020					Combined-2060				
	1-in-5	1-in-10	1-in-25	1-in-100	1-in-500	1-in-5	1-in-10	1-in-25	1-in-100	1-in-500
AAL-Baseline	102.42	103.85	109.03	119.79	142.23	105.75	114.12	121.00	130.39	151.58
AAL-Improvement	50.36	54.97	57.99	67.63	84.25	52.09	60.86	69.96	75.93	97.95
Avoided AAL	52.06	48.88	51.04	52.16	57.98	53.66	53.26	51.04	54.46	53.63
Adaptation Cost	33.89	29.22	30.69	31.75	35.27	32.32	32.18	30.69	33.28	32.31
B/C	1.54	1.67	1.66	1.64	1.64	1.66	1.66	1.66	1.64	1.66
Overall B/C	1.66					1.66				

Summary

The SH0006—Waco to Bryan/College Station case study showed a growing flood exposure and corresponding financial risk. This corridor had a lower overall criticality compared to other cases. The proposed adaptation strategy was found to be consistently cost-effective, confirming its value for mitigating future flood damage.

CASE NO. 5: US0290—AUSTIN TO HOUSTON

Background

US0290 is a major transportation artery connecting the major metropolitan areas of Austin and Houston. The analyzed corridor spans a significant length of 369.78 miles (see Figure C-17).

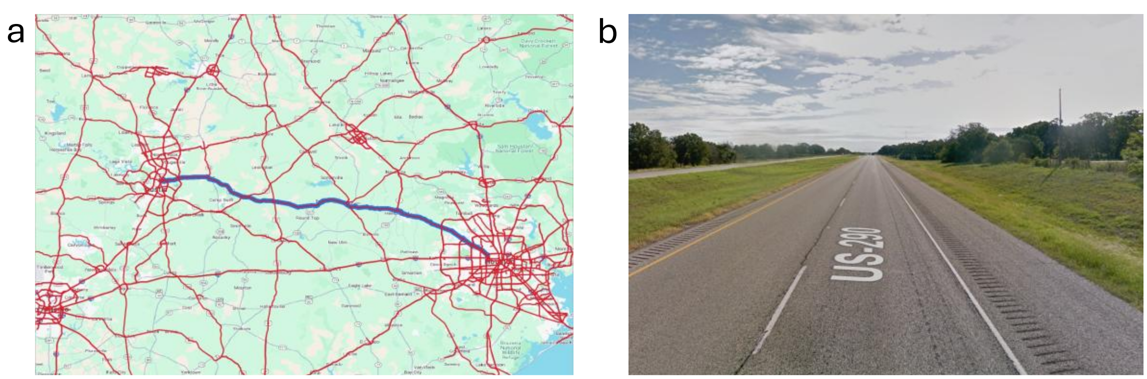

Figure C-17. US0290 Case Study: (a) Location and (b) Typical Pavement Surface View.

Hazard Exposure Quantification

The analysis for this extensive corridor considered the combined flooding effects. Figure C-18 shows a very high and increasing exposure to flooding. In the 2020 scenario, 179.64 miles of the highway experienced high exposure in a 100-year return period, increasing to 189.84 miles in a 500-year event. This exposure was projected to worsen by 2060, with the length of highly exposed roadway increasing to 183.35 miles for a 100-year event and 192.41 miles for a 500-year event.

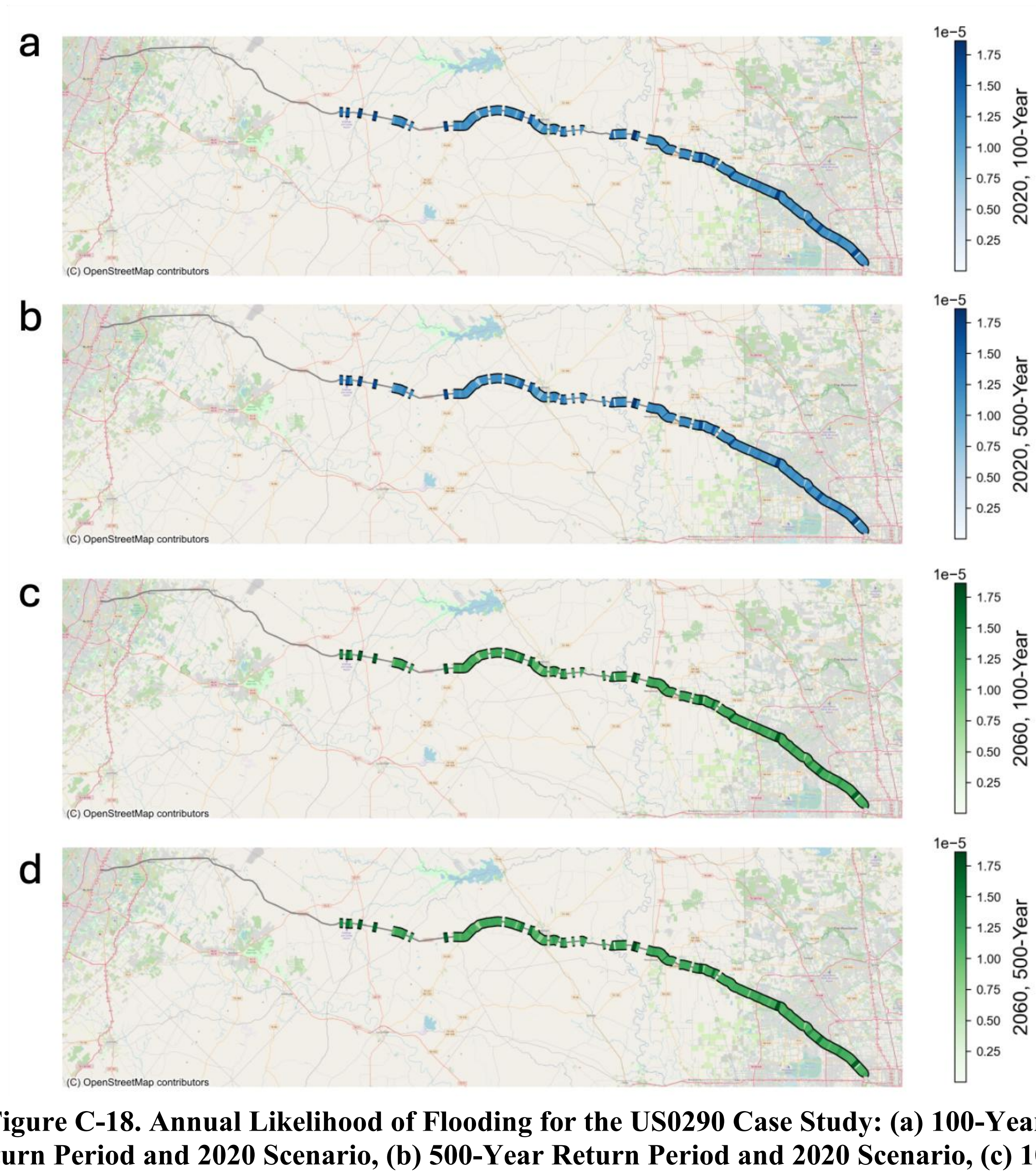

Figure C-18. Annual Likelihood of Flooding for the US0290 Case Study: (a) 100-Year Return Period and 2020 Scenario, (b) 500-Year Return Period and 2020 Scenario, (c) 100-Year Return Period and 2060 Scenario, and (d) 500-Year Return Period and 2060 Scenario.

Criticality Assessment

Figure C-19 shows the results of the criticality assessment for this segment. The most critical segments (L1) comprised 17.08 miles; the remaining segments were classified as L2 (51.72 miles), L3 (148.94 miles), and L4 (152.04 miles).

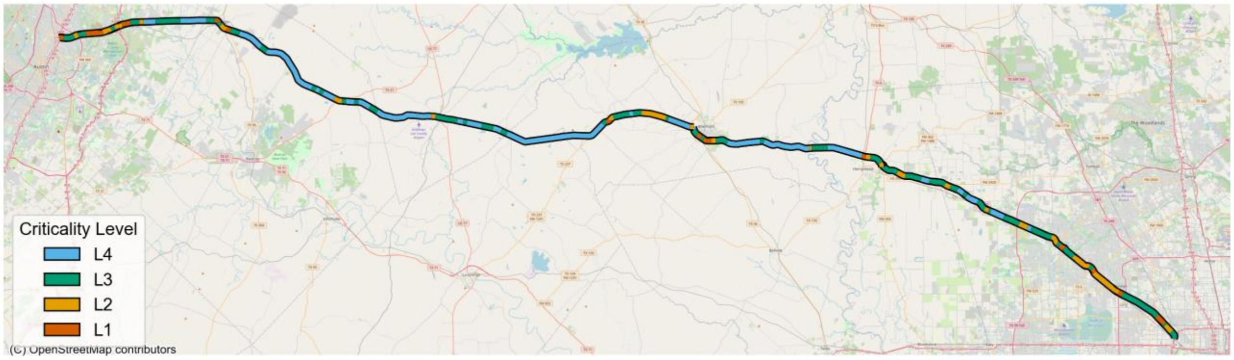

Figure C-19. Criticality Levels for the US0290 Case Study.

Vulnerability Assessment

The highway's vulnerability to damage was substantial and increased with the intensity of the flood event (see Table C-17 and Figure C-20). In the 2020 100-year scenario, 130.86 miles were expected to have major damage. By the 2060 100-year scenario, this length increased to 134.66 miles, indicating a significant and widespread vulnerability across this critical corridor.

Risk Assessment

Table C-18 shows the total AAL for this corridor. The total AAL increased significantly with the return period, from $390.93K for a 1-in-5-year event to $725.25K for a 1-in-500-year event in the 2020 scenario. This financial risk was projected to increase substantially, with the AAL for a 1-in-500-year event increasing to $766.56K by 2060.

Table C-17. Damage Length by Return Period under the 2020 and 2060 Scenarios for the US0290 Case Study.

Damage Length	Combined-2020					Combined-2060				
	1-in-5	1-in-10	1-in-25	1-in-100	1-in-500	1-in-5	1-in-10	1-in-25	1-in-100	1-in-500
Minor	286.10	244.89	227.97	205.31	194.80	255.46	229.34	218.34	201.28	192.23
Moderate	21.35	32.49	31.84	34.81	35.59	27.27	35.40	32.35	33.77	33.32
Major	72.38	102.44	115.11	130.86	137.81	96.55	113.22	120.02	134.66	137.78
Severe	14.55	14.55	19.46	23.40	26.17	15.1	16.41	23.68	24.67	31.05

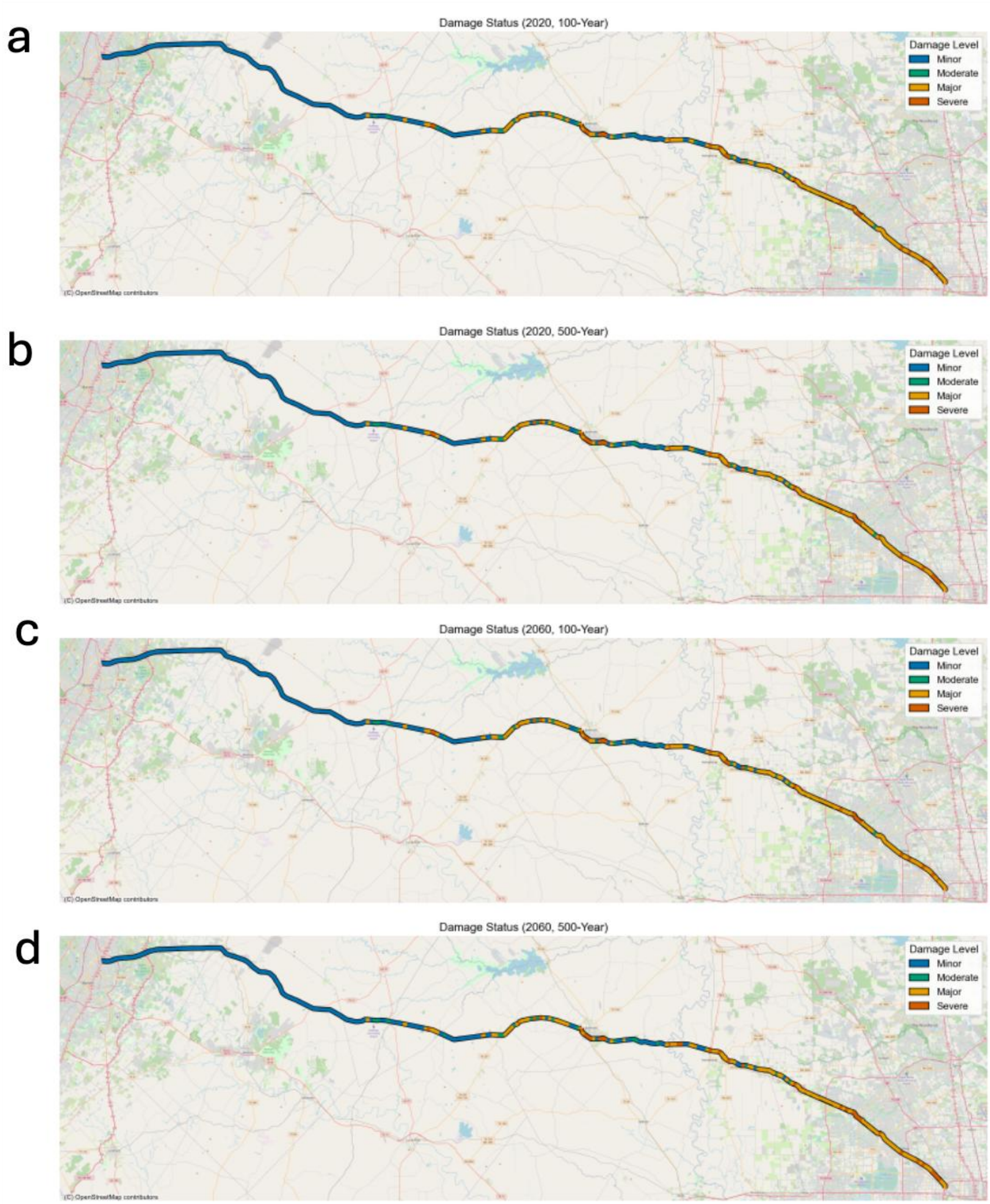

Figure C-20. Damage Status of Flooding for the US0290 Case Study: (a) 100-Year Return Period and 2020 Scenario, (b) 500-Year Return Period and 2020 Scenario, (c) 100-Year Return Period and 2060 Scenario, and (d) 500-Year Return Period and 2060 Scenario.

Table C-18. Annual Average Loss by Return Period under the 2020 and 2060 Scenarios for the US0290 Case Study.

Damage Status	Combined-2020					Combined-2060				
	1-in-5	1-in-10	1-in-25	1-in-100	1-in-500	1-in-5	1-in-10	1-in-25	1-in-100	1-in-500
Minor	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Moderate	50.64	75.50	74.87	80.78	82.81	62.34	82.97	73.42	77.99	77.27
Major	209.01	291.59	327.29	380.11	398.67	275.15	322.26	346.62	392.45	398.71
Severe	131.27	125.19	173.41	209.38	243.77	134.55	151.59	214.86	221.51	290.59
Total	390.93	492.28	575.58	670.27	725.25	472.04	556.82	634.89	691.96	766.56

Adaptation Evaluation

Table C-19 shows the economic viability of the proposed pavement upgrade strategy. The B/C ratio was exceptionally high across all analyzed return periods and scenarios, signifying that the financial benefits of the adaptation massively outweighed the costs. For the 2020 scenario, the B/C ratio ranged from 8.15 to over 11.0. The analysis showed the strategy was extremely well-justified economically, with avoided AAL reaching $241.35K for a 500-year event in 2020.

To capture the total economic picture, an overall B/C ratio was calculated. The result was an exceptionally high overall B/C ratio of 9.07 for the 2020 scenario, which remained stable at 9.06 for the 2060 scenario. This finding demonstrated that for every dollar invested in improving this critical corridor, over nine dollars in future flood-related damage costs were expected to be saved, making it an extremely strong investment.

Summary

The US0290 case study revealed extensive and growing flood exposure, with over 192 miles at high risk in a 500-year event by 2060. The associated financial risk was very high, with the AAL projected to exceed $766K by 2060 for a 500-year event. The proposed adaptation strategy was exceptionally cost-effective, with B/C ratios consistently > 8.0, indicating an extremely strong economic justification for proactive investment to protect this important artery.

Table C-19. Adaptation Strategy Effectiveness by Return Period under the 2020 and 2060 Scenarios for the US0290 Case Study.

	Combined-2020					Combined-2060				
	1-in-5	1-in-10	1-in-25	1-in-100	1-in-500	1-in-5	1-in-10	1-in-25	1-in-100	1-in-500
AAL-Baseline	390.93	492.28	575.58	670.27	725.25	472.04	556.82	634.89	691.96	766.56
AAL-Improvement	261.39	368.83	404.53	463.11	483.90	339.03	406.92	422.76	472.66	478.96
Avoided AAL	129.54	123.45	171.05	207.16	241.35	133.01	149.90	212.13	219.30	287.60
Adaptation Cost	14.96	14.95	20.98	20.11	21.77	13.26	14.74	24.11	20.11	26.70
B/C	8.66	8.26	8.15	10.30	11.09	10.03	10.17	8.80	10.91	10.77
Overall B/C	9.07					9.06				

CASE NO. 6: SH0288—PORT FREEPORT TO HOUSTON

Background

SH0288 serves as a vital commuter corridor connecting Port Freeport to the major metropolitan area of Houston. The analyzed segment spans 179 miles (see Figure C-21).

Hazard Exposure Quantification

Figure C-22 shows a significant and increasing exposure to flooding. In the 2020 scenario, 106.91 miles experienced high exposure in a 100-year return period, increasing to 117.81 miles in a 500-year event. This exposure was projected to worsen by 2060, with the length of highly exposed roadway increasing to 110.92 miles for a 100-year event and 119.73 miles for a 500-year event.

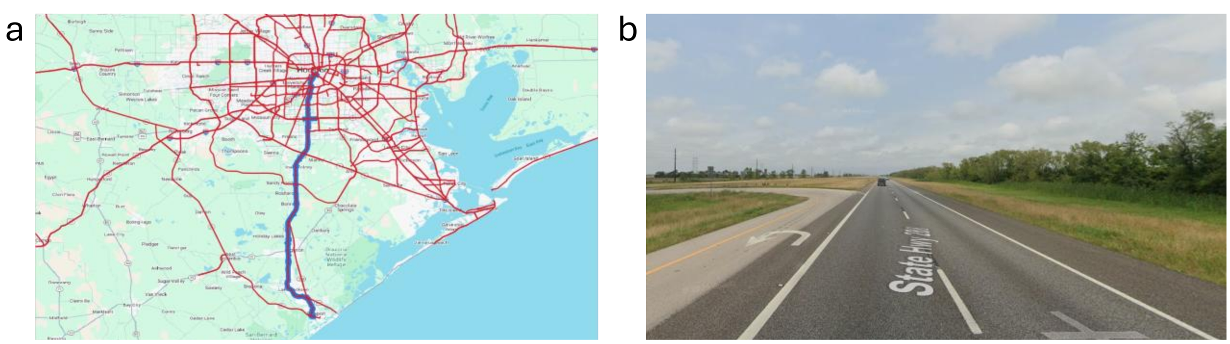

Figure C-21. SH0288 Case Study: (a) Location and (b) Typical Pavement Surface View.

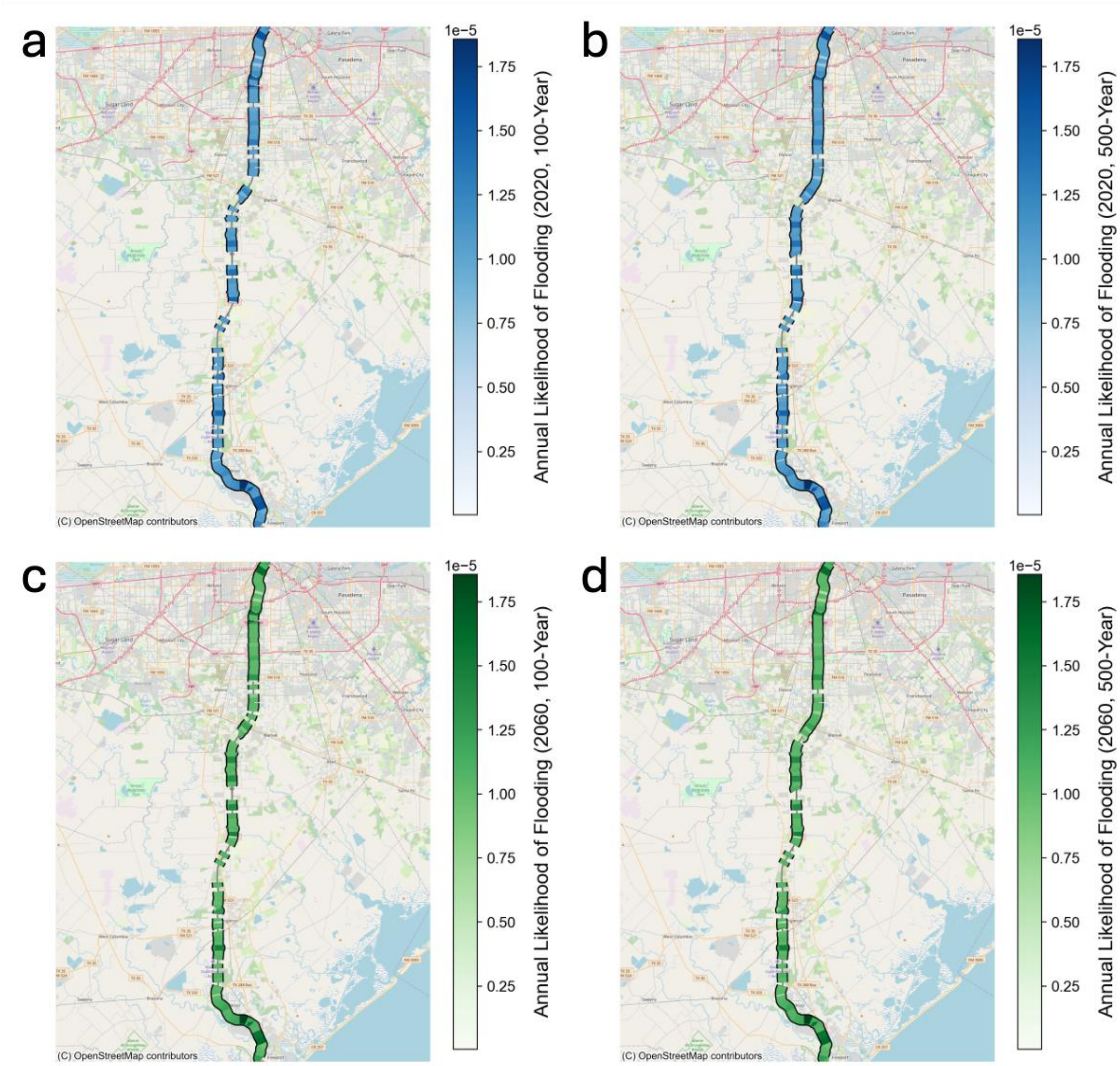

Figure C-22. Annual Likelihood of Flooding for the SH0288 Case Study: (a) 100-Year Return Period and 2020 Scenario, (b) 500-Year Return Period and 2020 Scenario, (c) 100-Year Return Period and 2060 Scenario, and (d) 500-Year Return Period and 2060 Scenario.

Criticality Assessment

Figure C-23 shows the results of the criticality assessment for SH0288. The most critical segments (L1) comprised 9.90 miles of the highway; the remaining segments were classified as L2 (30.90 miles), L3 (56.42 miles), and L4 (81.78 miles).

Vulnerability Assessment

The highway's vulnerability to damage was substantial and increased with flood intensity (see Table C-20 and Figure C-24). In the 2020 100-year scenario, 77.78 miles were expected to sustain major damage. By the 2060 100-year scenario, this length increased to 81.46 miles, highlighting the widespread vulnerability of this key route.

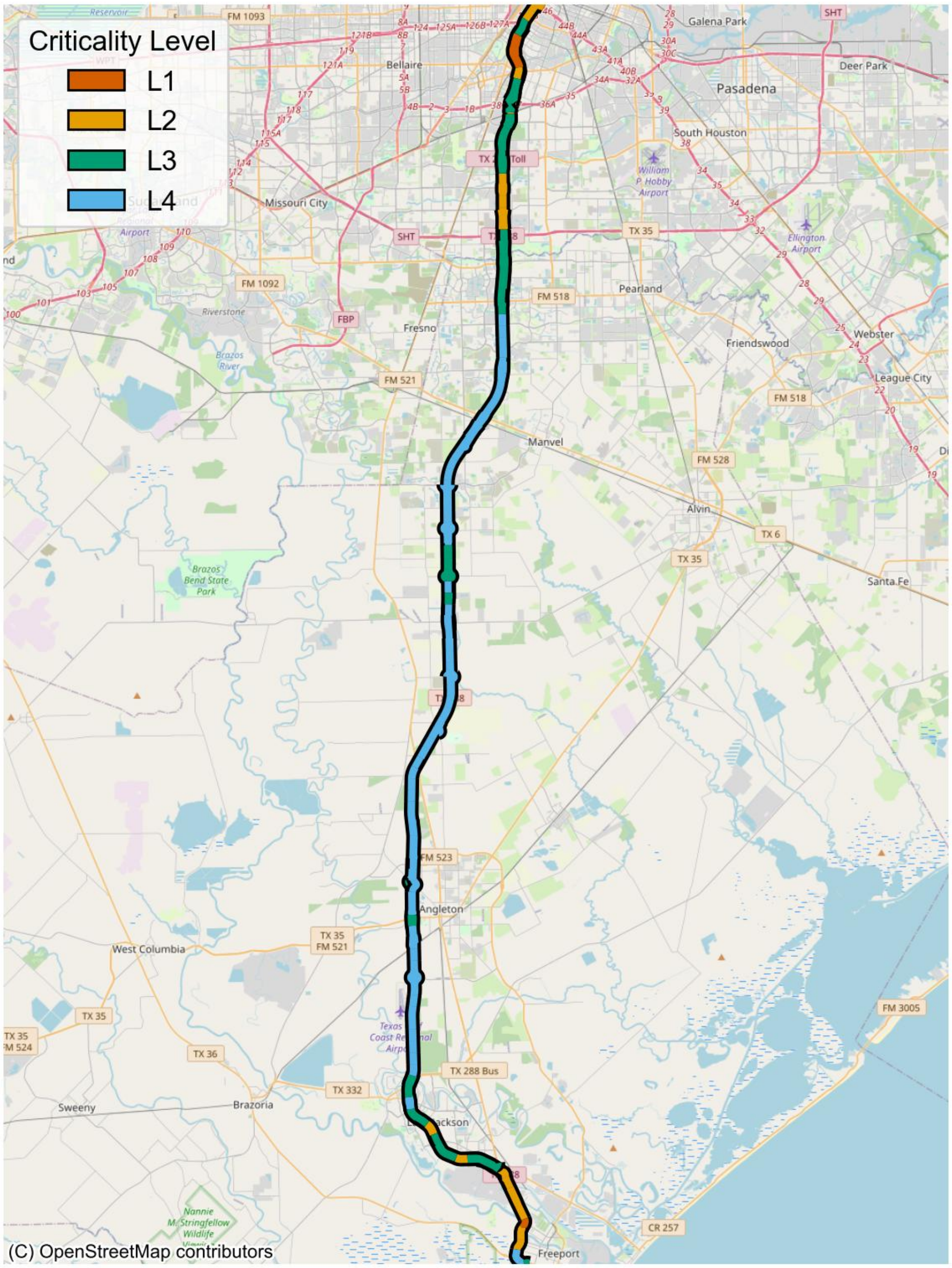

Figure C-23. Criticality Levels for the SH0288 Case Study.

Table C-20. Damage Length by Return Period under the 2020 and 2060 Scenarios for the SH0288 Case Study.

Damage Length	Combined-2020					Combined-2060				
	1-in-5	1-in-10	1-in-25	1-in-100	1-in-500	1-in-5	1-in-10	1-in-25	1-in-100	1-in-500
Minor	91.50	72.40	60.22	53.29	41.19	78.16	65.25	58.37	48.82	38.21
Moderate	14.24	18.73	15.24	16.09	21.21	16.74	17.12	15.34	18.75	22.23
Major	52.04	65.48	74.56	77.78	74.47	62.40	71.16	73.83	81.46	69.78
Severe	15.49	16.65	23.24	26.11	36.40	15.96	19.75	25.72	24.23	43.04

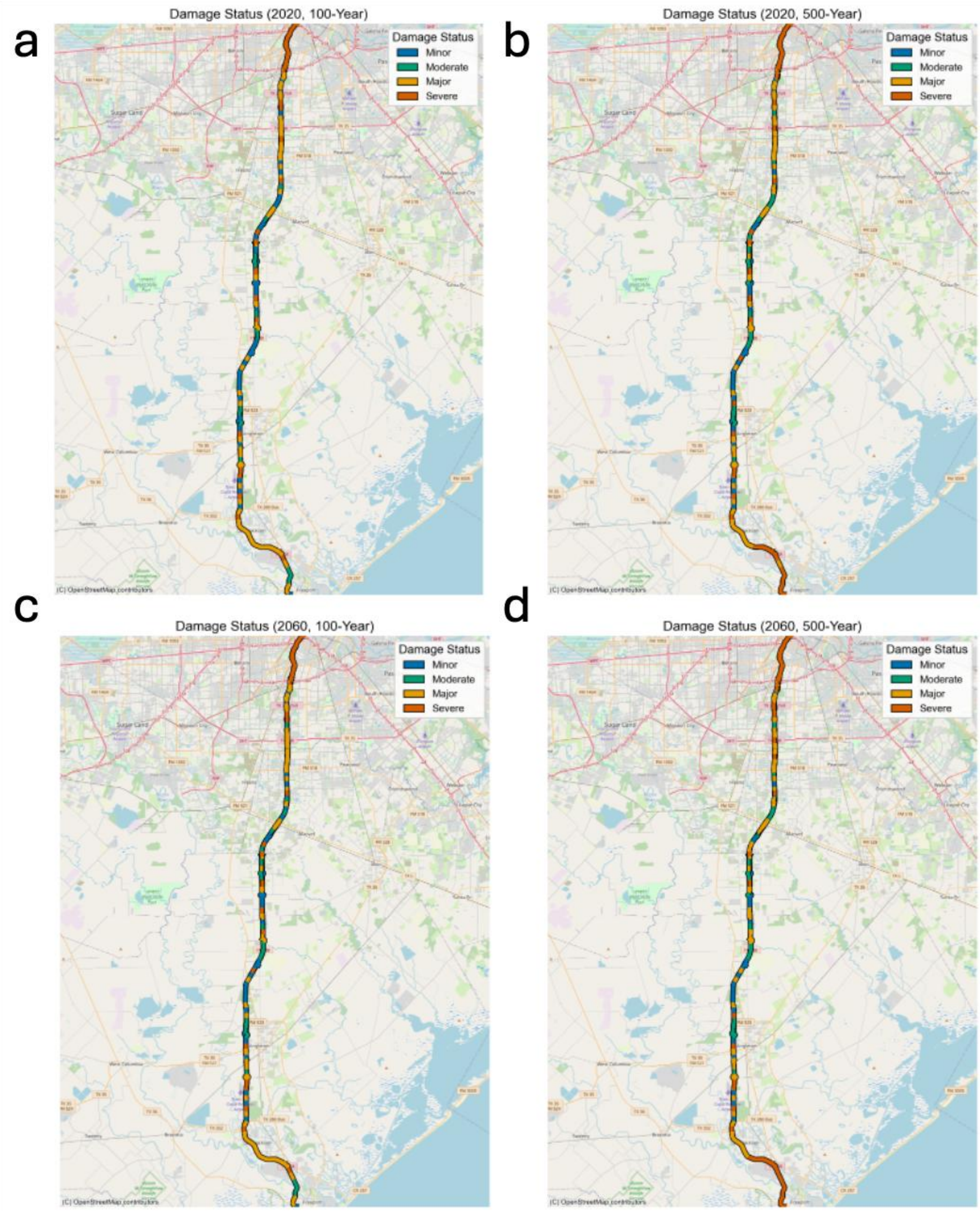

Figure C-24. Damage Status of Flooding for the SH0288 Case Study: (a) 100-Year Return Period and 2020 Scenario, (b) 500-Year Return Period and 2020 Scenario, (c) 100-Year Return Period and 2060 Scenario, and (d) 500-Year Return Period and 2060 Scenario.

Risk Assessment

Table C-21 shows the total AAL for this corridor. The total AAL increased significantly with the return period, from $295.13K for a 1-in-5-year event to $604.74K for a 1-in-500-year event in the 2020 scenario. This financial risk was projected to increase substantially, with the AAL for a 1-in-500-year event increasing to $682.81K by 2060.

Table C-21. Annual Average Loss by Return Period under the 2020 and 2060 Scenarios for the SH0288 Case Study.

Damage Status	Combined-2020					Combined-2060				
	1-in-5	1-in-10	1-in-25	1-in-100	1-in-500	1-in-5	1-in-10	1-in-25	1-in-100	1-in-500
Minor	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Moderate	30.29	39.26	31.48	31.96	41.97	35.03	36.11	31.58	37.01	44.37
Major	127.29	162.77	188.15	198.17	189.70	154.17	178.73	188.73	208.28	177.29
Severe	137.56	142.58	225.08	247.37	373.07	138.58	173.86	243.78	230.08	461.15
Total	295.13	344.11	444.71	477.49	604.74	327.78	388.70	464.09	475.37	682.81

Adaptation Evaluation

Table C-22 shows the economic viability of the proposed pavement upgrade strategy. The B/C ratio was exceptionally high across all analyzed return periods and scenarios, signifying that the financial benefits of the adaptation massively outweighed the costs. For the 2020 scenario, the B/C ratio ranged from 19.48 to over 116.0. The analysis showed the strategy was extremely well-justified economically, with avoided AAL reaching $372.65K for a 500-year event in 2020.

A single overall B/C ratio was calculated to represent the total economic value of the adaptation strategy. The result was an overwhelming overall B/C ratio of 116.04 for the 2020 scenario; this figure remained virtually unchanged for the 2060 scenario. This extremely high ratio indicated an exceptional return on investment, signifying that the avoided costs from flood damage were more than 100 times greater than the cost of the proactive pavement improvements.

Table C-22. Adaptation Strategy Effectiveness by Return Period under the 2020 and 2060 Scenarios for the SH0288 Case Study.

	Combined-2020					Combined-2060				
	1-in-5	1-in-10	1-in-25	1-in-100	1-in-500	1-in-5	1-in-10	1-in-25	1-in-100	1-in-500
AAL-Baseline	295.13	344.11	444.71	477.49	604.74	327.78	388.70	464.09	475.37	682.81
AAL-Improvement	158.28	202.38	219.90	230.40	232.09	190.05	215.54	220.58	245.56	221.81
Avoided AAL	136.85	141.73	224.81	247.09	372.65	137.73	173.16	243.51	229.81	461.00
Adaptation Cost	5.59	7.07	2.12	2.12	3.52	7.07	5.56	2.12	2.12	1.62
B/C	24.48	20.05	106.04	116.55	105.87	19.48	31.14	114.86	108.40	284.57
Overall B/C	116.04					116.04				

Summary

The SH0288 case study revealed high and growing flood exposure, with nearly 120 miles at high risk in a 500-year event by 2060. The associated financial risk was substantial, with the AAL projected to exceed $682K by 2060 for a 500-year event. The proposed adaptation strategy was exceptionally cost-effective, with B/C ratios frequently exceeding 100, indicating an overwhelming economic justification for proactive investment.

CASE NO. 7: US0087—VICTORIA TO PORT LAVACA

Background

US0087 connects Victoria to the coastal city of Port Lavaca. This corridor spans 49.62 miles and is a key route for coastal access and evacuation (see Figure C-25).

a b

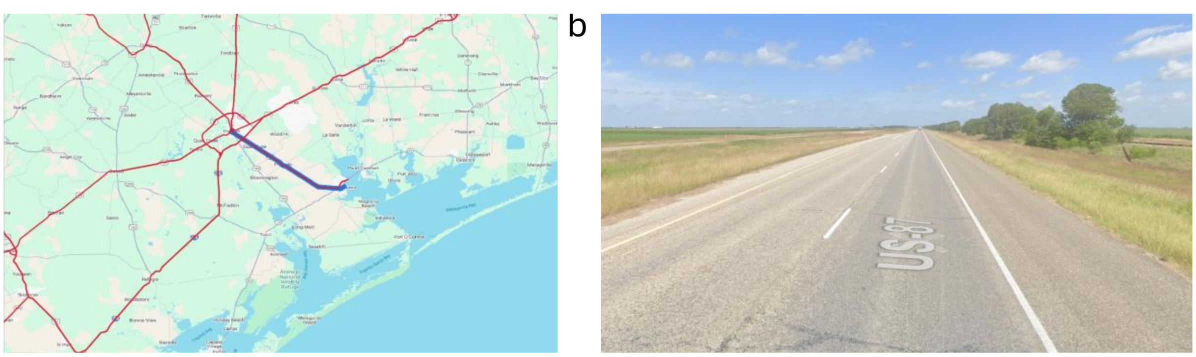

Figure C-25. US0087 Case Study: (a) Location and (b) Typical Pavement Surface View.

Hazard Exposure Quantification

Figure C-26 shows a growing exposure to flooding, concentrated closer to the coast. In the 2020 scenario, 8.25 miles of the highway experienced high exposure in a 100-year return period, increasing to 15.53 miles in a 500-year event. This exposure was projected to increase slightly by 2060, with the length of highly exposed roadway increasing to 8.77 miles for a 100-year event and 16.03 miles for a 500-year event.

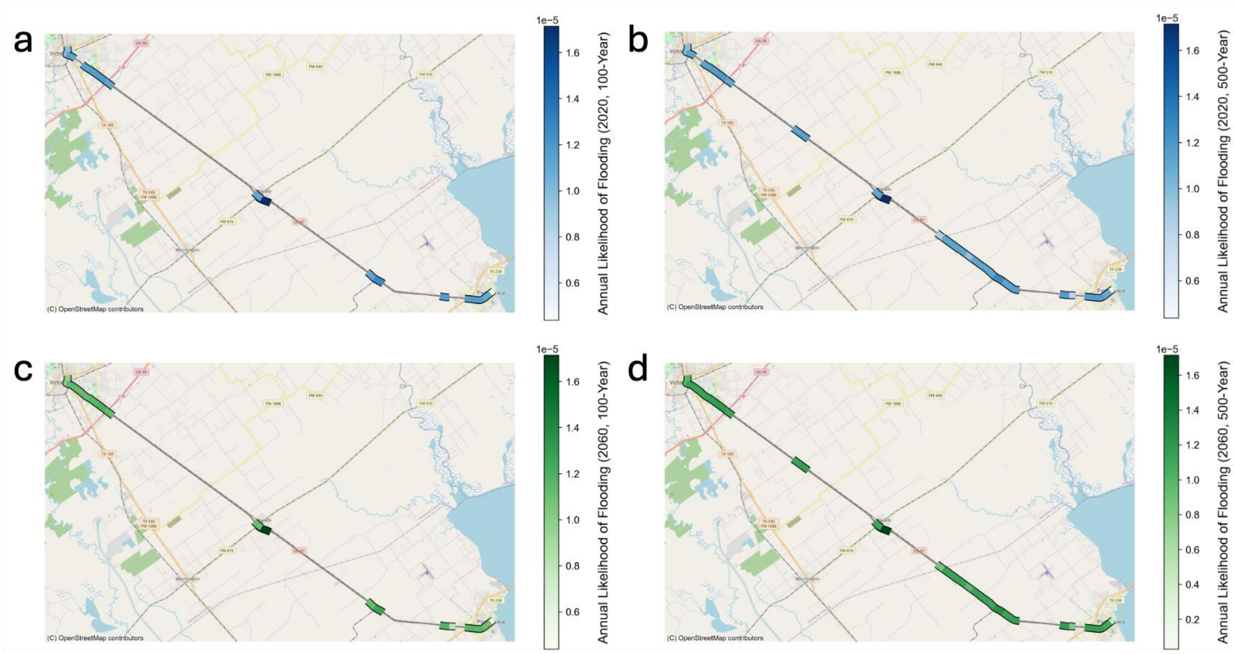

Figure C-26. Annual Likelihood of Flooding for the US0087 Case Study: (a) 100-Year Return Period and 2020 Scenario, (b) 500-Year Return Period and 2020 Scenario, (c) 100-Year Return Period and 2060 Scenario, and (d) 500-Year Return Period and 2060 Scenario.

Criticality Assessment

Figure C-27 shows the results of the criticality assessment for US0087. The most critical segments (L1) comprised only 0.98 miles of the highway; the remaining segments were classified as L2 (2.61 miles), L3 (26.65 miles), and L4 (19.38 miles).

Vulnerability Assessment

The highway's overall vulnerability to damage was relatively low compared to other corridors, but it increases with flood intensity (see Figure C-28 and Table C-23). For instance, in the 2020 500-year scenario, 5.54 miles were expected to sustain major damage. By the 2060 500-year scenario, this length increased slightly to 5.60 miles. Notably, severe damage was minimal or nonexistent in most scenarios.

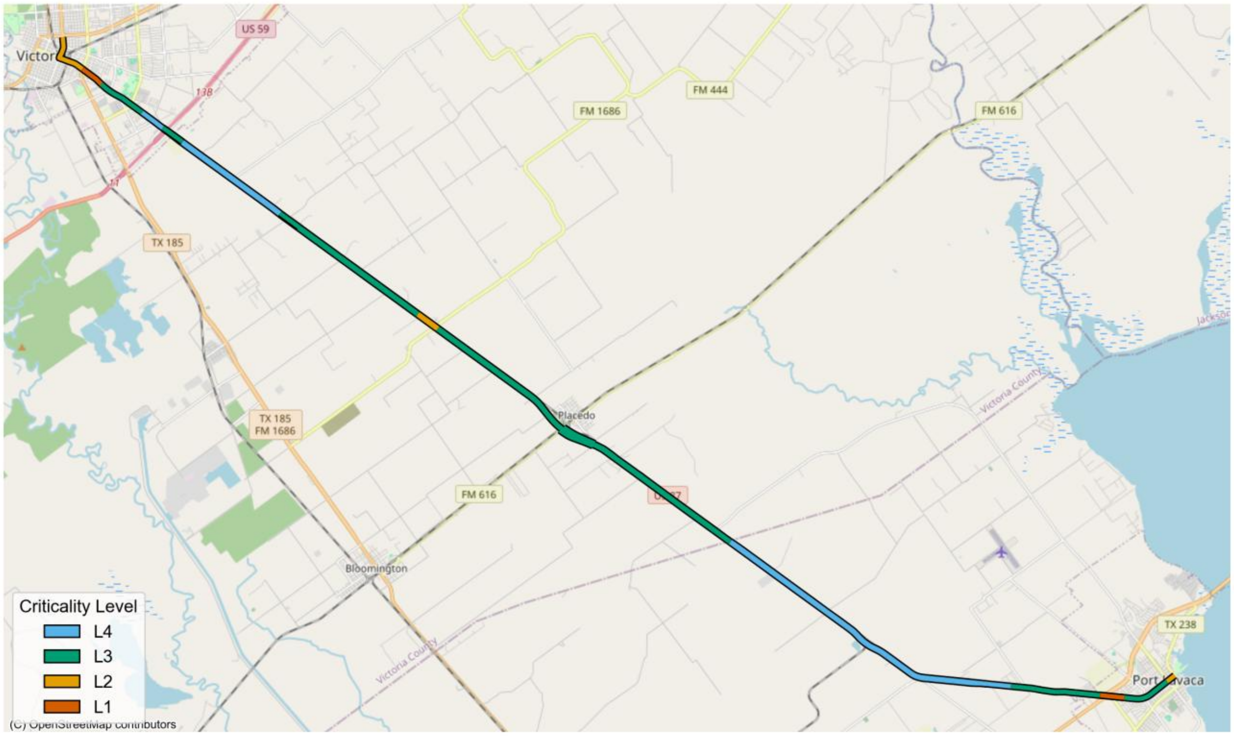

Figure C-27. Criticality Levels for the US0087 Case Study.

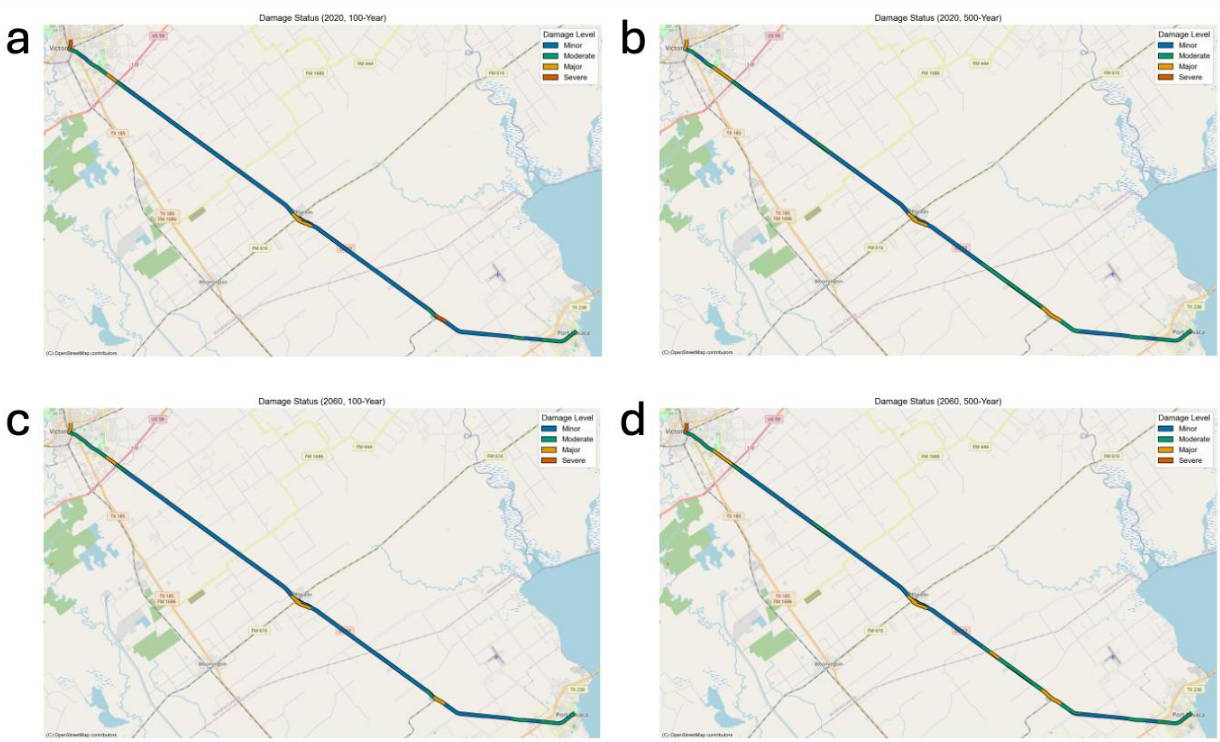

Figure C-28. Damage Status of Flooding for the US0087 Case Study: (a) 100-Year Return Period and 2020 Scenario, (b) 500-Year Return Period and 2020 Scenario, (c) 100-Year Return Period and 2060 Scenario, and (d) 500-Year Return Period and 2060 Scenario.

Table C-23. Damage Length by Return Period under the 2020 and 2060 Scenarios for the US0087 Case Study.

Damage Length	Combined-2020					Combined-2060				
	1-in-5	1-in-10	1-in-25	1-in-100	1-in-500	1-in-5	1-in-10	1-in-25	1-in-100	1-in-500
Minor	47.59	45.83	43.22	42.71	33.84	46.37	43.22	43.22	41.83	33.31
Moderate	1.86	3.62	5.20	4.92	12.24	3.08	5.20	4.41	5.80	12.25
Major	0.58	0.58	2.20	2.94	5.54	0.58	1.61	2.98	3.98	5.60
Severe	1.58	1.58	1.00	1.04	0.00	1.58	1.58	1.00	0.00	0.45

Risk Assessment

Table C-24 shows the total AAL for this corridor. The total AAL increased with the return period, from $18.95K for a 1-in-5-year event to $47.70K for a 1-in-500-year event in the 2020 scenario. This financial risk was projected to increase, with the AAL for a 1-in-500-year event increasing to $51.28K by 2060.

Table C-24. Annual Average Loss by Return Period under the 2020 and 2060 Scenarios for the US0087 Case Study.

Damage Status	Combined-2020					Combined-2060				
	1-in-5	1-in-10	1-in-25	1-in-100	1-in-500	1-in-5	1-in-10	1-in-25	1-in-100	1-in-500
Minor	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Moderate	5.43	9.10	12.80	11.06	28.50	7.87	12.80	9.81	12.76	28.28
Major	2.19	2.19	7.53	10.97	19.20	2.19	5.34	11.54	14.29	19.81
Severe	11.33	11.33	7.83	6.69	0.00	11.33	11.33	7.83	0.00	3.19
Total	18.95	22.62	28.17	28.72	47.70	21.39	29.47	29.18	27.05	51.28

Adaptation Evaluation

The B/C ratio was highly variable (see Table C-25). For lower return period events in 2020, the B/C ratio was high (e.g., 6.10 for a 1-in-5-year event). However, for several higher return period events (e.g., 500-year in 2020 and 100-/500-year in 2060), the B/C ratio was 0. This finding indicates that in those specific scenarios, no road segments met the combined criteria of high-criticality and severe-damage required to trigger the adaptation measure.

An overall B/C ratio was calculated to provide a holistic view of the investment. The overall B/C ratio was 6.08 for both the 2020 and 2060 scenarios. Because no segments met the criteria for adaptation under the 100-year or 500-year flood scenarios, this high ratio was driven entirely by the benefits of mitigating lower-return-period events.

Table C-25. Adaptation Strategy Effectiveness by Return Period under the 2020 and 2060 Scenarios for the US0087 Case Study.

	Combined-2020					Combined-2060				
	1-in-5	1-in-10	1-in-25	1-in-100	1-in-500	1-in-5	1-in-10	1-in-25	1-in-100	1-in-500
AAL-Baseline	18.95	22.62	28.17	28.72	47.70	21.39	29.47	29.18	27.05	51.28
AAL-Improvement	7.85	11.52	20.33	22.26	47.70	10.29	18.37	21.35	27.05	48.09
Avoided AAL	11.10	11.10	7.84	6.46	0.00	11.10	11.10	7.83	0.00	3.19
Adaptation Cost	1.82	1.82	0.00	1.82	0.00	1.82	1.82	0.00	0.00	0.00
B/C	6.10	6.10	0.00	3.55	0.00	6.10	6.10	0.00	0.00	0.00
Overall B/C	6.08					6.08				

Summary

This US0087 case study showed a relatively low but growing flood exposure. The associated financial risk was modest, with the AAL for a 500-year event projected to be just over $51K by 2060. The proposed adaptation strategy showed high cost-effectiveness for lower-return-period events but offered no benefit for more extreme flood scenarios where no segments met the criteria for improvement. This finding suggested that a targeted rather than broad application of adaptation measures would be most suitable for this corridor.

CASE NO. 8: SH0359—LAREDO TO SAN DIEGO US0044

Background

SH0359 connects the city of Laredo to US0044 in San Diego, Tx. This corridor is located in the Laredo District and spans 97.27 miles (see Figure C-29).

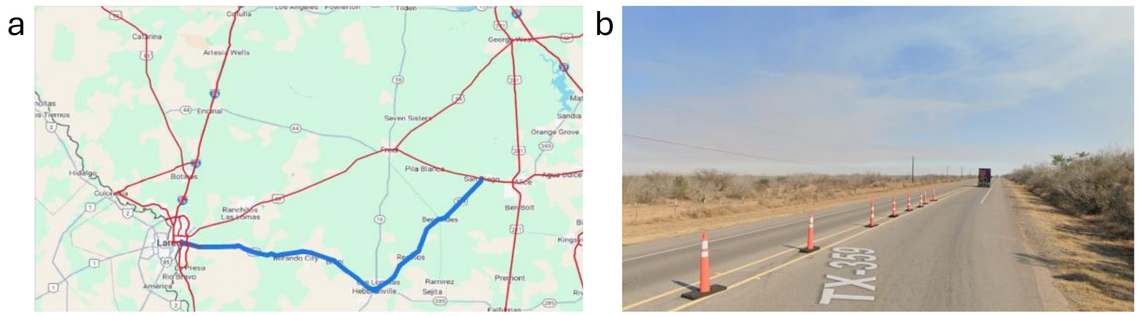

Figure C-29. SH0359 Case Study: (a) Location and (b) Typical Pavement Surface View.

Hazard Exposure Quantification

The analysis for this corridor considered the combined flooding effects. Figure C-30 shows a moderate and increasing exposure to flooding. In the 2020 scenario, 22.06 miles of the highway experienced high exposure in a 100-year return period, increasing to 31.18 miles in a 500-year event. This exposure was projected to grow by 2060, with the length of highly exposed roadway increasing to 27.09 miles for a 100-year event and 33.17 miles for a 500-year event.

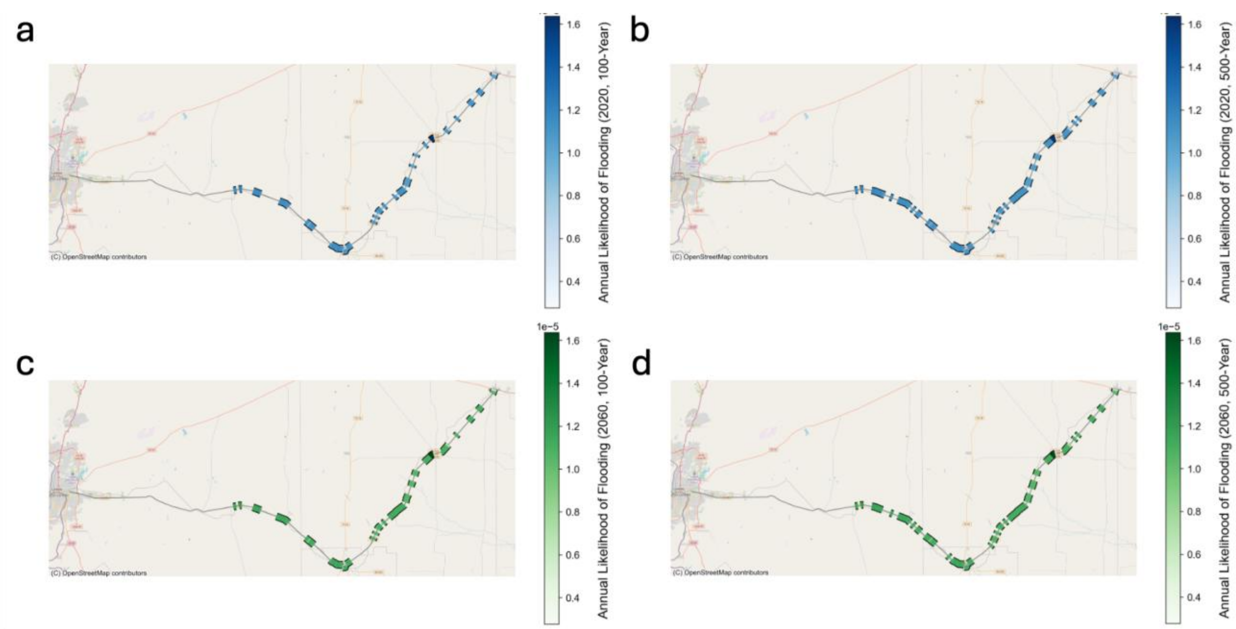

Figure C-30. Annual Likelihood of Flooding for the SH0359 Case Study: (a) 100-Year Return Period and 2020 Scenario, (b) 500-Year Return Period and 2020 Scenario, (c) 100-Year Return Period and 2060 Scenario, and (d) 500-Year Return Period and 2060 Scenario.

Criticality Assessment

Figure C-31 shows the results of the criticality assessment for SH0359. This corridor had no segments classified as most critical (L1). Instead, the segments were classified as L2 (6.00 miles), L3 (30.01 miles), and L4 (61.26 miles).

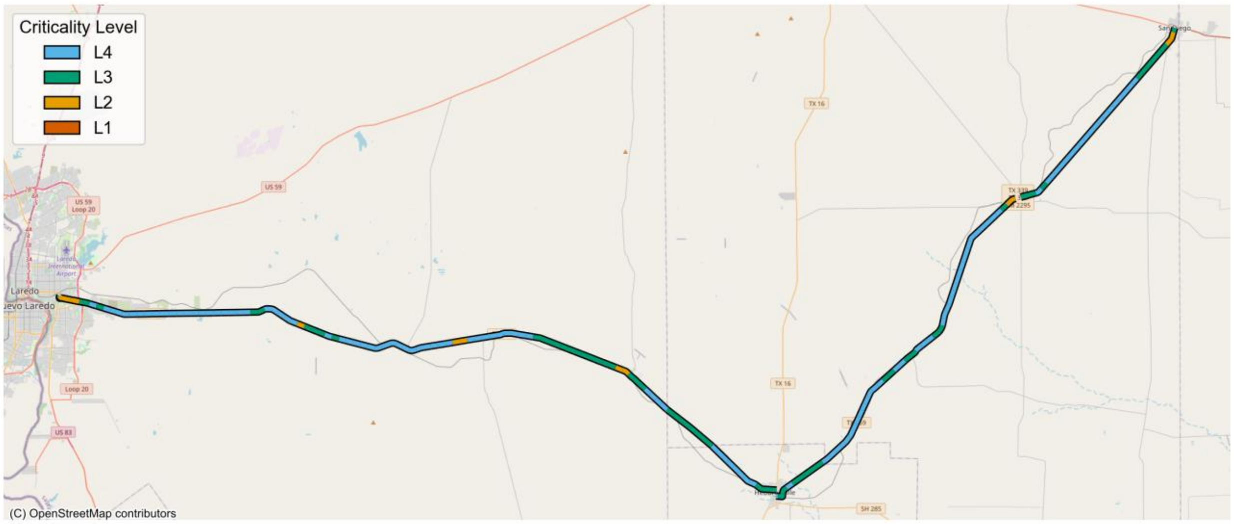

Figure C-31. Criticality Levels for the SH0359 Case Study.

Vulnerability Assessment

The highway's vulnerability to damage increased with flood intensity (see Figure C-32 and Table C-26). For instance, in the 2020 100-year scenario, 8.48 miles were expected to sustain major damage. By the 2060 100-year scenario, this length increased to 11.52 miles. Severe damage was minimal across most scenarios.

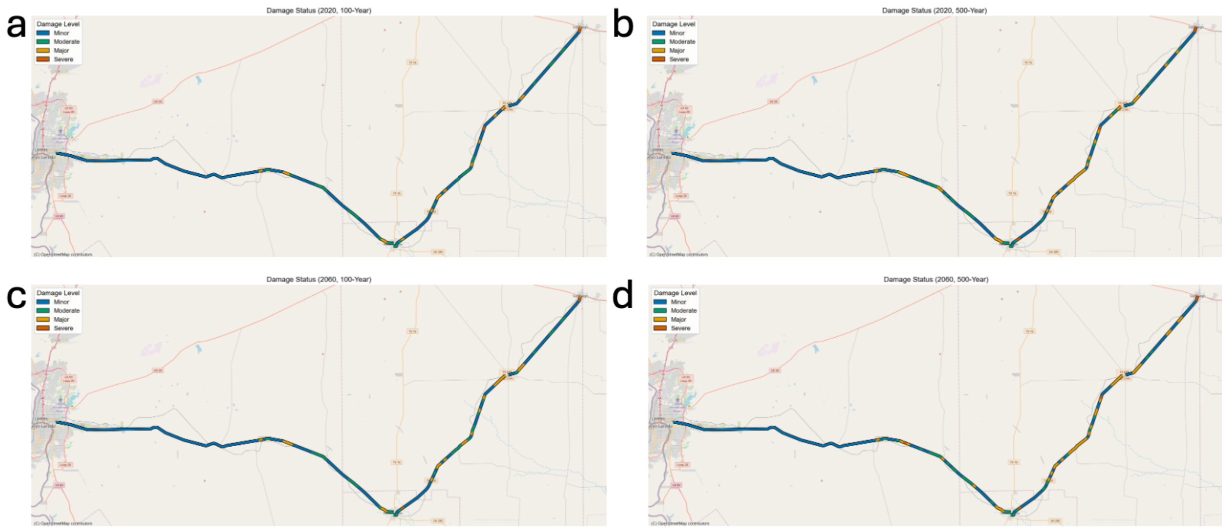

Figure C-32. Damage Status of Flooding for the SH0359 Case Study: (a) 100-Year Return Period and 2020 Scenario, (b) 500-Year Return Period and 2020 Scenario, (c) 100-Year Return Period and 2060 Scenario, and (d) 500-Year Return Period and 2060 Scenario.

Table C-26. Damage Length by Return Period under the 2020 and 2060 Scenarios for the SH0359 Case Study.

Damage Length	Combined-2020					Combined-2060				
	1-in-5	1-in-10	1-in-25	1-in-100	1-in-500	1-in-5	1-in-10	1-in-25	1-in-100	1-in-500
Minor	92.13	88.52	84.72	76.66	67.54	89.04	87.51	80.41	71.63	65.55
Moderate	3.44	6.55	9.83	13.82	14.36	6.04	6.56	12.84	15.79	13.35
Major	3.39	3.89	4.41	8.48	16.27	3.88	4.90	5.71	11.52	18.74
Severe	0.96	0.96	0.96	0.96	1.76	0.96	0.96	0.96	0.98	2.28

Risk Assessment

Table C-27 shows the total AAL for this corridor. The AAL was relatively low. The total AAL increased with the return period, from $23.06K for a 1-in-5-year event to $93.99K for a 1-in-500-year event in the 2020 scenario. This financial risk was projected to increase, with the AAL for a 1-in-500-year event rising to $104.24K by 2060.

Table C-27. Annual Average Loss by Return Period under the 2020 and 2060 Scenarios for the SH0359 Case Study.

Damage Status	Combined-2020					Combined-2060				
	1-in-5	1-in-10	1-in-25	1-in-100	1-in-500	1-in-5	1-in-10	1-in-25	1-in-100	1-in-500
Minor	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Moderate	8.14	15.42	24.04	32.60	33.57	14.17	15.47	31.43	37.25	31.12
Major	10.18	11.79	13.49	27.28	52.22	11.72	15.04	17.09	36.95	60.60
Severe	4.75	4.75	4.75	4.75	8.20	4.75	4.75	4.75	4.96	12.52
Total	23.06	31.96	42.28	64.63	93.99	30.64	35.25	53.27	79.17	104.24

Adaptation Evaluation

The B/C ratio was consistently > 1 across all analyzed return periods and scenarios, signifying that the financial benefits of the adaptation outweighed the costs (see Table C-28). For the 2020 scenario, the B/C ratio was stable at approximately 1.41–1.48. The analysis showed that the strategy was economically justified.

Providing a single summary metric, an overall B/C ratio was calculated. The result was a consistent overall B/C ratio of 1.48 for both the 2020 and 2060 scenarios. This value—comfortably > 1—confirmed that the proposed pavement improvement was a cost-effective measure for enhancing the resilience of this corridor.

Table C-28. Adaptation Strategy Effectiveness by Return Period under the 2020 and 2060 Scenarios for the SH0359 Case Study.

	Combined-2020					Combined-2060				
	1-in-5	1-in-10	1-in-25	1-in-100	1-in-500	1-in-5	1-in-10	1-in-25	1-in-100	1-in-500
AAL-Baseline	23.06	31.96	42.28	64.63	93.99	30.64	35.25	53.27	79.17	104.24
AAL-Improvement	18.63	27.52	37.84	60.19	86.33	26.20	30.82	48.83	74.53	92.26
Avoided AAL	4.43	4.44	4.44	4.44	7.66	4.44	4.43	4.44	4.64	11.98
Adaptation Cost	2.99	2.99	2.99	2.99	5.45	2.99	2.99	2.99	3.06	5.45
B/C	1.48	1.48	1.48	1.48	1.41	1.48	1.48	1.48	1.52	2.20
Overall B/C	1.48					1.48				

Summary

This SH0359 case study showed a moderate but growing flood exposure and a correspondingly low financial risk. The corridor had a low overall criticality. The proposed adaptation strategy was found to be consistently cost-effective, with B/C ratios around 1.5, confirming its value for mitigating future flood damage.

CASE NO. 9: SH0124—HIGH ISLAND TO BEAUMONT

Background

SH0124 provides a critical connection from the coastal community of High Island to the city of Beaumont. This corridor is located in TxDOT's Beaumont District and spans 43.05 miles (see Figure C-33).

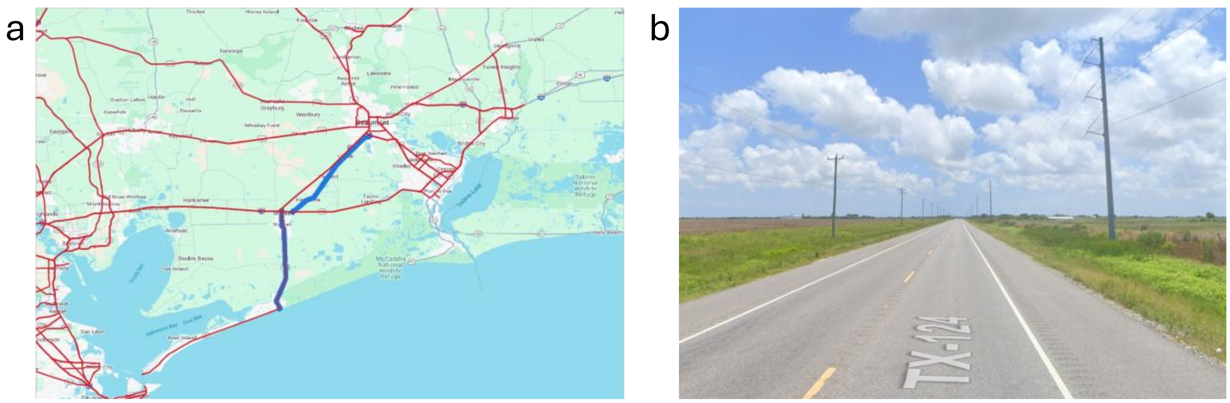

Figure C-33. SH0124 Case Study: (a) Location and (b) Typical Pavement Surface View.

Hazard Exposure Quantification

Figure C-34 shows a significant and increasing exposure to flooding. In the 2020 scenario, 16.98 miles of the highway experienced high exposure in a 100-year return period, increasing to 24.33 miles in a 500-year event. This exposure was projected to increase by 2060, with the length of highly exposed roadway increasing to 18.41 miles for a 100-year event and 26.36 miles for a 500-year event.

Criticality Assessment

Figure C-35 shows the results of the criticality assessment for SH0124. The most critical segments (L1) comprised 1.96 miles of the highway; the remaining segments were classified as L2 (7.01 miles), L3 (32.11 miles), and L4 (1.97 miles).

Vulnerability Assessment

The highway's vulnerability to damage was significant, particularly from severe events (see Table C-29 and Figure C-36). For instance, in the 2020 100-year scenario, 12.50 miles were expected to sustain severe damage. By the 2060 100-year scenario, this length increased to 13.47 miles, highlighting the substantial vulnerability of this coastal route.

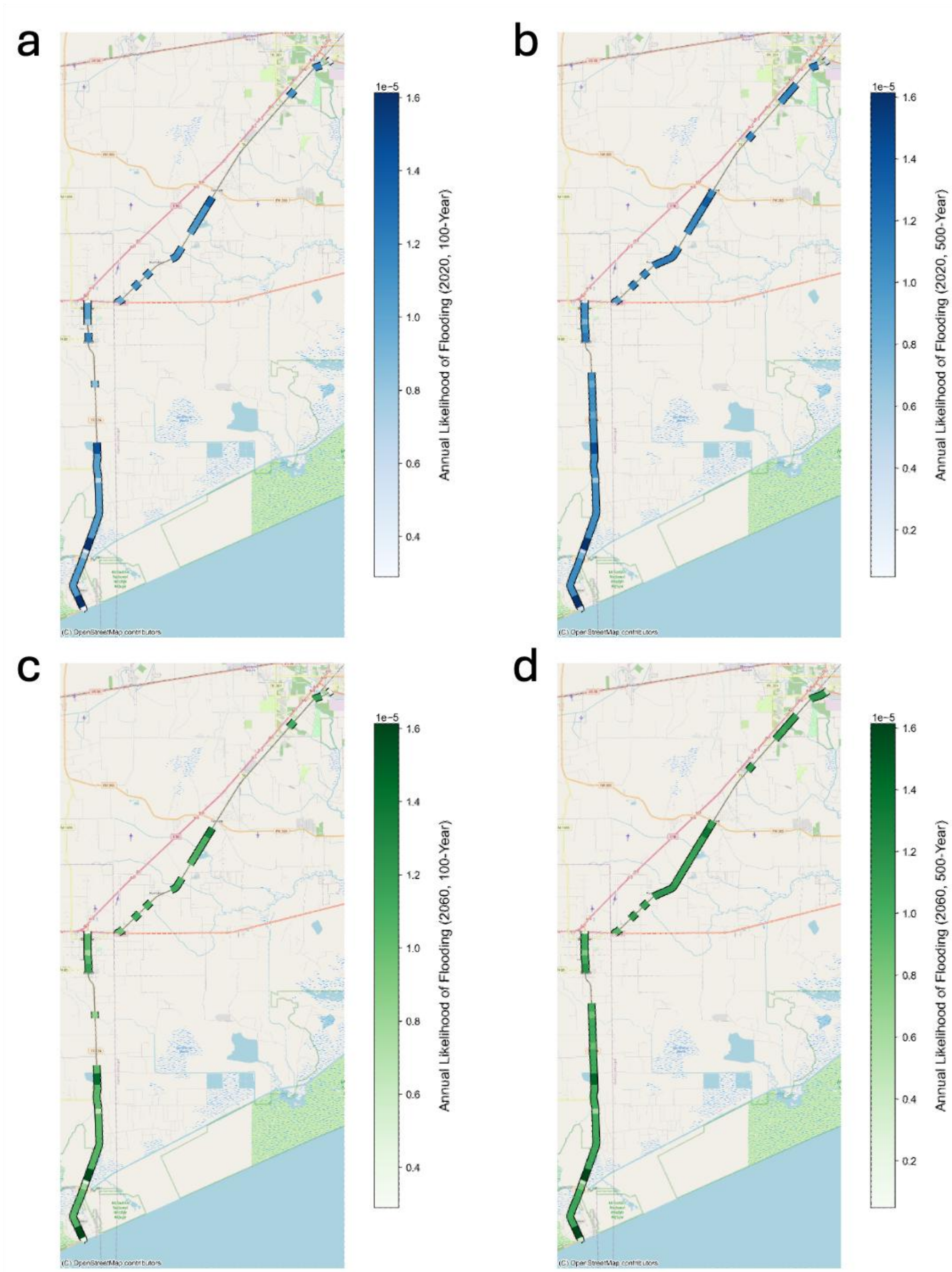

Figure C-34. Annual Likelihood of Flooding for the SH0124 Case Study: (a) 100-Year Return Period and 2020 Scenario, (b) 500-Year Return Period and 2020 Scenario, (c) 100-Year Return Period and 2060 Scenario, and (d) 500-Year Return Period and 2060 Scenario.

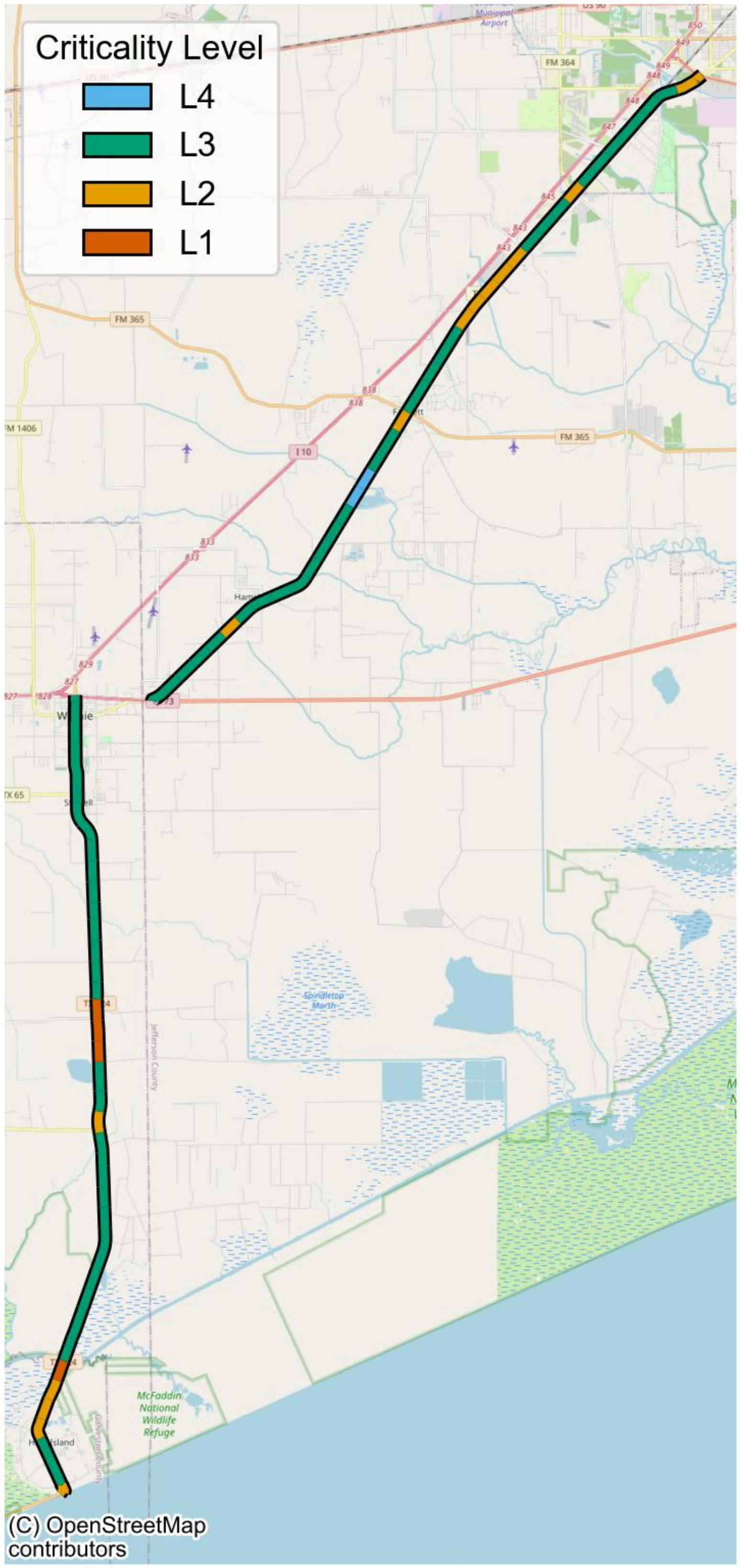

Figure C-35. Criticality Levels for the SH0124 Case Study.

Table C-29. Damage Length by Return Period under the 2020 and 2060 Scenarios for the SH0124 Case Study.

Damage Length	Combined-2020					Combined-2060				
	1-in-5	1-in-10	1-in-25	1-in-100	1-in-500	1-in-5	1-in-10	1-in-25	1-in-100	1-in-500
Minor	26.51	25.34	24.10	22.29	14.52	25.34	24.58	23.62	20.86	12.49
Moderate	3.24	2.97	2.38	1.81	6.47	2.97	2.09	1.43	2.29	6.86
Major	8.32	9.28	7.47	5.71	8.30	9.12	7.29	7.16	5.69	9.06
Severe	4.24	4.71	8.36	12.50	13.01	4.87	8.36	10.10	13.47	13.90

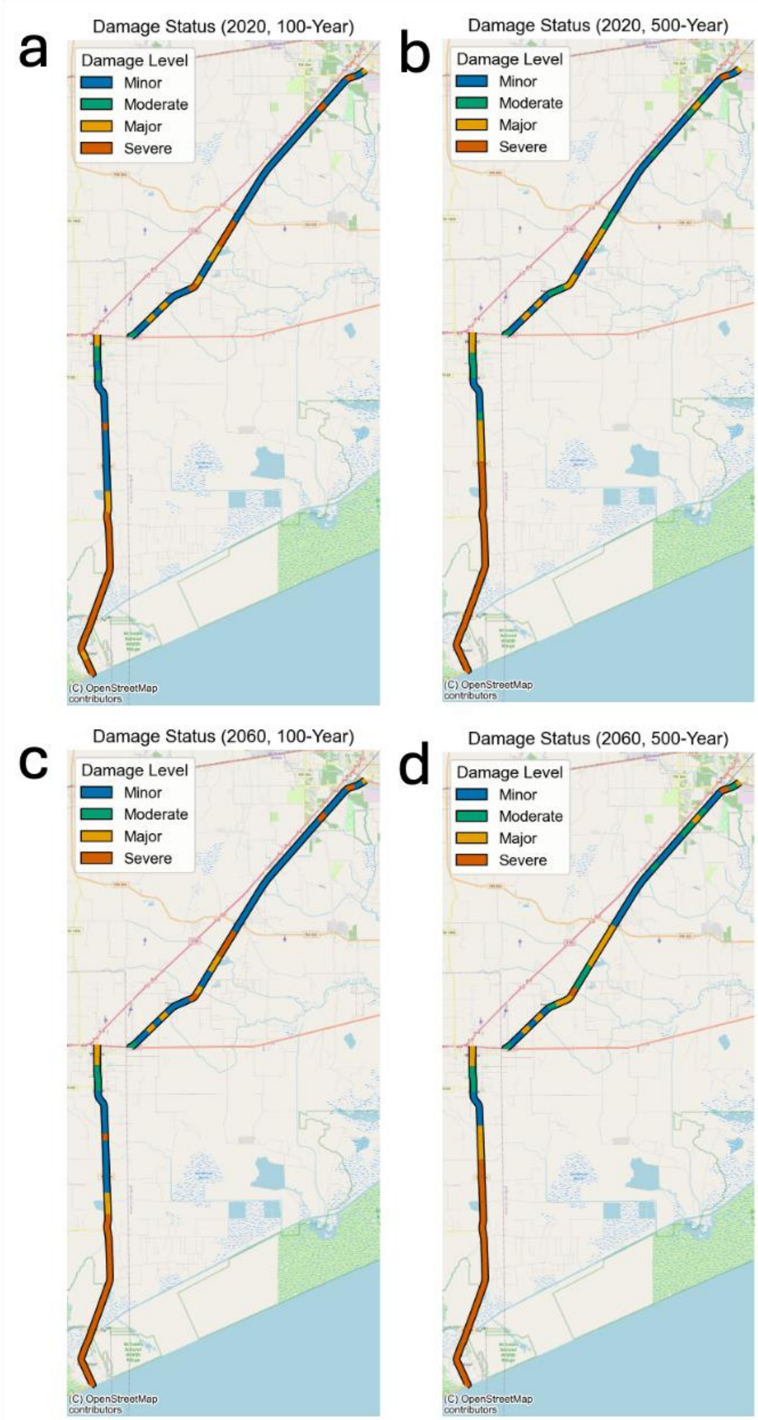

Figure C-36. **Damage Status of Flooding for the SH0124 Case Study: (a) 100-Year Return Period and 2020 Scenario, (b) 500-Year Return Period and 2020 Scenario, (c) 100-Year Return Period and 2060 Scenario, and (d) 500-Year Return Period and 2060 Scenario.**

Risk Assessment

Table C-30 shows the total AAL for this corridor. The AAL was considerable for a corridor of this length. The total AAL increased significantly with the return period, from $55.64K for a 1-in-5-year event to $108.02K for a 1-in-500-year event for the 2020 scenario. This financial risk was projected to increase, with the AAL for a 1-in-500-year event increasing to $115.96K by 2060.

Table C-30. Annual Average Loss by Return Period under the 2020 and 2060 Scenarios for the SH0124 Case Study.

Damage Status	Combined-2020					Combined-2060				
	1-in-5	1-in-10	1-in-25	1-in-100	1-in-500	1-in-5	1-in-10	1-in-25	1-in-100	1-in-500
Minor	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Moderate	6.19	5.30	4.21	3.35	14.66	5.30	3.28	2.78	4.20	15.25
Major	25.96	29.38	21.97	16.46	23.07	29.38	21.76	20.62	15.96	26.39
Severe	23.49	28.24	49.68	67.61	70.28	28.24	49.68	57.03	72.37	74.33
Total	55.64	62.92	75.86	87.43	108.02	62.92	74.72	80.44	92.54	115.96

Adaptation Evaluation

Table C-31 shows the economic viability of the proposed pavement upgrade strategy. The B/C ratio was consistently > 1 across all analyzed return periods and scenarios, signifying that the financial benefits of the adaptation outweighed the costs. For the 2020 scenario, the B/C ratio was stable at approximately 1.67–2.05. The analysis showed that the strategy was economically justified.

An overall B/C ratio was calculated to consolidate the economic findings into a single metric. The analysis yielded a strong and consistent overall B/C ratio of 2.05 for both the 2020 and 2060 scenarios. This finding indicated that for every dollar spent on the adaptation strategy, more than two dollars in future damage costs were avoided, confirming its value.

Table C-31. Adaptation Strategy Effectiveness by Return Period under the 2020 and 2060 Scenarios for the SH0124 Case Study.

	Combined-2020					Combined-2060				
	1-in-5	1-in-10	1-in-25	1-in-100	1-in-500	1-in-5	1-in-10	1-in-25	1-in-100	1-in-500
AAL-Baseline	55.64	62.92	75.86	87.43	108.02	62.92	74.72	80.44	92.54	115.96
AAL-Improvement	33.70	36.23	28.96	23.77	41.87	36.23	27.82	26.66	24.43	46.04
Avoided AAL	21.94	26.69	46.90	63.66	66.15	26.69	46.90	53.78	68.11	69.92
Adaptation Cost	13.16	13.16	22.84	35.72	37.29	13.16	22.84	28.26	38.71	40.04
B/C	1.67	2.03	2.05	1.78	1.77	2.03	2.05	1.90	1.76	1.75
Overall B/C	2.05					2.05				

Summary

The SH0124 coastal corridor case study showed a significant and growing flood exposure, with high vulnerability to severe damage. The financial risk was notable, with the AAL for a 500-year event projected to exceed $115K by 2060. The proposed adaptation strategy was found to be consistently cost-effective, with B/C ratios of 1.7–2.0, confirming its value for mitigating future flood damage on this critical coastal link.

CASE NO. 10: US0027/US0039—KERR COUNTY

Background

This case study focused on a 77.32-mile corridor in Kerr County, Texas, comprising segments of US0027 and US0039 (see Figure C-37). This corridor was selected because of a major flooding event in the region in July 2025 that caused widespread infrastructure damage. These recent, real-world impacts underscore the immediate need for resilient infrastructure planning.

Hazard Exposure Quantification

Although lower than the coastal regions, Figure C-38 still shows a concentrated and growing flood exposure risk for this corridor. In the 2020 scenario, 4.20 miles of the highway experienced high exposure in a 100-year return period, increasing to 6.37 miles in a 500-year event. This exposure was projected to increase by 2060, with the length of highly exposed roadway increasing to 4.74 miles for a 100-year event and 6.86 miles for a 500-year event.

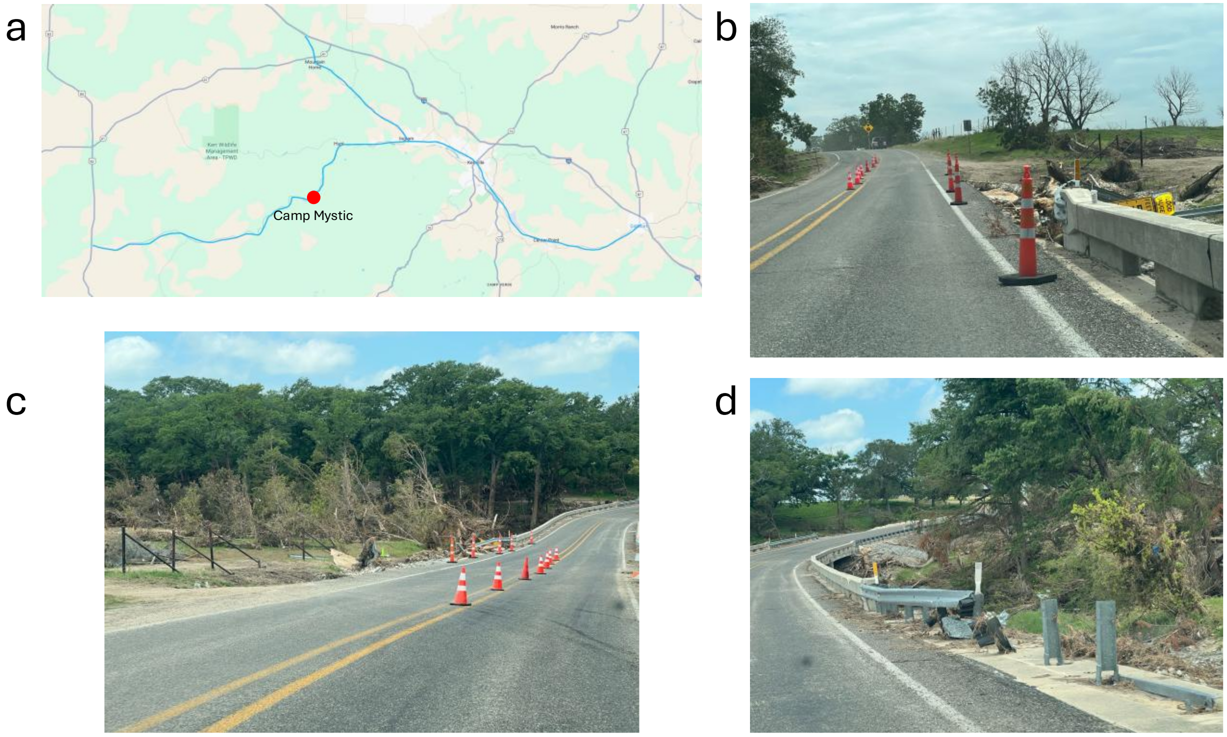

Figure C-37. US0027/US0039 Case Study: (a) Location, (b)/(c) Typical Pavement Surface Views, and (d) Guardrail Damage View (Photo Credit: TTI, July 19, 2025).

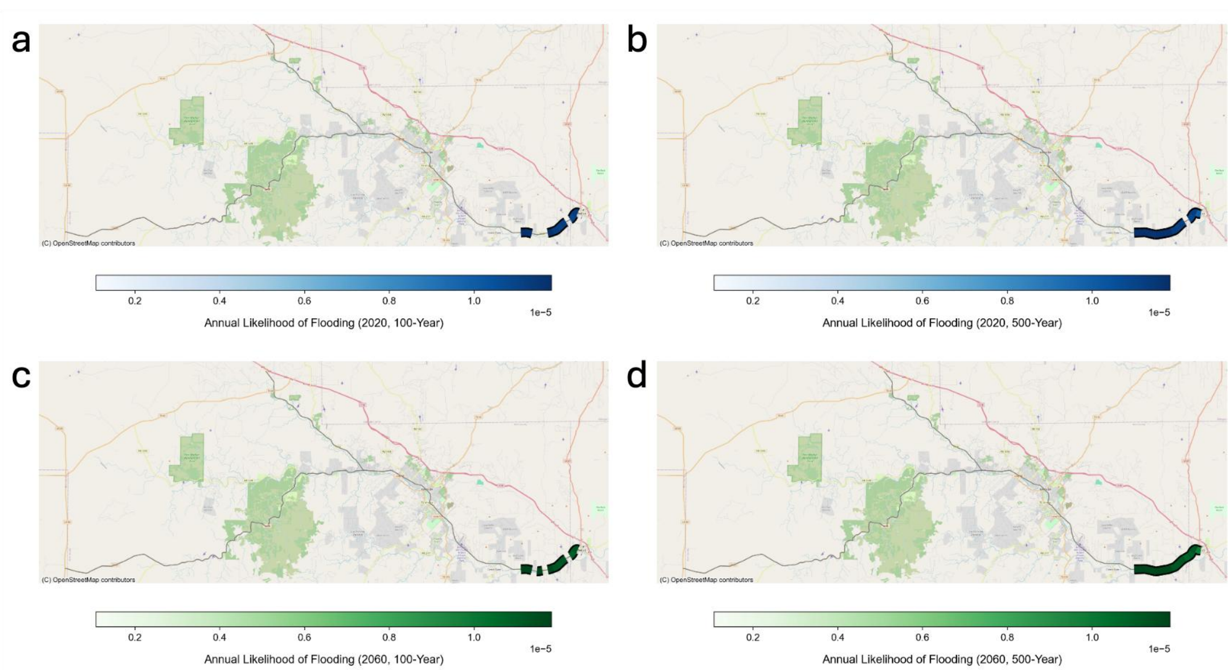

Figure C-38. Annual Likelihood of Flooding for the US0027/US0039 Case Study: (a) 100-Year Return Period and 2020 Scenario, (b) 500-Year Return Period and 2020 Scenario, (c) 100-Year Return Period and 2060 Scenario, and (d) 500-Year Return Period and 2060 Scenario.

Criticality Assessment

Figure C-39 shows the results of the criticality assessment for this corridor. While the lengths of the most critical segments were small, their locations were vital for local and regional connectivity. The most critical segments (L1) comprised 0.84 miles of the highway; the remaining segments were classified as L2 (6.52 miles), L3 (19.95 miles), and L4 (15.74 miles).

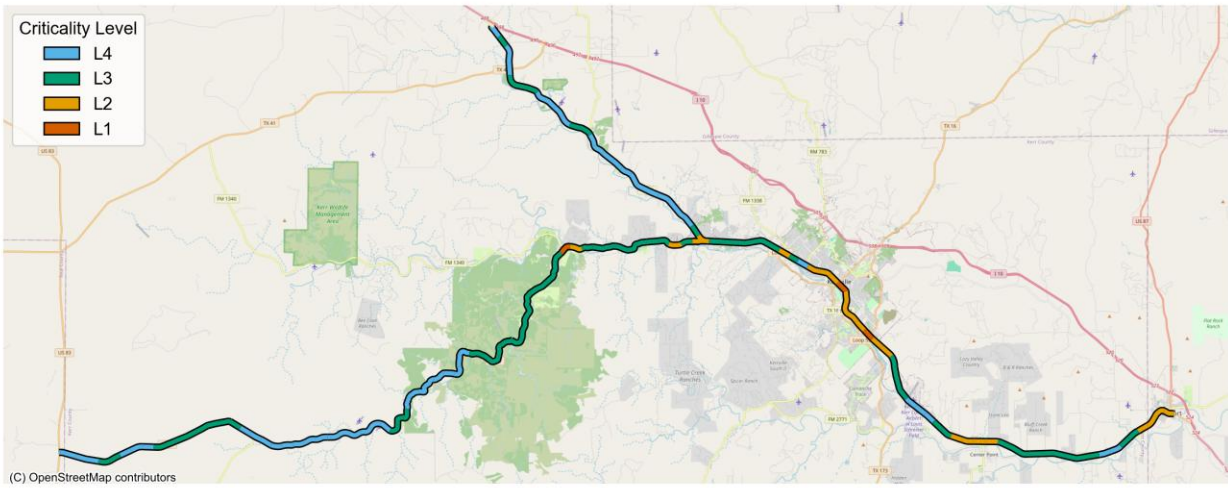

Figure C-39. Criticality Levels for the US0027/US0039 Case Study.

Vulnerability Assessment

The highway's vulnerability was particularly pronounced during more extreme events (see Table C-32 and Figure C-40). In the 2020 500-year scenario, 4.25 miles were projected to sustain severe damage. This projected vulnerability became more acute in the future, with the length of severely damaged roadway increasing to 4.80 miles in the 2060 500-year scenario. This finding highlighted that even corridors with relatively low high-exposure mileage can be highly vulnerable to catastrophic failure in specific locations.

Table C-32. Damage Length by Return Period under the 2020 and 2060 Scenarios for the US0027/US0039 Case Study.

Damage Length	Combined-2020					Combined-2060				
	1-in-5	1-in-10	1-in-25	1-in-100	1-in-500	1-in-5	1-in-10	1-in-25	1-in-100	1-in-500
Minor	75.75	74.69	74.14	73.07	70.44	75.75	74.14	74.14	72.52	69.95
Moderate	0.00	1.06	1.08	0.59	0.00	0.00	1.08	1.08	1.13	0.00
Major	0.00	0.00	0.52	2.09	2.62	0.00	0.52	0.52	2.09	2.57
Severe	1.57	1.57	1.57	1.57	4.25	1.57	1.57	1.57	1.57	4.80

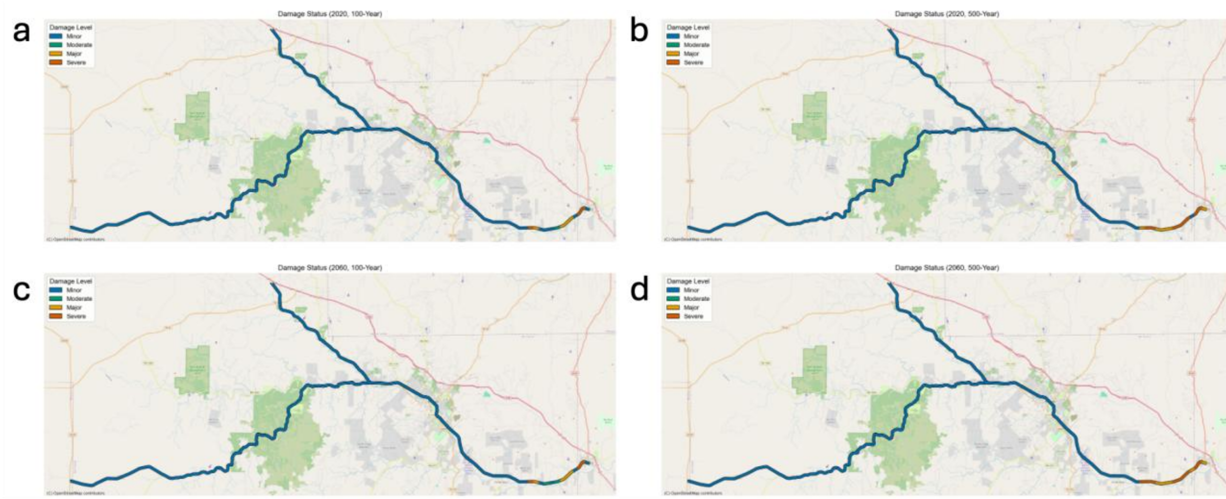

Figure C-40. Damage Status of Flooding for the US0027/US0039 Case Study: (a) 100-Year Return Period and 2020 Scenario, (b) 500-Year Return Period and 2020 Scenario, (c) 100-Year Return Period and 2060 Scenario, and (d) 500-Year Return Period and 2060 Scenario.

Risk Assessment

Table C-33 shows the total AAL for this corridor. The financial implications of the combined flood damage were significant for a rural corridor of this nature. The total AAL increased sharply with the return period, increasing from $8.39K for a 1-in-5-year event to $31.48K for a 1-in-500-year event in the 2020 scenario. This financial risk was projected to increase further by 2060, with the AAL for a 1-in-500-year event increasing to $34.17K. The recent damage in July 2025 suggested that the actual costs of a single major event can far exceed these annualized figures, reinforcing the value of preventative measures.

Adaptation Evaluation

Table C-34 shows the economic viability of the proposed pavement upgrade strategy. The B/C ratio was consistently > 1 across all analyzed return periods and scenarios, with a stable value of approximately 1.61. This finding signifies that even in an area with less extensive but more concentrated flood risk, the financial benefits of proactive adaptation clearly outweighed the costs. The avoided AAL for a 500-year event in 2060 was projected to be $23.95 K, demonstrating a solid return on investment.

To provide a single, comprehensive measure of economic viability, an overall B/C ratio was calculated by summing all benefits and costs across the different return periods. The result was a stable and positive overall B/C ratio of 1.61 for both the 2020 and 2060 scenarios. This finding signified that even in an area with less extensive but more concentrated flood risk, the financial benefits of proactive adaptation clearly outweighed the costs.

Table C-33. Annual Average Loss by Return Period under the 2020 and 2060 Scenarios for the US0027/US0039 Case Study.

Damage Status	Combined-2020					Combined-2060				
	1-in-5	1-in-10	1-in-25	1-in-100	1-in-500	1-in-5	1-in-10	1-in-25	1-in-100	1-in-500
Minor	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Moderate	0.00	2.71	2.82	1.41	0.00	0.00	2.82	2.82	2.83	0.00
Major	0.00	0.00	1.74	7.03	8.88	0.00	1.74	1.74	7.03	8.53
Severe	8.39	8.39	8.39	8.40	22.60	8.39	8.39	8.39	8.40	25.64
Total	8.39	11.10	12.94	16.85	31.48	8.39	12.94	12.94	18.26	34.17

Table C-34. Adaptation Strategy Effectiveness by Return Period under the 2020 and 2060 Scenarios for the US0027/US0039 Case Study.

	Combined-2020					Combined-2060				
	1-in-5	1-in-10	1-in-25	1-in-100	1-in-500	1-in-5	1-in-10	1-in-25	1-in-100	1-in-500
AAL-Baseline	8.39	11.10	12.94	16.85	31.48	8.39	12.94	12.94	18.26	34.17
AAL-Improvement	0.55	3.26	5.11	8.99	10.37	0.55	5.11	5.11	10.41	10.22
Avoided AAL	7.84	7.84	7.83	7.86	21.11	7.84	7.83	7.83	7.85	23.95
Adaptation Cost	4.87	4.87	4.87	4.87	13.19	4.87	4.87	4.87	4.87	14.89
B/C	1.61	1.61	1.61	1.61	1.60	1.61	1.61	1.61	1.61	1.61
Overall B/C	1.61					1.61				

Summary

The US0027/SH0039 case study in Kerr County showed a concentrated but growing flood exposure and a high vulnerability to severe damage in specific segments. The financial risk was notable for a rural corridor, with the AAL for a 500-year event projected to exceed $34K by 2060. The proposed adaptation strategy was found to be consistently cost-effective with a B/C ratio of 1.6, confirming its value for mitigating future flood damage and preventing the kind of destruction recently witnessed.

CASE STUDY SUMMARY

The 10 case studies presented in this report collectively underscored a critical and overarching finding—flood risk to the Texas transportation infrastructure is significant, widespread, and projected to increase substantially by 2060. While the magnitude of exposure and financial risk varied by location, major corridors near coastal and metropolitan areas like Houston (e.g., US0290, SH0288) had the highest AALs. Even inland corridors demonstrated a growing vulnerability that warrants proactive attention.

A key finding emerging from this analysis was the consistent economic viability of the proposed adaptation strategy. In nearly every scenario across all 10 cases, the B/C ratio for upgrading pavement structures on high-risk segments was well above 1, demonstrating that targeted, risk-informed investments in infrastructure resilience were not only necessary but also highly cost-effective. The avoided losses from implementing these measures consistently justified the upfront adaptation costs.

As TxDOT prepares for the 2026 TAMP, the findings from Task 7 and these case studies led the research team to identify the following key initiatives and frameworks that can be feasibly integrated to enhance the state's resilience posture:

- **Framework for integrated risk-based prioritization:** TxDOT can evolve its current project prioritization process by formally integrating the quantitative risk metrics developed here. A feasible framework would involve using the criticality level and the AAL as new scoring criteria within the existing performance metric data integration system. Use of these criteria would allow for a more efficient allocation of resources by ensuring that funds are directed not only to assets in poor condition but to those that are most critical and face the highest financial risk from future hazards. This change directly addresses the goal of achieving efficient spending on assets within important corridors.
- **Framework for corridor-level resilience planning:** Instead of viewing assets as individual points, TxDOT can adopt a corridor-level approach for its most vital and at-risk routes (e.g., US0039, SH0288). This framework would involve developing integrated resilience plans for entire corridors and bundling adaptation projects (e.g., pavement hardening, drainage improvements, and bridge elevation) to create a consistently

protected route. This holistic view ensures that investments are not undermined by an unaddressed weak link elsewhere in the corridor.

The 2026 TAMP can be strengthened by including specific initiatives to implement these frameworks. This could include a plan to expand this quantitative risk assessment to other major corridors and to incorporate additional climate stressors like extreme heat and wildfire. Furthermore, the TAMP can propose the development of a *Resilience Adaptation Playbook* that would use the data from this study to create standardized, cost-effective intervention strategies for different asset types based on their specific risk profiles. This resource would improve future risk assessment and response across the state.

Ultimately, this research provides TxDOT with a clear, data-driven path forward. It moves the conversation from abstract risk to concrete, quantifiable financial impacts and demonstrates the immense value of proactive adaptation. By integrating these findings and frameworks, the 2026 TAMP can further solidify TxDOT's position as a national leader in building a resilient transportation network for the future.