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Incorporating Resilience Considerations in Transportation Asset Management Planning and Project Selection Process

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16. Abstract This research develops and demonstrates a resilience-based transportation asset management (TAM) framework for the Texas Department of Transportation (TxDOT) to incorporate resilience into asset assessment and project screening. The study (i) reviewed current TAM and resilience practices, (ii) assessed climate-related vulnerability for bridges and bridge-class culverts, roadways, and selected retaining walls, (iii) developed asset-specific resilience measures that integrate hazard vulnerability, asset condition, functionality, and recovery-related factors, and (iv) incorporated asset-level resilience into a GIS-based project-prioritization framework. The project selection method links candidate projects to nearby transportation assets, aggregates multi-hazard resilience needs, and combines resilience need with project criticality and expected effectiveness to support priority screening. A software tool was developed to automate resilience estimation, mapping, sensitivity analysis, and risk–resilience ranking comparisons. The pilot studies evaluated selected Wichita Falls roadway segments under extreme cold and extreme heat and Houston District bridges under inland flooding. In the Wichita Falls pilot, existing pavement condition and functional performance had the greatest influence on roadway resilience, and extreme heat produced more priority changes than extreme cold. In the Houston pilot, inland-flood vulnerability had the greatest influence on bridge resilience, while bridge component condition also affected results. Both pilots identified assets whose priorities increased when resilience was considered. The results indicate that resilience-based TAM can supplement conventional risk-based screening by identifying assets with weaker capacity to maintain or recover functionality after disruption. The framework and software are intended for planning-level screening to support maintenance, rehabilitation, adaptation, and further engineering review. Additional asset, hazard, hydraulic, cost, treatment history, and recoverability data would improve future district- and statewide applications.		

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**INCORPORATING RESILIENCE CONSIDERATIONS IN
TRANSPORTATION ASSET MANAGEMENT PLANNING AND
PROJECT SELECTION PROCESS**

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Disclaimer

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Chapter 1

Literature Review

1.1 Introduction

Transportation infrastructure plays a crucial role in the socioeconomic development and well-being of communities. However, the increasing frequency and severity of natural events, such as coastal and rainfall flooding, extreme heat, extreme cold, and drought, are causing significant damage to Texas transportation assets, including pavements, bridges, culverts, drainage systems, tunnels, and other geotechnical assets (9). The impacts of these adverse events not only cause substantial direct socioeconomic losses within transportation systems but also trigger significant cascading effects on other critical infrastructure systems that rely on transportation systems, such as utilities and supply chains (10).

These challenges highlight the urgent need to integrate resilience and risk-management considerations into Transportation Asset Management (TAM). Resilience in the context of transportation infrastructure is defined as the system's ability to withstand, adapt to, and recover from disruptive events while continuing to perform its essential functions (11). Achieving this requires a proactive, systems-level approach to minimize the long-term impacts of hazards on infrastructure and society.

Recent studies highlight the importance of resilience in transportation planning and asset management. For instance, a report by National Academies of Sciences, Engineering, and Medicine (12) emphasizes the need for transportation agencies to adopt a systems approach to resilience, considering not only the physical infrastructure but also the organizational and operational aspects of transportation systems. The Federal Highway Administration (FHWA) also provides guidelines for incorporating resilience into transportation planning and asset-management processes, recognizing the long-term benefits of resilient infrastructure in reducing maintenance costs and improving system reliability (13). The integration of resilience considerations into TAM requires a multifaceted approach that includes:

- Assessing vulnerabilities of transportation assets to various hazards (14);

- Developing strategies to enhance the robustness and adaptability of infrastructure (15);
- Implementing risk-based decision-making processes in project selection and resource allocation (16);
- Incorporating climate-change projections into long-term planning and design standards (17).

To address these components comprehensively, this review examines current practices and frameworks that bridge resilience and TAM. Specifically, it is structured into the following main areas to provide a thorough exploration of key topics:

- **TAM Approaches.** This section offers a comprehensive introduction to TAM, detailing its process and the role it plays in maintaining and improving the performance of transportation infrastructure.
- **Resilience Assessment Approaches.** This section provides an overview of resilience assessment, including methods and frameworks used to evaluate the ability of transportation systems to withstand, recover from, and adapt to disruptions.
- **Datasets and Data Processing for Integrating Resilience into TAM.** This section emphasizes the importance of specific datasets for managing transportation assets effectively. It discusses the challenges and methods of integrating data from multiple sources, which is crucial for developing a comprehensive view of assets, and underscores the role of data fusion in creating a cohesive overview.
- **Tools for TAM.** This section covers the various software tools and applications used to facilitate the management of different types of transportation assets.
- **Current Gaps.** Areas where current practices, tools, or research in TAM are insufficient or lacking are identified to provide a basis for future research and improvements.

By synthesizing this information, this review aims to provide insights and recommendations for enhancing the resilience of Texas transportation infrastructure in the face of increasing environmental challenges.

1.2 Transportation Asset Management Approaches

The American Association of State Highway and Transportation Officials (AASHTO) defines TAM as a "strategic and systematic process for operating, maintaining, upgrading, and expanding physical assets effectively throughout their life cycles. It focuses on managing

assets, such as pavements, bridges, and roadside infrastructure to achieve desired service levels while minimizing life-cycle costs (18). Conventional TAM follows an iterative, risk-informed framework shown in Figure 1.2.1, enabling transportation agencies to mitigate risks proactively and avoid the escalated costs associated with reactive strategies. Key steps in this process include:

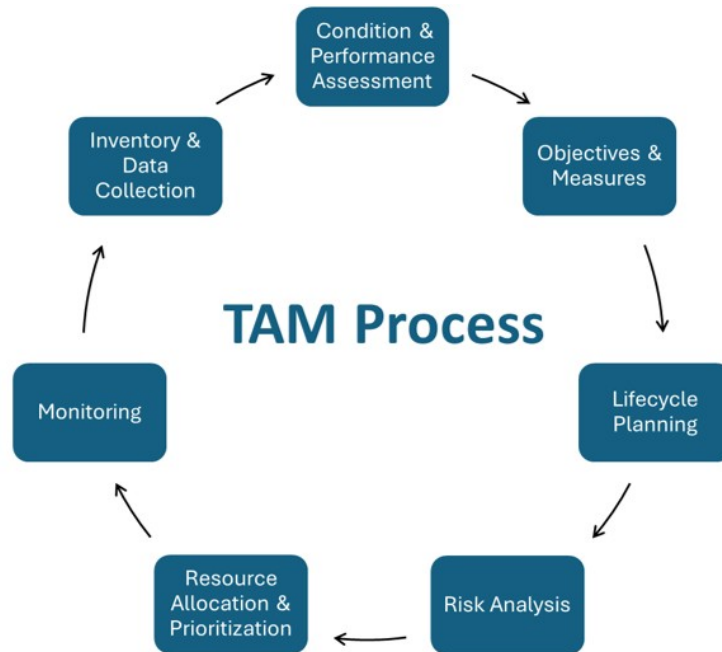


Fig. 1.2.1: Schematic of the TAM framework. The flowchart represents a systematic approach to managing transportation assets to enhance performance and minimize costs within resource constraints throughout their life cycles.

1. **Inventory and Data Collection:** Identification and cataloging of transportation assets, such as roads, bridges, tunnels, signage, and pavements, along with comprehensive data collection.
2. **Condition and Performance Assessment:** Assessment of the condition and performance of each asset using standardized methods to identify maintenance, repair, rehabilitation, or replacement needs. Then, the establishment of asset performance metrics to track effectiveness and efficiency, such as pavement condition index and bridge sufficiency rating.
3. **Objective Formulation:** Formulation of clear and measurable asset management objectives aligned with organizational goals, such as safety, reliability, and cost-effectiveness.
4. **Life-Cycle Planning:** Development of long-term strategies for asset management,

including setting maintenance schedules and budgeting for lifecycle costs. This can enable transportation agencies to maximize their abilities to maintain assets at a target level of service over their expected life, ranging from years to decades, in an efficient manner while supporting TAM objectives.

5. **Risk Analysis:** Identify and assess risks due to natural hazards and environmental factors that may impede the accomplishment of the objectives. This step can include the evaluation of the gaps between actual and desired asset performance due to risks.
6. **Resource Allocation and Prioritization:** Identify investment options and make decisions as to which investment strategies to prioritize, to allocate resources effectively and maximize the overall value of transportation assets. This step includes the implementation of asset management plans and programs.
7. **Monitoring:** Regularly tracking asset performance, costs, and schedules to ensure compliance with goals and objectives and adjust strategies as needed.

By integrating these steps, TAM enables agencies to prioritize investments, extend asset lifespans, and enhance transportation systems' overall efficiency and effectiveness. Effective management of different types of assets requires tailored approaches to achieve the expected level of service or performance. According to AASHTO's TAM Guide, there are three main approaches to TAM:

- **Condition-Based Approach:** This approach is arguably the most adopted one by U.S. transportation agencies. It focuses on selecting interventions based on the forecasted condition of the asset and the identified onset of failure. Preservation and maintenance activities are planned based on the expected exceedance of condition thresholds over the asset's lifecycle, to address the failure and restore or extend service life. This approach aims to optimize asset performance and longevity by strategically targeting maintenance efforts.
- **Interval-Based Approach:** This approach is most applied to operations or manufactured assets (e.g., striping, signs, guardrail, and other mechanical and electrical-related items) with highly uniform performance, where only an inventory is maintained, and condition assessments may not be financially feasible. With this approach, the manufacturer's suggested life estimates are typically used to establish a time interval beyond which the cost of asset failure outweighs the cost of replacement. Maintenance activities for those assets are scheduled based on a predetermined time frame or usage thresholds, irrespective of whether the asset requires attention.

- **Reactive-Based Approach:** Unlike condition- or interval-based approaches, the reactive-based approach does not rely on forecasting to anticipate the timing of preservation or maintenance activity. In this approach, maintenance or repairs are administered reactively only in response to identified problems or until an asset reaches an unacceptable condition. Therefore, a reactive-based approach is typically reserved for low-value or less critical assets, redundant assets, or assets whose failure represents an acceptable risk. However, implementing this strategy often necessitates an agency to have a mechanism in place to deliver necessary work within a specified timeframe to prevent the emergence of unacceptable levels of risk beyond the defined minimum acceptable thresholds.

Table 1.2.1: Comparison between different TAM approaches (8).

Approach	Condition-Based	Interval-Based	Reactive-Based
Description	Selects intervention based on a forecasted condition exceedance interval.	Asset is treated based on a time or usage basis whether it needs it or not.	Treatment is performed to fix a problem after it has occurred.
Usage	High-risk or high-value assets.	Moderate or low risk assets. Mandated manufactures management regimes or short-lived assets. Assets where the cost to collect condition data is expensive.	Low risk or criticality assets. Assets where the effects of accumulated defects are not critical to their functionality.

Each of these asset management approaches offers distinct advantages and challenges (Table 1.2.1), and the selection of the most suitable method depends on factors such as asset type, budget constraints, and performance objectives. It is worth noting that risk and resilience can be integrated into these approaches since risk and resilience considerations play a significant role in resource allocation, project selection, long-term planning, and other essential parts of the TAM process.

1.3 Resilience Assessment Approaches

This section presents an overview of approaches for assessing the resilience of transportation assets. It introduces the concept of resilience and quantification methods, and explores the relationship between resilience and risk within the context of TAM. This review serves as a foundation for understanding how resilience can be effectively integrated into TAM practices and project selection processes, which will be further examined in subsequent sections.

1.3.1 Engineering Resilience Concept

In engineering, resilience is a multifaceted concept, and it is typically defined as the capacity of an entity or a system to withstand, adapt to, and recover from a disruptive event (19–22). Researchers have identified four dimensions for resilience enhancement (20, 23) which can be indicated in the functionality curve.

- **Robustness:** strength or the ability of elements, systems, and other units of analysis to withstand a given level of stress or demand without suffering degradation or loss of function. It is therefore the residual functionality right after the hazard.
- **Redundancy:** the extent to which elements, systems, or other units of analysis exist that are substitutable, i.e., capable of satisfying functional requirements in the event of disruption, degradation, or loss of functionality.
- **Resourcefulness:** the capacity to identify problems, establish priorities, and mobilize resources when conditions exist that threaten to disrupt some element, system, or other unit of analysis; resourcefulness can be further conceptualized as consisting of the ability to apply material (i.e., monetary, physical, technological, and informational) and human resources to meet established priorities and achieve goals.
- **Rapidity:** the capacity to meet priorities and achieve goals promptly to contain losses and avoid future disruption. It represents the slope of the functionality curve.

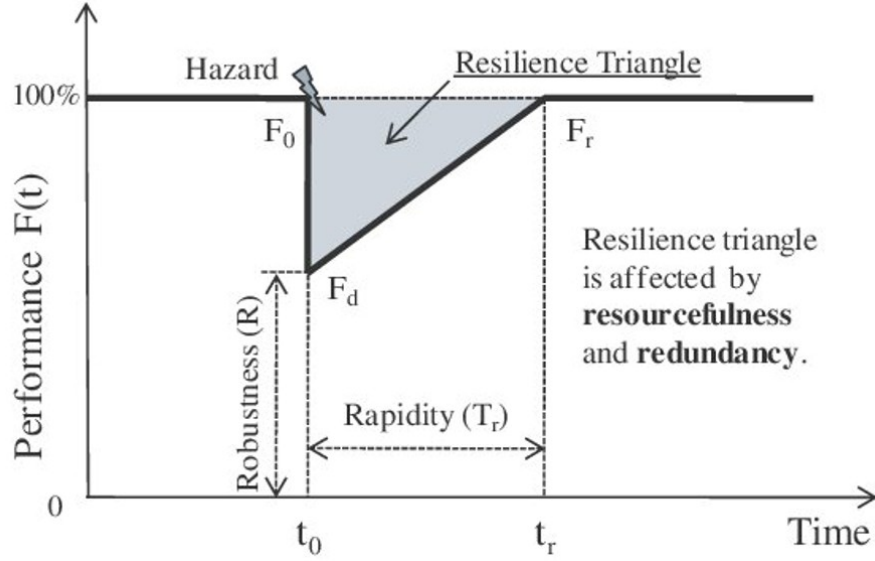


Fig. 1.3.1: Schematic for resilience (1).

Alternatively, the resilience of an entity or a system can be quantified using one metric: the area under the functionality curve, i.e., $1 - \text{the area of resilience triangle (loss)}$ in Figure 1.3.2. Depending on the entity or systems, the area for the resilience loss can have different shapes. Based on the shape of resilience loss, resilience planning and management can be broadly categorized into three types: (i) moderate (linear recovery), (ii) poor (trigonometric recovery), and (iii) well (exponential recovery). Effective resilient TAM planning should prioritize achieving resilience through well-planned and managed strategies.

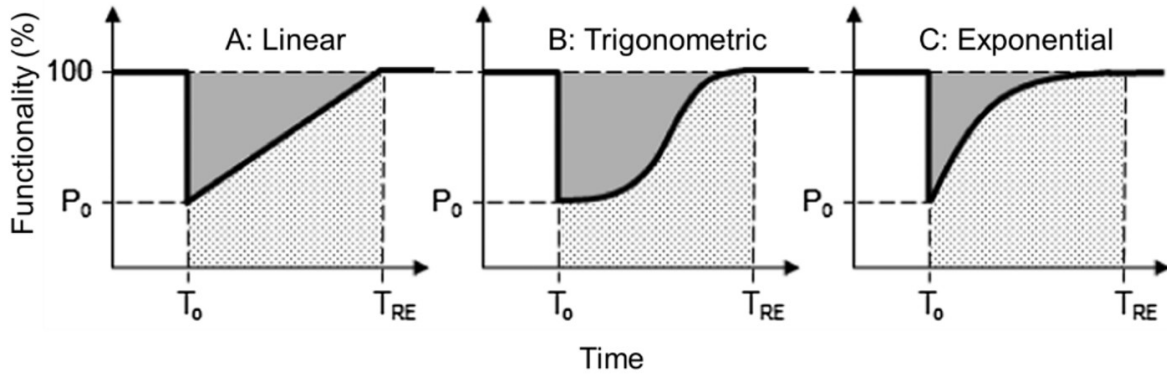


Fig. 1.3.2: Schematic illustration of functionality curves demonstrating different levels of resilience: (a) moderately planned and managed, (b) poorly planned and managed, and (c) well planned and managed. Adapted from (2).

Nonetheless, apart from robustness and rapidity, the four dimensions are typically challenging to measure, and the functionality curve of an asset is particularly difficult to obtain

in a practical setting due to uncertainty surrounding data, hazards, and resource constraints. As such, researchers have resorted to other metrics that can be more conveniently applied in practice, including: (i) time or cost to fully recover operations, performance, and functionality and (ii) the degree to which the pre-disruption functionality is restored.

1.3.2 Relation Between Risk and Resilience

As resilience and risk are frequently related in existing TAM frameworks, it is noteworthy to distinguish between these two concepts. Risks depend on the characterization of the threats, asset or system vulnerabilities, and consequences of adverse events to determine the expected loss of functionality, as shown in Figure 1.3.3(a). More formally, it is interpreted as the total loss of functionality caused by an adverse event. In contrast, resilience is determined by the area under the functionality curve after the event. The dashed line in Figure 1.3.3(a) suggests that highly resilient systems can adapt so that their functionality can improve over the initial performance, making the systems more resilient to future disruptions. In some sense, resilience analysis typically includes risk as a central component. However, it is noteworthy that an entity or system may have high resilience but still face high risks and vice versa, as shown in Figure 1.3.3(b).

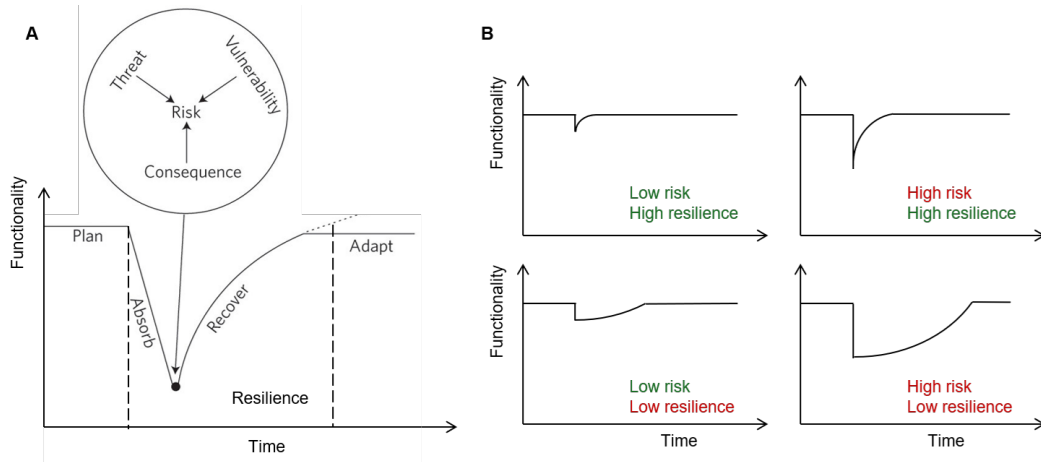


Fig. 1.3.3: Schematic illustration of the relationship between risk (and vulnerability) and resilience (3).

Regarding their applications to TAM, the risk-based approach strengthens asset management by recognizing the inherent uncertainty in asset vulnerability to disruptions and identifying strategies to reduce that uncertainty and its effects on asset functionality. Consequently, transportation agencies can proactively and strategically allocate available resources to maintain the performance of their assets in the face of risks. In comparison, resilience-based TAM not only seeks to reduce the vulnerability of assets in response to disruptive events

but also prioritizes ensuring the rapid restoration of asset functionality following disruptions. This dual focus ensures that transportation assets can withstand and quickly recover from adverse events, thereby bolstering overall system resilience under uncertainty.

1.3.3 Resilience in Transportation Asset Management

With the increasing frequency and intensity of natural disasters due to climate change, coupled with man-made disruptions, ensuring the resilience of transportation assets has become as critical as maintaining their efficiency and reliability. For transportation assets, resilience enhancement requires a holistic strategy to counter uncertain natural hazards, such as hurricanes, floods, and earthquakes, alongside anthropogenic threats like vandalism and cyber attacks. Recognizing the growing importance of resilience in transportation asset management, USDOT guidance (24, 25) and NCHRP Project 23-32 (26), emphasize the need to incorporate resilience into transportation planning, design, construction, operations, and maintenance. These efforts highlight the necessity of integrating resilience into the life cycle of TAM to mitigate disruptions, thereby ensuring the continued functionality of transportation systems while enhancing the longevity and effectiveness of investments (25).

In terms of methodologies for incorporating resilience into TAM, RAND Corporation proposes the AREA framework for resilience, which identifies Absorptive Capacity, Restorative Capacity, Equitable Access, and Adaptive Capacity as essential factors (27). This model enables transportation agencies to assess and enhance resilience across these areas, ensuring that each component of the system is prepared to handle different stresses and recover appropriately. Shah et al. (28) present a decision-support framework for evaluating the resilience of transportation design solutions amid changing socio-economic, technological, environmental, and political conditions. This framework enables decision-makers to evaluate the resilience of proposed asset management solutions. Herrera et al. (29) discuss the application of a quantitative framework for analyzing risks posed by physical threats to highway transportation systems and assets. The authors detail the utilization of this risk analysis framework by the Colorado Department of Transportation following the 2013 floods, which aided in soliciting federal emergency response funding. Although CDOT has developed the risk and resilience analysis procedure (30), its focus lies on calculating risks related to hazards like floods, rockfall, and debris flow. Moreover, while levels of resilience index are proposed, they are measured based on risk and criticality for system operations.

To manage and enhance resilience effectively, TAM frameworks incorporate performance metrics and indicators. Key metrics in resilience are:

- **Criticality and Exposure:** Assessing the importance of assets within the transportation network and their vulnerability to specific risks (e.g., extreme weather, traffic congestion).

- **System Redundancy:** The availability of alternative routes or backup systems that reduce the impact of asset failure.
- **Response and Recovery Time:** Measuring how quickly the system returns to functional status post-disruption.

These metrics allow transportation agencies to prioritize investments based on resilience and guide the deployment of resources toward the most critical assets. As RAND’s report suggests, identifying and measuring the criticality and exposure of assets helps in deciding which assets to prioritize during restoration efforts.

1.3.4 Existing State DOT Efforts to Integrate Resilience in Asset Management

Many state DOTs across the U.S. are increasingly integrating resilience into their TAM practices and project selection processes to address challenges posed by extreme weather and climate change. This section highlights current practices adopted by state DOTs to incorporate resilience into asset management and decision-making frameworks under various types of natural hazards.

1. Minnesota DOT (MnDOT)

- **Flood-Resilience Projects:** MnDOT has integrated resilience into its asset management by identifying flood-prone areas and prioritizing infrastructure improvements to mitigate flood risks (4). This includes designing elevated roadways, adding drainage improvements, and integrating flood-resilient materials into projects.

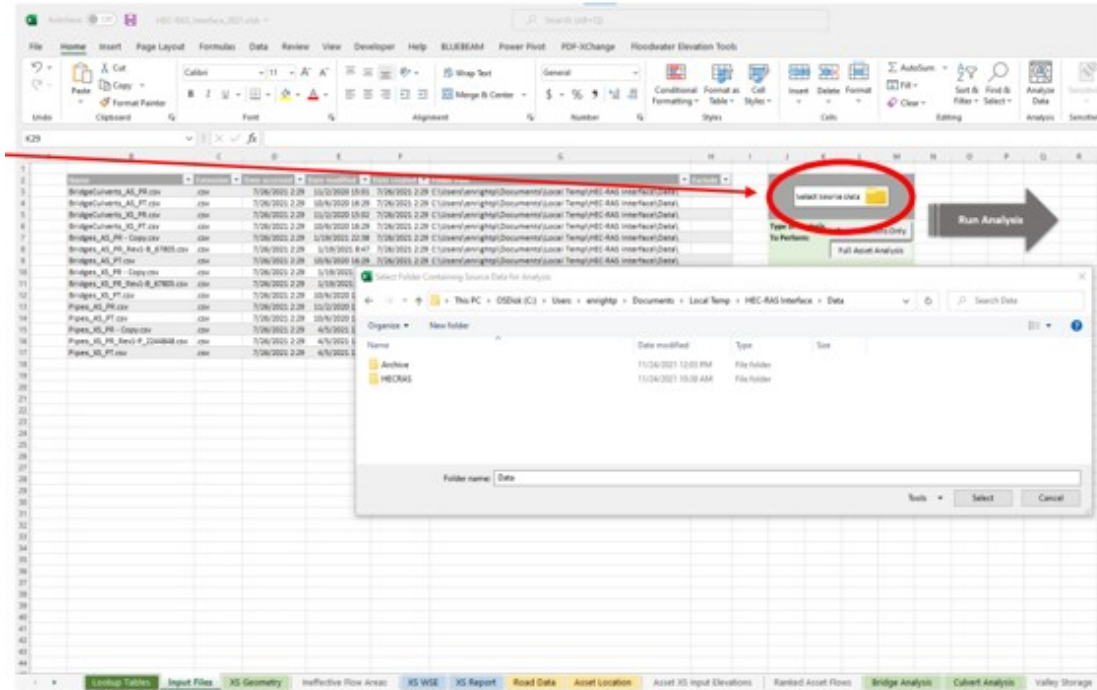


Fig. 1.3.4: Importing Model Inputs and Pre-Processing (4).

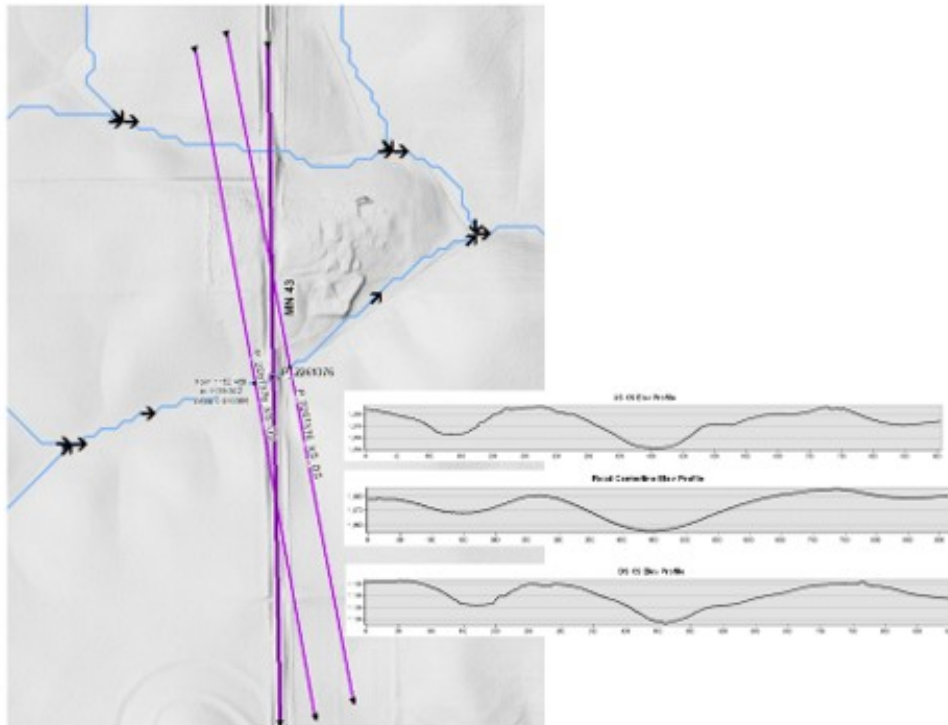


Fig. 1.3.5: Preparation of Hydraulic Model Inputs (Phase 1) (4).

- **Climate-Adaptation Planning:** MnDOT’s Climate Adaptation Plan outlines actions to protect transportation assets from extreme weather. This includes modifying TAM practices to prioritize assets critical for connectivity and emergency access, especially in areas vulnerable to flooding or extreme cold.

2. Pennsylvania DOT (PennDOT)

- **Resilience and Climate-Adaptation Program:** PennDOT has integrated resilience into its asset management and planning processes by developing a Climate Adaptation and Resilience Plan. This plan emphasizes asset vulnerability assessments, particularly for bridges and pavements, to identify critical assets requiring climate adaptation measures (31). PennDOT uses this data to inform project selection, prioritizing projects that mitigate flooding and landslide risks (32).
- **Community-Impact Focus:** PennDOT considers socio-economic impacts when selecting resilience projects, aiming to protect transportation routes that are critical for vulnerable communities, and ensuring essential access during and after extreme weather events (33).

3. Illinois DOT (IDOT)

- **Flood-Vulnerability Assessments:** IDOT has focused on improving infrastructure resilience in flood-prone areas, particularly by evaluating the flood vulnerability of bridges and culverts. Asset data and hazard exposure are used to prioritize projects that enhance resilience against water-related damage.
- IDOT collaborates with regional partners like CMAP to conduct climate vulnerability assessments and design transportation systems that can handle future weather events. The state is also advancing intelligent transportation systems (ITS) to improve traffic management during extreme weather, ensuring real-time updates and safer road conditions. These initiatives not only address current climate impacts but also align infrastructure planning with anticipated environmental challenges, balancing costs with resilience and reliability (CMAP).

4. New York State DOT (NYSDOT)

- **Climate and Resilience Policy:** NYSDOT incorporates resilience measures into project selection and design, aligning with the state’s broader climate change initiatives. The agency follows the Climate Resiliency Design Guidelines, which translates future-looking climate change projections into technical guidance for

infrastructure projects (34, 35). NYSDOT’s approach is informed by the Climate Leadership and Community Protection Act (CLCPA), which sets ambitious goals for reducing greenhouse gas emissions and increasing climate resilience statewide (36).

- **Green-Infrastructure Initiatives:** New York’s resilience efforts include green infrastructure approaches to manage stormwater runoff and reduce flood risk. The New York City Department of Transportation (NYC DOT) is implementing new cloudburst and green infrastructure projects to convey, detain, and store stormwater (36). These efforts are part of a broader strategy to adapt to climate change impacts, including sea-level rise, heavy rains, and extreme heat, which pose significant challenges to the city’s transportation infrastructure (36).

5. Colorado DOT (CDOT)

- **Resilient Infrastructure Design:** CDOT has incorporated resilience criteria into TAM practices, particularly in mountainous regions prone to rockfalls and landslides. CDOT prioritizes retaining walls, slope stabilization projects, and alternative routes that ensure continuous access during adverse conditions.
- **Avalanche Mitigation:** CDOT uses resilience data to select and fund avalanche mitigation projects, such as barriers and controlled blasting. This helps protect high-traffic routes that are vital for connecting remote communities and facilitating emergency response.

6. Denver Regional Council of Governments (DRCOG)

- **Sustainability and Resilience Framework:** Denver’s DRCOG emphasizes resilience in TAM by coordinating with local agencies to select projects that address urban heat, flooding, and infrastructure aging. Priorities include drainage improvement projects and reinforcing bridges to withstand flooding from sudden snowmelt.
- **Multi-Agency Collaboration:** DRCOG works with local DOTs and municipalities to assess vulnerabilities across the transportation network, especially in areas prone to extreme weather. The projects selected aim to maintain consistent service levels and support emergency evacuation during incidents.

7. Texas DOT (TxDOT)

- **Resilience Working Group and District-Level Resilience Projects:** TxDOT’s resilience efforts include forming a Resilience Working Group to address

infrastructure vulnerabilities and prioritize investments in resilience. This working group focuses on district-specific needs, with projects addressing coastal flooding, extreme heat, and storm impacts.

- **Statewide Resiliency Plan:** As part of its Statewide Resiliency Plan, TxDOT is implementing resilience-based project selection criteria that prioritize coastal bridge reinforcement, resilient drainage systems, and proactive repairs to pavements exposed to extreme weather. The framework incorporates resilience scoring to guide resource allocation based on criticality, exposure, and community impact.

8. California DOT (Caltrans)

- **Wildfire and Sea-Level-Rise Adaptation:** Caltrans prioritizes resilience projects in wildfire-prone and coastal areas. Projects include fire-resistant materials for roadside infrastructure, vegetation management along highways, and elevating coastal roads vulnerable to sea-level rise.
- **Climate Change Vulnerability Assessments:** Caltrans conducts statewide vulnerability assessments for all districts to identify critical infrastructure vulnerable to climate hazards. These assessments inform resilience investments for critical assets, such as highways and bridges impacted by flooding, landslides, and coastal erosion.

9. Florida DOT (FDOT)

- **Hurricane Resilience:** FDOT has demonstrated a long-standing commitment to improving the resilience of the state transportation system against hurricanes and other extreme weather events. The department's Resilience Action Plan (RAP) focuses on identifying risks related to storms, flooding, and sea level rise, and employs strategies to avoid, mitigate, or eliminate impacts (37). FDOT's approach includes the use of design techniques such as pavement markings, roundabouts, and high mast lighting, as well as planning tools like the Sea Level Rise Sketch Planning Tool, which provides roadway impact data for various climate and flooding scenarios (38).
- **Permeable Pavements and Drainage Enhancements:** To mitigate frequent rain-induced flooding, FDOT has implemented permeable pavements and improved drainage systems. These projects are prioritized in urban areas where flooding can disrupt major transportation routes and affect densely populated communities.

10. New Jersey DOT (NJDOT)

- **Coastal Flooding Mitigation:** NJDOT invests in coastal resilience projects to protect against sea-level rise and storm surges. This includes projects such as raising roadways, enhancing culverts and drainage near coastal communities, and installing tidal gates.
- **Asset Hardening for Flood-Prone Areas:** In inland areas, NJDOT focuses on reinforcing transportation assets, particularly bridges and culverts, against flood risks. Project selection incorporates resilience metrics that factor in community dependence on key infrastructure for emergency response.

11. Oregon DOT (ODOT)

- **Seismic Resilience:** ODOT's resilience focus is on seismic retrofitting for bridges and tunnels, especially in high-risk zones along fault lines. Projects are prioritized based on seismic vulnerability assessments, with an emphasis on critical routes that serve emergency services and evacuation needs.
- **All-Hazard Risk Management:** ODOT integrates resilience into TAM by evaluating the risk from multiple hazards, including wildfires and flooding. Project selection prioritizes investments in reinforcing infrastructure with materials and designs resistant to extreme heat and rapid water flow.

12. North Carolina DOT (NCDOT)

- **Stormwater Management:** NCDOT prioritizes projects that address flooding risks by investing in stormwater management solutions, such as enlarged culverts, improved drainage systems, and floodplain restoration. These projects are especially focused on areas frequently impacted by hurricanes and heavy rainfall.
- **Bridge-Resilience Improvements:** NCDOT has focused on enhancing bridge resilience by elevating structures and using corrosion-resistant materials in coastal regions prone to saltwater exposure. This approach is designed to extend asset lifecycles and ensure infrastructure stability after storm surges.

13. Virginia DOT (VDOT)

- **Hurricane and Coastal Resilience Initiatives:** VDOT prioritizes resilience in its project selection by reinforcing critical coastal highways and bridges to withstand hurricane winds and storm surges. Flood-resistant materials and elevated road designs are prioritized to safeguard routes vital for emergency evacuation.

- **Flood-Risk Mapping:** Using flood risk mapping, VDOT identifies high-risk areas and prioritizes projects that improve drainage and road elevations. The agency also incorporates natural resilience measures, like wetland restoration, to absorb floodwaters and protect nearby infrastructure.

14. Washington State DOT (WSDOT)

- **Landslide Mitigation and Slope Stability:** Given Washington’s mountainous terrain, WSDOT prioritizes slope stabilization and landslide mitigation projects. The agency’s Climate Impacts Vulnerability Assessment Report includes a qualitative assessment of all state highways, which helps inform these efforts (39). WSDOT’s approach to climate resilience considers future climate threats, including damage from extreme storms, which can contribute to landslides and slope instability (39).
- **Wildfire Resilience:** WSDOT implements wildfire resilience strategies as part of its overall climate resilience efforts. The agency recognizes increased wildfire activity as one of the new challenges brought by climate change (39). While specific details about fire-resistant vegetation management and non-combustible materials are not mentioned in the search results, WSDOT’s climate resilience approach aims to create a safe and sustainable transportation system in the face of various climate-related threats, including wildfires.

15. Georgia DOT (GDOT)

- **Flood Resilience in Urban Centers:** GDOT has focused on flood mitigation in urban areas, incorporating improved stormwater management and resilient culvert designs. This is especially important in cities like Atlanta, where flash flooding can significantly disrupt transportation (40).
- **Heat Resilience for Pavements:** GDOT has tested heat-resilient pavement materials in high-traffic areas, prioritizing those that experience rapid deterioration due to extreme summer temperatures. This extends the lifecycle of pavements and reduces maintenance costs (41).

16. Arizona DOT (ADOT)

- **Extreme-Heat and Drought Adaptation:** ADOT addresses extreme heat impacts by incorporating heat-resistant materials into pavement projects and modifying road designs to reduce heat-related degradation. They prioritize projects in high-traffic areas prone to asphalt softening and cracking (42, 43). ADOT

has developed a programmatic approach to addressing all aspects of weather and natural hazards, including extreme weather and future measurable climate trends, through a formal Resilience Program (43).

- **Dust-Storm Resilience:** In regions affected by dust storms, ADOT has implemented projects that reduce dust accumulation on roads. The agency’s Resilience Program specifically addresses drought-related dust storms as one of the stressors posing high threats to ADOT’s transportation system (43). This approach aims to minimize visibility hazards and improve road safety.

These examples illustrate the diversity of efforts in integrating resilience into the TAM process, ranging from climate adaptation and flood control measures to multi-agency collaboration and infrastructure hardening. Each state has adapted its TAM practices to local climate risks, asset vulnerabilities, and community needs, thereby emphasizing resilience as a core component of long-term infrastructure planning and sustainability.

1.4 Data Requirements and Data Fusion

This section highlights the critical role of data in TAM, particularly in integrating resilience considerations. It reviews the types of data essential for TAM, including asset inventories, condition data, and hazard-related datasets, and emphasizes the importance of historical and real-time data for proactive decision-making. The section also introduces data fusion techniques, focusing on their application in synthesizing information from diverse sources such as sensors, satellite imagery, and inspection records. By leveraging these methodologies, TAM can improve asset condition monitoring, enhance risk assessments, and support data-driven resilience strategies.

1.4.1 Datasets Required for Integrating Resilience into Transportation Asset Management

To effectively integrate resilience into TAM, a comprehensive set of datasets is needed to capture the conditions, vulnerabilities, and performance evolution of assets under varying stressors. The following categories of data are essential for building a robust, resilience-oriented TAM framework.

- **Asset Data**

1. **Inventory Information:** Detailed records of asset types (e.g., roads, bridges, drainage structures), materials, design specifications, and geographic locations form the foundation of TAM. This inventory data enables a systematic assessment of baseline conditions and facilitates planning for resilience enhancements. Data

on components, subcomponents, and materials can improve predictions of asset behavior under different stressors.

2. **Condition Data:** Comprehensive records of current and historical asset conditions, ideally spanning around five years, are essential for tracking performance trends and predicting future deterioration. Access to deterioration curves and condition ratings over time helps asset managers to project future needs, supporting both routine and emergency preparedness planning. Automated condition monitoring data from sensors can provide real-time insights, which are valuable for dynamic resilience modeling.
3. **Intervention History:** Detailed records of past interventions (e.g., maintenance, repairs, and upgrades), including maintenance types, costs, frequencies, and durations, reveal trends in asset management practices and highlight areas requiring resilience improvements. By analyzing intervention history, asset managers can assess the effectiveness of maintenance actions and make data-driven decisions for future resilience investments.
4. **Component-Specific Thresholds:** Data-driven thresholds for asset conditions provide benchmarks for triggering maintenance and repair actions. Establishing these thresholds based on specific component types enables targeted, proactive strategies that extend asset lifespan and enhance resilience by addressing vulnerabilities before failure.

- **Hazard Data**

1. **Natural-Hazard Events:** Comprehensive hazard datasets, encompassing diverse natural disaster types and their impacts, are crucial for understanding asset vulnerabilities. Relevant datasets include historical records and predictive models for hazards such as flooding, drought, heatwaves, and snowstorms, which inform risk assessments and resilience planning.

- **Flooding:** Detailed flood data, including peak flow rates, flood extent, depth, and duration, are necessary to evaluate asset exposure to inundation risks. Understanding flood patterns over time supports the development of flood-resilient designs and proactive flood management strategies.
- **Drought:** Drought data, including duration, frequency, soil moisture levels, and surface temperature, help in assessing the resilience of assets, particularly those reliant on water availability (e.g., green infrastructure, soil-sensitive roads). Drought impact assessments support planning for prolonged dry periods, especially under climate change scenarios.
- **Extreme Heat:** Data on maximum temperatures, humidity levels, heat-wave duration, and frequency inform the resilience of heat-sensitive assets, such as asphalt pavements and concrete structures. This data helps in identifying design adaptations needed to maintain asset integrity under rising temperatures.
- **Snowstorms:** Information on snowfall intensity, duration, accumulation rates, and ambient temperatures provides insights into the resilience of assets exposed to winter weather conditions. Understanding snowstorm impacts supports strategies for snow load management and road safety during extreme winter events.

- **Additional Data**

- **Life-Cycle Cost Data:** Lifecycle cost data for assets enable cost-benefit analysis of different TAM strategies, particularly in evaluating the economic viability of resilience measures. By understanding long-term costs associated with maintenance, repairs, and resilience enhancements, decision-makers can allocate resources effectively to optimize resilience investments. The main lifecycle cost data for bridges, pavements, drainage structures, as well as retaining walls and slopes are presented in the table below.

Table 1.4.1: Lifecycle cost examples for major transportation asset types.

Asset Type	Lifecycle Phase	Examples
Bridges	Initial Construction Costs	Steel or concrete girders, deck slabs, labor, equipment.
Bridges	Inspection and Maintenance	Inspections, cleaning, and reapplication of protective coatings every 5–10 years.
Bridges	Repair Costs	Fixing scour damage and replacing corroded bearings.
Bridges	Replacement Costs	Replacing decks and strengthening girders at lifecycle midpoint.
Bridges	Resilience Measure Costs	Adding seismic retrofitting, elevating structures for flood mitigation.
Bridges	Decommissioning/Disposal Costs	Demolition and recycling costs.
Pavements	Initial Construction Costs	Subgrade preparation, asphalt or concrete materials, and paving equipment.
Pavements	Inspection and Maintenance	Pavement inspections, crack sealing, and pothole repairs.
Pavements	Repair Costs	Overlay applications and full-depth patching.
Pavements	Replacement Costs	Complete reconstruction or milling and resurfacing.
Pavements	Resilience Measure Costs	Adding permeable pavement and strengthening layers for extreme weather.
Pavements	Decommissioning/Disposal Costs	Milling and recycling old pavement material.
Drainage Structures	Initial Construction Costs	Installing culverts, pipes, or channels, including excavation and backfill.

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Table 1.4.1 – *continued from the previous page*

Asset Type	Lifecycle Phase	Examples
Drainage Structures	Inspection and Maintenance	Inspections for blockages, sediment removal, and vegetation control.
Drainage Structures	Repair Costs	Repairing or replacing damaged culverts and erosion control at inlets/outlets.
Drainage Structures	Replacement Costs	Upgrading drainage systems to a larger capacity.
Drainage Structures	Resilience Measure Costs	Adding stormwater detention basins or upgrading for higher flood capacity.
Drainage Structures	Decommissioning/Disposal Costs	Removing old structures and stabilizing surrounding areas.
Retaining Walls and Slopes	Initial Construction Costs	Constructing reinforced concrete walls, gabion walls, and slope stabilization, e.g., vegetation and soil nails.
Retaining Walls and Slopes	Inspection and Maintenance	Inspections for cracks, drainage functionality, and vegetation management.
Retaining Walls and Slopes	Repair Costs	Repairing cracks and adding reinforcement to prevent failures.
Retaining Walls and Slopes	Replacement Costs	Reconstructing walls, regrading, and restabilizing slopes after failures.
Retaining Walls and Slopes	Resilience Measure Costs	Installing geosynthetic reinforcements and engineered drainage systems for landslide prevention.
Retaining Walls and Slopes	Decommissioning/Disposal Costs	Removal of old structures or stabilization of decommissioned slopes.

- **Fragility Curves:** Fragility curves are probabilistic tools used to estimate the likelihood that a structure, such as a bridge, will experience various levels of damage under a given hazard intensity (e.g., flood depth, scour, seismic ground motion). These curves vary by asset type and provide critical information for assessing structural vulnerabilities to hazards, aiding in the design of resilient infrastructure that withstands specific disaster intensities. Fragility curves are defined by their relationship to hazard intensity and the categorization of damage levels associated with different intensities (see Figure 1.4.1 for an example). In the case of bridges, the main elements in fragility curves include:
 - **Hazard-Intensity Relationship:** The x-axis represents the intensity of the hazard (e.g., water velocity, scour depth, seismic acceleration), while the y-axis shows the probability of reaching or exceeding a specific damage state.
 - **Damage Levels:** Fragility curves are typically categorized into discrete damage states, which may include:
 - * **No Damage:** The structure remains functional with negligible impact.
 - * **Minor Damage:** Small cracks, minor scour, or superficial wear; repairs are required but not urgent.
 - * **Moderate Damage:** Functional impairment, such as significant scour or structural cracking; immediate repair is necessary to prevent further degradation.
 - * **Major Damage:** Severe issues, such as pier instability, significant settlement, or structural deformation; bridge usability is compromised.
 - * **Complete Damage:** Complete structural failure, rendering the bridge unusable and requiring replacement.

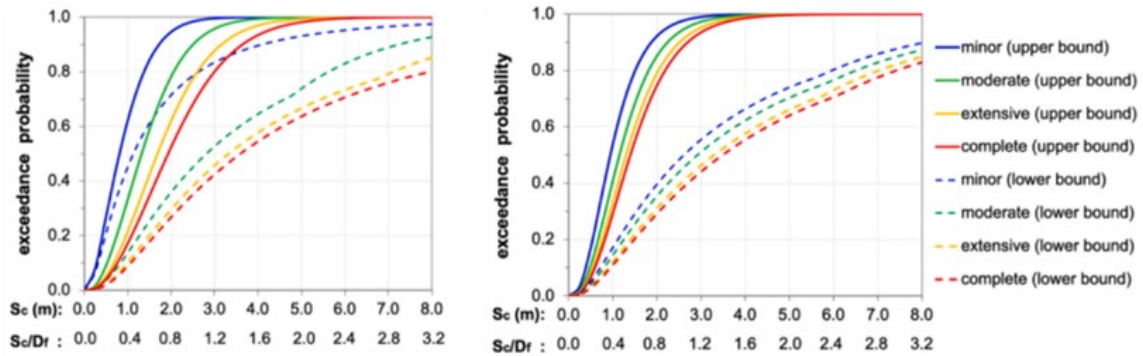


Fig. 1.4.1: Fragility curves for integral bridge for flood (5). Here, SC denotes scour depth, and DF denotes foundation depth.

- **GIS Database:** A GIS database with geo-referenced information for assets and associated hazards is vital for spatial analysis. GIS mapping facilitates visualization of asset locations relative to hazard-prone areas, enabling a geographic understanding of risks. This spatial perspective supports decision-making for location-specific resilience measures, especially for assets in high-risk zones.

1.4.2 Introduction to Data Fusion

Data fusion combines data through various computational and statistical methods to enhance the reliability and completeness of information (44). Mathematically, data fusion can be represented as a function F that maps multiple input data sources $X_1, X_2, \dots, X_n$ to an output Y representing the fused information:

$$Y = F(X_1, X_2, \dots, X_n), \quad (1.4.1)$$

where X_i represents each data source (e.g., sensor readings, images), F can be an algorithm or function designed to merge, filter, or interpret the data, and Y is the resultant fused data, providing insights with higher reliability or detail.

The function F often relies on statistical or machine learning techniques to handle noise, discrepancies, and uncertainties from the various data sources (45). Simple implementations of data fusion often employ averaging or weighted combinations for homogeneous data types. For example, given n data sources $X_1, X_2, \dots, X_n$ that provide scalar or vector values, a straightforward arithmetic mean can be used as the fusion function F .

$$Y = \frac{1}{n} \sum_{i=1}^n X_i. \quad (1.4.2)$$

When the data sources contribute unequally to the reliability of the fused output, weighted averaging can be employed, where each source is assigned a weight w_i based on its confidence level or quality:

$$Y = \frac{\sum_{i=1}^n w_i X_i}{\sum_{i=1}^n w_i}. \quad (1.4.3)$$

More advanced techniques are designed to address challenges such as noise, inconsistencies, and uncertainty by leveraging methods like Bayesian inference, Kalman filtering, and neural network models. These approaches can incorporate temporal, spatial, and contextual information to enhance the fusion process (46, 47).

- **Bayesian Inference:** Bayesian inference explicitly models uncertainty and integrates

data by updating probabilities based on prior knowledge and observed evidence.

- **Kalman Filtering:** Kalman Filtering accounts for temporal dependencies and optimally combines predictions and noisy measurements dynamically.
- **Machine Learning:** Machine learning algorithms like deep neural network and ensemble learning can learn complex, nonlinear relationships and adaptively fuse diverse data sources while considering spatial or contextual features.

1.4.3 Data Fusion Techniques for Transportation Asset Management

Data fusion is essential for understanding asset conditions and performance, enabling transportation agencies to make informed decisions, improve efficiency, and enhance resilience. By synthesizing information from diverse sources—such as sensors, satellite images, climate data, inspection records, and historical logs—agencies can dynamically assess road conditions. This approach, which includes fusing data from smartphone sensors like accelerometers and GPS, offers a more cost-effective and efficient alternative to traditional methods (48).

Sensor data fusion has become particularly prominent in structural health monitoring for transportation assets. Figueiredo et al. (49) illustrate how machine learning algorithms can combine data from multiple sensors to detect damage under varying operational and environmental conditions. This capability is crucial for managing bridges and pavements, where early identification of deterioration can significantly reduce maintenance costs and extend asset lifespans.

Beyond monitoring, data fusion plays a pivotal role in risk assessment and performance modeling, providing insights for proactive management strategies. For example, Dong et al. (50) develop a data fusion framework that integrates asset condition data, environmental factors, and historical performance to improve risk estimates. Such an approach enables agencies to anticipate and mitigate threats to transportation assets more effectively. Similarly, Chen et al. (51) demonstrate how combining information from visual inspections, non-destructive testing, and operational data improves performance modeling accuracy, guiding maintenance strategies with greater precision.

Temporal data fusion has further advanced the predictive capabilities of TAM. Chu and Huang (52) highlight how the fusion of historical maintenance records with real-time sensor data supports the development of accurate predictive models. These models enable proactive maintenance, reducing the risk of costly failures and service disruptions. In budget-constrained environments, such predictive capabilities allow agencies to optimize resource allocation, focusing interventions on the most critical areas.

Data fusion in TAM operates at several levels (53, 54):

1. **Low-Level (Sensor-Level):** Raw data from sensors are merged directly. For example, sensor readings of temperature and humidity could be combined to better understand pavement conditions.
2. **Mid-Level (Feature-Level):** Features or patterns extracted from raw data are fused. For example, statistical patterns from both historical traffic data and real-time sensor data can predict deterioration rates.
3. **High-Level (Decision-Level):** Decision-level fusion combines interpretations from different data sources. For instance, combining risk assessments from structural health data and environmental hazard data can inform maintenance scheduling.
4. **Hybrid Fusion:** This approach combines sensor, feature, and decision-level fusion techniques to address complex transportation challenges like multi-modal traffic management.

These fusion levels provide transportation agencies with a robust framework to address the multifaceted challenges of maintaining and improving transportation infrastructure.

Transportation agencies like state DOTs typically employ simpler, well-established data fusion methods due to constraints on staff expertise and resource availability. The basic yet effective techniques include:

1. **Data Averaging and Aggregation:** This is the simplest form of data fusion where similar data points (e.g., sensor readings on pavement temperatures) are averaged or aggregated over time. This technique smooths out noise and variability, providing a stable input for decision-making. State DOTs can use this approach to monitor infrastructure conditions over seasons and detect long-term trends. The FHWA mentions that data integration often involves aligning data using Geographic Information System (GIS) software, which can include aggregation techniques (FHWA, 2020). Iowa DOT uses this method to combine Waze data with other traditional data sources to track highway crashes and create public-facing (55).
2. **Rule-Based Fusion:** A straightforward and commonly used method where decision rules are established to interpret data from various sources. For example, a rule might specify that if both rainfall data and water level sensors indicate potential flooding, the drainage structures in that area require immediate inspection. Rule-based systems allow DOTs to set specific criteria for triggering maintenance actions without the need for complex analysis.
3. **Threshold-Based Alerts:** State DOTs often set thresholds for critical parameters like vibration levels in bridges or moisture content in embankments. Data fusion in this

context involves aggregating sensor data and comparing it against preset thresholds to trigger alerts. This approach is practical for real-time monitoring of infrastructure health and requires minimal computational power. Iowa DOT's Traffic Management Center utilizes crowdsourced data to identify and support crashes in real-time, especially in rural areas. (55).

4. **Simple Regression Models:** Basic statistical models, such as linear regression, can be used to combine data sources to predict asset conditions or maintenance needs. For example, a regression model could combine traffic load and historical pavement condition data to forecast future deterioration. These models are easy to implement and interpret, providing state DOTs with predictive insights without requiring complex machine learning expertise.
5. **GIS Overlay Analysis:** Geographic Information System (GIS) overlay is used to integrate spatial data with infrastructure data. For instance, by overlaying floodplain maps with the locations of bridges and drainage structures, DOTs can identify assets at high risk for water-related damage. This spatial fusion approach is widely accessible and allows for straightforward visualization of infrastructure vulnerabilities.

The above discussion shows that data fusion in TAM need not be overly complex to be effective. By utilizing practical techniques, e.g., rule-based systems, threshold alerts, simple regression, and GIS overlays, state DOTs can make data-informed decisions on maintenance prioritization and resource allocation within budgetary and resource constraints.

However, as mentioned before, data fusion in TAM extends beyond simple data aggregation and encompasses sophisticated techniques to enable more accurate and dynamic asset management. State DOTs are increasingly adopting more advanced data fusion techniques to improve asset management. For example, the FHWA is developing user-friendly data fusion and visualization tools that use cutting-edge techniques in machine learning, deep learning, and AI for bridge inspections (FHWA, 2023). These tools represent a shift toward more intelligent, automated approaches in asset monitoring and decision-making. Li et al. (56) discuss the challenges and opportunities in handling big geospatial data, emphasizing the need for fusion techniques that can combine data from multiple sources and formats. In TAM, this can involve integrating satellite imagery, LiDAR data, and GPS-based asset location information to create comprehensive digital representations of transportation networks. Such geospatial data enhances the accuracy of asset inventories, thereby enabling more effective planning and risk assessment. These advancements demonstrate the evolving role of technology in shaping smarter, data-driven TAM strategies, where integrating complex data sources is crucial for improving decision-making and operational efficiency. As technology continues

to evolve, transportation agencies are better equipped to manage infrastructure proactively, ensuring greater asset resilience for the future.

1.5 Tools for Transportation Asset Management

Transportation agencies employ a wide range of tools in TAM to optimize the performance of transportation assets. Below are some of the key tools that can be used to support highway TAM:

AASHTO TAM Gap Analysis Tool.

The AASHTO TAM Gap Analysis Tool is an Excel-based resource designed to help transportation agencies assess and improve their asset management practices, particularly in terms of resilience. Below are its key benefits:

1. **Comprehensive Assessment:** The tool provides a structured evaluation of current asset management practices, helping agencies identify strengths and weaknesses related to resilience.
2. **Prioritization Guidance:** It assists agencies in prioritizing enhancements, allowing them to focus resources on critical areas for improving resilience.
3. **Standardized Framework:** Based on the AASHTO TAM Guide, the tool offers a consistent framework for benchmarking across different agencies.
4. **Customization Options:** Agencies can tailor the tool to fit their specific needs, making the assessment more relevant to their context.
5. **Promotes Continuous Improvement:** Regular use encourages ongoing assessment and enhancement of asset management practices.

However, this tool has the following limitations in TAM:

1. **Complexity:** The tool's comprehensive nature may be overwhelming for some agencies, especially those new to TAM.
2. **Subjectivity:** Some assessments rely on subjective judgments, which can lead to inconsistencies in results.
3. **Resource Intensive:** Conducting a thorough gap analysis requires significant time and effort, which may be challenging for agencies with limited resources.

4. **Limited Focus on Emerging Issues:** The tool may not fully address new resilience challenges or innovative practices that are not yet widely adopted.
5. **Implementation Challenges:** Identifying gaps is just the first step; agencies may struggle with implementing recommended improvements due to various constraints.
6. **Data Dependence:** The effectiveness of the tool relies on the quality and availability of data, which may be lacking in some agencies.

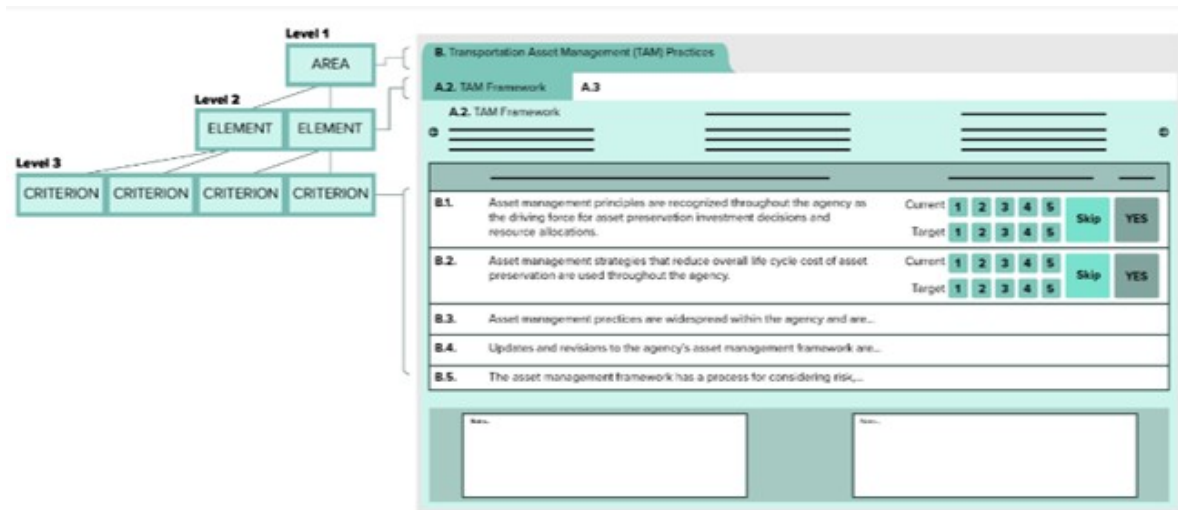


Fig. 1.5.1: AASHTO TAM Gap Analysis Tool interface (6)

In summary, while the AASHTO TAM Gap Analysis Tool offers valuable insights for enhancing resilience in TAM, its effectiveness depends on how well agencies apply their findings and address potential challenges in implementation.

AASHTO Pavement ME Design and Texas ME Pavement Design:

These software tools are designed to assist transportation agencies in pavement design and management, integrating performance modeling, analysis, and design features. The Texas ME Pavement Design is specifically tailored for TxDOT's flexible pavement structures. The advantages of this tool in TAM include:

1. **Climate Adaptation:** These tools incorporate climate data, allowing agencies to design pavements that are more resilient to changing environmental conditions.
2. **Long-Term Performance Modeling:** By simulating pavement performance over extended periods, these tools help in planning long-term resilience against deterioration and extreme events.

3. **Scenario Analysis:** Agencies can model various scenarios, including extreme weather events or increased traffic loads, to enhance asset resilience.
4. **Material Optimization:** The tools allow for the evaluation of different materials and mixes, potentially leading to more durable and resilient pavement structures.

Some limitations of this tool in TAM include:

1. **Limited Scope of Resilience:** While these tools address pavement resilience, they may not fully capture all aspects of system-wide resilience in transportation networks.
2. **Uncertainty in Long-Term Predictions:** As climate patterns change, the historical data used in these models may become less reliable for long-term resilience planning.
3. **Focus on New Construction:** These tools are primarily designed for new pavement construction, potentially overlooking resilience strategies for existing assets.
4. **Complexity in Resilience Modeling:** Incorporating complex resilience factors (e.g., social and economic impacts of asset failure) may be challenging within the current framework of these tools.

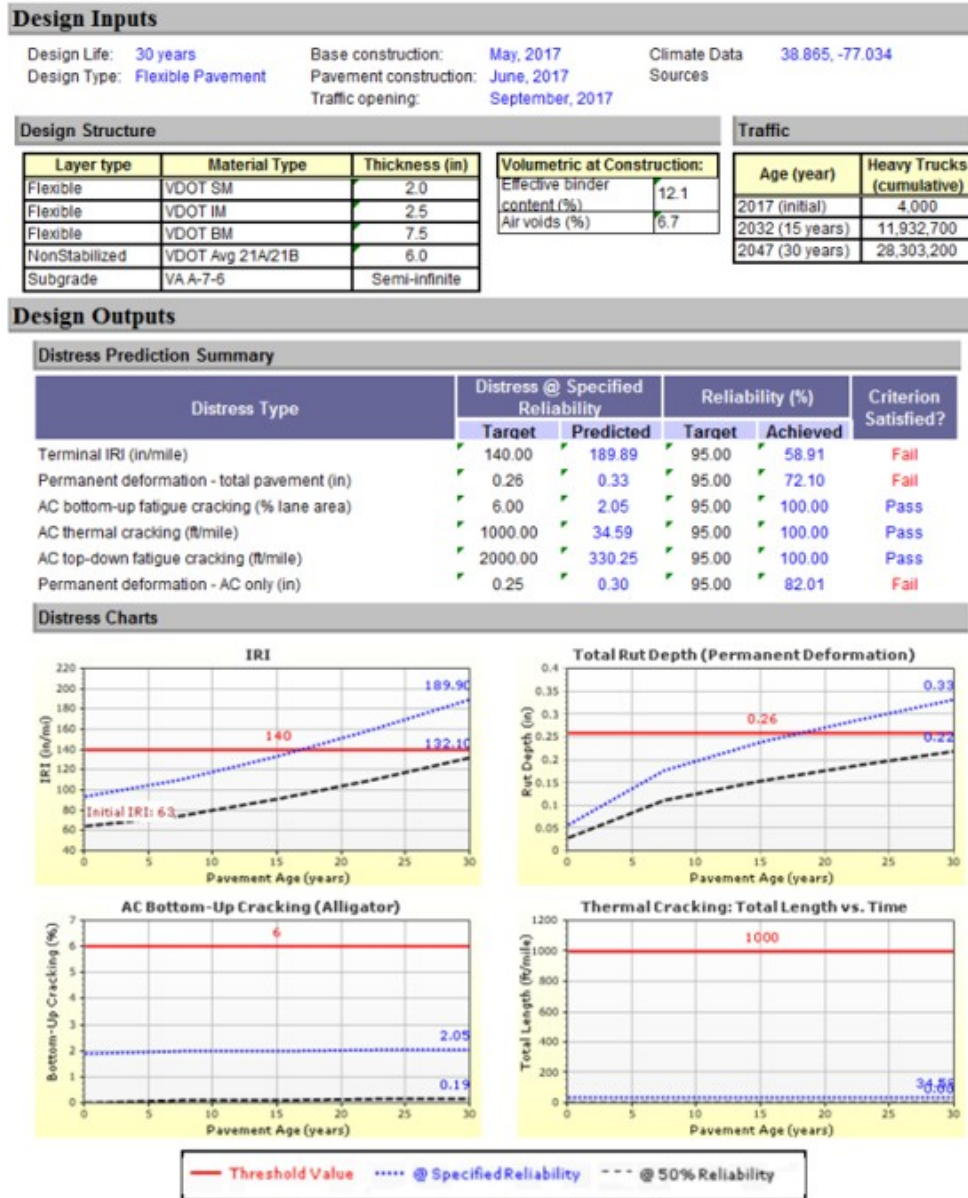


Fig. 1.5.2: AASHTO Pavement ME Design interface.

In summary, while AASHTO Pavement ME Design and Texas ME Pavement Design offer powerful capabilities for enhancing pavement design and potentially improving resilience, their effective use requires significant resources and expertise. Agencies must weigh these factors against the potential benefits when considering the implementation of these tools in their asset management strategies.

AASHTOWare Bridge Management (BrM):

Another product from AASHTO, BrM is a comprehensive bridge management system that helps agencies manage their bridge assets by providing tools for inventory management, condition assessment, inspection scheduling, and prioritization of maintenance and rehabilitation activities. Some advantages of this tool in TAM include:

1. **Comprehensive Asset Tracking:** BrM allows agencies to maintain detailed inventories of bridge assets, supporting a more resilient approach to TAM.
2. **Condition-Assessment Tools:** The software provides robust condition assessment capabilities, enabling agencies to identify vulnerabilities and prioritize resilience-enhancing interventions.
3. **Risk-Based Decision-Making:** BrM incorporates risk assessment features, helping agencies make more informed decisions about resilience investments.
4. **Long-Term Planning:** The system supports life-cycle cost analysis and long-term performance modeling, essential for building resilience over time.
5. **Customizable Performance Measures:** Agencies can set and track custom performance measures related to resilience, aligning with their specific goals and objectives.

Some limitations of this tool in TAM include:

1. **Complexity:** The comprehensive nature of BrM may require significant training and expertise to fully utilize its resilience-related features.
2. **Data Demands:** Effective use of BrM for resilience planning requires extensive, high-quality data, which some agencies may struggle to provide consistently.
3. **Limited Scope:** While comprehensive for bridges, BrM may not fully integrate with other asset types, potentially limiting system-wide resilience planning.
4. **Resource Intensive:** Implementing and maintaining BrM can be costly and time-consuming, potentially diverting resources from direct resilience investments.
5. **Adaptation Challenges:** As resilience needs to evolve with changing climate and asset conditions, agencies may face challenges in adapting BrM's models and processes.

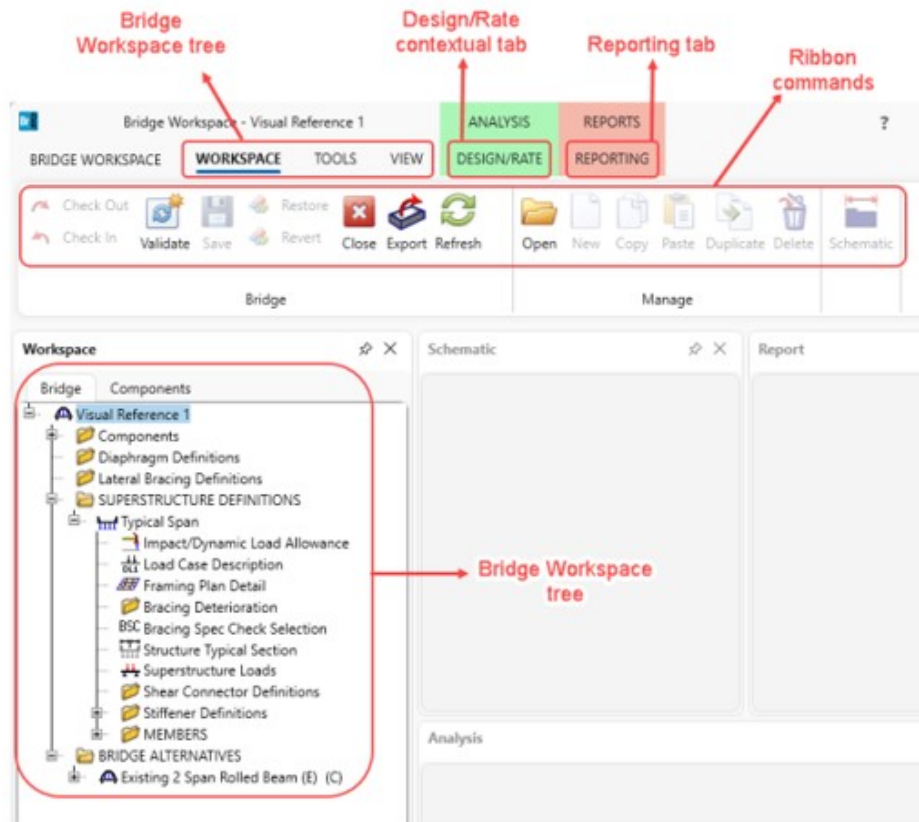


Fig. 1.5.3: Bridge Workspace Window.

PAVER:

Developed by the U.S. Army Corps of Engineers over the past 10 years, PAVER is a pavement management software widely used by military installations, cities, and counties. It facilitates pavement condition assessment, budget optimization, and long-term planning for pavement maintenance and rehabilitation. PAVER is commonly used for smaller streets or road networks. The advantages of this tool for TAM include:

1. **Condition Assessment:** PAVER uses a standardized Pavement Condition Index (PCI), allowing for consistent evaluation of pavement conditions, which is crucial for resilience planning.
2. **Long-Term Planning:** The software supports multi-year projections and life-cycle cost analysis, enabling agencies to plan for long-term resilience.
3. **Budget Optimization:** PAVER helps agencies allocate limited resources effectively, potentially allowing for more investment in resilience measures.

4. **Customization:** The software can be tailored to specific agency needs, allowing for the incorporation of local resilience priorities.
5. **Scenario Analysis:** PAVER enables agencies to model various maintenance scenarios, which can include resilience-focused strategies.

Some limitations of this tool in TAM include:

1. **Learning Curve:** The comprehensive nature of PAVER may require significant training for effective use, potentially delaying the implementation of resilience strategies.
2. **Data Demands:** Effective use of PAVER for resilience planning requires extensive, high-quality data, which some agencies may struggle to provide consistently.
3. **Limited Scope:** While comprehensive for pavements, PAVER may not fully integrate with other asset types, potentially limiting system-wide resilience planning.
4. **Focus on Condition:** PAVER's primary focus is on pavement conditions, which may not capture all aspects of resilience, such as vulnerability to extreme events.
5. **Resource Intensive:** Implementing and maintaining PAVER can be resource-intensive, potentially diverting resources from direct resilience investments.

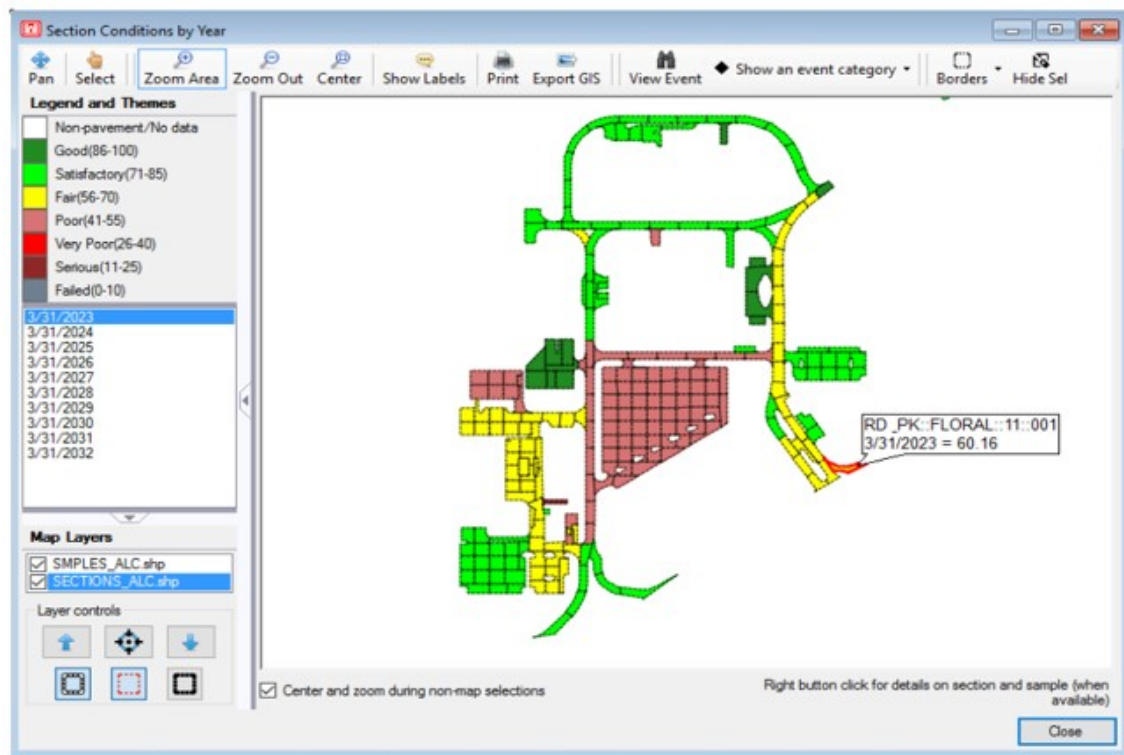


Fig. 1.5.4: Internal GIS displays condition analysis and work planning results.

In summary, PAVER offers valuable tools for enhancing pavement management and indirectly supporting resilience through improved asset management. However, its effectiveness for comprehensive resilience planning in TAM may be limited by its pavement-specific focus and resource requirements. Agencies should consider how to integrate PAVER's capabilities with broader resilience strategies.

Roadsoft:

Roadsoft is a popular asset management software that offers modules for inventory management, condition assessment, work programming, budgeting, and reporting for various transportation assets, including roads, bridges, signs, and signals. The advantages of this tool in TAM include:

1. **Comprehensive Asset Management:** Roadsoft covers various transportation assets, allowing for a holistic approach to resilience planning across different asset types.
2. **GIS Integration:** The GIS-based map interface provides a visual representation of assets, which can be crucial for identifying vulnerable areas and planning resilience improvement strategies.
3. **Mobile Data Collection:** The Laptop Data Collector and mobile apps enable efficient field data collection, thereby supporting up-to-date asset information for resilience planning.
4. **Analysis Tools:** Roadsoft's analysis capabilities can help agencies identify trends and prioritize resilience investments across their asset portfolio.
5. **Customization:** The software can be tailored to specific agency needs, allowing for the incorporation of local resilience priorities and metrics.

The limitations of this tool in TAM include:

1. **Learning Curve:** The comprehensive nature of Roadsoft may require significant training for effective use, potentially delaying the implementation of resilience strategies.
2. **Data Demands:** Effective use of Roadsoft for resilience planning requires extensive, high-quality data, which some agencies may struggle to provide consistently.
3. **Resource Intensive:** Implementing and maintaining Roadsoft can be resource-intensive, potentially diverting resources from direct resilience investments.
4. **Limited Availability:** While freely available to Michigan agencies, other users must purchase licenses, which could limit adoption for smaller agencies focusing on resilience.

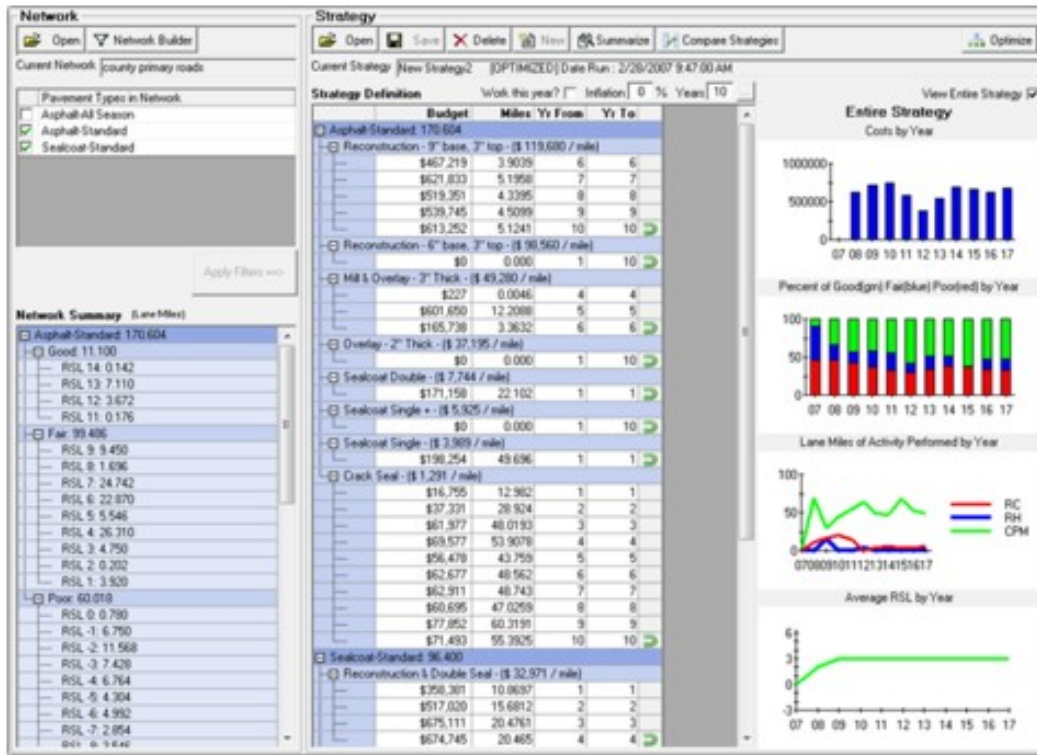


Fig. 1.5.5: Pavement-management and analysis-tools interface.

In summary, Roadsoft offers a powerful and comprehensive platform for managing transportation assets, which can significantly contribute to resilience planning and implementation. However, its effectiveness for enhancing resilience in TAM depends on the agency's capacity to fully utilize its features and integrate them into broader resilience strategies.

dTIMS:

The dTIMS (Deighton Total Infrastructure Management System) software suite, developed by Deighton, provides modules for pavement management, bridge management, safety management, maintenance management, and capital planning. The advantages of this tool in TAM include:

1. **Comprehensive Asset Coverage:** dTIMS covers multiple asset types including pavements, bridges, and other infrastructure, allowing for a holistic approach to resilience planning.
2. **Advanced Modeling Capabilities:** The software supports both deterministic and probabilistic modeling, enabling more accurate long-term performance predictions crucial for resilience planning.

3. **Scenario Analysis:** dTIMS allows for unlimited "what-if" scenarios, helping agencies evaluate different resilience strategies under various conditions.
4. **Cross-Asset Optimization:** The software's ability to analyze and optimize across different asset types supports system-wide resilience planning.
5. **Customization:** dTIMS can be tailored to specific agency needs, allowing for the incorporation of local resilience priorities and metrics.

The limitations of this tool in TAM include:

1. **Complexity:** The comprehensive nature of dTIMS may require significant training and expertise to fully utilize its resilience-related features.
2. **Data Demands:** Effective use of dTIMS for resilience planning requires extensive, high-quality data, which some agencies may struggle to provide consistently.
3. **Resource Intensive:** Implementing and maintaining dTIMS can be resource-intensive, potentially diverting resources from direct resilience investments.
4. **Learning Curve:** The software's advanced features may take time to master, potentially delaying the implementation of resilience strategies.
5. **Potential Over-Reliance on Technology:** There is a risk that agencies might focus too much on the software capabilities rather than on developing comprehensive resilience strategies.

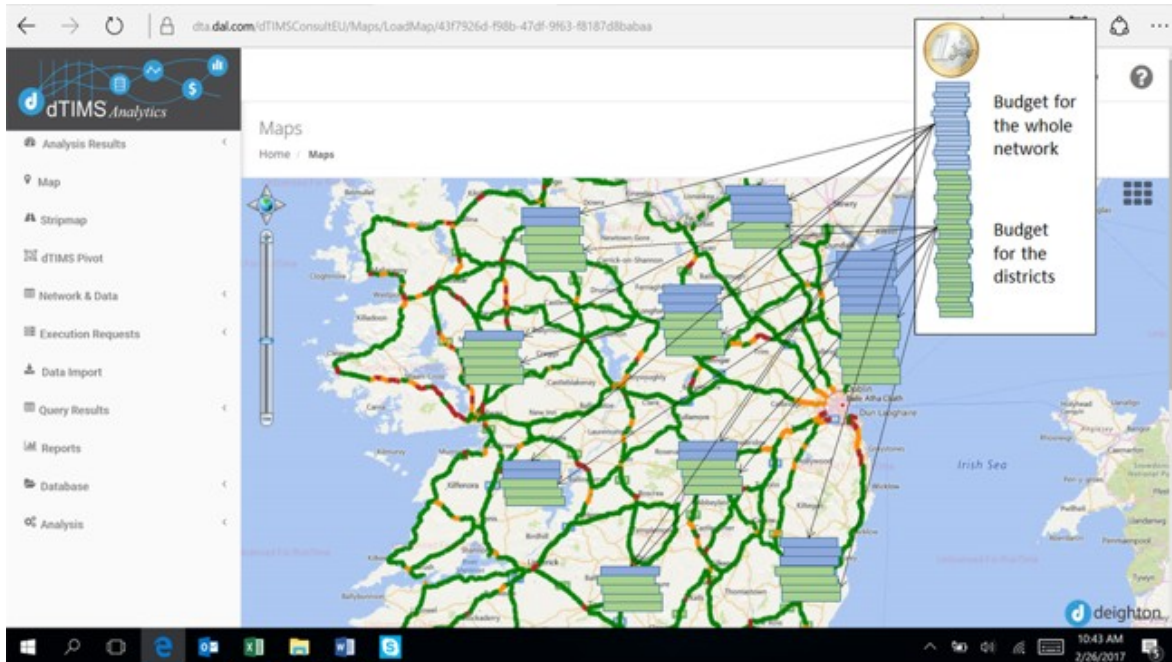


Fig. 1.5.6: dTIMS Transportation Infrastructure Asset Management.

In summary, dTIMS offers a powerful and comprehensive platform for managing multiple types of transportation assets, which can significantly contribute to resilience planning and implementation. Its cross-asset optimization and scenario analysis capabilities are particularly valuable for resilience planning. Similar to Roadsoft, its effectiveness for enhancing resilience relies on the capacity to fully utilize its features and integrate them into broader resilience strategies.

Vulnerability Assessment Scoring Tool (VAST):

Developed by the U.S. DOT, VAST assists state departments of transportation and other entities in implementing an indicator-based vulnerability assessment of their assets. VAST enables users to identify indicators of exposure, sensitivity, or adaptive capacity in transportation assets, facilitating a comprehensive assessment of their vulnerability. The advantages of this tool in TAM include:

1. **Comprehensive Assessment:** VAST covers multiple asset types and climate stressors, allowing for a holistic approach to resilience planning across different infrastructure types.
2. **Customizable Framework:** The tool allows users to select appropriate indicators and adjust scoring weights, enabling tailored assessments for specific agency needs and local priorities.

3. **Quantitative Approach:** VAST provides a structured, quantitative method for assessing vulnerability, which can help prioritize assets for adaptation measures.
4. **Scenario Analysis:** The tool supports "what-if" scenarios, helping agencies evaluate different resilience strategies under various conditions.
5. **Integration with Planning:** VAST results can inform long-range planning, asset management plans, and project prioritization, thereby supporting system-wide resilience planning.

The limitations of this tool in TAM include:

1. **Data Demands:** Effective use of VAST requires extensive, high-quality data about assets and climate projections, which some agencies may struggle to provide consistently.
2. **Complexity:** The comprehensive nature of VAST may require significant training and expertise to fully utilize its features and interpret results accurately.
3. **Resource Intensive:** Implementing and maintaining VAST can be time-consuming and resource-intensive, which potentially diverts resources from direct resilience investments.
4. **Subjectivity in Indicator Selection:** The choice of indicators and their weighting involves subjective judgment, which could affect the consistency of results across different users or agencies.
5. **Limited to Vulnerability Assessment:** While VAST is powerful for assessing vulnerability, it does not directly address other aspects of resilience planning, such as developing adaptation strategies.

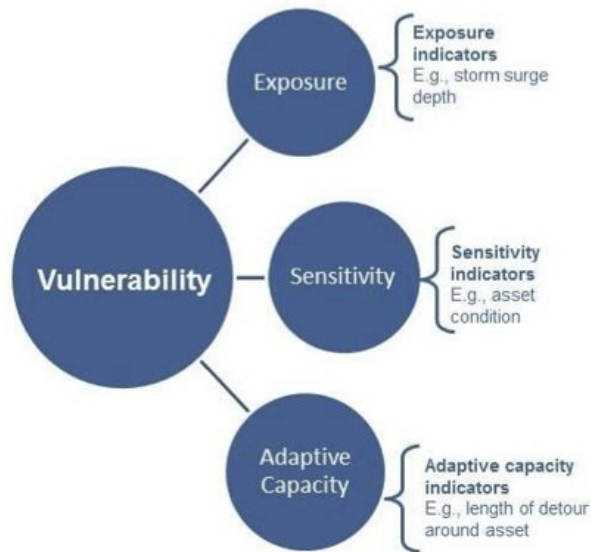


Fig. 1.5.7: Components and examples of vulnerability for transportation assets (7).

In summary, VAST offers a robust and flexible framework for assessing the vulnerability of transportation assets to climate stressors, which is crucial for resilience planning in TAM. Its ability to cover multiple asset types and stressors, along with its customizable approach, makes it a valuable tool for agencies. However, its effectiveness depends on the availability of quality data and the expertise of users in selecting appropriate indicators and interpreting results. Agencies should consider these factors when implementing VAST as part of their broader resilience strategy.

While these tools excel in their respective areas of asset management, they may not fully address the need for integrating resilience into asset management practices. They lack specific features, modules, or functionalities for assessing and prioritizing resilience-enhancing investments and do not directly address resilience factors, such as climate change impacts, extreme weather events, or other external disruptions affecting asset performance.

The review above underscores the increasing importance of integrating resilience into TAM practices to enhance asset performance against unpredictable hazards. However, there remains a notable absence of quantitative frameworks specifically designed for resilience-based TAM as well as corresponding tools for TAM at both federal and state levels.

1.6 Current Gaps

The integration of resilience into TAM faces several significant challenges, which can be categorized into four main areas.

1. Complexity of Resilience Assessment Approaches

The inherent complexity of resilience assessment methods creates critical gaps in their practical application, including:

- **Divergence in Existing Methods:** Existing resilience assessment approaches are often not specifically designed for TAM. They exhibit significant variation in their scope and practical utility, making it difficult for agencies like TxDOT to select methods suited to their diverse asset types and operational contexts (25). This divergence highlights the need for adaptable frameworks that account for the unique challenges of TAM.
- **Predominance of Risk-Analysis Paradigms:** Most frameworks adopt a risk analysis paradigm, focusing heavily on immediate risks rather than the broader, multifaceted concept of resilience. This limits their ability to account for dynamic recovery processes, long-term performance, and adaptive capacities (57).
- **Lack of a Standardized Framework:** The absence of quantitative, resilience-focused TAM frameworks is a major gap, impeding the ability of agencies to systematically evaluate resilience and prioritize investments effectively. Without standardization, agencies struggle to align resilience metrics with actionable strategies (30).

2. Integration with Existing TAM Methodologies

Incorporating resilience considerations into established TAM methodologies also introduces significant challenges.

- **Balancing Objectives:** Resilience-based TAM requires balancing new resilience objectives with traditional asset management goals focused on performance optimization, lifecycle cost minimization, and maintenance prioritization (58).
- **Metric Alignment:** A comprehensive understanding is needed to determine how resilience metrics align or compete with existing asset performance metrics and decision-making criteria.
- **Long-Term Effects:** Traditional TAM approaches often neglect the long-term effects of natural hazards on asset performance, which can contribute to the decline of assets and reduce their useful life (25).

3. Data Availability and Quality

The reliance on high-quality data exposes critical gaps in TAM frameworks:

- **Dynamic and Uncertain Hazards:** Accurately assessing the resilience of transportation assets requires near-real-time data to capture the dynamic nature of hazards and environmental conditions. However, agencies often face challenges in acquiring, processing, and integrating such data across asset types and geographic regions (59).
- **Data Collection and Standardization:** The lack of uniform data collection practices and standardization protocols undermines the ability of agencies to make consistent, data-driven decisions. This gap is particularly pronounced for assets affected by varying types of disruptions, such as floods, wildfires, or earthquakes (58).
- **Need for Data Infrastructure:** Addressing these gaps requires investment in comprehensive data management systems and infrastructure, ensuring data reliability, accessibility, and interoperability. Without such investments, the development and implementation of resilience-based TAM frameworks remain limited (60).

4. Operationalization and Implementation

Even when resilience-based TAM frameworks are developed, their practical application remains constrained by several gaps.

- **Resource Constraints:** Transportation agencies face challenges in securing the financial, technical, and human resources needed to operationalize resilience-focused frameworks. This gap can delay or hinder the adoption of resilience-based TAM strategies.
- **Tool Usability and Accessibility:** Analytical tools and dashboards must be designed with end-users in mind. Many current tools lack the user-friendly interfaces and accessibility needed to facilitate widespread adoption and effective decision-making (25).
- **Indirect Consequences:** Existing TAM frameworks primarily focus on physical damage and direct costs. They often neglect broader indirect impacts such as network disruptions, travel delays, increased emissions, and social consequences, which are critical for holistic resilience planning (61).

To address current gaps TAM practices, future research should focus on several key areas:

1. **Advanced Modeling Approaches:** Developing robust, multi-hazard predictive models is critical for assessing extreme events and their cascading impacts across interdependent infrastructure systems. These models should account for climate change projections and uncertainties using probabilistic approaches to prioritize resilience measures.

2. **Innovative Materials and Technologies:** Emerging materials like self-healing pavements and corrosion-resistant coatings can extend asset lifespans while reducing maintenance costs. Smart sensors and IoT devices enable real-time monitoring for early detection of vulnerabilities, supporting proactive maintenance and enhancing infrastructure resilience.
3. **Economic Analysis of Resilience Measures:** Detailed cost-benefit analyses that account for lifecycle costs and avoided disaster recovery expenses are essential for justifying resilience investments. Exploring innovative funding mechanisms, such as resilience bonds and public-private partnerships, can support these efforts and align resilience measures with budgetary constraints.
4. **Integration of Big Data and Artificial Intelligence:** Big data analytics and AI empower transportation agencies to make more informed decisions in TAM by identifying trends across diverse datasets and improving hazard forecasting. This, in turn, enhances predictive maintenance, allowing agencies to shift from reactive to proactive asset management and ultimately strengthen system resilience.
5. **Adaptive Management Strategies Under Uncertainty:** Adaptive management involves flexible, iterative policies that evolve with emerging risks and technologies. Scenario-based planning evaluates resilience strategies under uncertain future conditions, enabling continuous improvement and ensuring that transportation systems remain reliable despite changing challenges.
6. **Performance Metrics for Resilience:** Standardized metrics for recovery time, adaptive capacity, and redundancy allow for effective resilience measurement and comparison. Composite indices provide a comprehensive assessment, supporting better decision-making and progress tracking within TAM frameworks.

Chapter 2

Vulnerability Assessment for Transportation Assets

2.1 Introduction

Texas transportation assets are increasingly exposed to climate-related disruptions, including extreme heat, extreme cold, inland flooding, coastal flooding, storm surge, hurricanes, drought, and wildfire. Recent statewide events, including Winter Storm Uri in 2021 and severe summer heat during 2022 and 2023, illustrate the operational and physical stresses that climate extremes can impose on the transportation system. In response, the Texas Department of Transportation (TxDOT) is developing a Statewide Resiliency Plan to identify, evaluate, and address vulnerabilities across critical transportation assets.

This task provides a vulnerability assessment to support statewide resilience planning. The assessment evaluates the susceptibility of major transportation asset classes—including bridges and bridge-class culverts, roadways, and selected geotechnical assets—to projected climate disruptors. Vulnerability varies by geographic location, asset characteristics, structural condition, functional role, and exposure to specific climate hazards.

The assessment is aligned with TxDOT long-range planning horizons, including *Connecting Texas 2050* and *Texas Delivers 2050*. It uses mid-century climate projections and two complementary methods to accommodate differences in asset characteristics and data availability: an exposure–sensitivity framework for bridges, bridge-class culverts, and roadways, and a weighted scoring method for retaining walls.

2.2 Climate Projections

The vulnerability assessment uses projections derived from numerical climate models that simulate interactions among atmospheric, oceanic, and land-surface processes. These

projections provide spatially resolved indicators of future climate conditions and support consistent exposure scoring across TxDOT districts.

The mid-century period, defined as 2040–2069, is selected because it is relevant to the service life of many transportation assets currently in operation, under design, or planned for construction and is consistent with TxDOT statewide planning initiatives. The assessment applies RCP 8.5, which assumes continued growth in greenhouse gas emissions and limited mitigation, as a conservative scenario for evaluating potential high-stress conditions affecting long-lived infrastructure. Under this scenario, Texas is expected to experience higher temperatures, more frequent extreme heat events, and changes in the intensity and distribution of precipitation-related hazards. These projected changes provide the basis for assessing future exposure to heat, cold, inland flooding, coastal flooding, and related disruptors.

Although uncertainty remains in the timing, magnitude, and local expression of future climate conditions, the projections provide a consistent and forward-looking basis for screening asset vulnerability. The results should be interpreted as planning-level indicators to support prioritization, adaptation planning, and future detailed engineering analysis.

2.3 Methodology

Because asset data availability differs by asset type, the methodology is organized into two categories: (i) bridges, bridge-class culverts, and roadways, and (ii) geotechnical assets, represented by retaining walls.

For bridges, bridge-class culverts, and roadways, vulnerability is computed as the product of an exposure score and a sensitivity score for each asset–disruptor pair and then normalized to support comparison across assets and regions. Exposure reflects the projected intensity or presence of a hazard at the asset location, while sensitivity reflects the expected physical or operational susceptibility of the asset when exposed.

For retaining walls, a weighted multi-criteria scoring method uses available engineering attributes and site conditions to generate an interpretable planning-level vulnerability score. This method addresses the current absence of a centralized statewide database of retaining wall condition, design, and inspection information.

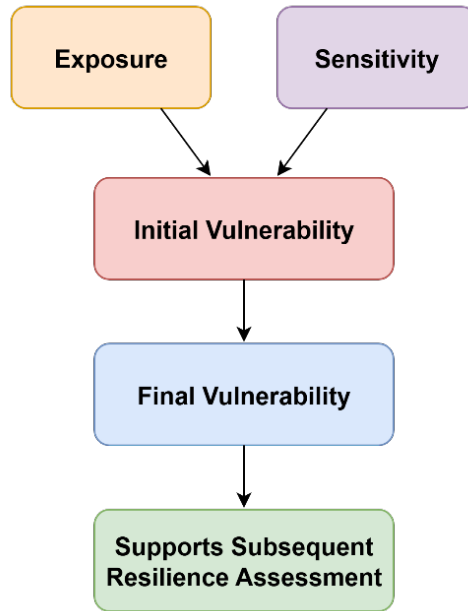


Fig. 2.3.1: Vulnerability Assessment Framework Supporting Resilience Assessment

2.3.1 Data Sources

Table 2.3.1 summarizes the asset datasets used in the vulnerability assessment. These data are compiled primarily from TxDOT sources and supplemented with federal, regional, and external datasets where appropriate.

Table 2.3.1: Asset Data Sources

Asset Type	Dataset Name	Source	Date
Roadways	TxDOT Roadway Inventory On-System	TxDOT	2022
Roadways	National Highway Freight Network	Federal Highway Administration (FHWA)	2023
Roadways	Critical Roadways from <i>Establish TxDOT Transportation Resilience Planning Scorecard and Best Practices: Technical Report</i>	Texas A&M Transportation Institute (TTI)	2023

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Table 2.3.1 – *continued from the previous page*

Asset Type	Dataset Name	Source	Date
Roadways – Hazardous Materials	National Hazardous Materials Route Registry by State	U.S. DOT	2023
Highways	Energy Sector Corridors	TxDOT	2022
Bridges and Culverts	TxDOT Bridges	TxDOT	2023
Intelligent Transportation Systems (ITS)	ITS Gap Plan	TxDOT	2023
Maintenance Facilities	TxDOT Offices	TxDOT	2023
Border Crossings	Texas Border Crossings	TxDOT	2023
Maritime Ports	TxDOT Seaports	TxDOT	2022
Bike and Pedestrian	Existing and planned bikeways, trails, and paths	TxDOT	Surveyed 2019–2020
Airports	Publicly owned public-use airports	TxDOT	2023
Transit	Transit stops and stations	Various	2023
Railways	Texas Railroads	TxDOT	2016

2.3.2 Bridges, Bridge-Class Culverts, and Roadways

The assessment for bridges, bridge-class culverts, and roadways follows five steps: data collection, asset filtering, exposure scoring, vulnerability calculation, and final normalization. A geospatial overlay analysis is used to integrate asset locations with climate and hazard datasets.

Data Collection

Two major categories of data are compiled. The first category includes transportation asset data for roadways, bridges, bridge-class culverts, maintenance facilities, transit stops, ports, airports, and other system elements. These data are obtained primarily from TxDOT and supplemented with federal and regional sources. The second category includes climate and hazard data for disruptors, such as extreme heat, extreme cold, inland flooding, coastal flooding, sea level rise, storm surge, hurricanes, wildfires, and drought. These data are also obtained from TxDOT and originate from federal agencies (e.g., NOAA and the National Weather Service).

Asset Filtering

Because the statewide system includes more than 345,000 miles of roadway and approximately 57,000 bridges and bridge-class culverts, asset filtering is used to focus the assessment on assets most relevant to statewide resilience planning. Filtering criteria included functional classification, National Highway System designation, proximity to critical facilities, bridge detour length, freight significance, evacuation function, and other indicators of operational importance. Stakeholder input and desktop analysis are used to refine the asset set for evaluation.

Exposure Scoring

Each filtered asset is assigned an exposure score for each relevant climate disruptor. Exposure scores represent the projected likelihood or intensity of hazard exposure at the asset location during the mid-century planning horizon. Scores range from 0 to 5, where 0 represents no or negligible exposure and 5 represents very high exposure. For continuous indicators, such as projected days above 100°F, scores are assigned using percentile-based thresholds. For discrete hazards, such as whether an asset is located within a mapped floodplain, scores are assigned based on spatial inclusion or hazard category.

Vulnerability Calculation

For each asset–disruptor pair, initial vulnerability is calculated as

$$V_{\text{initial}} = E \times S, \quad (2.3.1)$$

where E is the exposure score and S is the sensitivity score. The resulting score ranges from 0 to 15. Assets with zero exposure or zero sensitivity receive a vulnerability score of zero. Nonzero scores are grouped into qualitative tiers: low vulnerability for scores of 1–5, moderate vulnerability for scores of 6–9, and high vulnerability for scores of 10–15.

A separate coastal bridge overtopping analysis is also conducted for sea level rise and

storm surge conditions. Bridges projected to be overtopped under the selected future scenario are assigned the highest exposure category for the corresponding disruptor.

Final Vulnerability Normalization

To support comparison across asset classes and districts, initial vulnerability scores are normalized to a 20%–100% scale:

$$V_{\text{final}} = 0.2 + 0.8 \times \frac{V_{\text{initial}}}{15}. \quad (2.3.2)$$

The lower bound of 20% means that assets with functionality below this threshold are likely to be considered failed for resilience assessment and may require replacement rather than restoration. This normalization supports planning-level interpretation while maintaining consistency with asset functionality concepts in resilience analysis.

For map visualization and planning-level interpretation, the normalized vulnerability scores are presented using qualitative categories ranging from Very Low to Very High vulnerability. These categories provide a more intuitive representation of relative hazard susceptibility than the continuous numerical scores alone and facilitate statewide comparison among assets and geographic regions. Assets classified as Very Low or Low vulnerability generally represent locations with comparatively limited hazard exposure and sensitivity, whereas Moderate vulnerability identifies assets that may warrant additional monitoring or consideration in asset-management planning. High and Very High vulnerability categories identify assets with comparatively greater hazard exposure and sensitivity and therefore indicate locations where more detailed engineering evaluation, inspection, maintenance, or adaptation measures may be appropriate. The categories are intended as screening-level indicators and should be interpreted together with asset condition, operational importance, and other project-specific considerations.

2.3.3 Retaining Walls

A statewide retaining wall vulnerability map is not developed because a centralized database of retaining wall inventory, condition, design, and annual evaluation data is not currently available across TxDOT districts. Instead, a weighted scoring method is developed and demonstrated using representative retaining walls from the Waco and Fort Worth districts.

Each wall is evaluated using six parameters that influence structural vulnerability: wall age, foundation soil properties, drainage condition, flood proximity, structural redundancy, and inspection or repair history. Each parameter is assigned a score s_i , with lower values indicating lower risk. Each parameter is also assigned a weight w_i reflecting its relative importance. The overall vulnerability score is calculated as

$$V = \sum_{i=1}^n w_i s_i, \quad (2.3.3)$$

where the weights sum to 1. The resulting score is interpreted as follows: $V < 0.15$ indicates very low vulnerability; $0.15 \leq V \leq 0.25$ indicates moderate vulnerability; and $V > 0.25$ indicates elevated vulnerability that may warrant additional evaluation, inspection, or maintenance action.

This rating-based method supports consistent comparison among walls with different designs, materials, and site conditions. It also identifies the parameters that contribute most to vulnerability, supporting prioritization of inspection, maintenance, and retrofit decisions.

2.4 Vulnerability Assessment Results

Results are reported by asset class and climate disruptor, with emphasis on assets and regions with moderate or high vulnerability. At the statewide level, vulnerability varies substantially by asset type, geographic region, hazard exposure, and structural condition. The following subsections present the principal spatial patterns and planning implications to support prioritization and identify locations where more detailed engineering evaluation may be warranted.

2.4.1 Bridges and Bridge-Class Culverts

Extreme Cold Vulnerability

Figure 2.4.1 presents the statewide distribution of categorical extreme cold vulnerability for bridges and bridge-class culverts. The spatial pattern shows a strong concentration of High and Very High vulnerability in northern Texas, particularly in the Panhandle and High Plains near Amarillo and the Oklahoma–New Mexico border. These assets experience greater exposure to cold-weather hazards and may be more susceptible to freeze–thaw cycles, ice accumulation, and thermal contraction stresses.

In contrast, bridges and culverts across much of central, southern, and eastern Texas are predominantly classified as Very Low vulnerability. Low and Moderate categories form a transition toward north-central and west-central Texas, while the highest categories are concentrated farther north. From the planning perspective, assets classified as High or Very High may warrant greater attention in winter weather inspection, maintenance, and adaptation planning, whereas those in lower categories indicate comparatively limited cold-related vulnerability.

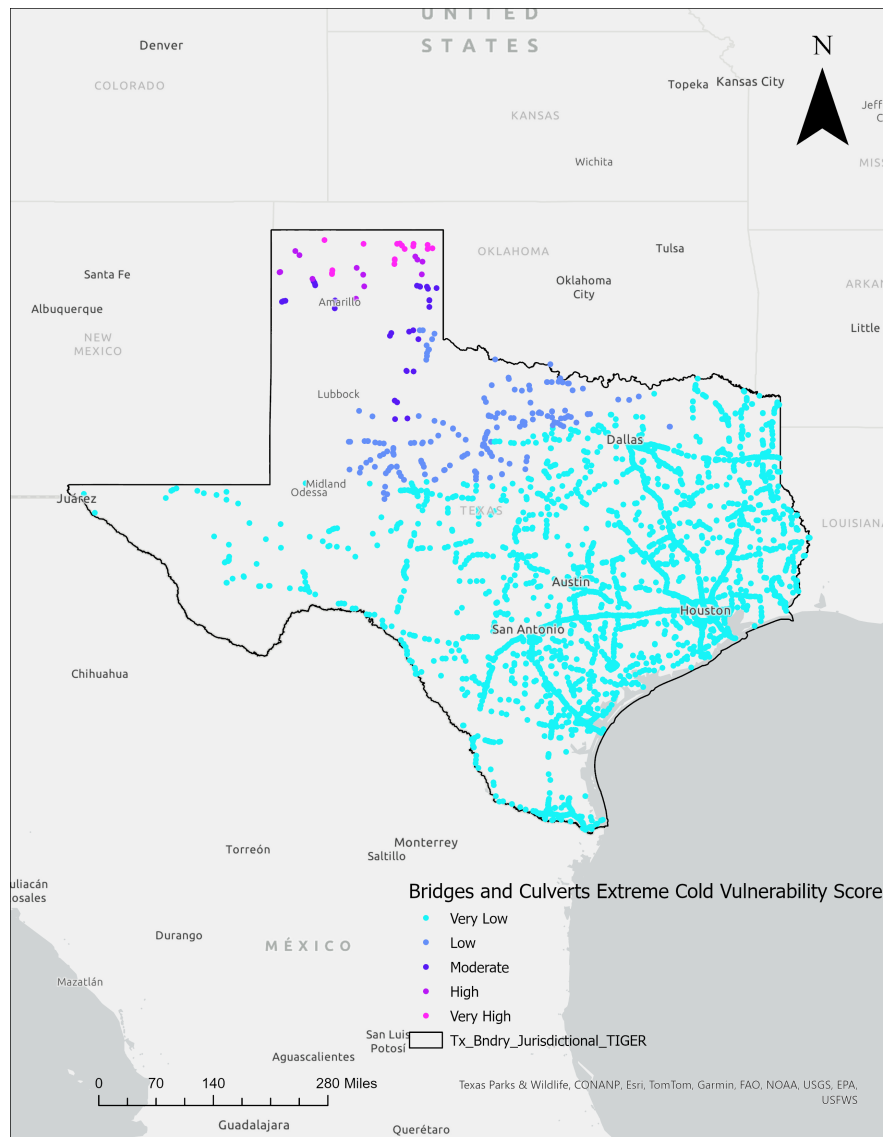


Fig. 2.4.1: Extreme Cold Vulnerability Categories for Bridges and Bridge-Class Culverts in Texas

Extreme Heat Vulnerability

Figure 2.4.2 presents the categorical extreme heat vulnerability of bridges and bridge-class culverts across Texas. The statewide pattern differs substantially from the extreme cold scenario. High and Very High vulnerability is more prominent across portions of central, western, and southern Texas, including corridors extending toward the Rio Grande Valley, while Moderate vulnerability is widespread across much of the central portion of the state.

Lower vulnerability categories are more prevalent in eastern and southeastern Texas, including portions of the Houston and Gulf Coast regions. The categorical distribution highlights the relative geographic variation in heat susceptibility and identifies areas where

prolonged high-temperature exposure may contribute to thermal expansion, material degradation, and increased maintenance needs. Bridges classified as High or Very High vulnerability may therefore warrant consideration of enhanced inspection, heat-resistant materials, or other heat-adaptation measures.

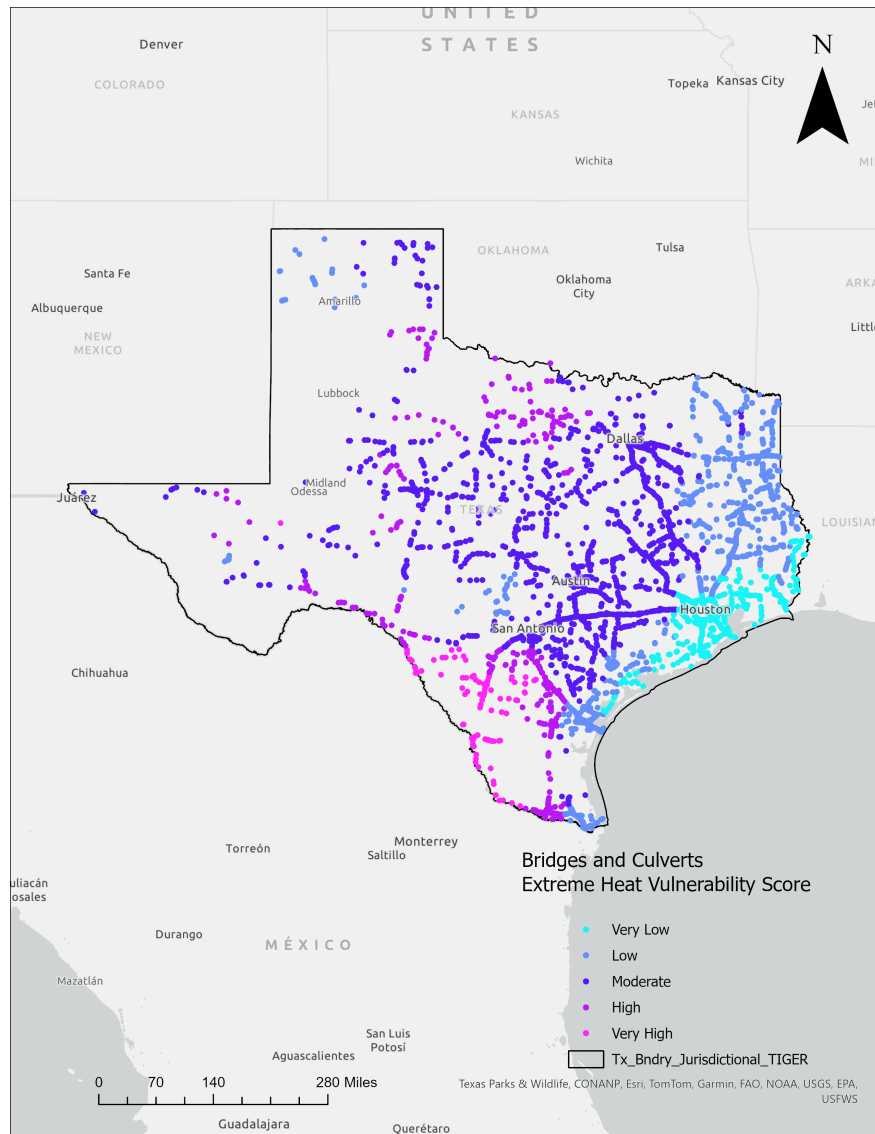


Fig. 2.4.2: Extreme Heat Vulnerability Categories for Bridges and Bridge-Class Culverts in Texas

Inland Flood Vulnerability

Figure 2.4.3 shows the categorical inland flood vulnerability of bridges and bridge-class culverts throughout Texas. Unlike the clearer regional gradients observed for extreme temperature hazards, inland flood vulnerability is more spatially heterogeneous. Moderate, High, and Very High vulnerability assets occur throughout central, eastern, and southeastern

Texas, including major corridors around Dallas, Austin, San Antonio, Houston, and other flood-prone areas. These locations contain numerous bridges and culverts that interact with river corridors, drainage networks, floodplains, and low-lying terrain.

At the same time, many assets remain within the Very Low and Low vulnerability categories, demonstrating that flood vulnerability can vary considerably even among nearby structures. The categorical map is therefore useful for identifying localized clusters of higher vulnerability rather than interpreting inland flooding solely as a broad regional pattern. Assets classified as High or Very High may warrant closer evaluation of hydraulic capacity, scour potential, drainage performance, and post-event inspection requirements.

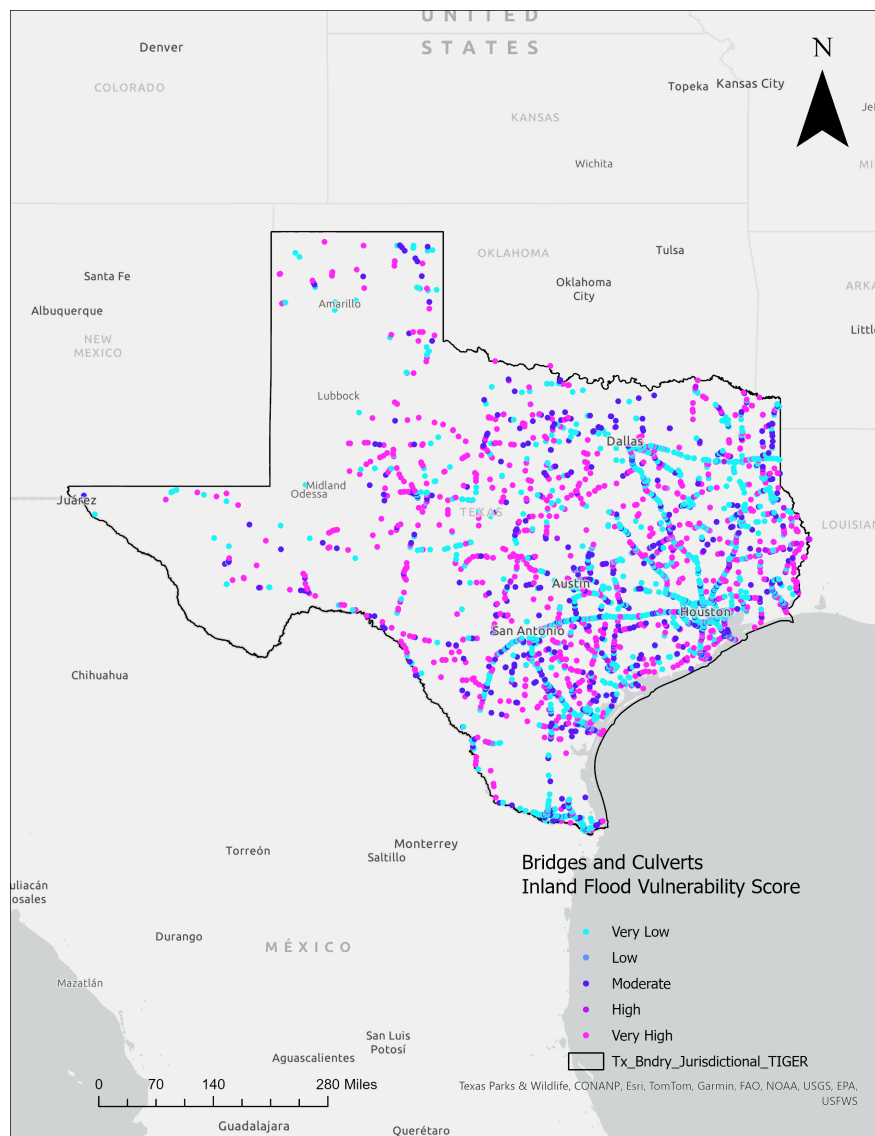


Fig. 2.4.3: Inland Flood Vulnerability Categories for Bridges and Bridge-Class Culverts in Texas

2.4.2 Roadways

Extreme Cold Vulnerability

Figure 2.4.4 presents the categorical distribution of roadway vulnerability to extreme cold across Texas. A clear geographic gradient is evident, with roadway segments in the northern Panhandle generally falling within the High and Very High vulnerability categories. Moving southward, vulnerability gradually transitions through Moderate and Low categories, while much of central, southern, and eastern Texas is classified as Very Low vulnerability.

The categorical pattern reflects the greater exposure of northern roadway infrastructure to severe winter weather, freeze–thaw cycles, ice accumulation, and thermal contraction. From an asset-management perspective, High and Very High vulnerability corridors in northern and northwestern Texas may warrant greater emphasis on winter operations, cold-weather pavement performance, inspection, and preventive maintenance, while lower-category segments represent comparatively limited cold-related vulnerability.

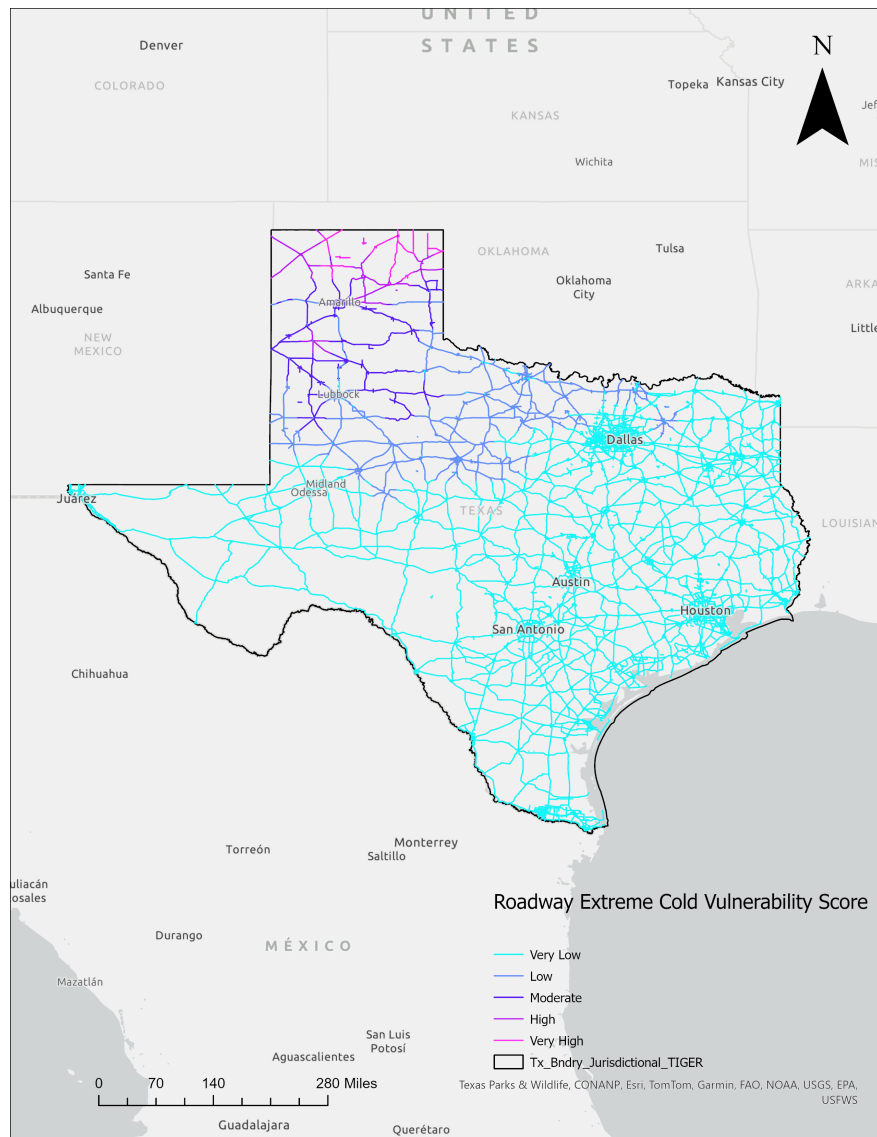


Fig. 2.4.4: Extreme Cold Vulnerability Categories for Texas Roadways

Extreme Heat Vulnerability

Figure 2.4.5 presents the categorical distribution of roadway vulnerability to extreme heat. The map shows substantial spatial variation across the state, with High and Very High vulnerability occurring along portions of north-central, west-central, southern, and southwestern Texas. Several corridors in the Rio Grande region and other high-temperature areas are particularly prominent within the Very High category.

Moderate vulnerability is widespread across much of the statewide network, while Low vulnerability is more evident in portions of eastern and southeastern Texas. These categories provide a planning-level indication of where roadway materials may be comparatively more susceptible to prolonged heat exposure. Segments classified as High or Very High vulnera-

bility may warrant consideration of heat-resistant pavement materials, revised maintenance schedules, enhanced condition monitoring, or other adaptation strategies.

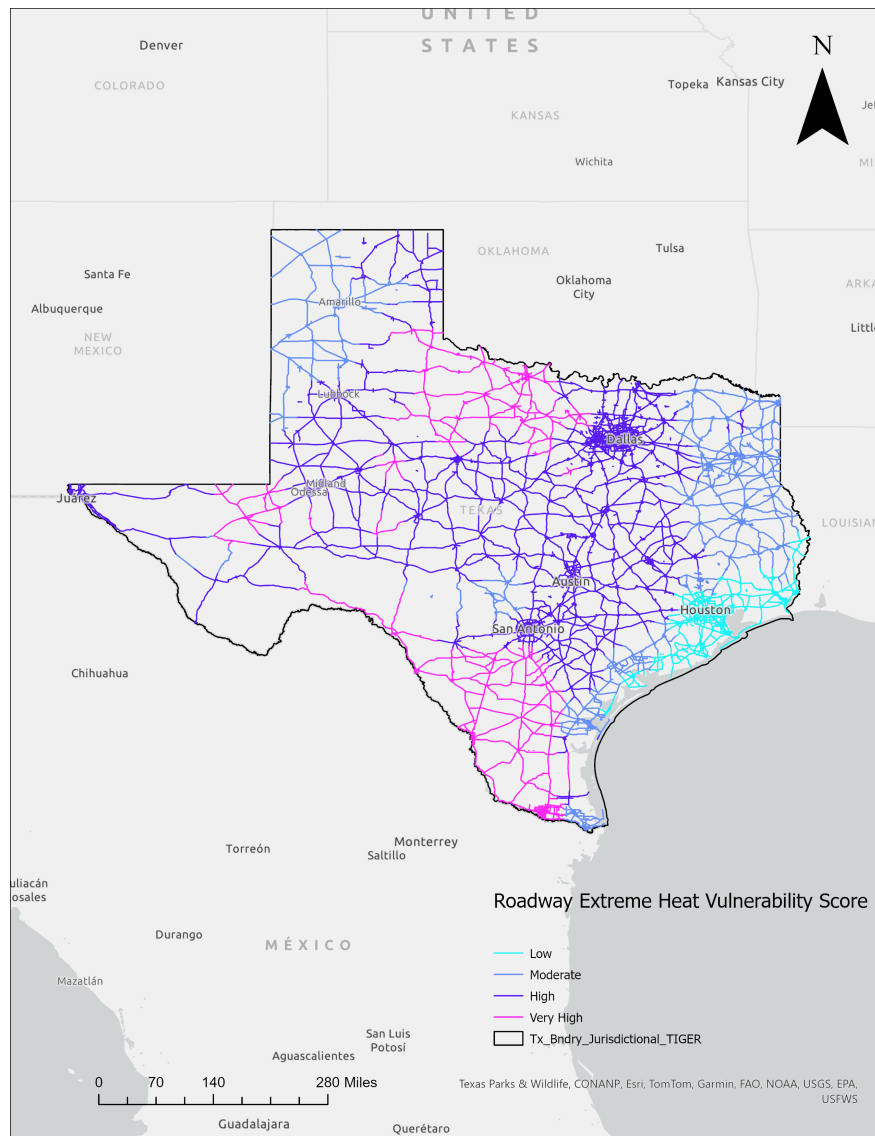


Fig. 2.4.5: Extreme Heat Vulnerability Categories for Texas Roadways

Inland Flooding Vulnerability

Figure 2.4.6 shows the categorical distribution of roadway vulnerability to inland flooding. Much of the statewide roadway network is classified within the Very Low category, while Moderate and Very High vulnerability occur as localized segments distributed across the state. Higher-category roadway segments are particularly evident in portions of eastern and southeastern Texas and around several major metropolitan and flood-prone corridors.

The spatially localized nature of the Moderate and Very High categories reflects differences in rainfall exposure, drainage conditions, floodplain interaction, and local terrain. Accordingly,

the inland flooding map should be interpreted as a screening tool for identifying specific roadway segments that may warrant additional hydraulic or drainage evaluation rather than as an indication that an entire region has uniformly high flood vulnerability. Higher-category segments may benefit from drainage improvements, maintenance planning, flood-adaptive design, and enhanced emergency-response consideration.

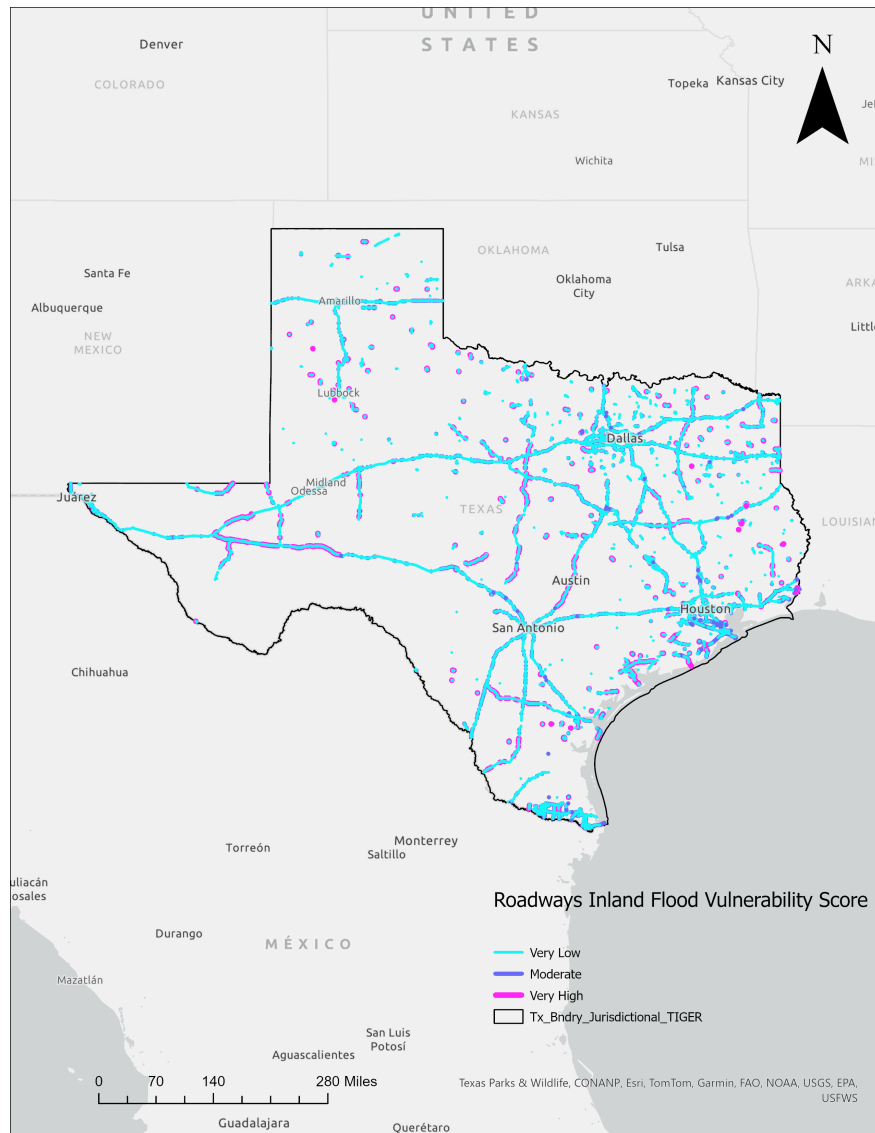


Fig. 2.4.6: Inland Flooding Vulnerability Categories for Texas Roadways

2.4.3 Retaining Walls

Because statewide retaining wall inventory and evaluation data are limited, the retaining wall assessment is presented as a demonstration of the scoring method using walls from the Waco and Fort Worth districts. The results should be interpreted as illustrative planning-level assessments rather than a statewide vulnerability inventory.

Waco Wall 1

This retaining wall in the Waco District uses a hybrid system consisting of cantilevered concrete elements and mechanically stabilized earth (MSE) walls with precast concrete panels. The wall is founded on 48-inch-diameter drilled shafts, which provide deep support for both new and existing MSE structures.

The wall uses Class C or Class H concrete, Grade 60 reinforcement, and ASTM A572 Grade 50 structural steel. Reinforcement includes #4 bars at 12-inch spacing. Expansion joints with bituminous material or roofing felt are included to reduce cracking associated with thermal movement.

Drainage features include 4-inch-diameter weep holes, a Type I underdrain system wrapped in filter fabric, toe drains, and 5-inch concrete riprap for erosion protection at drainage outfalls. Drainage features are sloped at a minimum gradient of 2.5% to promote water evacuation. The wall was constructed in 2019 and is approximately 6 years old at the time of assessment. No distress, failure, or repair history is reported. Backfill and embankment materials conform to TxDOT Type BS and Type C specifications, with limited plasticity ($LL < 40$, $PI\ 6\text{--}20$), reducing shrink-swell potential. Although the project includes work near stream zones, erosion and sediment controls are specified and enforced.

Table 2.4.1: Waco Wall 1 Vulnerability Assessment

Parameter	Risk Factor	Score	Weight	Rationale
Age of Wall	6 years	0.10	0.20	Recent construction; limited deterioration expected
Foundation Soil	Low PI and LL; low expansiveness	0.10	0.20	Controlled material with low movement risk
Drainage Condition	Weep holes, underdrain, riprap, and toe drain	0.10	0.20	Multiple drainage features reduce hydraulic risk

Continued on the next page

Table 2.4.1 – *continued from the previous page*

Parameter	Risk Factor	Score	Weight	Rationale
Flood Proximity	Stream nearby; mitigation specified	0.15	0.10	Limited flood-related concern, with nearby stream exposure
Structural Redundancy	MSE, cantilevered elements, and drilled shafts	0.10	0.10	Robust composite system
Inspection & Repair	No repairs reported; assumed good condition	0.05	0.20	No reported distress or failure
Final Vulnerability	—	0.095	—	Weighted average

Waco Wall 1 has a very low vulnerability score of 0.095. The low score is primarily attributable to recent construction, robust structural design, favorable backfill properties, and comprehensive drainage provisions.

Fort Worth Wall 2

This wall is located along SH 199 in Tarrant County. It is a soil-nailed fascia wall constructed with pneumatically placed concrete (PPC). The wall height ranges from 6 to 22 feet and is supported by a permissible unreinforced concrete leveling pad. Drainage is provided through a prefabricated underdrain system and typical drainage details. Reinforcement includes welded wire mesh and #5 reinforcing bars spaced at 12 inches on center. The wall was constructed in 2012 and is approximately 13 years old.

The surrounding soil consists of clay and sand. No current signs of distress are reported, although a historical failure event is noted at this site. The wall is located near Eagle Mountain Lake and within FEMA Zone X, indicating low flood hazard. Specific inspection and maintenance records are not available.

Table 2.4.2: Fort Worth Wall 2 Vulnerability Assessment

Parameter	Risk Factor	Score	Weight	Rationale
Age of Wall	13 years	0.15	0.20	Relatively young wall with limited age-related deterioration
Foundation Soil	Clay and sand	0.30	0.20	Moderate shrink-swell and movement potential
Drainage Condition	Underdrain system	0.20	0.20	Drainage system present and expected to reduce hydraulic risk
Flood Proximity	FEMA Zone X	0.10	0.10	Low flood hazard
Structural Redundancy	Soil-nailed fascia	0.30	0.10	Lower redundancy than MSE or anchored systems
Inspection & Repair	No records available	0.05	0.20	No current distress reported; uncertainty remains
Final Vulnerability	—	0.180	—	Weighted average

Fort Worth Wall 3

This wall is located along IH 20 westbound at the Oak Grove Exit in Tarrant County. It consists of a tied-back anchored system with precast concrete panels. Wall height ranges from 6.8 to 21 feet. The wall is constructed using Class C concrete and supported by spread footings. Drainage is provided by weep holes, although current drainage functionality is unknown. The wall was constructed in 1991 and is approximately 34 years old.

The site includes sand and clay soils and is located in FEMA Zone X, indicating low flood hazard. No maintenance or inspection records are identified, and no structural concerns are reported.

Table 2.4.3: Fort Worth Wall 3 Vulnerability Assessment

Parameter	Risk Factor	Score	Weight	Rationale
Age of Wall	> 30 years	0.40	0.20	Older wall with increased potential for age-related deterioration
Foundation Soil	Sand and clay	0.30	0.20	Moderate shrink-swell and movement potential
Drainage Condition	Weep holes; status unknown	0.35	0.20	Drainage is present but unverified
Flood Proximity	FEMA Zone X	0.10	0.10	Low flood hazard
Structural Redundancy	Anchors and precast panels	0.15	0.10	Anchored system provides redundancy
Inspection & Repair	No records; no issues reported	0.05	0.20	No distress reported; uncertainty remains
Final Vulnerability	—	0.245	—	Weighted average

Fort Worth Wall 4

This MSE wall, identified as Wall 197L, is located along IH 820 northbound at Glenview/Pipeline Road. Wall height ranges from 2 feet to 27.77 feet. The wall uses cement-stabilized backfill and standard precast panels and is supported by leveling pads. Drainage provisions are provided in the design details. Site soils include clay, sandy soils, and limestone. The wall is located within a 500-year floodplain. It was constructed in 1998 and is approximately 27 years old. No repair history is identified.

Table 2.4.4: Fort Worth Wall 4 Vulnerability Assessment

Parameter	Risk Factor	Score	Weight	Rationale
Age of Wall	27 years	0.35	0.20	Aging wall approaching 30 years of service
Foundation Soil	Clay and limestone	0.30	0.20	Moderate movement potential
Drainage Condition	Drainage details present	0.20	0.20	Drainage design present; field condition not verified
Flood Proximity	500-year floodplain	0.10	0.10	Low flood hazard
Structural Redundancy	MSE wall	0.20	0.10	Standard MSE redundancy
Inspection & Repair	No records available	0.05	0.20	No repairs reported; uncertainty remains
Final Vulnerability	—	0.230	—	Weighted average

Fort Worth Wall 5

This MSE wall is located on SH 114 at FM 1938. It uses precast concrete panels and cement-stabilized backfill and reaches a maximum height of 25.22 feet. The foundation consists of leveling pads, and drainage provisions include underdrain and special drainage details. The wall was constructed in 2004 and is approximately 21 years old. It is located within FEMA Zone X. Site soils include clay and sandstone. No repairs are reported.

Table 2.4.5: Fort Worth Wall 5 Vulnerability Assessment

Parameter	Risk Factor	Score	Weight	Rationale
Age of Wall	21 years	0.25	0.20	Middle-aged structure

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Table 2.4.5 – *continued from the previous page*

Parameter	Risk Factor	Score	Weight	Rationale
Foundation Soil	Clay and sandstone	0.30	0.20	Moderate shrink–swell and movement potential
Drainage Condition	Underdrain and special drainage details	0.25	0.20	Drainage present; field condition not verified
Flood Proximity	FEMA Zone X	0.10	0.10	Low flood hazard
Structural Redundancy	MSE system	0.25	0.10	Moderate redundancy
Inspection & Repair	No records available	0.05	0.20	No repairs reported; uncertainty remains
Final Vulnerability	—	0.220	—	Weighted average

Fort Worth Wall 6

This MSE wall is located at IH 820/183 near Northeast Mall. The wall uses precast panels and cement-stabilized backfill. Wall height ranges from 10 to 24 feet. Drainage includes underdrain and surface drainage details. The wall was constructed in 2001 and is approximately 24 years old. It is located in FEMA Zone X, and no repair history is available.

Table 2.4.6: Fort Worth Wall 6 Vulnerability Assessment

Parameter	Risk Factor	Score	Weight	Rationale
Age of Wall	24 years	0.30	0.20	Moderate aging
Foundation Soil	Clay	0.30	0.20	Moderate shrink–swell and movement potential
Drainage Condition	Underdrain and surface drainage	0.20	0.20	Drainage design present; field condition not verified

Continued on the next page

Table 2.4.6 – *continued from the previous page*

Parameter	Risk Factor	Score	Weight	Rationale
Flood Proximity	FEMA Zone X	0.10	0.10	Low flood hazard
Structural Redundancy	MSE wall	0.25	0.10	Typical MSE redundancy
Inspection & Repair	No records available	0.05	0.20	No repairs reported; uncertainty remains
Final Vulnerability	—	0.210	—	Weighted average

The six representative retaining walls have vulnerability scores ranging from 0.095 to 0.245, indicating very low to moderate vulnerability. Waco Wall 1 has the lowest score because of its recent construction, robust hybrid design, drilled-shaft foundation, and comprehensive drainage system. Fort Worth Walls 2 through 6 have moderate scores, primarily due to age, moderate-risk foundation soils, limited inspection records, and in some cases unverified drainage performance. Fort Worth Wall 3 has the highest score because it is the oldest wall evaluated and has uncertain drainage functionality.

All evaluated walls are located in areas with low flood hazard, such as FEMA Zone X or the 500-year floodplain. No active structural distress is reported for the evaluated walls. However, the absence of recent inspection and repair records introduces uncertainty. Walls with scores above 0.20 may benefit from targeted field inspection, drainage verification, and documentation updates.

2.5 Summary

This vulnerability assessment evaluates selected TxDOT transportation assets under projected mid-century climate-related disruptors to support asset management, project prioritization, and long-range planning. The results show distinct geographic patterns: northern Texas has elevated vulnerability to extreme cold; central, southern, and western Texas show elevated vulnerability to extreme heat; and eastern and southeastern Texas show elevated vulnerability to inland flooding. Coastal and urban districts, particularly Houston, face additional multi-hazard concerns because of their infrastructure density, freight activity, and exposure to coastal and inland hazards.

Bridges and bridge-class culverts in flood-prone and coastal areas warrant continued attention where structural condition or overtopping potential increases vulnerability. The

retaining wall demonstrations in the Waco and Fort Worth districts indicate very low to moderate vulnerability, with age, foundation soil, drainage condition, and limited inspection records as key drivers. Walls with higher scores should be considered for targeted inspection and drainage verification.

The findings provide a planning-level basis for screening assets for further engineering review, informing district-level resilience strategies, prioritizing maintenance and inspection, and guiding future updates to asset data and climate-resilience planning.

Chapter 3

Resilience Assessment for Transportation Asset Management

3.1 General Resilience Assessment Framework

3.1.1 Resilience Measurement

Resilience represents the capacity of a transportation asset to withstand a disruptive event, limit the immediate loss of functionality, and recover performance over time (20, 23). In the context of this project, resilience is quantified using the area under the functionality curve, a representation of how an asset performs immediately after a hazard and how quickly it returns to normal service. The resilience metric is formally expressed as the normalized area under the observed or modeled functionality curve relative to the ideal “no-loss” functionality baseline, which can be expressed as

$$\text{Resilience} = \frac{\text{area under the functionality curve}}{\text{area under the ideal no-loss curve}}. \quad (3.1.1)$$

The functionality curve has two distinct components: (i) Vulnerability, defined as the immediate loss of functionality following a hazard event. Because vulnerability is mathematically equal to $1 - \text{robustness}$, it represents the depth of the initial performance drop when the asset is subjected to a disruption. (ii) Recoverability, which characterizes how quickly and effectively the asset regains functionality through repair, maintenance, or reconstruction.

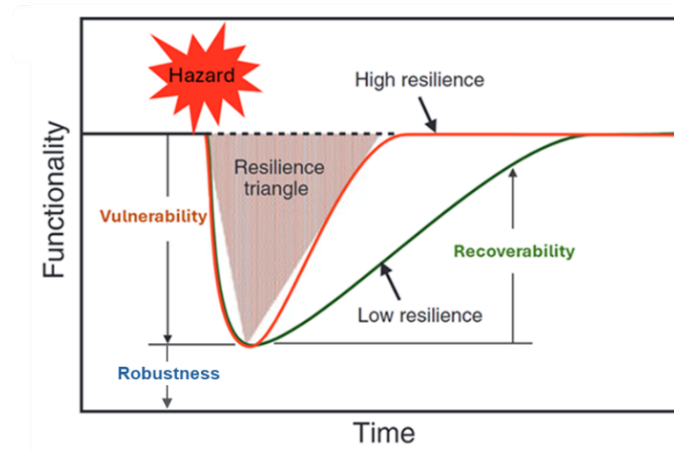


Fig. 3.1.1: The relationship between vulnerability, recoverability, and resilience

Figure 3.1.1 illustrates the relationship between vulnerability, recoverability, and resilience for transportation assets subjected to external hazards. The functionality curve shows how an asset’s performance declines rapidly following a disruption (vulnerability), then gradually recovers over time (recoverability). The area under the curve, often called the “resilience triangle”, quantifies the system’s loss of functionality and recovery efficiency. Assets with smaller shaded areas demonstrate higher resilience, indicating lower performance loss and faster restoration to normal operations. This diagram provides the foundation for the resilience assessment framework by connecting vulnerability to hazards, robustness, and recoverability.

3.1.2 General Framework

The general framework integrates asset data, hazard relationships, recovery modeling, and resilience metrics into transportation asset management (TAM) through:

1. Asset data and condition integration, such as by incorporating inventory, condition ratings, inspections, IRI, distress, and structural configurations.
2. Hazard and vulnerability analysis, typically conducted using fragility curves to quantify how hazard intensity translates into expected damage and loss of functionality. When the required datasets are limited, a simplified vulnerability/robustness evaluation can be performed by mapping asset conditions and structural performance directly to immediate post-hazard functionality.
3. Recoverability estimation, based on material, structural, and operational characteristics that influence the repair or restoration trajectory, depending on the asset type and the TAM approach used.

4. Resilience metric computation, expressed as the relative area under the functionality curve. The estimated resilience values can then be integrated into TAM planning and project prioritization.

Vulnerability Analysis

Figure 3.1.2 outlines the procedure for estimating asset vulnerability under uncertain disruptions. This component of the framework quantifies both the likelihood and the severity of asset degradation when subjected to hazard conditions of varying intensity and probability. The assessment integrates hazard exposure, fragility-based damage modeling, scenario-dependent failure estimation, and consequence evaluation to produce an asset-specific vulnerability value.

Two primary inputs support this process: (i) hazard intensity information across multiple disruption scenarios and (ii) asset inventory attributes such as location, structural configuration, criticality, and historical condition records. These datasets jointly characterize how each asset responds when exposed to one or more hazard types.

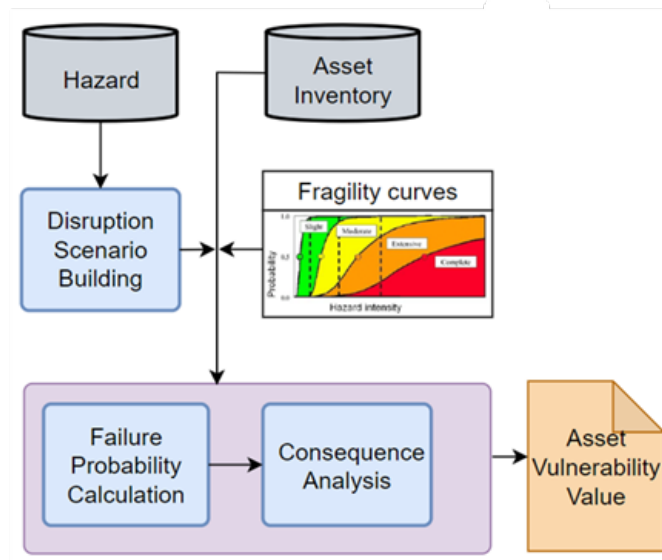


Fig. 3.1.2: Procedure for asset vulnerability assessment under uncertain disruption

The procedure includes three steps:

- Translation of hazard intensity into probabilistic asset damage under different scenarios. For each asset, the hazard intensity at its location is translated into damage probabilities using fragility curves, which define the likelihood of reaching various damage states. To capture uncertainty in both hazard severity and spatial extent, this calculation

is performed across all disruption scenarios. The result is a scenario-specific failure probability $P_{\text{fail}}(i, s)$ for each asset under scenario s .

- The framework then evaluates the operational consequences $C(i, s)$ associated with asset failure. Consequences may include loss of connectivity, diminished service levels, or increased travel delays, which represent the magnitude of disruption if asset i fails under scenario s .
- The overall vulnerability value is then calculated by aggregating the expected losses across all scenarios.

$$V_i = \sum_s P_{\text{fail}}(i, s) C(i, s). \quad (3.1.2)$$

This vulnerability value reflects how strongly hazard exposure, structural fragility, and operational criticality jointly influence the risk profile of each asset. Assets that are highly exposed, structurally susceptible, and operationally important receive proportionally higher values. Finally, vulnerability scores are normalized to ensure they are comparable across asset types and hazard classes and can be integrated consistently into the overall resilience assessment framework.

The vulnerability estimation procedure provides a data-driven characterization of how hazards translate into expected asset damage and operational loss. However, it requires hazard intensity data, asset-specific fragility curves, and consequence data, which may be incomplete or unavailable for some asset classes. When full vulnerability modeling is not feasible, robustness provides an alternative estimate of immediate post-hazard functionality because vulnerability represents lost functionality, whereas robustness represents the functionality that remains.

Robustness can be derived from observable condition indicators and structural performance attributes, such as bridge component ratings, pavement condition scores, and retaining-wall inspection findings. Assets in poorer pre-event condition generally retain less functionality, experience greater initial performance loss, and require more time and resources to recover. Conversely, well-maintained assets typically sustain smaller losses and recover more efficiently. Incorporating these condition-driven robustness measures allows the framework to reflect both pre-event asset health and post-event recovery potential when hazard-specific fragility information is limited.

Recoverability Estimation

Recoverability represents an asset's capacity to regain functionality following a disruptive event and reflects the speed and effectiveness of restoration actions. Recoverability estimation

begins by identifying the factors that most strongly shape post-event restoration for each asset type. For example, bridges may exhibit faster recovery when constructed with resilient structural systems, readily accessible components, or when supported by frequent maintenance. Pavements may recover gradually through scheduled repairs or overlays that improve surface condition and ride quality over time. Retaining walls may depend on drainage performance, soil behavior, or ease of access for remediation. These asset-specific characteristics determine the functional recovery model used in the TAM framework.

Mathematically, the recovery trajectory is expressed as a time-dependent functionality curve $F(t)$, where the initial value $F(0)$ is defined by the robustness of the asset, and the shape of the curve is governed by asset-specific recovery parameters that reflect material, structural, and operational characteristics. Recoverability is therefore essential for distinguishing assets that not only withstand hazards but also return to service efficiently. When incorporated into the resilience framework, recoverability highlights assets that may benefit from targeted maintenance or structural improvements to reduce recovery time and enhance overall system performance.

Resilience Computation

The resilience metric combines the vulnerability/robustness assessment and the recoverability model into a single measure bounded between 0 and 1. Higher values indicate assets that limit performance degradation and restore functionality efficiently. These scores support comparison across assets, hazards, and regions and can be incorporated into TAM planning and project prioritization to identify needs for condition improvements or monitoring.

3.1.3 Asset Management Approaches

As different types of assets require different data and management approaches to attain the expected level of performance, main TAM approaches are introduced here to make this chapter self-contained. According to AASHTO's Guide (25), there are three main approaches:

- **Condition-based approach:** This approach is arguably the most widely used by U.S. transportation agencies. It schedules interventions based on the measured or forecasted asset condition and the anticipated onset of failure. Repair and maintenance activities are planned based on the expected exceedance of condition thresholds, allowing agencies to address deterioration and restore or extend service life. The goal is to optimize performance and longevity by targeting maintenance where and when it is most needed.
- **Interval-based approach:** This approach is commonly applied to operations or manufactured assets (e.g., striping, guardrail, and other mechanical and electrical-related items) with uniform performance, where only an inventory is maintained and condition assessments are not cost-effective. Manufacturers' life-expectancy estimates

are typically used to establish an interval, beyond which failure costs exceed replacement costs. Maintenance for those assets is scheduled at predetermined time or usage intervals, regardless of actual asset condition.

- **Reactive-based approach:** This approach does not rely on forecasting to anticipate the timing of interventions. Instead, maintenance or repairs are administered reactively only in response to identified problems or until an asset reaches an unacceptable condition. Therefore, this approach is typically reserved for low-value or less critical assets or assets whose failure represents an acceptable risk. However, implementing this strategy often necessitates timely interventions within a specified timeframe to avoid unacceptable levels of risk beyond the defined minimum acceptable thresholds.

While these three approaches differ in how decisions are triggered and how maintenance is scheduled, they also vary substantially in their underlying data requirements, the types of assets for which they are best suited, and the level of risk they are designed to manage. To clarify these distinctions and illustrate how each approach aligns with asset characteristics and management, Table 3.1.1 compares the three TAM approaches in terms of their descriptions, data needs, and typical applications.

Table 3.1.1: Comparison of TAM approaches (8)

Approach	Condition-Based	Interval-Based	Reactive-Based
Descrip- tion	Selects intervention based on a forecasted condition exceedance interval.	Schedules interventions at predetermined time or usage intervals, regardless of actual condition.	Performs maintenance or repair only after a problem is observed or failure occurs.
Data Needs	Asset/component type, material, and design characteristics; historical and current condition data; historical intervention data; inventory information.	Asset/component age and service life; timing and type of last maintenance action; remaining useful life estimates; inventory information.	Current condition data; intervention thresholds for unacceptable performance; historical intervention data; inventory data.

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Table 3.1.1 – *continued from the previous page*

Approach	Condition-Based	Interval-Based	Reactive-Based
Typical Usage	High-risk or high-value assets. Long-lived assets that can have numerous management approaches.	Moderate- or low-risk assets. Manufacturer-mandated management regimes or short-lived assets. Assets where the cost to collect condition data is expensive.	Low-risk or low-criticality assets. Assets where the effects of accumulated defects are not critical to their functionality.

3.2 Asset-Specific Resilience Assessment

This section presents resilience assessment methods and results for bridges, pavements/roadways, and geotechnical assets, particularly retaining walls. The analytical methods vary across asset types because each asset type:

- performs distinct structural and functional roles;
- responds to hazards through different degradation mechanisms; and
- has different types, resolution, and quality of available condition and performance data.

Accordingly, the framework is tailored to each asset class. Bridges and culverts use FHWA condition ratings, structural configuration, and hazard-specific robustness factors with a log-linear recovery curve. Pavements integrate surface condition, IRI, distress, traffic criticality, and climate exposure. Retaining walls use structural configuration scoring for anchors, panels, and drainage systems to represent redundancy and load-path behavior. These adaptations align the resilience indices with asset-specific performance mechanisms and data availability.

3.2.1 Bridges

The bridge resilience assessment focuses on quantifying the ability of each structure to maintain and recover functionality under adverse conditions. The dataset includes key attributes such as Structure ID, year of construction, average daily traffic (ADT), bridge length, and geographic coordinates, along with condition ratings for the deck, superstructure, and substructure, each measured on a 0–9 scale following FHWA guidelines. These parameters represent both the physical and operational characteristics of the bridge network.

The mathematical framework integrates robustness, which measures the bridge's inherent resistance to damage, and recoverability, which captures how quickly performance can return to acceptable or pre-disruption levels. For each bridge, the normalized condition index $C_{\text{avg,norm}}$ is derived by averaging the scaled ratings of critical components (deck, superstructure, and substructure) within a 0–1 range.

The overall robustness R_0 is calculated as the product of two components. The first component is the hazard-specific robustness R_h , derived by converting the previously computed asset vulnerability score V as part of the Statewide Resiliency Plan (62). Formally, R_h is calculated as

$$R_h = \frac{1 - V}{0.8}. \quad (3.2.1)$$

where V represents the hazard-specific normalized vulnerability, whose range is $[0, 1]$. The robustness is then bounded between 0.05 and 0.99 for numerical stability. The second component is the normalized average asset condition. The combined robustness value is

$$R_0 = R_h \times C_{\text{avg,norm}}. \quad (3.2.2)$$

To incorporate post-disturbance recovery potential, resilience is expressed using a formulation that penalizes low robustness and rewards recoverability:

$$\text{Resil} = -\frac{1 - R_0}{\ln(R_0)}. \quad (3.2.3)$$

This expression is obtained by computing the relative area under the recovery curve, normalized by the total potential area of full functionality. In this formulation, bridge recovery is assumed to follow a log-linear trajectory (rapid early recovery), consistent with restoration dynamics observed in structural and lifeline systems subjected to sudden degradation. The recovery path is given by

$$F(t) = R_0^{1-t/T}, \quad 0 \leq t \leq T. \quad (3.2.4)$$

where $F(t)$ is the functionality level at time t , and T is the total recovery horizon. This formulation bounds resilience between 0 and 1, providing a consistent measure across bridge assets. Higher values indicate stronger structural condition and greater capacity to maintain or restore service following disruptions. The framework therefore links condition data with hazard-specific robustness to support bridge maintenance and adaptation planning.

To demonstrate how bridge conditions and hazard exposures jointly influence the resilience estimate, consider a representative bridge subjected to extreme heat. The bridge has three primary condition ratings, including deck, superstructure, and substructure, each measured

on the FHWA 0–9 scale. Suppose the deck, superstructure, and substructure ratings are 6, 7, and 7, respectively. The normalized condition index is therefore computed as

$$C_{\text{avg, norm}} = \frac{6 + 7 + 7}{3 \times 9} = 0.74. \quad (3.2.5)$$

If the hazard-specific robustness is assumed to be 0.80, the resulting overall robustness is calculated as

$$R_0 = 0.80 \times 0.74 = 0.59. \quad (3.2.6)$$

Substituting this value into the resilience formula yields

$$\text{Resil} = -\frac{1 - 0.59}{\ln(0.59)} = 0.78. \quad (3.2.7)$$

This resilience value indicates a moderately high resilience level despite the reduction in immediate post-event functionality.



Fig. 3.2.1: Sample trends of bridge component condition ratings (2015–2022)

Figure 3.2.1 provides additional context on how component ratings evolve over time by illustrating the temporal trends of deck, superstructure, and substructure condition scores for six representative bridges across Texas from 2015 to 2022. The majority of bridges exhibit stable condition ratings, with component scores generally remaining above 7 on the standard 0–9 scale, indicating satisfactory to good performance throughout the period. Only minor

fluctuations are observed, primarily in the deck and substructure ratings of select bridges, which show isolated declines of one to two points over the study horizon.

These trends suggest that bridge deterioration is slow and well-managed, implying that hazard-based robustness differences, rather than progressive condition degradation, are the primary drivers of resilience variation across the network. Temporal stability further supports the use of averaged normalized condition scores in the resilience calculations.

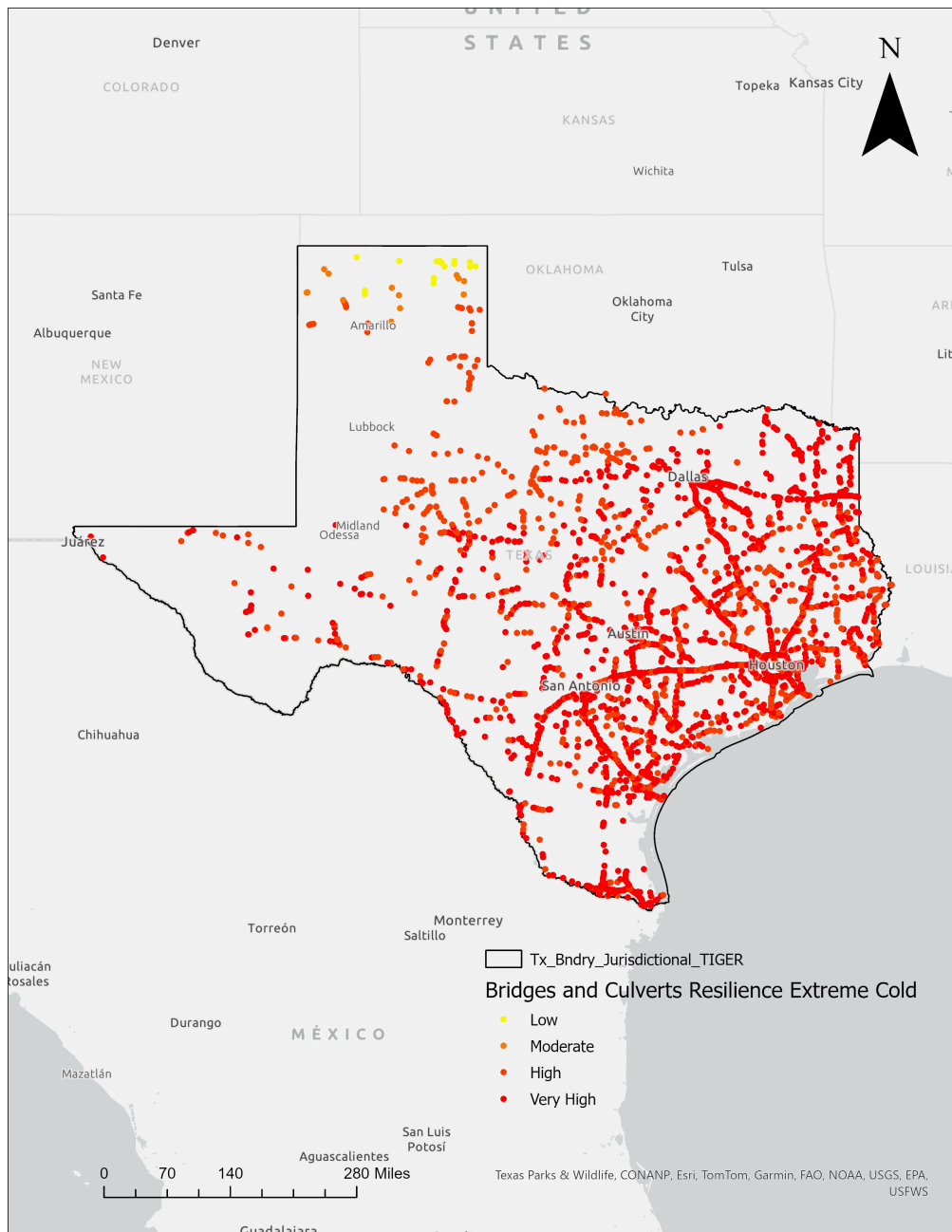


Fig. 3.2.2: Bridges and culverts resilience under extreme cold conditions

Figure 3.2.2 presents the categorical distribution of bridge and culvert resilience under extreme cold conditions across Texas. The map shows that most bridge and culvert assets fall within the High and Very High resilience categories, particularly across central, eastern, southern, and coastal Texas. This pattern suggests that, for much of the state, bridge and culvert assets are expected to retain comparatively strong performance and recovery potential under extreme cold conditions.

Lower resilience categories are concentrated primarily in the northern and northwestern portions of Texas, especially in the Panhandle region, where Low and Moderate resilience are more prevalent. These patterns are consistent with greater cold-weather exposure and more severe winter conditions in northern Texas. From a transportation asset management perspective, the categorical results indicate that bridges and culverts in the Panhandle and adjacent northern areas may warrant greater attention for cold-weather preparedness, inspection, and resilience improvement, while much of the remaining statewide inventory exhibits relatively strong resilience under this hazard.

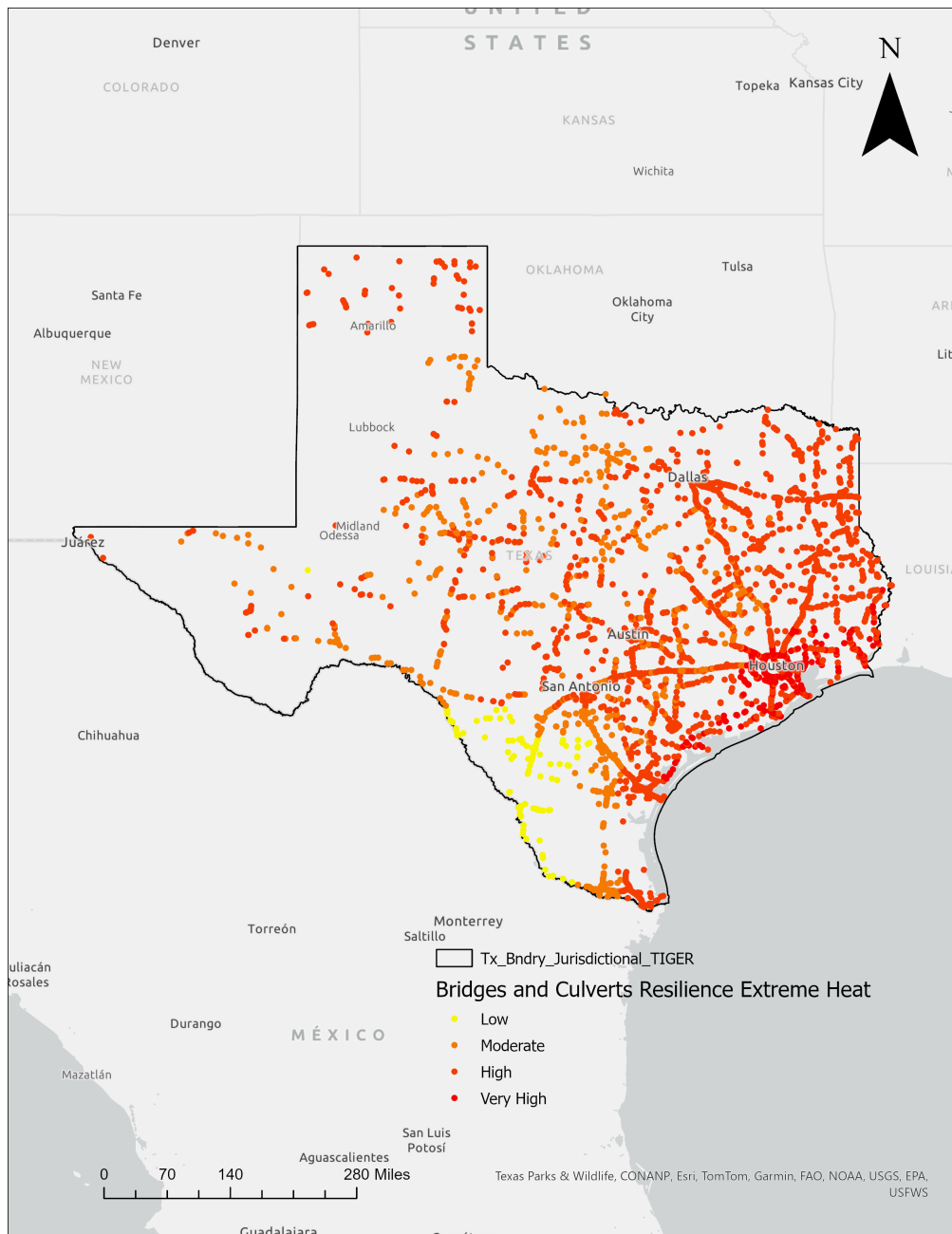


Fig. 3.2.3: Bridges and culverts resilience under extreme heat conditions

Figure 3.2.3 presents the categorical resilience of bridges and culverts under extreme heat conditions. The map indicates substantial spatial variation across Texas. High and Very High resilience categories dominate much of eastern, central, and northeastern Texas, suggesting that a large share of bridge and culvert assets are expected to maintain relatively strong functionality and recovery potential under heat-related stress.

In contrast, lower resilience categories, particularly Low resilience, are more visible in southern Texas and along portions of the Rio Grande region, with Moderate resilience also

appearing across parts of western and central Texas. This pattern suggests that heat-related stress may pose greater challenges for some assets in southern areas of the state. In a planning context, bridges and culverts classified as Low or Moderate resilience may warrant closer monitoring, targeted maintenance, or consideration of heat-adaptive strategies, while those in the High and Very High categories exhibit comparatively stronger resilience to extreme heat.

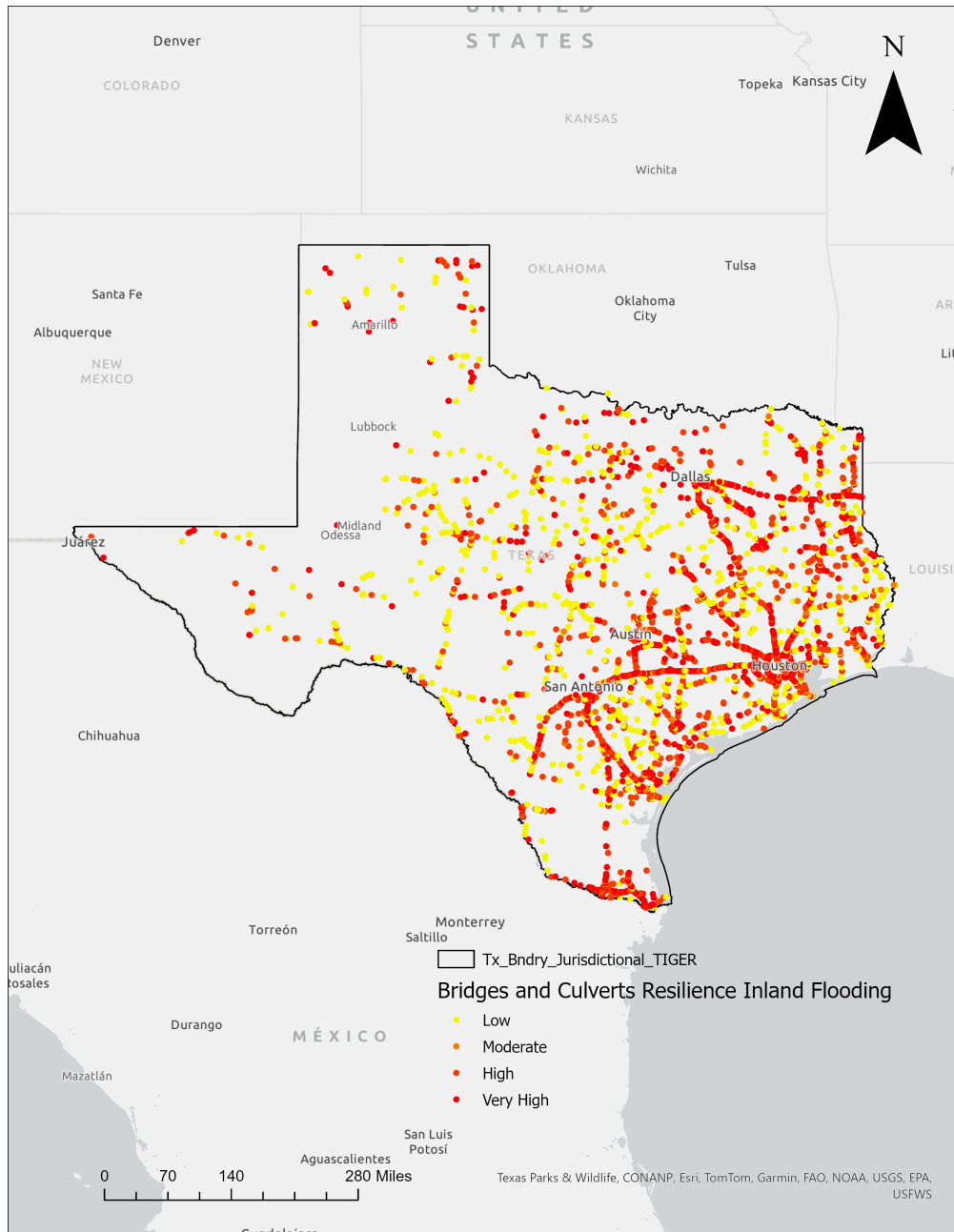


Fig. 3.2.4: Bridges and culverts resilience under inland flooding

Figure 3.2.4 illustrates the categorical distribution of bridge and culvert resilience under

inland flooding. Unlike the clearer regional patterns observed for the temperature-related hazards, the inland flooding resilience pattern is more spatially mixed across the state. Low and Moderate resilience categories are distributed widely throughout Texas, while High and Very High resilience assets also appear across many regions, including portions of central, eastern, and southern Texas.

This spatial variability suggests that bridge and culvert resilience to inland flooding is influenced by localized combinations of hazard exposure, asset condition, and recovery potential rather than by a single broad statewide gradient. The categorical representation is particularly useful for identifying areas where lower-resilience assets are clustered and may require additional hydraulic evaluation, drainage review, inspection planning, or flood-related adaptation measures. At the same time, the presence of High and Very High resilience assets across multiple regions indicates that many bridges and culverts retain comparatively strong capacity to withstand and recover from inland flooding impacts.

3.2.2 Pavements

The resilience assessment for pavements builds upon a multi-component analytical framework that integrates physical robustness, surface functionality, and traffic criticality into a single quantitative measure. The method captures how pavement segments respond to and recover from degradation under climate stressors such as extreme heat and extreme cold, using both performance indicators and hazard-specific robustness factors derived from statewide roadway data.

The hazard-specific robustness represents the pavement segment's inherent capacity to sustain its performance under a given hazard type. It is computed using a similar methodology applied to bridges in the preceding subsection.

Relative functionality, F_{rel} , combines two primary performance indicators: the condition score and the International Roughness Index (IRI). The condition-based functionality F_{cond} is calculated by normalizing the condition score over 100, while the ride-based functionality F_{IRI} is determined relative to an ideal smoothness threshold:

$$F_{\text{cond}} = \frac{\text{Condition Score}}{100}, \quad F_{\text{IRI}} = \frac{\text{IRI}_{\text{good}} - \text{IRI}_{\text{avg}}}{\text{IRI}_{\text{good}}}. \quad (3.2.8)$$

The overall functionality is then expressed as

$$F_{\text{rel}} = 0.5F_{\text{cond}} + 0.5F_{\text{IRI}}. \quad (3.2.9)$$

The base resilience, representing the inherent condition of the pavement before being weighted by contextual factors, is defined as the average of functionality and robustness:

$$F_{\text{base}} = \frac{F_{\text{rel}} + R_0}{2}. \quad (3.2.10)$$

To account for operational, structural, and environmental variability, a weight factor ω is introduced to capture four secondary influences, such as distress, trend, criticality, and thickness:

$$\omega = 0.3D_f + 0.2T_f + 0.3C_f + 0.2P_f. \quad (3.2.11)$$

Here, the distress component D_f is based on mean distress utilization and increases as distress decreases. The term T_f represents the normalized trend in condition, International Roughness Index (IRI), or distress over time. C_f accounts for traffic and network criticality using normalized factors such as Average Annual Daily Traffic (AADT), lane count, and speed, while P_f adjusts for pavement thickness or type. The coefficients can be modified to reflect regional priorities, asset characteristics, or agency-specific considerations.

Finally, the weighted resilience combines all components to yield a more representative measure of pavement performance and redundancy:

$$\text{Resil}_{\text{weighted}} = \text{Resil}_{\text{base}} + \frac{\omega}{2} (F_{\text{rel}} - R_0). \quad (3.2.12)$$

Each pavement's weighted resilience is then aggregated to the network level using overlap-length weighting, ensuring that longer or more critical segments exert proportionally greater influence in the resilience map. This integrated approach allows direct comparison of pavement segments across environmental and operational conditions, facilitating region-specific adaptation and maintenance prioritization.

functional performance, and cold-related robustness may justify closer review. Moderate resilience represents intermediate performance, while High and Very High categories indicate comparatively stronger ability to maintain and recover functionality under extreme cold conditions.

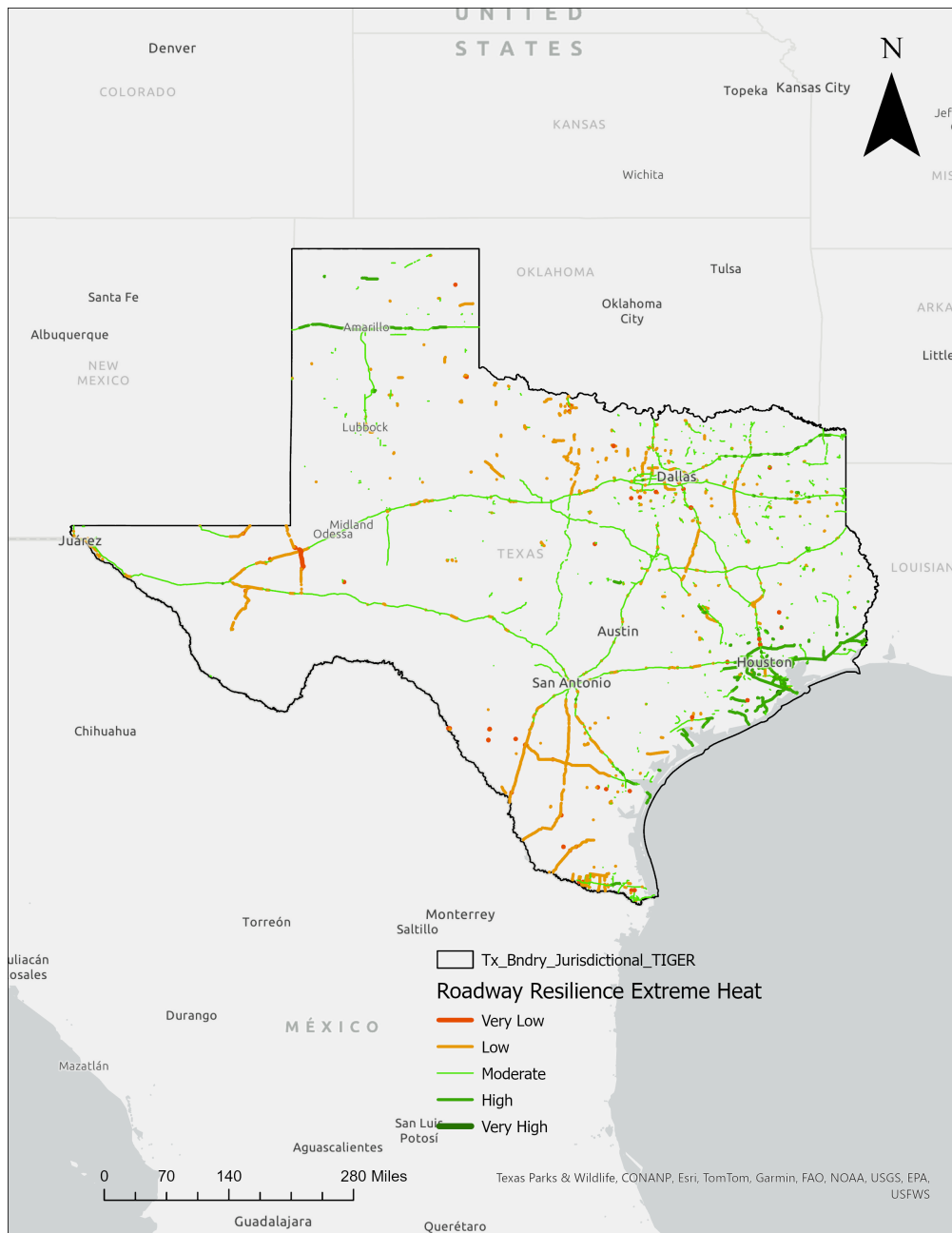


Fig. 3.2.6: Roadway resilience under extreme heat conditions in Texas

Figure 3.2.6 presents the distribution of categorical roadway resilience under extreme heat. Most roadway segments fall within the Moderate-to-High resilience categories, although

localized Low and Very Low segments are present in several parts of the state. Very High resilience is concentrated along selected corridors, particularly in portions of eastern and southeastern Texas.

The categorical representation allows lower-resilience roadway segments to be identified directly for planning purposes. Segments classified as Very Low or Low may warrant additional pavement-condition review, heat-related deterioration monitoring, or adaptation measures, whereas High and Very High categories indicate comparatively stronger performance under the modeled extreme heat scenario.

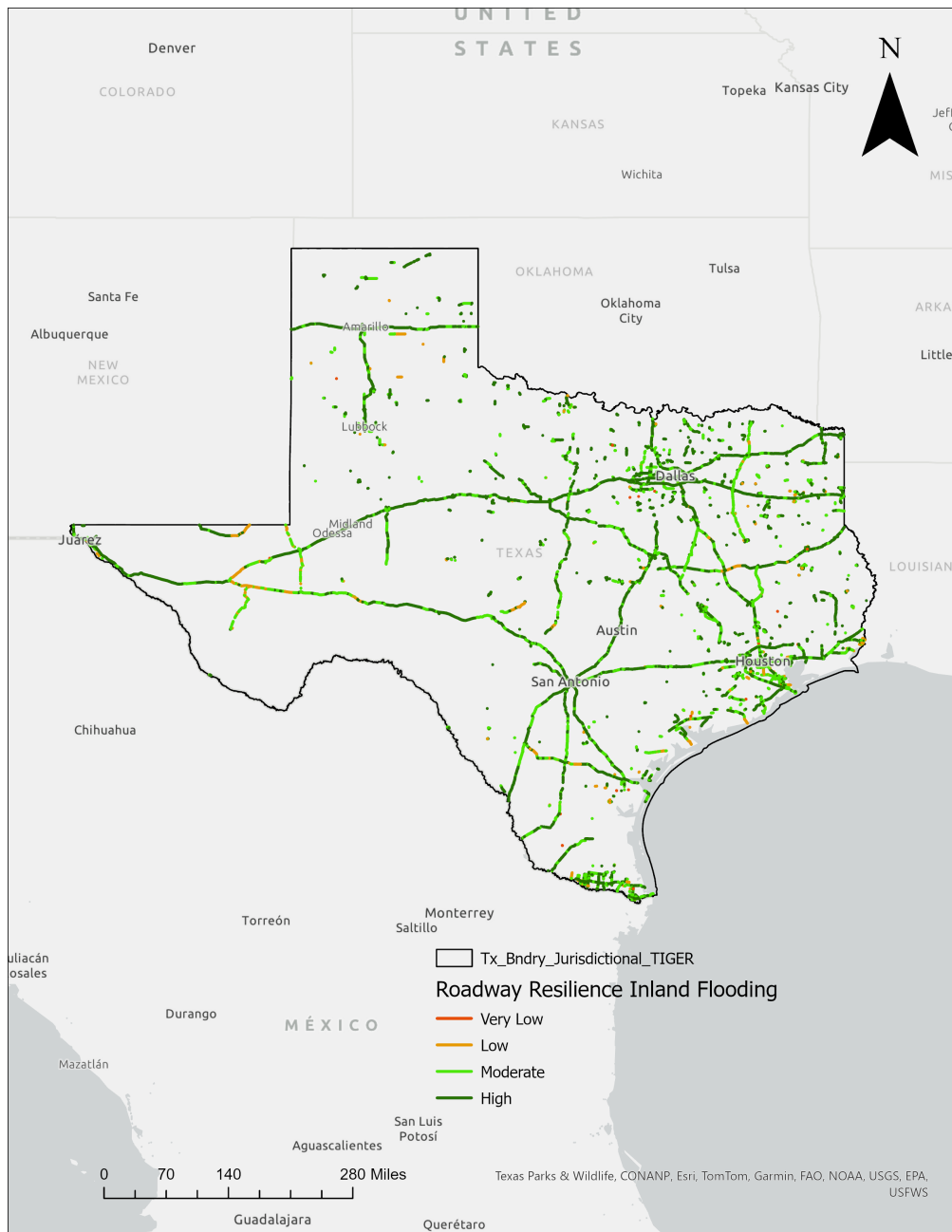


Fig. 3.2.7: Roadway resilience under inland flooding in Texas

Figure 3.2.7 presents the categorical distribution of roadway resilience under inland flooding using the five resilience classes defined in Table 3.2.3. The map identifies roadway segments with varying levels of expected ability to maintain and recover functionality under flood-related disruption.

Segments classified as Very Low or Low resilience represent locations where flood-related robustness, pavement condition, and functional performance combine to produce comparatively weaker resilience. These segments may warrant closer evaluation of drainage capacity,

pavement condition, flood exposure, and maintenance needs. Moderate resilience represents intermediate performance, while High and Very High categories identify roadway segments with comparatively stronger expected performance under inland flooding.

3.2.3 Retaining Walls

The resilience of retaining walls is evaluated by integrating structural configuration data with qualitative information from field inspections and maintenance records. Each wall is characterized by its anchors, panel system, and drainage configuration, as well as contextual hazard and maintenance observations that influence redundancy and failure likelihood. These attributes collectively describe how a wall can resist, absorb, and recover from external stressors such as lateral soil pressure, groundwater buildup, or climatic extremes.

The assessment framework defines resilience as the mean of two complementary attributes: robustness, which represents the inherent strength and durability of the system, and redundancy, which measures the degree of backup or alternative load paths within the structure. Formally, the resilience of retaining walls is computed as

$$\text{Resilience} = \frac{\text{Robustness} + \text{Redundancy}}{2}. \quad (3.2.13)$$

The redundancy of each wall is quantified using a weighted component approach, in which the main structural and drainage elements, such as anchors, panels, and drainage systems, are each assigned a score s_i and an importance weight ω_i :

$$\text{Redundancy} = \sum_i s_i \omega_i. \quad (3.2.14)$$

This method captures how the configuration and interdependence of wall components affect overall system reliability. For example, walls with multiple tied-back anchors or hybrid structural systems exhibit higher redundancy due to the presence of independent load paths, while those with single-line drainage systems or rigid panel connections may display lower redundancy because a single failure could compromise overall performance.

By combining both robustness and redundancy, this framework provides a comprehensive measure of a retaining wall's capacity to sustain structural integrity and serviceability following disturbance. It allows for the differentiation between walls that are merely strong and those that are structurally resilient, capable of redistributing loads and maintaining stability even when individual components degrade or fail.

Table 3.2.1: Structural and functional redundancy assessment—Fort Worth Wall 3 example

Parameter	Factor Description	Score	Weight	Rationale
Anchor	Tied-back anchors (multiple anchors typical)	0.9	0.4	Tied-back anchors are strong, independent structural elements that directly resist lateral earth pressures. If configured with multiple anchors at different elevations and redundantly anchored into competent soils or rock, they provide very high redundancy; loss of a single anchor rarely leads to collapse.
Panel	Precast panel system	0.85	0.4	Precast panels are modular and can locally redistribute loads; panel joints and connections allow alternate load paths when individual panels are damaged.
Drainage	Weep-hole type drainage; single primary system	0.4	0.2	Weep holes relieve hydrostatic pressure but represent a single line of defense. Without a continuous underdrain or toe drain, drainage redundancy is limited; a clog or sedimentation event could temporarily remove the drainage path.

Table 3.2.1 summarizes the anchor, panel, and drainage subsystem scores for Fort Worth Wall 3. The tied-back anchors and modular precast panels provide the primary redundancy, while the single weep-hole drainage system represents the principal limitation. The resulting redundancy index is

$$\begin{aligned}
 \text{Anchor} &= 0.9 \times 0.4, \\
 \text{Panel} &= 0.85 \times 0.4, \\
 \text{Drainage} &= 0.4 \times 0.2, \\
 \text{Redundancy} &= 0.78.
 \end{aligned}
 \tag{3.2.15}$$

Combined with the corresponding robustness metric, this redundancy value yields an overall resilience score of 0.77, indicating moderate-to-high resilience. The drainage subsystem is the clearest opportunity for improvement.

Table 3.2.2: Structural and functional redundancy assessment—Waco Wall example

Parameter	Factor Description	Score	Weight	Rationale
Anchor	Hybrid structural system: drilled shafts + MSE + cantilever connections	0.85	0.4	Drilled shafts provide deep, independent support; the hybrid MSE and cantilever geometry provides multiple load paths through pile action from shafts, soil reinforcement, and panel stiffness. This combination yields high redundancy under lateral load or local panel damage.
Panel	Precast panels + tied elements/cast elements	0.85	0.4	Precast panels with keyed joints and chamfers, plus cantilever/MSE interaction, permit local redistribution of loads; panels and pilasters offer alternate load paths if one element is damaged.
Drainage	Weep holes, Type I underdrain, toe drain, riprap outfall	0.4	0.2	The multi-layer drainage system includes weep holes, a wrapped underdrain, toe or granular drainage, and a riprap outfall. Multiple components reduce single-point failure risk; for example, a clogged weep hole still leaves other drainage paths available.

Table 3.2.2 summarizes the subsystem scores for the Waco Wall. Its hybrid drilled-shaft, MSE, and cantilever system provides multiple load paths, while the layered drainage configuration reduces single-point failure risk. Applying the defined scoring framework, the redundancy index is

$$\begin{aligned}
 \text{Anchor} &= 0.85 \times 0.4, \\
 \text{Panel} &= 0.85 \times 0.4, \\
 \text{Drainage} &= 0.4 \times 0.2, \\
 \text{Redundancy} &= 0.84.
 \end{aligned}
 \tag{3.2.16}$$

Integrating this redundancy with the corresponding robustness metric yields a final resilience score of 0.87, indicating high resilience under lateral and hydraulic loading conditions.

3.2.4 Planning Interpretation of Resilience Categories

To support transportation asset management (TAM), continuous resilience values are converted into categorical classes for map visualization and screening-level planning. These classes support district review, corridor comparison, maintenance planning, and resilience-oriented project development.

Table 3.2.3: Interpretation of resilience categories for TAM applications

Resilience Value	Category	Meaning for Asset Performance
$0.0 \leq R < 0.2$	Very Low	The asset is expected to have limited ability to maintain or recover functionality under the selected hazard.
$0.2 \leq R < 0.4$	Low	The asset may experience substantial performance degradation and should be reviewed more closely.
$0.4 \leq R < 0.6$	Moderate	The asset exhibits intermediate resilience; planning decisions should consider local context and other risk factors.
$0.6 \leq R < 0.8$	High	The asset is expected to maintain relatively strong performance under the selected hazard.
$0.80 \leq R \leq 1.00$	Very High	The asset is expected to experience limited disruption and exhibit strong relative resilience.

Table 3.2.3 summarizes the interpretation of the resilience categories used in this study. The categorical maps are screening-level planning tools rather than final project-selection outputs. Assets classified as *Very Low* or *Low* may warrant additional engineering review, monitoring, maintenance, rehabilitation, or resilience-focused design improvements. Assets classified as *Moderate* may be monitored or incorporated into medium-term planning, while *High* and *Very High* assets generally indicate comparatively favorable performance.

TxDOT districts can use the maps to identify corridors or clusters of low-resilience assets, compare hazard-specific needs, and support maintenance, capital-planning, and adaptation discussions. Potential measures include improved pavement materials and drainage, overlays, preventive maintenance, hydraulic-capacity review, scour protection, structural retrofits, and post-event inspection. The resilience category should be considered together with asset condition, traffic volume, functional classification, emergency access, freight importance,

equity considerations, project cost, and engineering judgment.

3.3 Summary

The assessment applies a unified resilience assessment framework while tailoring the indicators to each asset class. Bridges and culverts combine condition ratings with hazard-specific robustness and recovery; pavements integrate condition, roughness, distress, traffic criticality, and climate exposure; and retaining walls emphasize structural and drainage redundancy. Fort Worth Wall 3 and the Waco Wall produce resilience scores of 0.77 and 0.87, respectively, while the pavement analysis identifies regional differences associated with climate exposure and material performance. These asset-specific methods provide a planning-level basis for prioritizing maintenance, monitoring, and adaptation investments under evolving climatic and loading conditions.

Chapter 4

Resilience-Informed Project Selection

4.1 Introduction

The preceding chapter establishes a resilience assessment framework for bridges, pavements, and retaining walls by integrating hazard-specific vulnerability or robustness, existing condition information, and recovery-related considerations into asset-level resilience scores. These values provide a systematic basis for identifying assets that are more susceptible to hazard-induced performance loss and slower recovery and can therefore support transportation asset management planning, risk-informed decision-making, and investment prioritization.

However, transportation investment decisions are generally made at the project level rather than at the level of individual assets. In practice, TxDOT districts and statewide programming processes prioritize projects such as overlays, bridge maintenance, roadway rehabilitation, drainage improvements, widening, safety improvements, and reconstruction packages. A resilience-informed project selection framework is therefore needed to translate the asset-level resilience information developed in this chapter into a project-level methodology that can support project screening, ranking, and programming decisions.

A recent statewide resilience project identification effort provides a practical starting point for this integration. That effort compiles projects from the Unified Transportation Program (UTP), Statewide Transportation Improvement Program (STIP), freight plans, corridor studies, and related planning documents, and then applies a staged filtering process to identify candidate projects that may be eligible for Promoting Resilient Operations for Transformative, Efficient, and Cost-Saving Transportation (PROTECT) program funding or otherwise improve transportation system resilience. The filtering process considers project phase, asset type, project descriptions, geospatial relationships to evacuation routes, coastal exposure, and proximity to highly vulnerable assets.

This chapter extends that staged filtering process into a resilience-informed project selection framework. The method retains the practical candidate-project screening procedure,

links each project to nearby infrastructure assets through GIS-based proximity analysis, and aggregates hazard-specific asset resilience to quantify project-level resilience need. This need is combined with project criticality and project-type-specific effectiveness to produce a project priority score for ranking and prioritization. The resulting score is intended for comparative screening and should complement, rather than replace, detailed engineering evaluation, benefit–cost analysis, and TxDOT programming judgment.

4.2 Methodology and Framework

The proposed framework consists of four main components: candidate project filtering, project-to-asset linkage, project resilience score computation, and project ranking or selection.

The first step is to define the candidate project pool using existing project records from UTP, STIP, freight plans, and related planning sources. Projects are retained if they meet criteria related to the project phase, resilience-related descriptions, evacuation-route relevance, coastal exposure, and proximity to vulnerable assets. This staged filtering process ensures that the candidate project pool focuses on projects with potential resilience relevance while remaining consistent with existing planning and programming processes.

The second step is project-to-asset linkage. In this study, project locations are approximated using available spatial descriptors, including route, county, and descriptive fields. These project records are geocoded into point representations. A proximity-based GIS implementation is then used to associate each project with nearby infrastructure assets. Specifically, spatial join operations with a 500-ft search radius are applied to link each project to roadway segments and bridge assets for which hazard-specific resilience scores are available. This proximity-based linkage provides a practical approximation of the infrastructure assets influenced by each project in the absence of detailed project geometry.

For each asset a , hazard-specific resilience values $\text{Resil}_{a,h}$ are obtained from the resilience layers developed in earlier sections. A resilience deficiency measure is defined as

$$D_{a,h} = 1 - \text{Resil}_{a,h}. \quad (4.2.1)$$

This measure represents the lack of resilience or resilience need associated with the asset under hazard h . Project-level hazard-specific resilience need is computed by averaging the deficiencies of nearby assets:

$$N_{p,h} = \frac{1}{|A(p)|} \sum_{a \in A(p)} D_{a,h}, \quad (4.2.2)$$

where $A(p)$ represents the set of assets associated with project p . The mean aggregation gives each linked asset equal influence and avoids inflating scores for projects associated with

more mapped assets. With richer data, assets may instead be weighted by length, traffic, condition, or network importance.

An infrastructure-based multi-hazard resilience need score is then computed as

$$N_p^{\text{infra}} = \sum_{h \in H} \alpha_h N_{p,h}, \quad (4.2.3)$$

where equal weights are used for extreme heat, extreme cold, and inland flooding. Alternative weighting schemes could reflect hazard likelihood, expected damage severity, economic consequences, or policy priorities.

Project-level planning indicators are incorporated through a proxy resilience need score:

$$N_p^{\text{proxy}} = 0.4I_p^{\text{vuln}} + 0.2I_p^{\text{evac}} + 0.2I_p^{\text{coast}} + 0.2I_p^{\text{res}}, \quad (4.2.4)$$

where I_p^{vuln} indicates proximity to a highly vulnerable asset, I_p^{evac} indicates whether the project is located on or supports an evacuation route, I_p^{coast} represents coastal relevance, and I_p^{res} indicates whether the project is explicitly classified as a resilience improvement. Each indicator equals 1 when the condition is satisfied and 0 otherwise.

The final resilience need score is computed as a weighted combination of the infrastructure-based and proxy-based measures:

$$N_p = \lambda N_p^{\text{proxy}} + (1 - \lambda) N_p^{\text{infra}}, \quad (4.2.5)$$

where λ is a weighting parameter reflecting the relative importance of planning-based indicators and engineering-based resilience measures. In this implementation, equal weighting ($\lambda = 0.5$) is adopted. In future applications, sensitivity testing of λ can be used to evaluate whether project rankings remain stable under alternative planning and engineering priorities.

Project criticality is estimated based on available project priority indicators, including the project's priority level. The priority level is mapped to a normalized criticality scale as

$$C_p = \begin{cases} 1.0 & \text{if Priority Level} = \text{High}, \\ 0.5 & \text{if Priority Level} = \text{Medium}, \\ 0.2 & \text{if Priority Level} = \text{Low}, \\ 0.5 & \text{if Priority Level is missing or not specified.} \end{cases} \quad (4.2.6)$$

In cases where the priority level is missing or not specified, a neutral value of 0.5 is assigned to reflect an intermediate level of criticality. This ensures that projects without criticality data are still considered in the analysis, without assuming them to be of no importance. This criticality score quantifies the importance of the project to the overall system's resilience and its capacity to withstand disruptions.

Project effectiveness is estimated based on project type using engineering judgment. The effectiveness of each project type is scored as follows:

$$E_p = \begin{cases} 0.9 & \text{if Project Type = Major Reconstruction or Widening,} \\ 0.7 & \text{if Project Type = Operational Improvements or Maintenance,} \\ 0.5 & \text{if Project Type = Traffic Control, ITS, or Low Impact Projects.} \end{cases} \quad (4.2.7)$$

This effectiveness score reflects the relative impact of each project type on improving overall transportation network resilience.

These components are combined with the resilience need score to compute the final priority score for the project:

$$S_p = \text{Resilience Need} \times \text{Criticality} \times \text{Effectiveness}. \quad (4.2.8)$$

This multiplicative structure ensures that projects receive high priority only when resilience need, consequence or criticality, and expected effectiveness are all high.

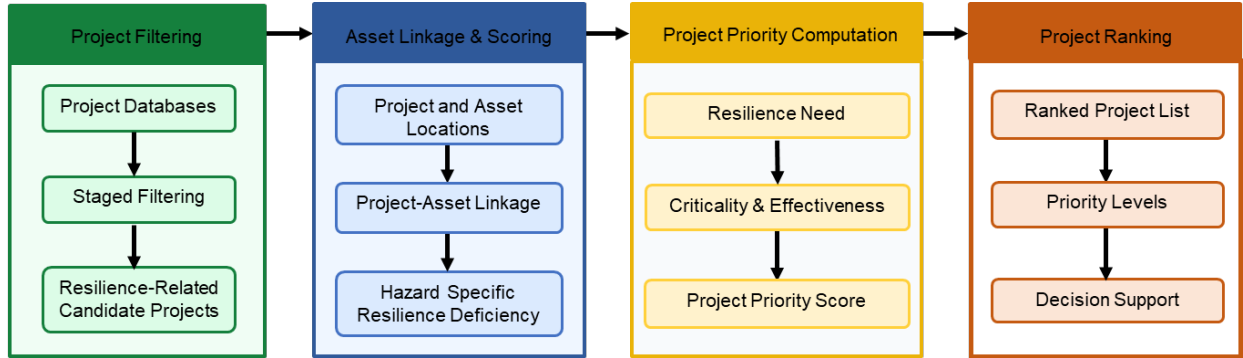


Fig. 4.2.1: Resilience-informed project ranking framework

4.3 Results and Summary

The framework is implemented using the compiled candidate-project dataset and the resilience layers developed in the preceding chapter. Project locations are geocoded and linked to nearby roadway and bridge assets using a GIS-based spatial join with a 500-ft proximity threshold, consistent with the statewide STRP analysis framework and used as a practical approximation of project influence areas. Hazard-specific asset resilience values are aggregated into the infrastructure-based need measure and are combined with planning-level proxy indicators, project criticality, and project-type effectiveness. The resulting priority scores are classified as low, medium, or high for project screening and prioritization.

Figure 4.3.1 presents the spatial distribution of candidate projects across Texas. The map illustrates the statewide coverage of projects identified through the staged filtering process and highlights concentrations of projects in major metropolitan areas and coastal regions.

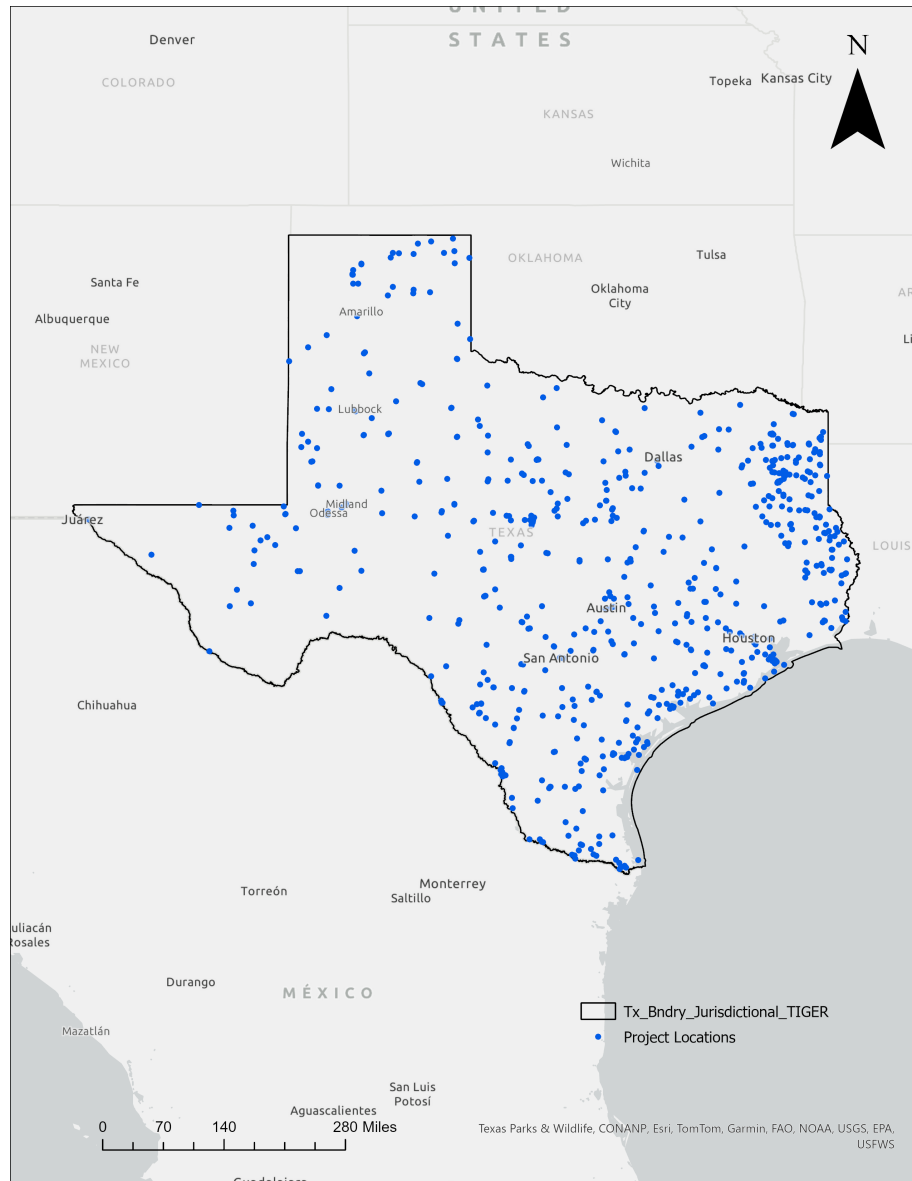


Fig. 4.3.1: Spatial distribution of candidate projects across Texas

Figure 4.3.2 shows the distribution of resilience need across projects based on the multi-hazard aggregation framework. Higher values indicate locations where infrastructure exhibits lower resilience and therefore greater need for intervention. As expected, higher resilience need is observed in coastal regions and selected inland corridors exposed to flooding and other hazards.

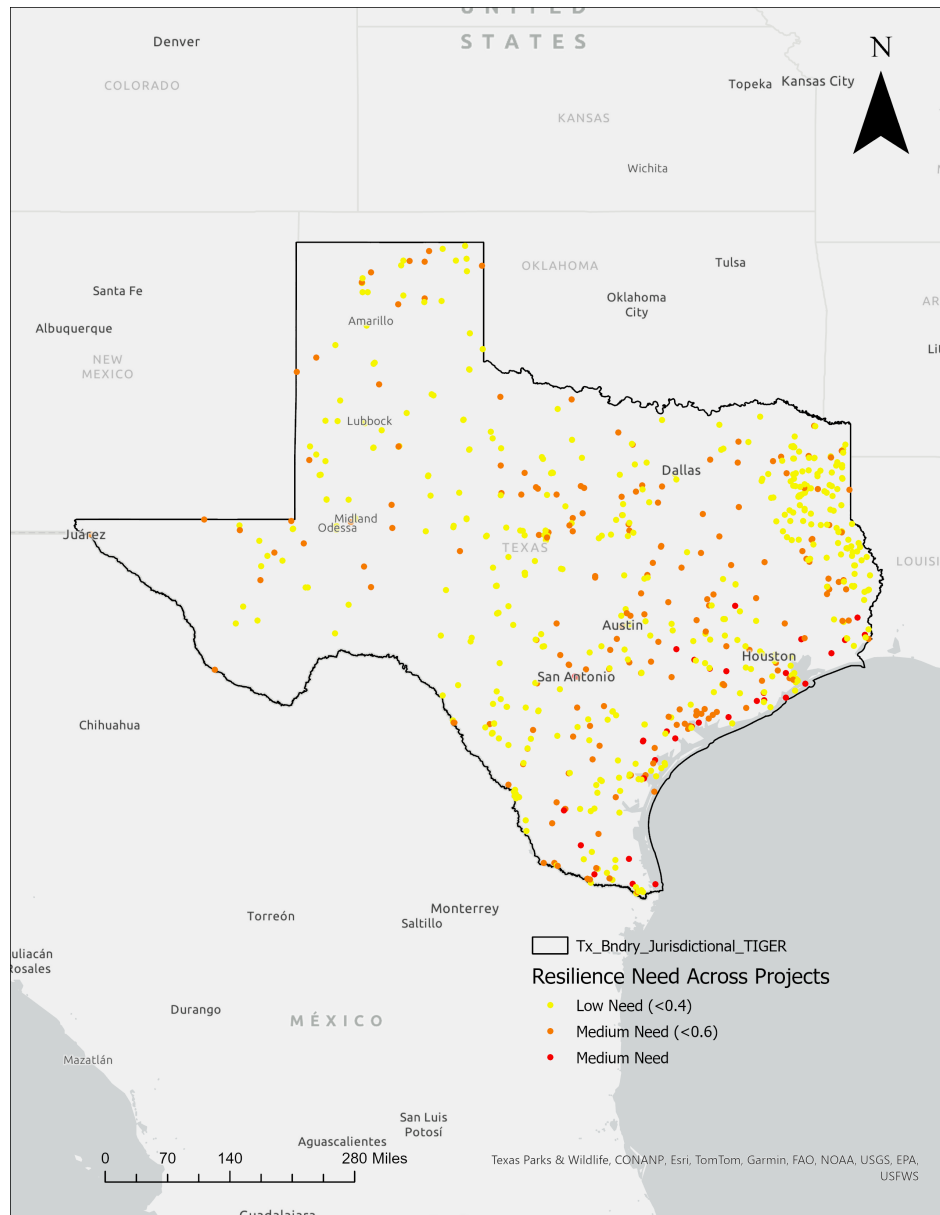


Fig. 4.3.2: Project-level resilience need based on multi-hazard aggregation

Figure 4.3.3 shows the final resilience-informed project priority classification. The priority score integrates resilience need, location criticality, and project effectiveness. Projects classified as high priority represent locations where low resilience, high consequence, and strong expected intervention benefits coincide. The map demonstrates a clear spatial differentiation of priority levels, supporting decision-making for resilience-focused investment.

multiple hazards. The observed spatial patterns are consistent with known vulnerability trends in coastal and high-demand corridors, supporting the framework’s potential application in statewide resilience planning.

Chapter 5

Pilot Studies of the Resilience-Based TAM Framework

5.1 Introduction

This chapter presents the pilot implementation of the resilience-based Transportation Asset Management (TAM) framework. The pilot study applies the developed software tool to selected asset-hazard cases in two TxDOT districts: roadway segments in the Wichita Falls District under extreme cold and extreme heat scenarios, and bridges in the Houston District under inland flooding conditions.

The purpose of the pilot study is to demonstrate how the resilience-based TAM framework can support district-level planning and project screening. The pilot uses available asset data, hazard-related vulnerability information, and the methods developed in earlier chapters to generate practical decision-support outputs. These outputs include functional performance and condition maps, vulnerability maps, robustness maps, resilience maps, sensitivity-analysis results, risk-resilience ranking tables, and rank-shift maps.

The pilot study is organized around three main objectives:

1. **Assess asset conditions and estimate hazard impacts.** The software tool is used to evaluate existing roadway and bridge conditions and estimate how selected hazards affect those assets.
2. **Identify variables with the highest impact on asset resilience.** Sensitivity analysis is conducted to determine which input variables have the greatest effect on the final resilience score.
3. **Compare resilience-based TAM with conventional risk-based TAM.** Asset-priority rankings are generated using both conventional risk-based and resilience-based

approaches. Rank-shift maps and summary tables are then used to show how project priorities change when resilience is incorporated.

The pilot study builds on the project methods developed earlier. Hazard impact and vulnerability assessment follow the framework developed in Chapter 2. Resilience evaluation, including asset functionality, robustness, and final resilience calculation, follows the asset-specific framework developed in Chapter 3. This chapter demonstrates how those methods are applied to available roadway and bridge datasets through the software tool. The results are intended to support screening-level interpretation, comparison of asset priorities, identification of influential variables, and documentation of data needs for future resilience-based TAM implementation.

Because the pilot relies on available data, the results should be interpreted as a practical screening-level demonstration rather than a complete districtwide assessment of all roadway and bridge assets. For the Wichita Falls roadway pilot, only roadway segments with available resilience-related input data are displayed. For the Houston bridge pilot, the available data support condition-based and flood-vulnerability screening, but additional hydraulic, structural, cost, and recoverability datasets are needed for detailed project-level analysis.

5.2 Pilot-Study Methodology

5.2.1 Overall Workflow

The following general workflow is used for both the roadway and bridge pilots. As shown in Figure 5.2.1, the workflow includes the following steps:

1. **Prepare asset data.** Check data completeness, remove unusable records, standardize field names, and prepare the data for mapping and analysis.
2. **Assess current asset condition.** Use available condition and performance indicators to describe the baseline condition of each asset.
3. **Estimate hazard exposure and vulnerability.** Use hazard layers or controlled hazard scenarios to estimate the impact of the selected hazard on each asset following the vulnerability framework in Chapter 2.
4. **Compute asset resilience.** Use the asset-specific resilience framework in Chapter 3 to calculate the resilience score for each asset.
5. **Conduct sensitivity analysis.** Identify which input variables have the greatest influence on the final resilience score.

6. **Compare risk-based and resilience-based priorities.** Generate and compare project-priority rankings from conventional risk-based TAM and resilience-based TAM perspectives.



Fig. 5.2.1: Pilot study workflow.

The pilot implements the vulnerability and resilience steps using the frameworks in Chapters 2 and 3. Where spatial hazard layers are available, the software tool uses geospatial overlay. For example, bridge locations are overlaid with floodplain or inundation layers, and roadway segments can be overlaid with temperature, flooding, snowstorm/cold, drought, or other hazard-related layers. Where detailed hazard layers are unavailable at the required spatial resolution, the pilot uses available hazard-related variables or controlled scenarios to demonstrate the workflow and document data limitations.

For roadway and pavement assets, available data are mapped to functionality, hazard-specific robustness, distress condition, performance trend, criticality, and pavement type or thickness. For bridges, available data are mapped to component condition, hazard-specific robustness, criticality, and recoverability.

5.2.2 Sensitivity Analysis

The purpose of sensitivity analysis is to identify which variables have the greatest impact on the final asset resilience score. This is different from identifying variables that only affect vulnerability. In this pilot, the output of interest is the final resilience score.

Formally, let R_i denote the final resilience score for asset i , and let x_{ij} denote input variable j for asset i . For each candidate variable, the variable is changed by a small amount, the resilience score is recomputed, and the resulting change in resilience is measured. Other variables are held fixed during the perturbation. A one-at-a-time sensitivity index can be given by:

$$S_j = \frac{1}{N} \sum_{i=1}^N \left| \frac{R_i(x_{ij} + \Delta_j) - R_i(x_{ij} - \Delta_j)}{2\Delta_j} \right|, \quad (5.2.1)$$

where S_j is the average sensitivity of resilience to variable x_j , N is the number of assets, and Δ_j is the perturbation size.

For normalized variables, Δ_j is set to 0.05. For raw variables, the perturbation is easy to interpret. For example, bridge condition ratings are changed by one rating point, and normalized pavement indicators are changed by five percent. The variable with the highest impact on resilience is identified as: $x_j^* = \arg \max_j S_j$.

In the pilot implementation, this procedure is applied to the roadway and bridge variables available in the GIS outputs. For the Wichita Falls roadway pilot, functional performance, hazard-specific robustness, and the inferred weighting factor are evaluated. For the Houston bridge pilot, inland flood vulnerability, deck condition, superstructure condition, and substructure condition are evaluated. The resulting sensitivity values are reported in the asset-specific pilot sections.

5.2.3 Risk-Based and Resilience-Based TAM Comparison

The pilot compares two types of project-priority rankings. The first is a conventional risk-based ranking. This ranking prioritizes assets based on hazard exposure, vulnerability, and consequence or criticality. This approach is useful for identifying assets with high expected hazard-related losses. The second is a resilience-based ranking. This ranking uses the resilience score in Chapter 3 and gives higher priority to assets with lower resilience, especially when those assets are operationally important. This approach is useful for identifying assets that may have difficulty maintaining or recovering functionality after a disruption.

The rank shift for each asset is calculated as:

$$\Delta \text{Rank}_i = \text{RiskRank}_i - \text{ResilienceRank}_i. \quad (5.2.2)$$

A large rank shift means that the asset's priority changes when resilience is considered. These assets are important because they show where resilience-based TAM leads to different decisions than conventional risk-based TAM.

The overlap between the two selected project lists is calculated as:

$$\text{Overlap} = \frac{|\mathcal{P}^{risk} \cap \mathcal{P}^{res}|}{|\mathcal{P}^{res}|}, \quad (5.2.3)$$

where $\mathcal{P}^{risk}$ is the set of top-ranked assets under the risk-based plan and $\mathcal{P}^{res}$ is the set of top-ranked assets under the resilience-based plan.

If project cost data are available, the two plans are compared under the same budget. If project cost data are not available, the pilot compares the top M assets under each approach, such as the top 20, top 50, or top 10 percent of assets.

In the pilot study results, the primary comparison metric is the rank-shift category because project cost data and final programmed project lists are not available. The overlap metric can be applied in future implementations when TxDOT staff selects a specific top-ranked

project list or budget-constrained candidate set.

5.3 Wichita Falls Roadway/Pavement Pilot

The Wichita Falls pilot evaluates selected roadway segments under extreme cold and extreme heat scenarios. Although the Wichita Falls District was originally selected in the project as the pavement pilot location for severe snowstorm/cold and drought-related impacts, the available dataset used in this implementation primarily supports roadway-level screening for extreme cold and extreme heat. The analysis therefore focuses on the roadway segments for which resilience-related input data are available, including functional performance, hazard vulnerability, hazard-specific robustness, traffic criticality, and final resilience outputs.

It is important to note that the maps in this section do not represent the full roadway network in the Wichita Falls District. Only roadway segments with available data are displayed. Blank areas on the maps do not indicate the absence of roadways, zero vulnerability, or zero resilience; they indicate locations outside the available pilot roadway dataset. This is important for interpreting the figures because the selected roadway segments are spatially scattered across the district.

5.3.1 Pilot Data and Analysis Scope

The roadway pilot uses available GIS and asset-condition information to evaluate the selected roadway segments. Each segment is identified using the available roadway segment identifier and associated asset attributes. The analysis includes three main groups of variables. First, functional performance represents the baseline operating and pavement-condition status of each segment. Second, hazard vulnerability and robustness describe the segment's exposure and sensitivity to extreme cold and extreme heat stressors. Third, traffic volume and related criticality information support the comparison between conventional risk-based ranking and resilience-based ranking.

The pilot is interpreted as a screening-level application of the resilience-based TAM framework. It is intended to demonstrate how the developed software tool can convert available roadway and hazard information into map-based decision-support outputs. The results can help TxDOT staff identify locations that may require additional review, field validation, or more detailed engineering analysis.

5.3.2 Functional Performance and Criticality Inputs

Functional performance represents the baseline ability of each roadway segment to provide service before considering a hazard event. In this pilot, functional performance is used as an important input to the resilience calculation because roadways with weaker baseline performance may have less capacity to maintain service under disruptive conditions. Figure 5.3.1

presents the functional performance and traffic volume layers used in the Wichita Falls pilot.

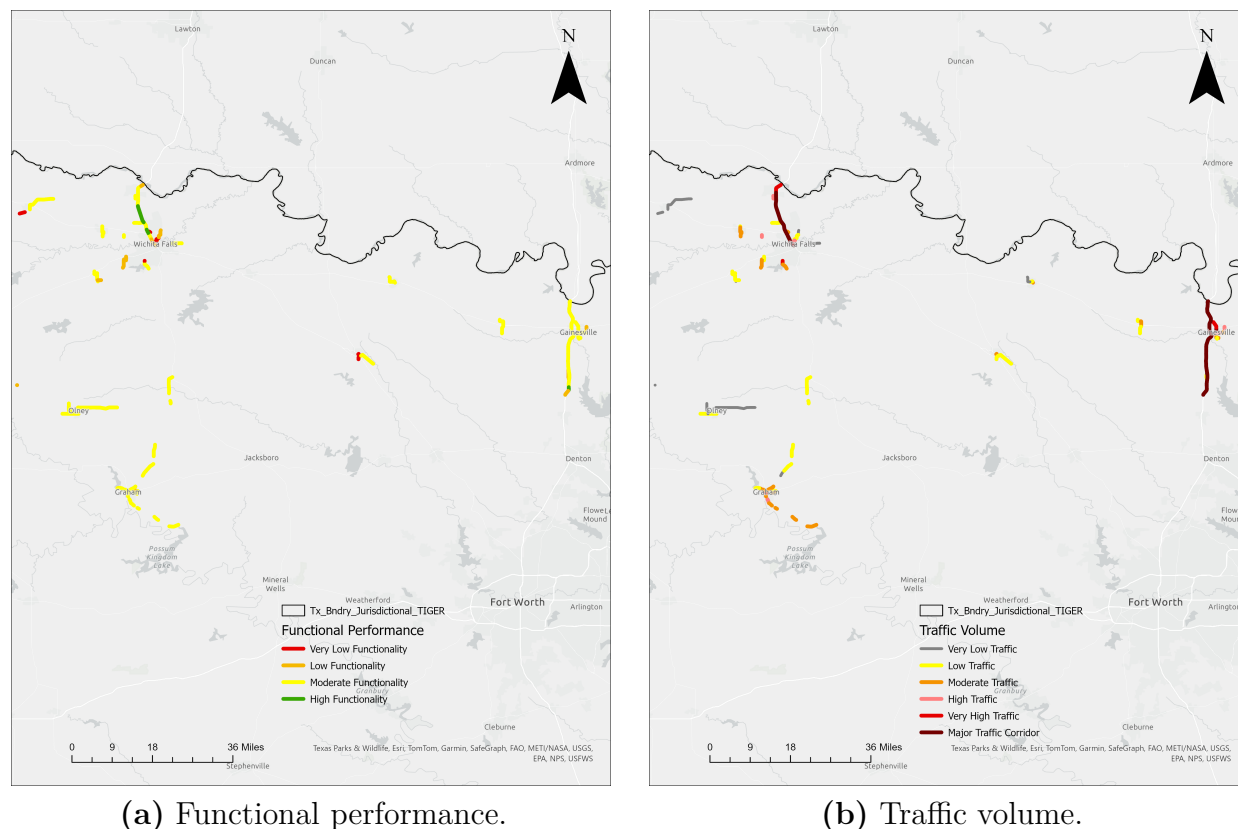


Fig. 5.3.1: Functional performance and traffic-volume inputs for the Wichita Falls roadway pilot. Only roadway segments with available pilot-study data are displayed.

The functional performance map shows that the selected roadway segments include a mix of very low, low, moderate, and high functionality. Several segments near Wichita Falls, Graham, Olney, and Gainesville show lower functional performance, while other selected segments show moderate or high functionality. These differences are important because the final roadway resilience score depends not only on hazard vulnerability but also on the segment's baseline ability to provide service.

The traffic volume map is used as a criticality input in the risk-based and resilience-based ranking comparison. Higher-volume segments are more important from a system-operation perspective because disruption on these roadways may affect more users and freight or regional mobility. Therefore, traffic volume is not interpreted as a resilience score by itself. Instead, it provides a criticality layer used to weight the ranking comparison between conventional risk-based TAM and resilience-based TAM.

Figure 5.3.2 presents the freight network indicator for the selected Wichita Falls roadway segments. Freight designation provides additional context for asset criticality and goods-movement importance. However, the quantitative roadway ranking comparison in this pilot

uses traffic volume as the available criticality measure; the freight network indicator is not included in the ranking calculation. As with the other Wichita Falls maps, only roadway segments with available pilot-study data are displayed.

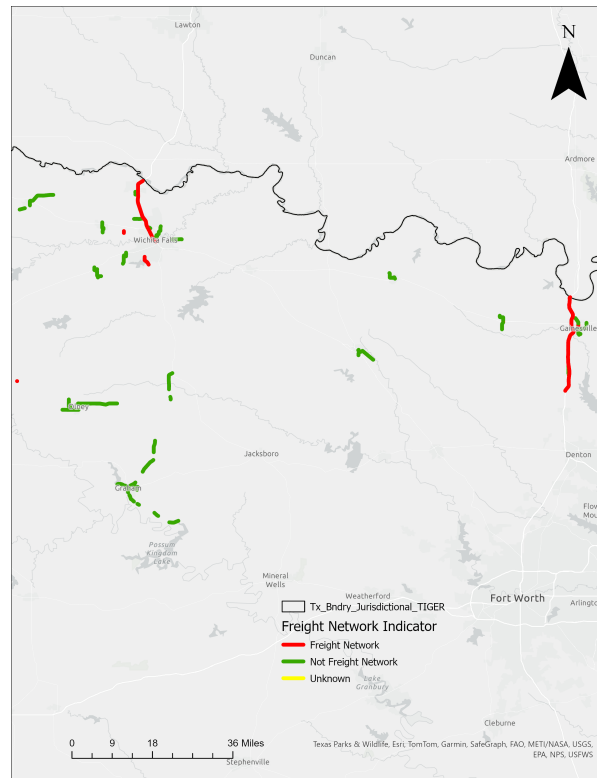
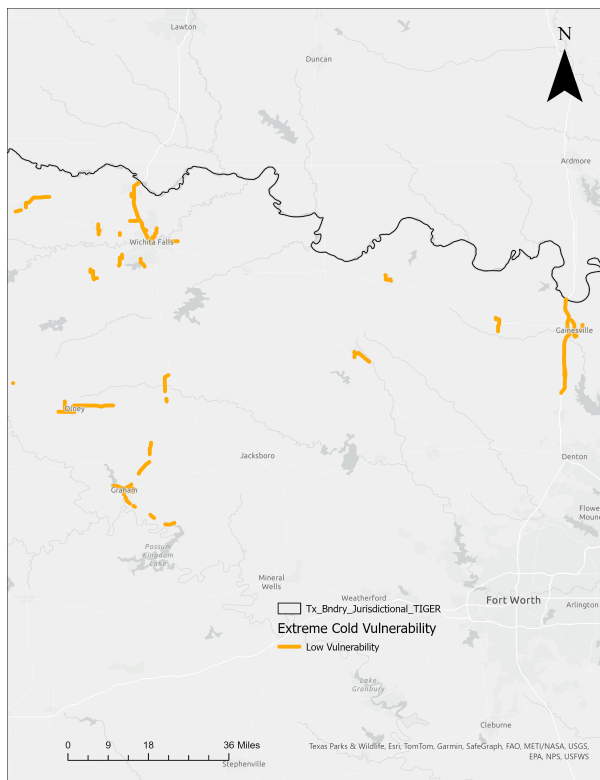


Fig. 5.3.2: Freight network indicator for selected Wichita Falls roadway segments. Only roadway segments with available pilot-study data are displayed.

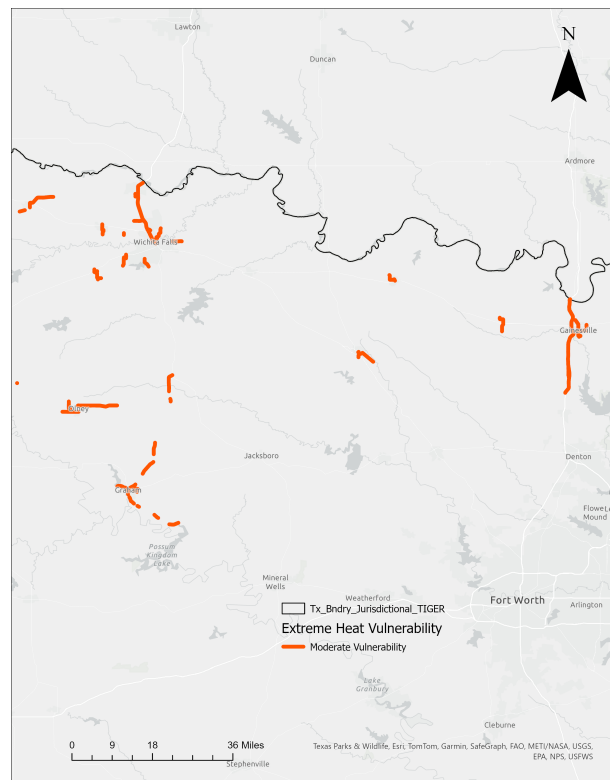
5.3.3 Extreme Cold and Extreme Heat Vulnerability

Hazard vulnerability maps are developed for the selected roadway segments under extreme cold and extreme heat scenarios. These maps represent the hazard-impact input layer used before computing robustness and resilience. Figure 5.3.3 presents the vulnerability results for the two hazard scenarios.

The extreme cold vulnerability map indicates that the selected roadway segments are generally classified as low vulnerability under the cold scenario. In contrast, the extreme heat vulnerability map shows moderate vulnerability for the selected segments. These maps should be interpreted as screening-level hazard-impact layers rather than final project-priority maps. A roadway segment with moderate vulnerability may not necessarily have low resilience if its functional performance and robustness remain strong. Similarly, a roadway segment with low vulnerability may still require attention if it has weak functional performance or high criticality.



(a) Extreme cold vulnerability.



(b) Extreme heat vulnerability.

Fig. 5.3.3: Extreme cold and extreme heat vulnerability maps for the Wichita Falls roadway pilot. Only roadway segments with available pilot-study data are displayed.

5.3.4 Hazard-Specific Robustness

Hazard-specific robustness represents the ability of a roadway segment to resist performance loss under a selected hazard scenario. In this pilot, robustness is derived from the hazard-specific vulnerability layer and is then used as one component of the final resilience calculation. Figure 5.3.4 shows the robustness results for extreme cold and extreme heat.

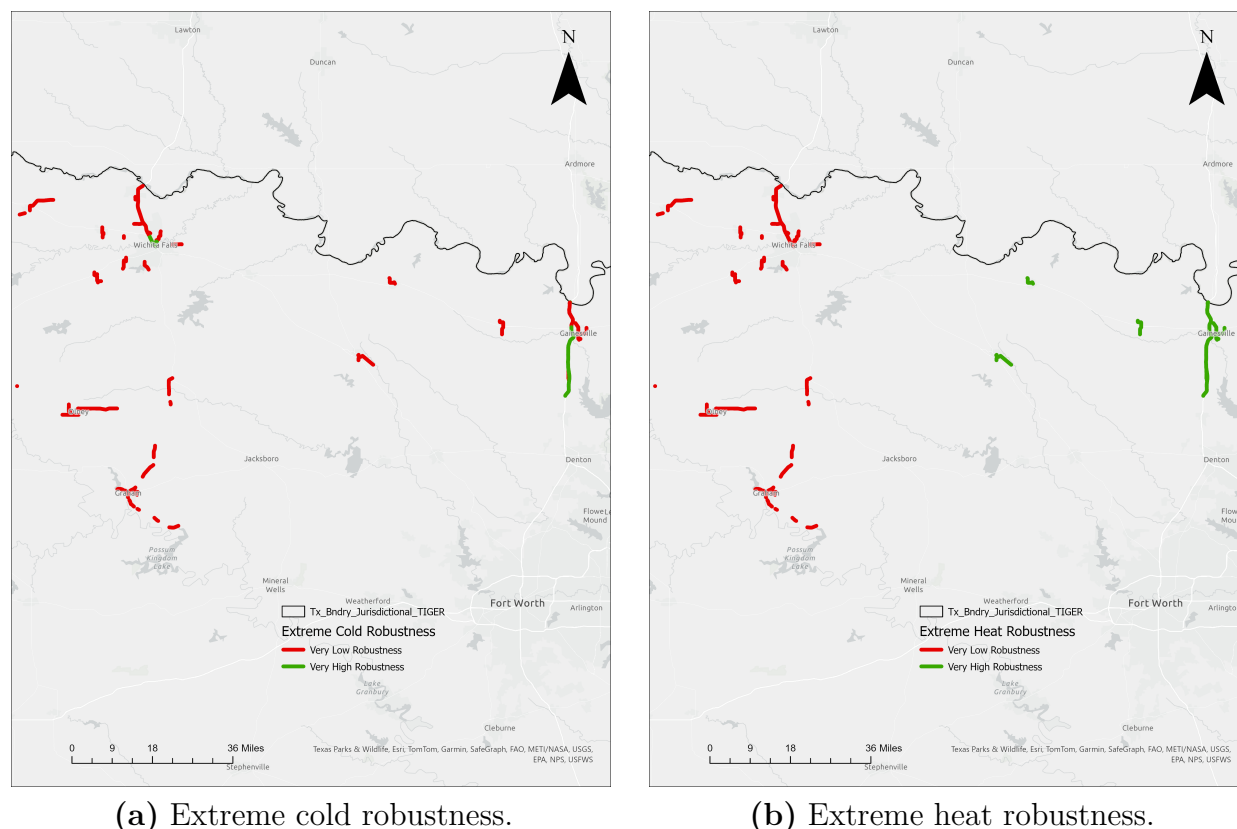
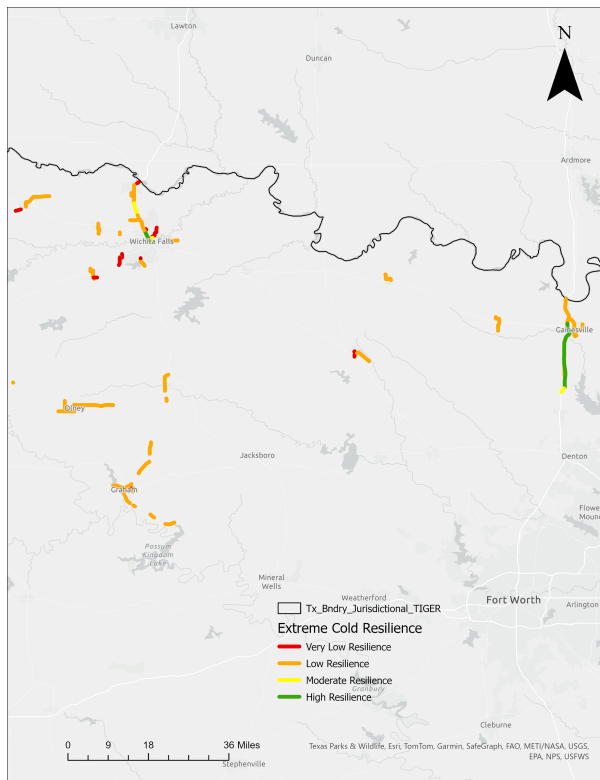


Fig. 5.3.4: Hazard-specific robustness maps for the Wichita Falls roadway pilot. Robustness is an intermediate component of the final resilience calculation.

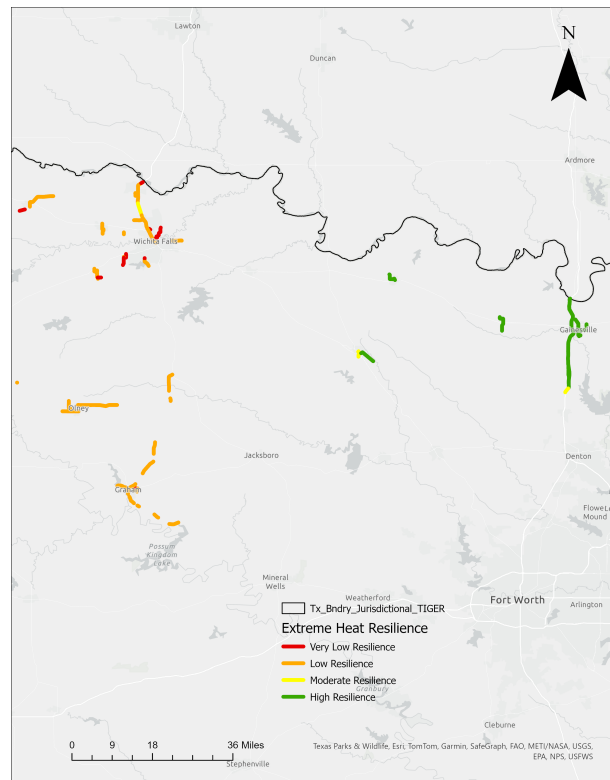
The robustness maps show a clear contrast between roadway segments with very low robustness and those with very high robustness. Under both extreme cold and extreme heat, some selected segments show lower resistance to hazard-related performance loss. These results provide an intermediate diagnostic layer. They help explain why final resilience scores may vary even among roadway segments with similar functional performance.

5.3.5 Roadway Resilience Results

The final resilience maps combine functional performance, hazard-specific robustness, and weighting factors used in the roadway resilience framework. Figure 5.3.5 presents the final roadway resilience outputs for extreme cold and extreme heat.



(a) Extreme cold resilience.



(b) Extreme heat resilience.

Fig. 5.3.5: Final roadway resilience maps for the Wichita Falls pilot under extreme cold and extreme heat scenarios.

The resilience maps provide information beyond the vulnerability maps alone. For example, a segment’s resilience depends not only on its hazard vulnerability but also on its baseline functional performance and robustness. The extreme cold resilience map shows that many selected segments fall within low or moderate resilience categories, with a smaller number of high-resilience segments. The extreme heat resilience map shows a stronger spatial contrast, with some selected segments classified as very low or low resilience and others classified as high resilience. These results demonstrate how resilience-based TAM can identify roadway segments that may require additional attention even when vulnerability alone does not fully explain their priority.

5.3.6 Sensitivity Analysis Results

A one-at-a-time sensitivity analysis is conducted to identify which variables have the greatest influence on the final roadway resilience score. Functional performance, hazard-specific robustness, and the inferred weighting factor are perturbed individually, and the average absolute change in resilience is calculated for each variable. The inferred weighting factor is an intermediate parameter (see Chapter 3) estimated from the available roadway pilot data. It represents the relative weighting used in the roadway resilience calculation when combining baseline functional performance with hazard-specific robustness, rather than a directly observed roadway attribute. Figure 5.3.6 summarizes the sensitivity results for the extreme cold and extreme heat scenarios.

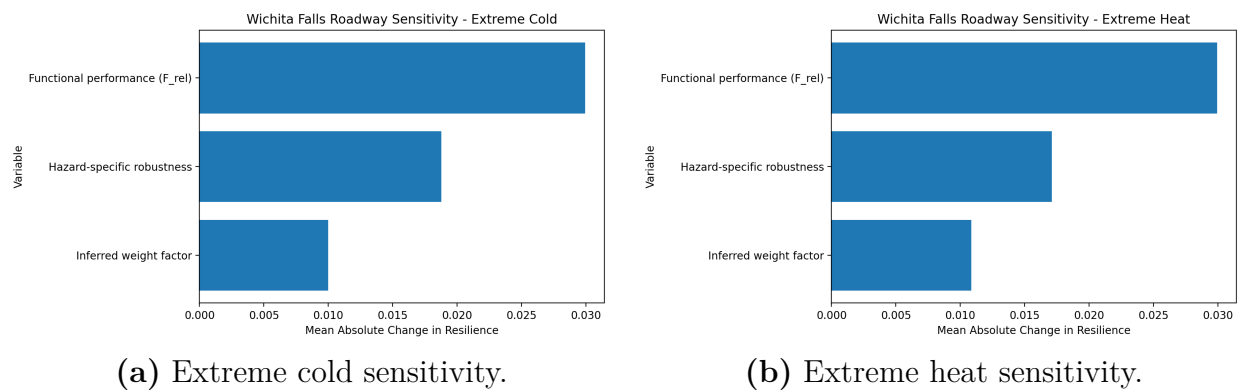


Fig. 5.3.6: Sensitivity-analysis results for the Wichita Falls roadway pilot. The horizontal axis shows the mean absolute change in resilience resulting from perturbing each variable.

The sensitivity results show that functional performance is the most influential variable for roadway resilience under both extreme cold and extreme heat. For the extreme cold scenario, functional performance produces an average absolute change in resilience of approximately 0.030, followed by hazard-specific robustness at approximately 0.019 and the inferred weighting factor at approximately 0.010. For the extreme heat scenario, functional performance again

produces the largest average absolute change, approximately 0.030, followed by hazard-specific robustness at approximately 0.017 and the inferred weighting factor at approximately 0.011.

These findings indicate that, within the adopted resilience assessment framework and available Wichita Falls pilot data, the condition and functional status of roadway segments have a strong influence on the computed resilience outcomes. From a TAM perspective, this suggests that roadway segments with lower baseline functionality may warrant closer review when identifying resilience-oriented maintenance, preservation, or rehabilitation needs under temperature-related hazard scenarios.

5.3.7 Risk-Based and Resilience-Based Ranking Comparison

The final step in the Wichita Falls pilot applies the risk-based and resilience-based ranking procedure described in Section 5.2.3. The conventional score combines normalized vulnerability and criticality, while the resilience-based score combines inverse resilience and criticality. Rank shifts are calculated using Equation 5.2.2.

To classify rank-shift results, a threshold equal to 10 percent of the number of ranked assets is used. For the Wichita Falls roadway pilot, 384 segments are ranked, so the similarity threshold is set to approximately 38 rank positions. Segments with rank shifts between -38 and $+38$ are classified as similar priority. Segments with rank shifts greater than $+38$ are classified as higher priority under resilience-based TAM, while segments with rank shifts less than -38 are classified as lower priority under resilience-based TAM.

Table 5.3.1: Wichita Falls roadway risk–resilience rank-shift results.

Scenario	Ranked	Higher	Similar	Lower
Cold	384	12	359	13
Heat	384	34	281	69

Table 5.3.1 shows that 384 roadway segments are ranked for each hazard scenario. Under the extreme cold scenario, most segments remain in a similar priority category under both methods, while 12 segments move higher and 13 segments move lower when resilience is considered. Under the extreme heat scenario, the difference between the two ranking approaches is more pronounced: 34 segments move higher under resilience-based TAM, 281 remain similar, and 69 move lower.

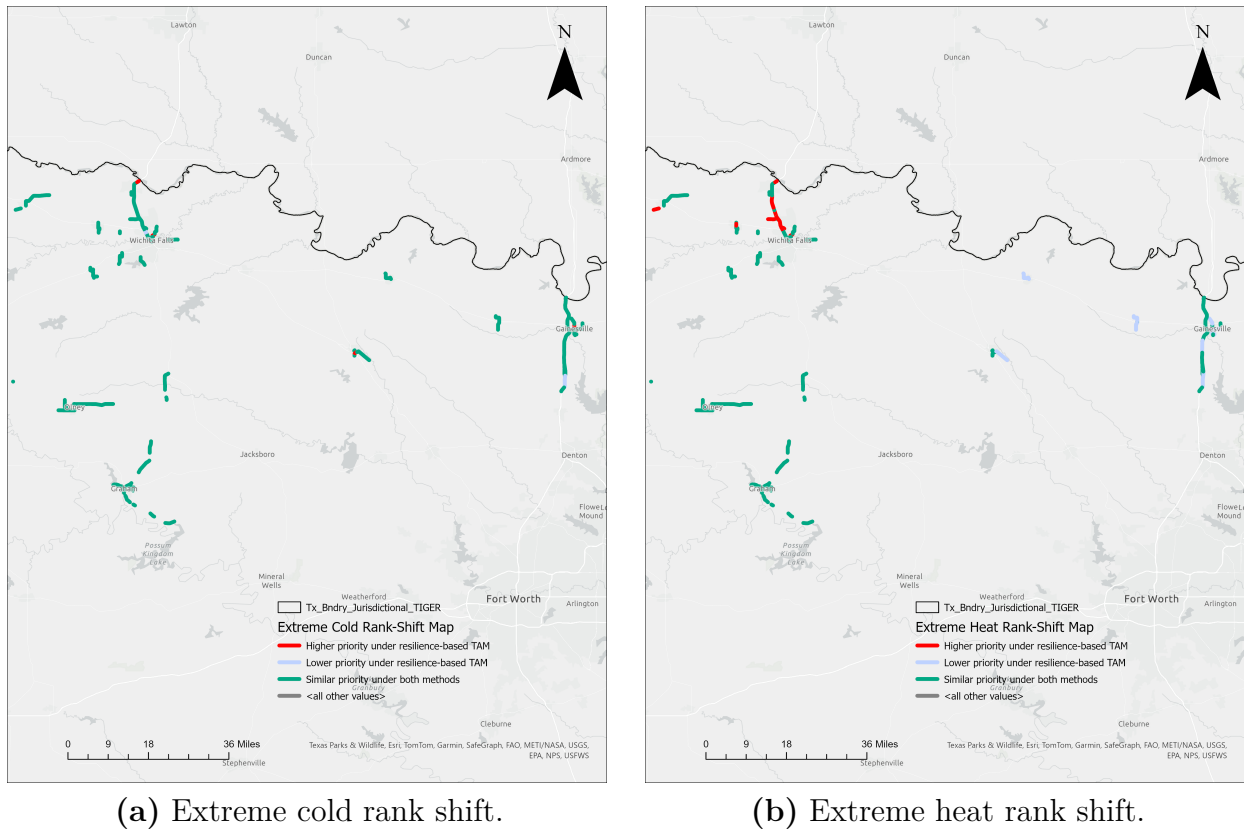


Fig. 5.3.7: Risk-resilience rank-shift maps for the Wichita Falls roadway pilot. Segments classified as higher priority under resilience-based TAM move up when low resilience is considered together with criticality.

Figure 5.3.7 presents the spatial distribution of these rank-shift categories for the two hazard scenarios. The rank-shift maps demonstrate that resilience-based TAM does not simply reproduce the conventional risk-based ranking. Under the extreme cold scenario, the majority of selected roadway segments have similar priority under both methods, suggesting that the cold risk and resilience rankings are relatively consistent for most of the pilot segments. Under the extreme heat scenario, more segments change priority, indicating that heat-related resilience provides additional information beyond vulnerability and criticality alone.

These results are useful for project screening because they identify roadway segments that may be under-prioritized by a conventional risk-based approach. Segments that move higher under resilience-based TAM may warrant additional review, field validation, or consideration in future maintenance and resilience planning.

5.3.8 Interpretation and Data Limitations

The Wichita Falls pilot demonstrates that the resilience-based TAM framework can produce practical district-level screening outputs using available roadway and hazard-related data. The functional performance, vulnerability, robustness, resilience, sensitivity, and rank-shift results together provide a structured way to move from raw asset and hazard information to planning-oriented decision support.

However, the results should be interpreted with the limitations of the pilot dataset in mind. First, only selected roadway segments with available resilience-related input data are displayed in the maps. Therefore, the maps should not be interpreted as a complete assessment of all roads in the Wichita Falls District. Second, the drought component identified in the project agreement cannot be fully evaluated because drought-specific roadway vulnerability, soil moisture, drought severity, or related hazard fields are not available at the necessary spatial resolution. The TxDOT Roadways open-data layer¹ can partially support implementation by improving roadway inventory coverage and asset matching, but additional hazard-specific and pavement-specific datasets are still needed to fully evaluate drought and snowstorm resilience. Accordingly, the current Wichita Falls pilot focuses on available temperature-related screening scenarios, including extreme cold and extreme heat. Third, additional variables such as treatment history, pavement layer thickness, detailed cost data, lane count, functional class, and project-level maintenance information would support a more detailed future implementation.

Despite these limitations, the pilot demonstrates that the framework can convert available roadway and hazard data into screening outputs that distinguish project priorities, particularly under the extreme heat scenario.

5.4 Houston Bridge Pilot

The Houston bridge pilot evaluates selected bridges under inland flooding conditions. This pilot demonstrates how the resilience-based TAM framework can be applied to bridge assets by combining component condition, flood-related vulnerability, traffic criticality, and final resilience outputs. The Houston District is selected because flooding is a major hazard concern for bridges in the region, particularly for assets located near bayous, drainage corridors, coastal areas, and low-lying roadway networks.

The bridge pilot is also interpreted as a screening-level analysis. The available data support condition-based and flood-vulnerability screening, but they do not fully support detailed hydraulic or structural fragility modeling. Therefore, the results should be used to identify bridges that may warrant additional review, field validation, or more detailed

¹<https://gis-txdot.opendata.arcgis.com/datasets/TXDOT::txdot-roadways/about>

hydraulic and structural analysis.

5.4.1 Pilot Data and Analysis Scope

The Houston bridge dataset includes bridge location, deck, superstructure, and substructure condition ratings, bridge age, traffic volume, scour-related information, flood vulnerability, and resilience outputs generated by the software tool. The component ratings characterize the physical condition of each bridge before hazard impacts are considered.

For the inland flooding scenario, flood vulnerability and scour concern are especially important. Inland flood vulnerability provides the hazard-impact input for the resilience calculation, while scour concern provides an additional screening variable related to bridge performance under flood conditions. Traffic volume is used as a criticality indicator in the risk-based and resilience-based ranking comparison. Bridges carrying higher traffic volumes may receive greater planning attention because disruptions on these assets can create larger mobility and operational consequences.

5.4.2 Bridge Component Condition

Bridge resilience depends on both flood exposure and physical condition before the hazard event. Figures 5.4.1, 5.4.2, and 5.4.3 present the component-condition maps used in the Houston bridge pilot.

The deck condition map shows that many bridges in the pilot dataset are classified as good or very good, while a smaller number of bridges are classified as fair or poor. The superstructure condition map shows similar variation in the condition of the main load-carrying bridge elements. The substructure condition map is particularly important for the flood pilot because flood and scour-related effects are more directly related to bridge foundations, supports, and substructure systems than to the deck alone. Bridges with lower component condition ratings may require closer review when they are also exposed to inland flooding, scour concern, or high traffic criticality.

5.4.3 Bridge Age and Traffic Criticality

Bridge age and traffic volume provide additional context for interpreting bridge resilience. Older bridges may be more sensitive to deterioration and may require more detailed review when combined with lower component condition or higher flood vulnerability. Traffic volume represents a criticality input because bridges carrying larger traffic volumes may create greater network disruption if service is reduced or interrupted. Figure 5.4.4 presents the bridge age and traffic-volume maps.

The bridge age map shows a wide distribution of bridge ages across the Houston District. Several bridges are more than 40 years old, and some are more than 60 years old. These older

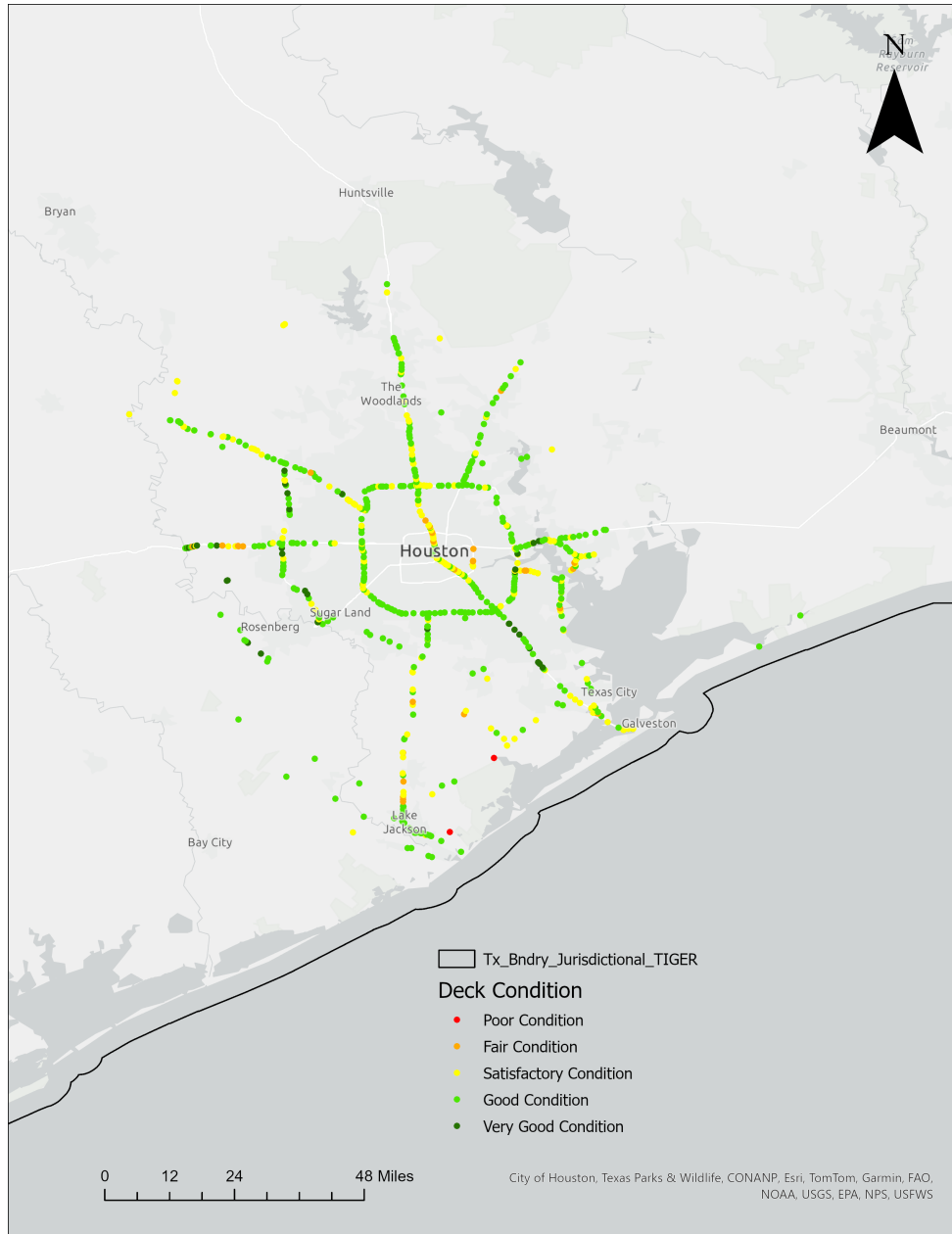


Fig. 5.4.1: Deck condition map for bridges in the Houston District, showing the condition of the bridge deck and riding surface that directly support traffic operations.

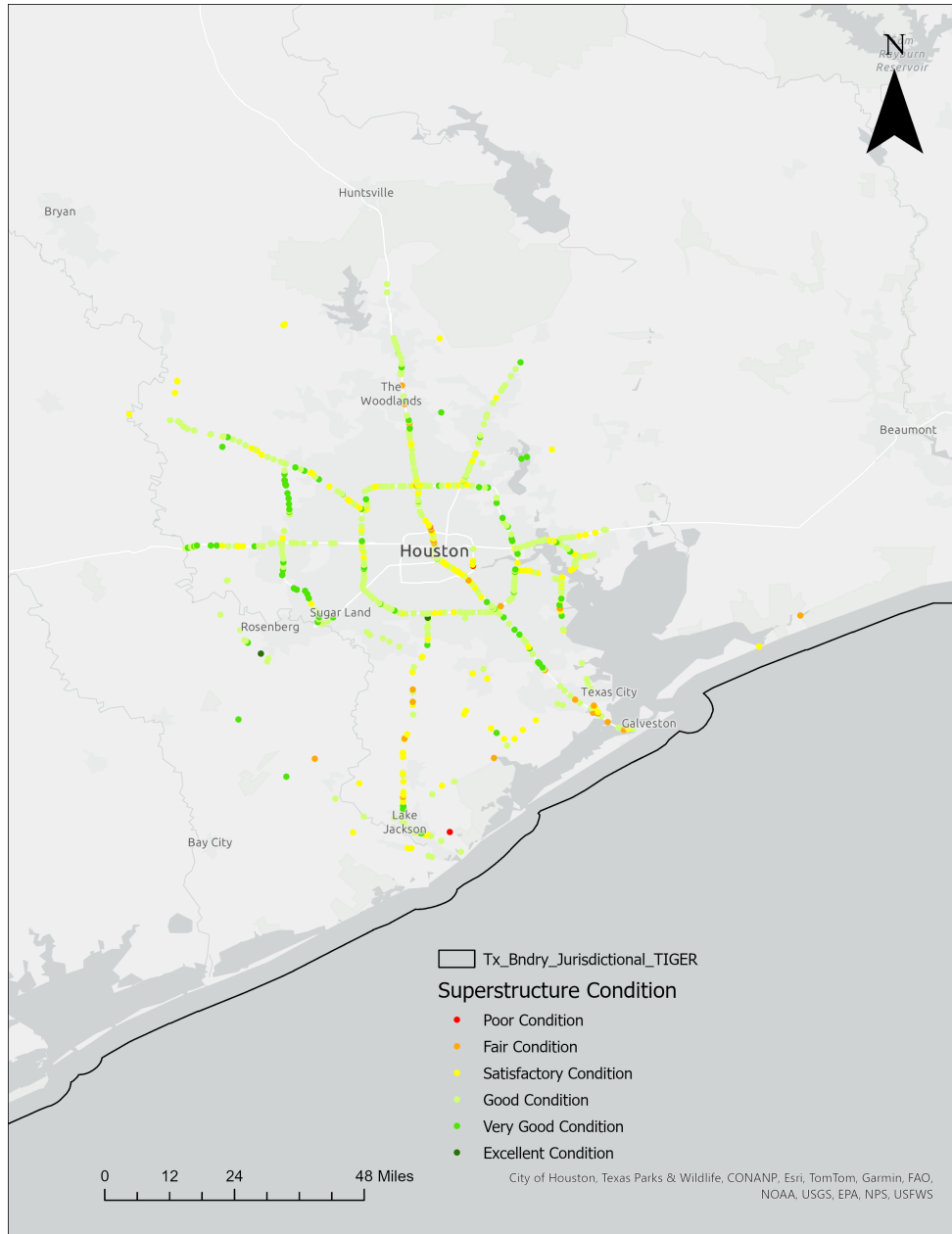


Fig. 5.4.2: Superstructure condition map for bridges in the Houston District, showing the condition of the primary load-carrying bridge elements above the substructure.

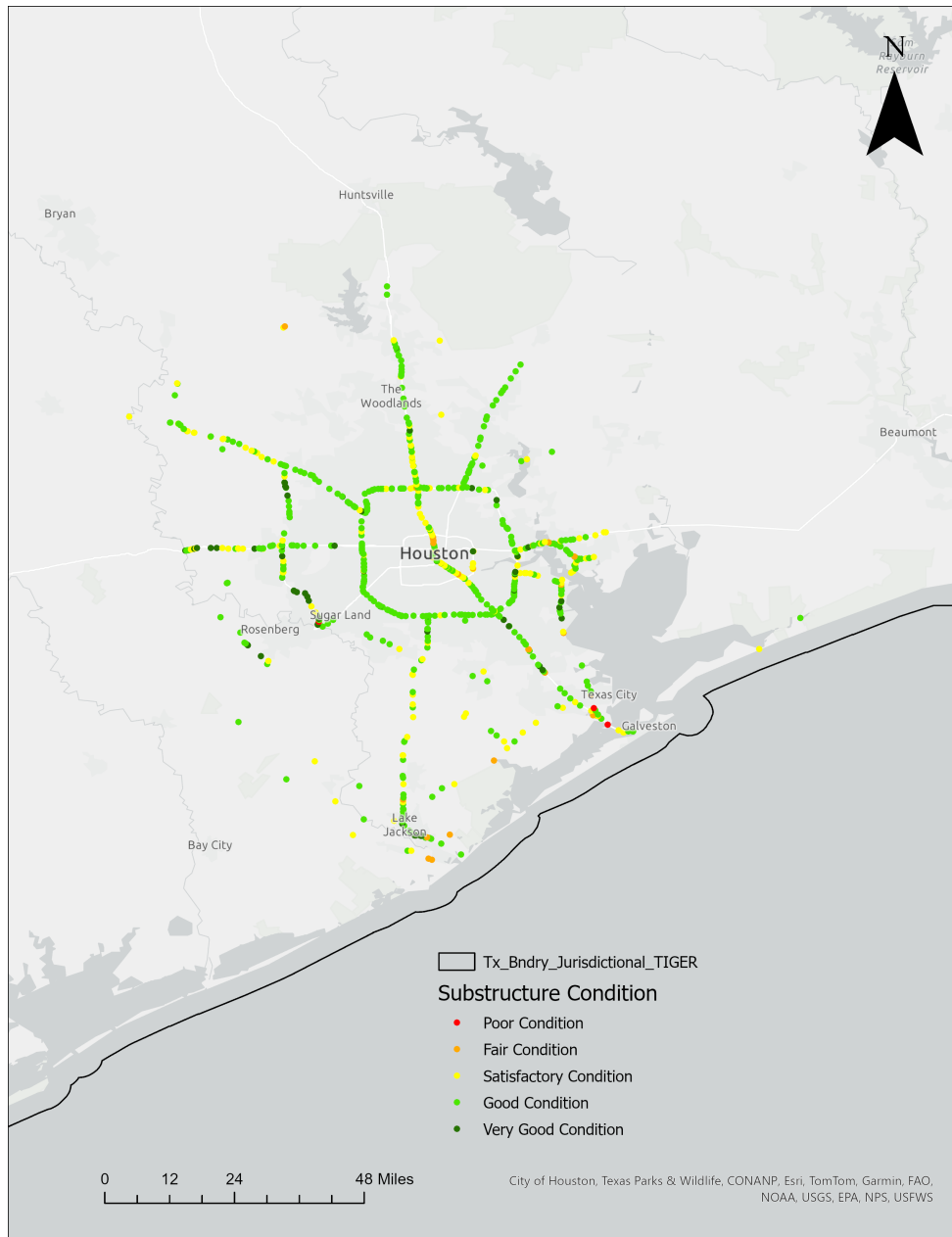
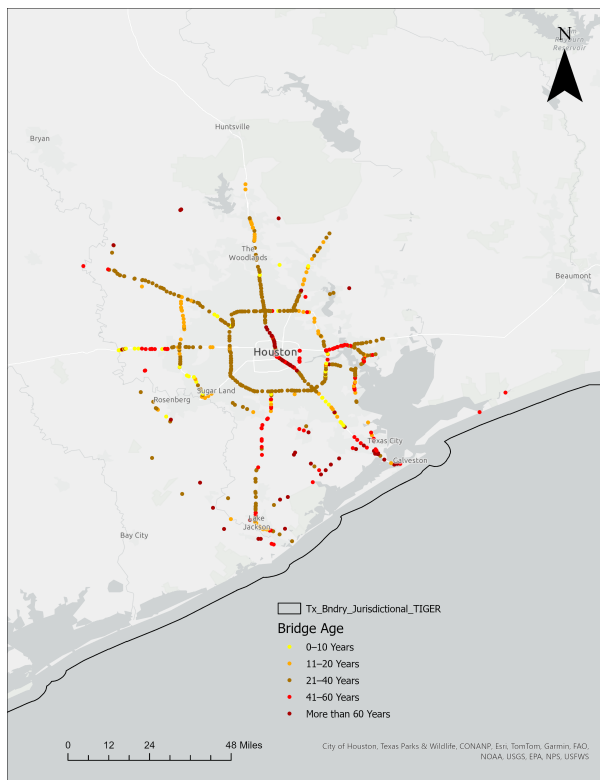
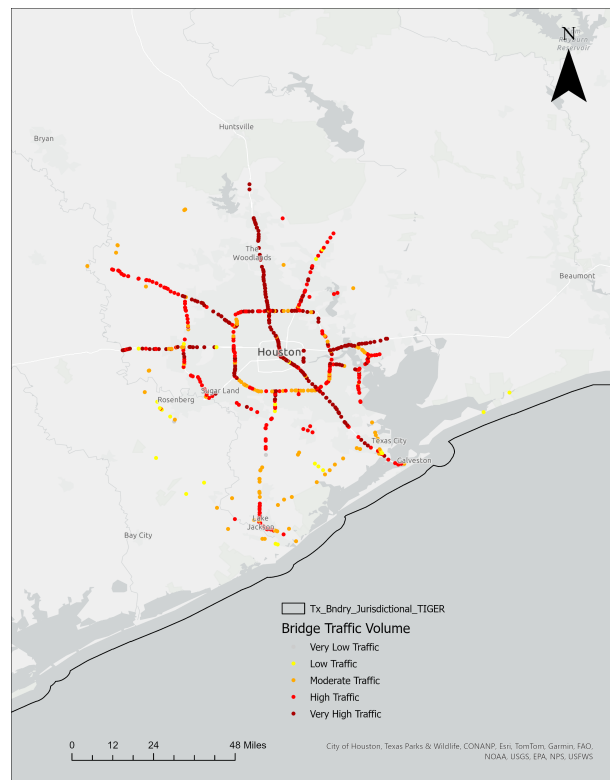


Fig. 5.4.3: Substructure condition map for bridges in the Houston District. Substructure condition is especially relevant for flood-related screening because flood and scour effects are more directly related to bridge supports, foundations, and substructure systems.



(a) Bridge age.



(b) Bridge traffic volume.

Fig. 5.4.4: Bridge age and traffic-volume inputs for the Houston bridge pilot. Traffic volume is used as a criticality input in the risk-resilience ranking comparison.

bridges are not automatically low-resilience assets, but age provides useful context when interpreted together with component condition, flood vulnerability, and traffic criticality. The traffic-volume map highlights bridges with higher operational importance. These bridges are especially relevant in the ranking comparison because both conventional risk-based TAM and resilience-based TAM should account for the consequences of disruption.

5.4.4 Flood-Related Vulnerability and Scour Concern

Flood-related vulnerability is evaluated using the inland flood vulnerability layer, while scour concern is used as an additional flood-related screening variable. Figure 5.4.5 presents the inland flood vulnerability and scour concern maps.

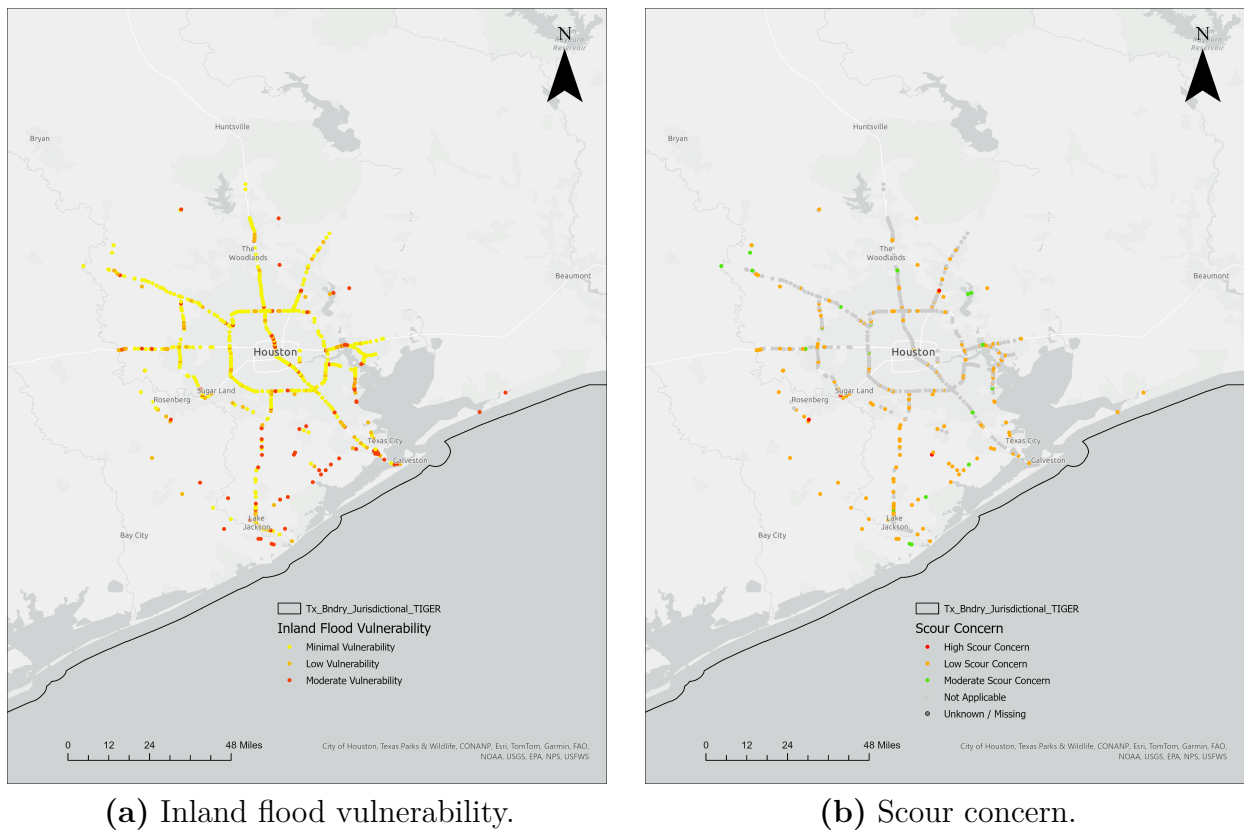


Fig. 5.4.5: Flood-related vulnerability and scour-screening inputs for the Houston bridge pilot.

The inland flood vulnerability map shows that most bridges are classified as minimal or low vulnerability, while a smaller number of bridges are classified as moderate vulnerability. These moderate-vulnerability bridges are important because they represent locations where flood-related exposure and bridge sensitivity may require closer review. The scour concern map provides a complementary screening layer. Although many bridges are classified as low concern or not applicable, bridges with moderate or high scour concern may require

additional engineering attention, especially when they also have lower substructure condition or higher traffic criticality.

5.4.5 Bridge Flood Resilience Results

The bridge flood resilience map combines flood vulnerability, component condition, and the bridge resilience framework to produce a final resilience classification. Figure 5.4.6 presents the inland flood resilience results for the Houston bridge pilot.

The flood resilience map provides information beyond flood vulnerability alone. Many bridges are classified as high or very high resilience, indicating stronger expected ability to maintain service under the inland flooding scenario. However, several bridges are classified as low or moderate resilience. These bridges are important candidates for additional review because they may combine lower condition, higher vulnerability, or weaker resilience characteristics. The map demonstrates how the resilience-based TAM framework can distinguish between bridges that have similar flood vulnerability but different structural or functional resilience.

5.4.6 Sensitivity Analysis Results

A one-at-a-time sensitivity analysis is conducted to identify the variables with the greatest influence on the final bridge flood resilience score. Inland flood vulnerability, deck condition, superstructure condition, and substructure condition are perturbed individually, and the resulting average absolute change in resilience is calculated and summarized in Figure 5.4.7.

The sensitivity results show that inland flood vulnerability is the most influential variable for bridge flood resilience in the Houston pilot. Perturbing inland flood vulnerability produces the largest average absolute change in resilience, approximately 0.034. The bridge component-condition variables have smaller but still meaningful effects. Deck condition and substructure condition each produce an average absolute change of approximately 0.015, while superstructure condition produces a similar but slightly smaller effect.

These results indicate that flood-related vulnerability is the dominant driver of bridge flood resilience in the current pilot dataset. However, component condition also remains important because lower deck, superstructure, or substructure ratings can reduce a bridge's ability to maintain service under flood-related stress. From a TAM perspective, bridge flood resilience should therefore be interpreted by considering both hazard-vulnerability and asset-condition information together.

5.4.7 Risk-Based and Resilience-Based Ranking Comparison

The Houston bridge pilot applies the same risk-based and resilience-based ranking procedure described in Section 5.2.3. The conventional score combines normalized inland flood

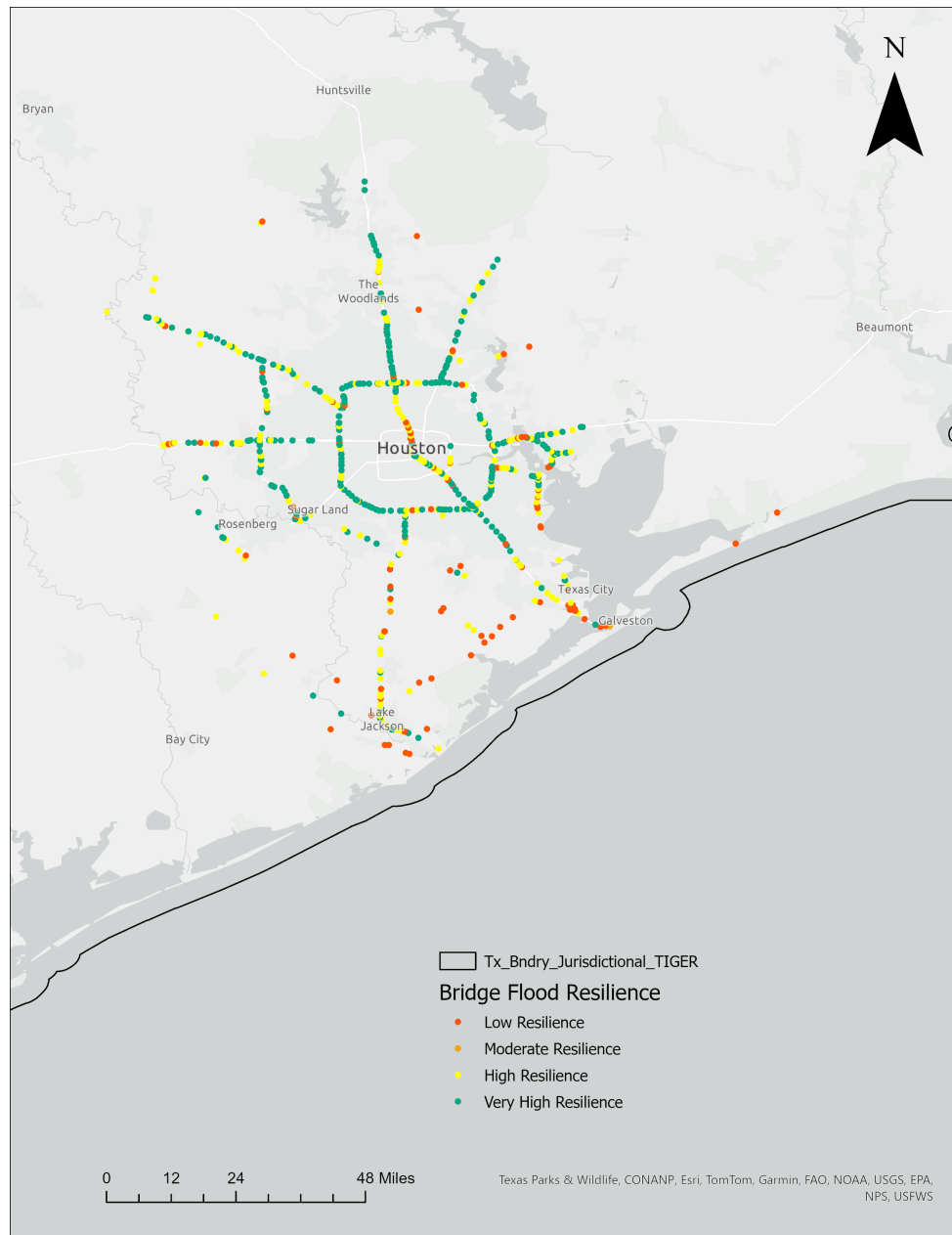


Fig. 5.4.6: Bridge resilience under inland flooding for the Houston bridge pilot, showing how bridge condition and flood-related vulnerability are combined to support screening-level TAM decisions.

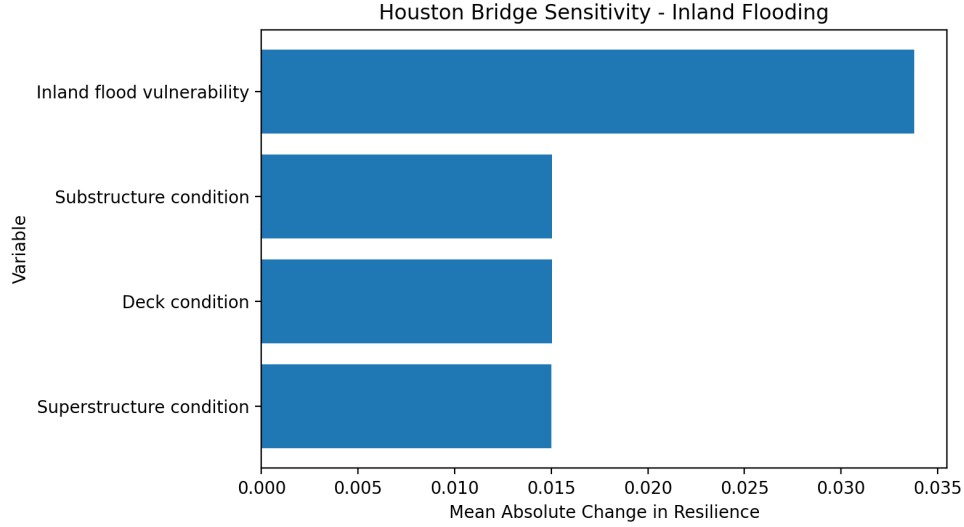


Fig. 5.4.7: Sensitivity-analysis results for the Houston bridge inland flooding pilot, showing the mean absolute change in resilience after each variable is perturbed.

vulnerability and criticality, while the resilience-based score combines inverse bridge resilience and criticality. Rank shifts are calculated using Equation 5.2.2.

To maintain consistency with the Wichita Falls pilot, the Houston bridge rank-shift categories are also defined using a threshold equal to 10 percent of the number of ranked assets. For the Houston bridge pilot, 849 bridges are ranked, so the similarity threshold is set to approximately 85 rank positions. Bridges with rank shifts between -85 and $+85$ are classified as similar priority. Bridges with rank shifts greater than $+85$ are classified as higher priority under resilience-based TAM, while bridges with rank shifts less than -85 are classified as lower priority under resilience-based TAM.

Table 5.4.1: Risk–resilience rank-shift summary for Houston bridges under inland flooding.

Total	Higher	Similar	Lower
849	83	225	541

Table 5.4.1 shows that 849 Houston bridges are ranked under the inland flooding scenario. Among these bridges, 83 move higher under resilience-based TAM, 225 remain in a similar priority category, and 541 move lower under the resilience-based approach. The bridges that move higher are especially important because they may not be the highest-priority assets under conventional flood-risk ranking alone, but they become more important when low resilience is considered together with criticality.

Figure 5.4.8 presents the spatial distribution of the risk–resilience rank-shift categories. The rank-shift map demonstrates that resilience-based TAM does not simply reproduce

conventional risk-based prioritization. Some bridges move higher in priority because their resilience score indicates weaker ability to maintain or recover functionality under inland flooding. These bridges may require additional review, field validation, or consideration in future bridge maintenance, rehabilitation, or resilience planning.

5.4.8 Supplementary Extreme Heat Resilience Screening

Although the primary Houston bridge pilot focuses on inland flooding, Figure 5.4.9 presents a supplementary bridge resilience output under extreme heat. The map demonstrates that the software tool can generate hazard-specific bridge resilience outputs for additional hazard scenarios. This output is provided to illustrate the tool’s multi-hazard screening capability; it is not used in the Houston sensitivity analysis or the risk–resilience ranking comparison, both of which are based on the inland flooding scenario. Additional hazard-specific validation and engineering data would be needed before using the extreme heat results for detailed project-level prioritization.

5.4.9 Interpretation and Data Limitations

The Houston bridge pilot demonstrates that the resilience-based TAM framework can produce useful screening-level outputs for bridge assets exposed to inland flooding. The condition maps, vulnerability map, resilience map, sensitivity-analysis results, and rank-shift map collectively support a structured workflow for identifying bridges that may require additional attention in resilience-based planning.

The analysis also highlights important data limitations. The available data support practical condition-based and flood-vulnerability screening, but they are not sufficient for detailed hydraulic, scour, or structural fragility modeling. Future bridge-flooding analysis would benefit from additional variables, such as flood depth, flood duration, overtopping depth, low-chord elevation, deck elevation, foundation type, waterway adequacy, detour length, repair duration, repair cost, and route redundancy. These additional variables would help the software tool support more detailed recoverability assessment, lifecycle cost analysis, and project selection decisions.

Despite these limitations, the Houston pilot demonstrates how bridge condition, flood vulnerability, and criticality can be integrated to identify assets for additional review and supplement conventional risk-based planning.

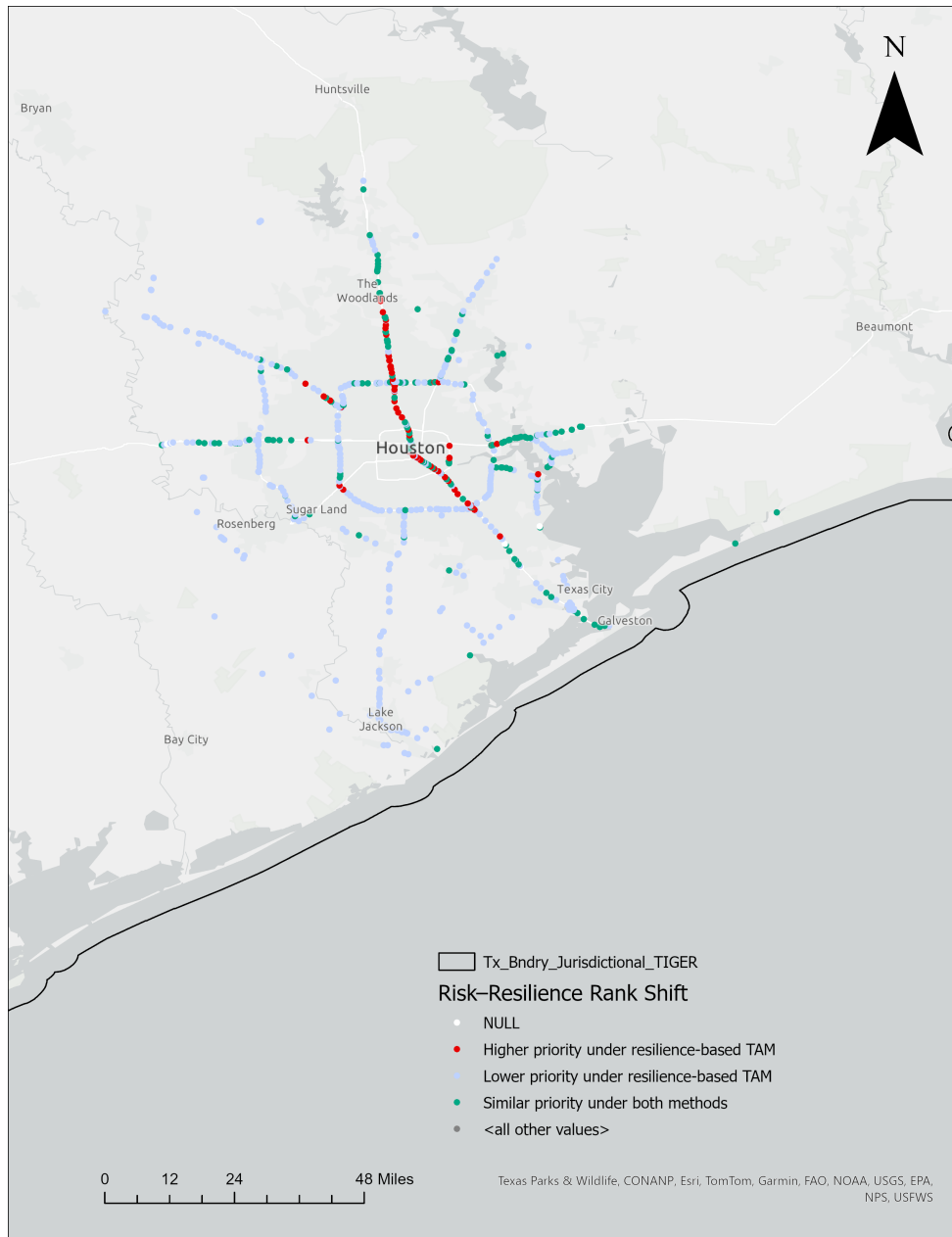


Fig. 5.4.8: Risk-resilience rank-shift map for Houston bridges under inland flooding. Bridges classified as higher priority under resilience-based TAM move up when low resilience is considered together with criticality.

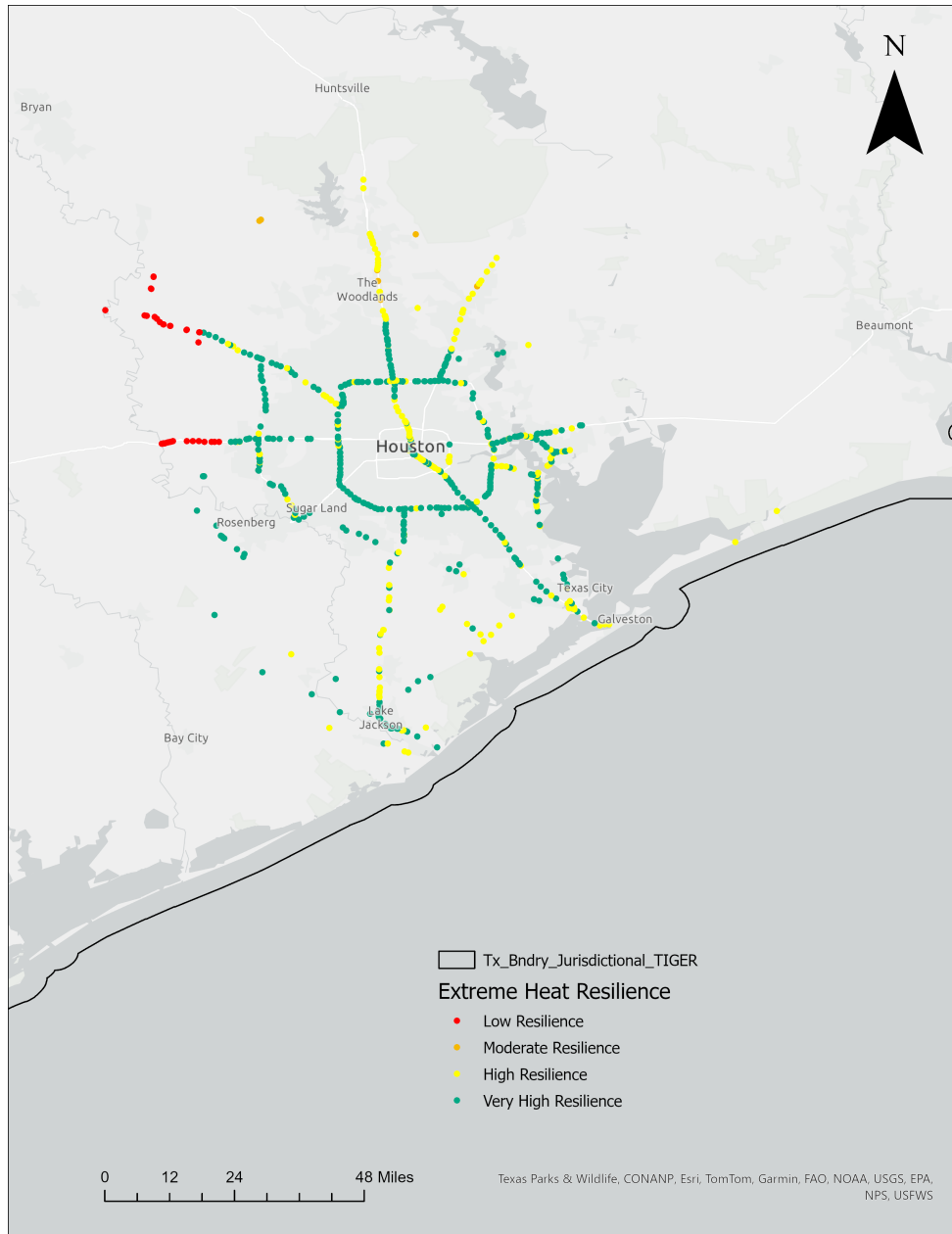


Fig. 5.4.9: Supplementary bridge resilience screening under extreme heat in the Houston District.

5.5 Discussion

5.5.1 Implications for TAM Planning

The pilot study demonstrates that resilience-based TAM provides additional information beyond conventional risk-based asset screening. Conventional risk-based TAM is useful for identifying assets with high vulnerability and high operational consequence. However, resilience-based TAM adds another planning perspective by identifying assets that may have weaker ability to maintain or recover functionality after a disruptive event.

For the Wichita Falls roadway pilot, the sensitivity results imply that actions improving baseline condition and service performance can support normal operations while also strengthening resilience to temperature-related stressors. The framework can therefore help identify segments where maintenance or rehabilitation may provide both routine and hazard-related benefits.

For the Houston bridge pilot, the results indicate that flood screening should combine hazard-vulnerability information with bridge component condition. Considering either source alone may overlook bridges with limited capacity to maintain or recover functionality under flooding.

Overall, the pilot results show that resilience-based TAM can support district-level screening by integrating asset condition, hazard vulnerability, functionality, robustness, and criticality into a single planning-oriented workflow.

5.5.2 Implications for Project Selection

The risk–resilience ranking comparison demonstrates how project priorities can change when resilience is incorporated into TAM decision-making. Under the conventional risk-based approach, assets are prioritized based on vulnerability and criticality. Under the resilience-based approach, assets with lower resilience receive higher priority, especially when they are also operationally important.

The Wichita Falls results in Table 5.3.1 show that the extreme cold rankings are largely consistent under the two approaches, whereas extreme heat produces more substantial priority changes. The Houston results in Table 5.4.1 also show meaningful reprioritization. Assets that move higher under resilience-based TAM are particularly relevant because they may not be emphasized by conventional risk ranking alone.

These results show that resilience-based TAM should not replace existing project-selection practices. Instead, it can serve as an additional screening layer that helps TxDOT staff identify assets that may require further review, field validation, targeted maintenance, rehabilitation, or resilience-focused design consideration.

5.5.3 Implications for Data Needs

The pilot-specific limitations discussed above identify the datasets that would provide the greatest value in future applications. For the Wichita Falls roadway pilot, priorities include more complete district coverage, pavement structure and treatment history, cost and operational attributes, and locally resolved temperature, freeze–thaw, snowstorm, and drought data. For the Houston bridge pilot, priorities include hydraulic exposure, bridge elevation and foundation characteristics, scour and waterway information, detour and route redundancy, and repair duration and cost. These additions would support improved recoverability modeling, lifecycle-cost analysis, and project-level evaluation.

The identified data gaps are therefore useful outputs of the pilot, as they clarify priorities for expanding resilience-based TAM at the district or statewide level.

5.6 Summary

This chapter presents the pilot implementation of the resilience-based TAM framework for selected Wichita Falls roadway segments under extreme cold and extreme heat and Houston District bridges under inland flooding. The software tool generates condition and functionality maps, vulnerability and robustness outputs, resilience maps, sensitivity results, and risk–resilience ranking comparisons.

In the Wichita Falls pilot, baseline functional performance has the greatest influence on roadway resilience, and the extreme heat scenario produces more priority changes than the extreme cold scenario. In the Houston pilot, inland flood vulnerability has the greatest influence on bridge resilience, while component condition also contributed to the results. Both pilots identify assets that move higher when resilience is incorporated into prioritization.

The results demonstrate that resilience-based TAM can supplement, rather than replace, conventional risk-based screening by identifying assets with weaker capacity to maintain or recover functionality. The pilot remains a screening-level demonstration based on available data; additional asset, hazard, cost, hydraulic, treatment-history, and recoverability information would support more detailed future applications.

Chapter 6

Value of Research Summary

6.1 Purpose and Scope

This value-of-research (VoR) summary identifies the qualitative and quantified benefits of this project. The assessment focuses on benefits attributable to the research findings, methods, software products, and implementation guidance.

The project developed a planning-level framework for incorporating hazard vulnerability, asset condition, robustness, recoverability, criticality, and expected project effectiveness into transportation asset management (TAM) and project screening. The framework was implemented through statewide analyses, district-level pilot studies, a Weather Projection App, and an ArcGIS Pro Resilience Toolbox, as documented in the respective chapter. The benefits are reported in the following two forms: (i) qualitative benefits expected from implementation of the framework and tools, and (ii) quantified, nonmonetary benefits demonstrated through the pilot applications and research products. Note that potential economic benefits are also identified, but a monetary net present value or benefit–cost ratio is not reported because the available project data do not support a robust estimate at this stage.

6.2 Qualitative Benefits

Table 6.2.1 summarizes the principal benefit areas. Benefits classified as “potential economic” may ultimately produce measurable agency or user cost savings, but those savings depend on implementation decisions and future observed performance.

Table 6.2.1: Value-of-research benefit areas

Benefit Area	Benefit Type	Primary Beneficiary	Definition in the Context of this project
Level of knowledge and decision quality	Qualitative	TxDOT	Provides a consistent definition and measurement framework for distinguishing vulnerability, robustness, recoverability, risk, and resilience. The research gives TxDOT a traceable basis for explaining how resilience information supplements existing condition- and risk-based TAM decisions.
System reliability and continuity	Qualitative and potential economic	Both state and traveling public	Supports identification of critical assets that may experience substantial functionality loss or extended recovery following extreme heat, extreme cold, flooding, or other disruptions. Earlier identification can support actions that maintain essential mobility, freight movement, emergency access, and network continuity.
Asset-management and project-selection improvement	Qualitative	TxDOT	Combines resilience need, criticality, and expected intervention effectiveness in a transparent screening process. This helps distinguish assets that are merely exposed to a hazard from projects that are important and capable of producing a meaningful resilience improvement.

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Benefit Area	Benefit Type	Primary Beneficiary	Definition in the Context of this project
Infrastructure condition and service life	Qualitative and potential economic	Both state and traveling public	Connects resilience with preventive maintenance, pavement rehabilitation, drainage improvement, bridge component work, scour mitigation, inspection, and other routine asset-management activities. Interventions that improve normal-condition performance may also reduce hazard-related performance loss and support faster recovery.
Data and workflow efficiency	Qualitative and potential economic	TxDOT	Provides reusable weather-projection and ArcGIS-based tools for preparing hazard indicators, calculating vulnerability and resilience, producing maps, and comparing priorities. The standardized workflow can reduce repeated development of separate district-specific methods and improve consistency among analyses.
Targeted data collection	Qualitative and potential economic	TxDOT	Uses sensitivity analysis to identify the variables that most influence resilience results. This allows TxDOT to prioritize high-value condition, hydraulic, recovery, cost, detour, and network-redundancy data rather than attempting to collect every potentially relevant variable.

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Table 6.2.1 – *continued from the previous page*

Benefit Area	Benefit Type	Primary Beneficiary	Definition in the Context of this project
Reduced construction, operations, maintenance, and recovery costs	Potential economic	TxDOT	More effective screening may help TxDOT identify preventive or rehabilitation actions before disruptive events, avoid inappropriate project prioritization, reduce reactive repairs, and incorporate resilience improvements into already-planned projects. These savings have not yet been measured.
Reduced user costs and mobility disruption	Potential economic	State and traveling public	Resilience-informed investments may reduce closure duration, detour distance, travel delay, vehicle operating costs, freight disruption, and loss of access following hazard events. These benefits require project-specific network and post-event data for monetization.
Safety and critical access	Qualitative and potential economic	Both state and traveling public	Supports screening of assets serving evacuation routes, emergency services, critical facilities, freight corridors, ports, border crossings, and energy-sector access. Maintaining these connections can support safer emergency operations and reduce disruption consequences.

6.3 Quantified Benefits Demonstrated by the Research

The top quantified benefits are the additional decision information generated by the pilot studies and the reusable analytical capabilities delivered by the project. The project produced two principal software products—the Weather Projection App and the ArcGIS Pro Resilience Toolbox—with user guidance for data preparation, analysis, mapping, and interpretation.

The pilot studies evaluated 384 Wichita Falls roadway segments under each of two temperature-related hazard scenarios and 849 Houston bridges under inland flooding. Table 6.3.1 summarizes the resulting risk–resilience ranking comparisons.

Table 6.3.1: Quantified pilot decision-support benefits

Pilot Application	Ranked	Higher Priority under Resilience- Based TAM	Similar Priority	Lower Priority under Resilience- Based TAM
Wichita Falls roadways—extreme cold	384	12 (3.1%)	359 (93.5%)	13 (3.4%)
Wichita Falls roadways—extreme heat	384	34 (8.9%)	281 (73.2%)	69 (18.0%)
Houston bridges—inland flooding	849	83 (9.8%)	225 (26.5%)	541 (63.7%)
All pilot asset–hazard ranking instances	1,617	129 (8.0%)	865 (53.5%)	623 (38.5%)

The combined row represents asset–hazard ranking instances rather than 1,617 unique assets because the same Wichita Falls roadway segments were evaluated under both extreme cold and extreme heat. Across the three pilot applications, 129 asset–hazard cases moved substantially higher when resilience was considered. These cases represent assets that may have received less attention under conventional vulnerability- and criticality-based screening alone. The 129 cases should not be interpreted as 129 projects that must be funded or as 129 instances of realized cost savings. They quantify the additional screening information produced by the research. In particular:

- 83 individual Houston bridges moved substantially higher when low flood resilience was considered together with criticality;
- 34 Wichita Falls roadway segments moved higher under extreme heat, compared with 12 under extreme cold, demonstrating that the decision value of resilience information varies by hazard; and
- assets moving lower can also help TxDOT focus validation and engineering resources on locations where resilience need, criticality, and expected intervention effectiveness

coincide.

The sensitivity analyses provide an additional quantified benefit by identifying the data elements with the greatest decision value. In the Wichita Falls pilot, functional performance produced an average absolute resilience change of approximately 0.030 under both extreme cold and extreme heat. Hazard-specific robustness produced changes of approximately 0.019 and 0.017, respectively. In the Houston pilot, inland flood vulnerability produced the largest average absolute resilience change, approximately 0.034, while deck and substructure condition each produced changes of approximately 0.015. These results provide an empirical basis for prioritizing condition and hazard-specific data improvements during implementation.

6.4 Economic Benefit Status and Future Quantification

Potential economic benefits include: avoided emergency repair and maintenance costs, reduced service disruption, shorter closures and detours, reduced user delay and vehicle operating costs, improved allocation of resilience funding, and reduced staff effort associated with repeated data preparation and analysis. Note that the project did not include the information needed to convert these potential benefits into a robust monetary value. Specifically, the pilot studies did not include final programmed project lists, detailed intervention costs, observed before-and-after failure probabilities, event-specific closure and detour durations, repair costs, user-delay costs, statewide adoption rates, or measured staff hours with and without the software tools.

The annual economic benefits may be estimated by comparing expected agency and user losses before and after each resilience-informed project or management action. The comparison should be conducted for each relevant hazard and should account for the estimated annual probability or frequency of that hazard. Verified reductions in staff or consultant effort associated with the reusable software tools and standardized workflow may also be included. The agency and user losses considered in this comparison may include direct repair and maintenance costs, emergency response costs, travel delay, vehicle operating costs, freight disruption, closure and detour impacts, and loss of access to critical facilities. Once implementation costs and annual benefits are documented, the economic assessment should:

1. estimate the annual benefits resulting from avoided agency and user losses and verified workflow savings;
2. estimate the research, implementation, operation, maintenance, training, and data-management costs associated with use of the framework and tools;
3. convert future benefits and costs to present values using an appropriate analysis period and discount rate;

4. calculate net present value as the present value of benefits minus the present value of costs; and
5. calculate the benefit–cost ratio as the present value of benefits divided by the present value of costs.

The analysis period and discount rate should be selected in coordination with the TxDOT Project Manager and/or current VoR assessment guidance. Economic benefits should initially be reported as a range or through multiple scenarios to reflect uncertainty in hazard occurrence, statewide adoption, intervention effectiveness, and avoided losses.

6.5 Implementation and Benefit-Tracking Requirements

Realization and future monetization of the benefits will require TxDOT to:

1. define the intended uses of resilience scores for statewide screening, district review, project scoping, and funding support;
2. standardize asset identifiers and geospatial linkages among inventory, condition, hazard, project, cost, and recovery datasets;
3. validate high-priority results using district personnel, subject-matter experts, field observations, and detailed engineering analysis;
4. document which maintenance, rehabilitation, or capital decisions were influenced by the research products;
5. establish baseline values for expected disruption, repair cost, closure duration, detour effects, and staff analysis effort; and
6. track post-project and post-event outcomes so that avoided losses and workflow savings can be calculated using observed data.

6.6 Overall Value-of-Research Assessment

This project provides strong qualitative value by establishing a consistent and implementable connection between resilience assessment, transportation asset management, and project selection. It gives TxDOT a scientifically valid method for supplementing condition- and risk-based processes with information about an asset’s ability to withstand disruption and recover functionality.

The quantified results demonstrate that this additional information can materially affect asset priorities. Across the pilot applications, 129 of 1,617 asset–hazard ranking instances,

or approximately 8.0 percent, moved substantially higher under resilience-based TAM. The project also delivered two reusable software products and sensitivity diagnostics that identify high-value data priorities.

The principal measurable benefit at project completion is therefore improved screening, prioritization, and decision support rather than realized monetary savings. Potential agency and user cost savings can be substantial when the methods are implemented, but they should be monetized only after TxDOT has documented adoption, project costs, intervention effects, and observed operational or recovery outcomes.

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Appendix A

Weather Projection App User Manual

A.1 Overview

The Weather Projection App is designed to help users visualize projected weather data for cities in Texas. The app displays daily weather figures and extreme weather metrics based on climate model output. It provides interactive visualizations for:

- **Minimum Temperature** (°F)
- **Maximum Temperature** (°F)
- **Precipitation** (mm)
- **Extreme Metrics:** Combined estimates of the average number of days per year with:
 - Extreme high temperatures (above a specified threshold, e.g., 105°F)
 - Extreme low temperatures (below a specified threshold, e.g., 32°F)
 - Extreme precipitation (days exceeding the historical 99th percentile)

A.2 Requirements

Before running the app, ensure you have the following installed:

- Python (3.7 or higher)
- Required packages (see `requirements.txt`):
 - `streamlit`
 - `xarray`
 - `numpy`

- matplotlib
- pandas
- geopy
- haversine

You can install the dependencies using:

```
pip install -r requirements.txt
```

A.3 Running the App

1. Activate Your Virtual Environment (if using one):

- On Windows:

```
venv\Scripts\activate
```

- On macOS/Linux:

```
source venv/bin/activate
```

2. Launch the App:

From your project root directory, run:

```
streamlit run src/main.py
```

If you renamed the interface file to `app.py`, use that file name instead.

A.4 User Interface Walk-Through

When the app launches in your web browser, you will see the following elements:

A.4.1 Input Fields

- **City Name:**

Enter the name of a city in Texas (default is “Austin”).

Example: Houston, Dallas, or Austin.

- **Year for Inset Plot:**

Specify a year (within the model’s simulation period) that will be used to display a detailed inset plot for that year.

Example: 2029

- **Parameter Selection Dropdown:**

Choose one of the following options:

- **Minimum Temperature:** Displays the projected daily minimum temperature plot.
- **Maximum Temperature:** Displays the projected daily maximum temperature plot.
- **Precipitation:** Displays the projected daily precipitation plot.
- **Extreme Metrics:** Displays a combined table of extreme weather metrics.

A.4.2 Extreme Metrics Options

If you select **Extreme Metrics** from the dropdown, additional threshold input fields will appear:

- **High Temperature Threshold (°F):**
Set the temperature above which days are considered extremely hot (default is 105°F).
- **Low Temperature Threshold (°F):**
Set the temperature below which days are considered extremely cold (default is 32°F).
- **Precipitation Percentile Threshold:**
Set the percentile for extreme precipitation (default is 99). This value is used to determine the threshold based on historical data.

A.4.3 Action Button

- **Generate Plot / Metrics:**

Click this button after entering your inputs. Depending on your parameter selection:

- For **Minimum Temperature, Maximum Temperature, or Precipitation**, a corresponding plot will be generated and displayed.
- For **Extreme Metrics**, the app computes and displays a combined table showing the average annual extreme events:
 - * Average number of days above the high temperature threshold.
 - * Average number of days below the low temperature threshold.
 - * Average number of days with precipitation above the historical 99th percentile.

A.5 Outputs

A.5.1 Visual Plots

- **Daily Weather Plots:**

These are time-series plots that show the evolution of the selected weather parameter (temperature or precipitation) over the full simulation period. An inset focuses on the selected year for a more detailed view.

A.5.2 Extreme Metrics Table

- When **Extreme Metrics** is selected, a table is displayed that combines:
 - **Extreme Temperature Days:** The average annual count of days with temperatures above/below the set thresholds.
 - **Extreme Precipitation Days:** The average annual count of days where precipitation exceeds the historical 99th percentile.

The table provides an aggregated view across the simulation period.

A.6 Data Files and Mapping

- **NetCDF Files:**

The app uses NetCDF files located in the `./data` folder. Make sure the file paths in the code match your local file structure.

- **CSV Export (Optional):**

The code can also export a CSV file containing spatial data (latitude, longitude) and weather intensity metrics. This CSV can be used as input for a GIS mapping tool to visualize spatial variations.

A.7 Troubleshooting

- **City Not Found:**

If the geocoding service (Nominatim) cannot locate the city, ensure that you have spelled the city name correctly and that it exists in Texas.

- **Plot Not Displaying:**

Verify that your NetCDF file paths are correct and that the files are accessible. Check for error messages in the Streamlit app log.

- **Threshold Issues:**

If the extreme metrics table seems to have little variation (e.g., all values are 0 or 4),

consider adjusting the thresholds or reviewing the historical data used to compute the precipitation percentile.

A.8 Customization and Extensions

- **Threshold Adjustments:**

You can modify default threshold values in the code if domain knowledge or additional data suggests different criteria for extreme events.

- **Adding More Metrics:**

The modular structure of the code (with separate modules for geolocation, data processing, plotting, and metrics) allows you to easily extend functionality. For example, you could add further calculations or incorporate additional weather parameters.

- **GIS Mapping:**

The CSV file export provides a basis for integration with GIS software. You can import the CSV into mapping tools like QGIS or ArcGIS to spatially analyze the risk to transportation assets.

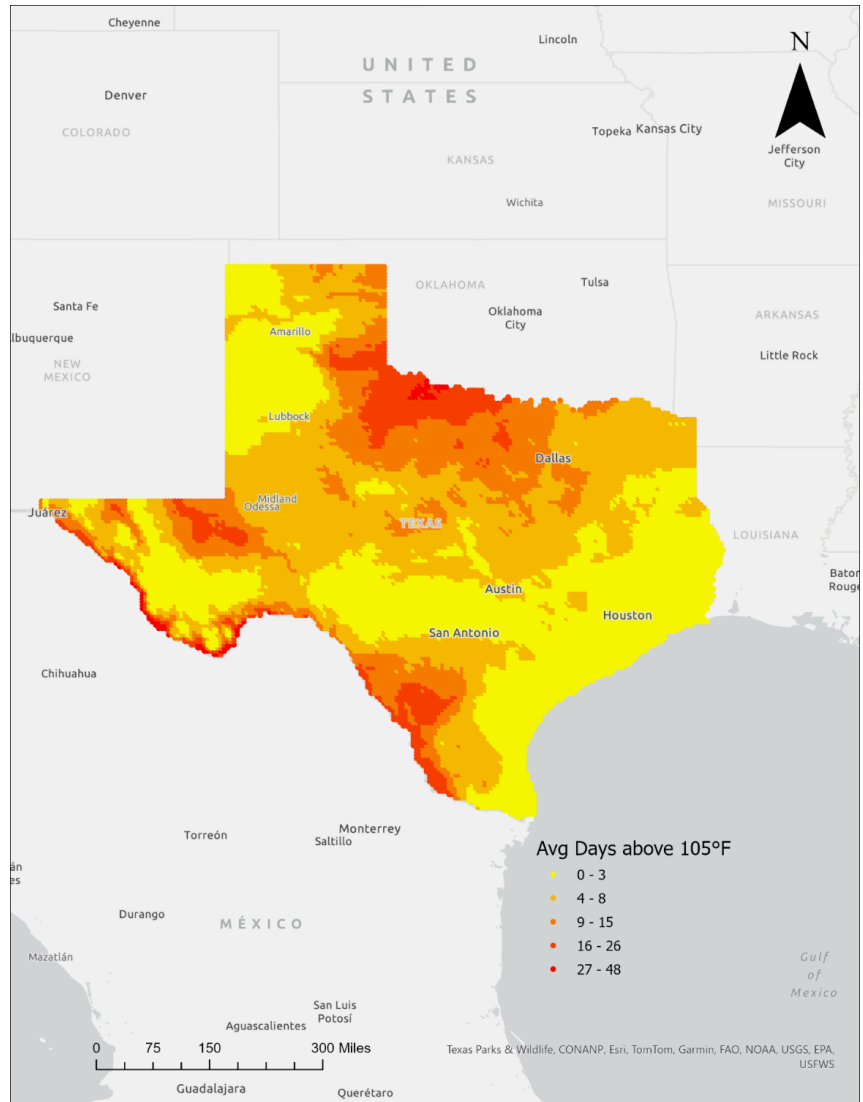


Fig. A.8.1: Average Days Above 105°F Across Texas

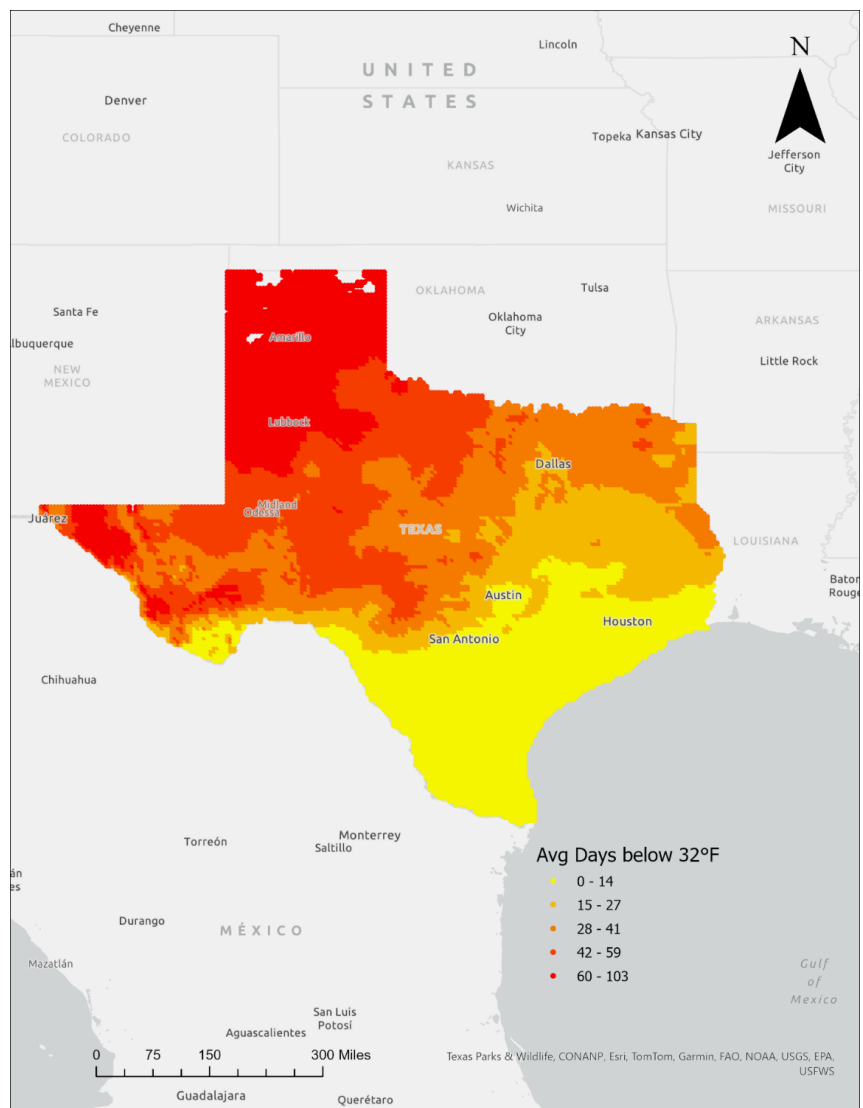


Fig. A.8.2: Average Days Below 32°F Across Texas

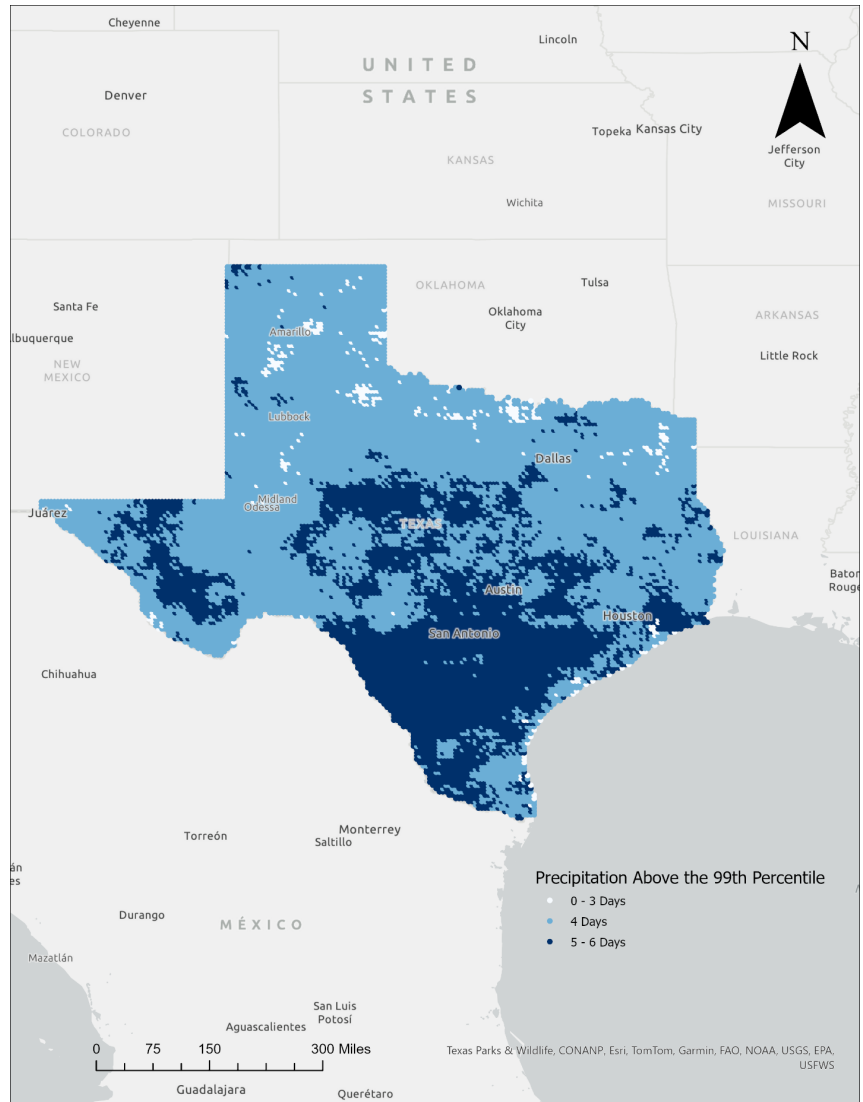


Fig. A.8.3: Precipitation Above the 99th Percentile

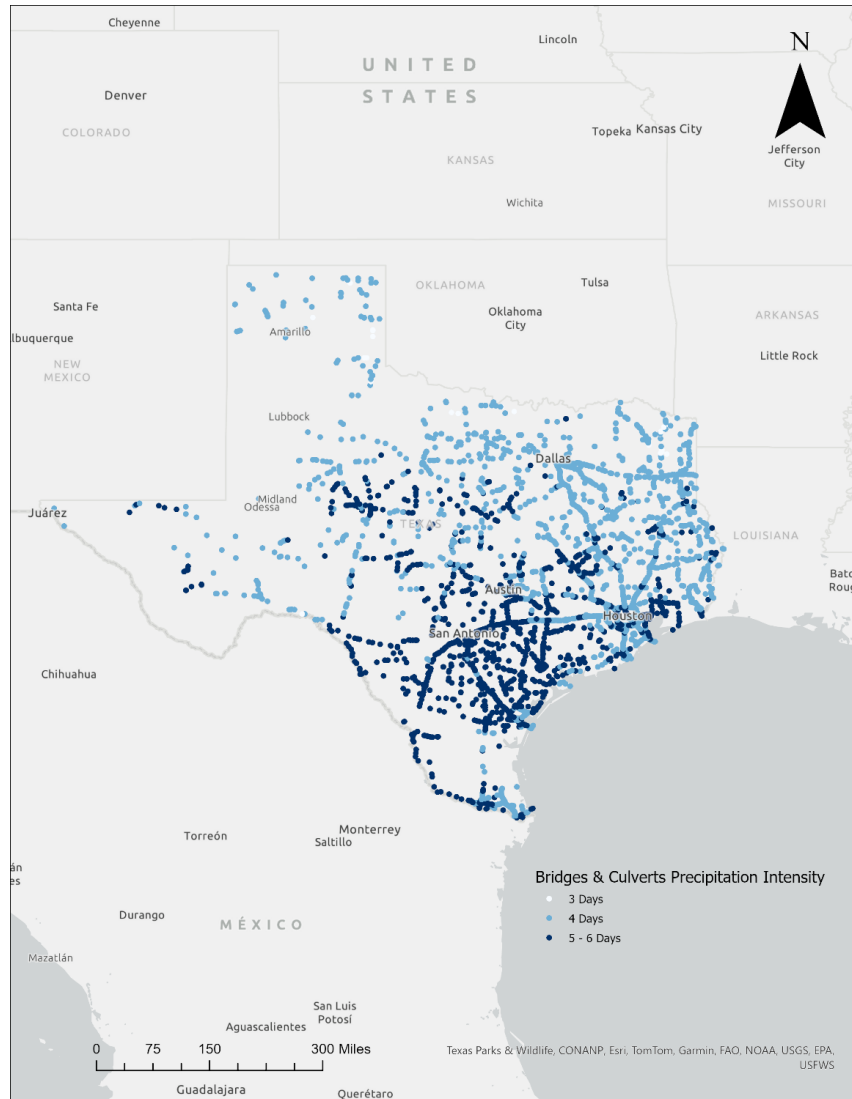


Fig. A.8.4: Precipitation Intensity at Bridges and Culverts in Texas

This map shows the precipitation intensity at bridges and culverts across Texas, based on weather data from the Loca2 database. The precipitation intensity is categorized into three groups: areas with 3 days, 4 days, and 5–6 days of precipitation intensity. Spatial join analysis is performed between the asset locations (bridges and culverts) and weather intensity metrics, allowing us to visualize the correlation between these assets and precipitation levels in different regions.

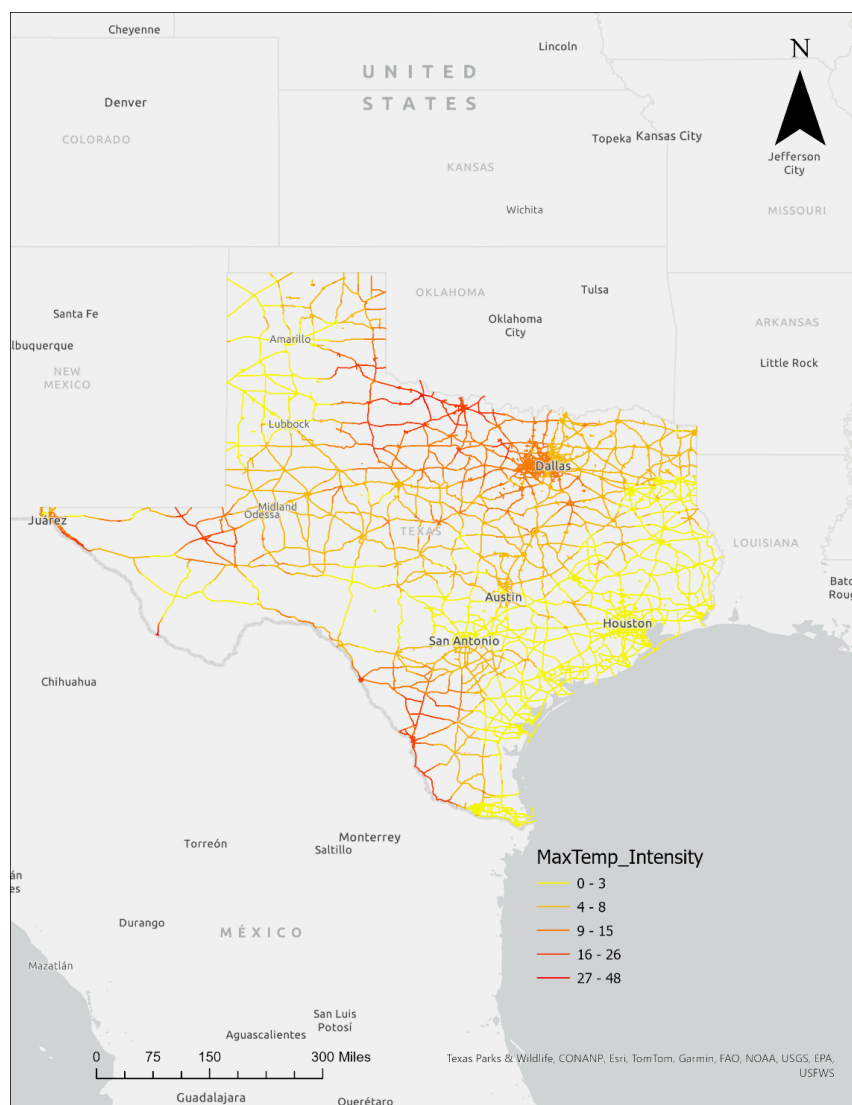


Fig. A.8.5: Maximum Temperature Intensity Across Texas Roadways

This map visualizes the maximum temperature intensity across Texas roadways, indicating how different areas experience varying temperature extremes. The temperatures are grouped into several ranges, from 0–3°F to 27–48°F. The data are spatially joined with temperature intensity metrics derived from the Loca2 database, highlighting areas with the most significant temperature impacts on road infrastructure.

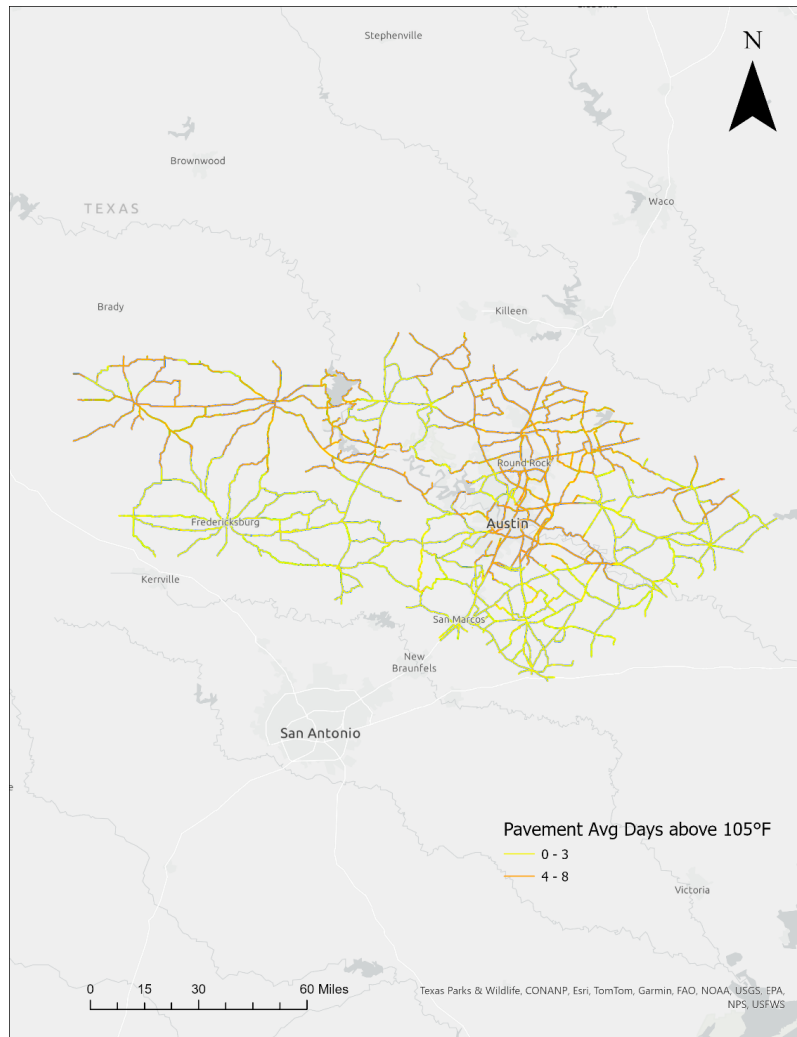


Fig. A.8.6: Pavement Average Days Above 105°F

This map shows the average number of days that pavement temperatures exceed 105°F, with categories representing 0–3 days and 4–8 days. This dataset is sourced by spatially joining Loca2’s temperature data with roadway infrastructure. This analysis helps to identify the areas of Texas where pavement may be most vulnerable to heat-related wear and tear.

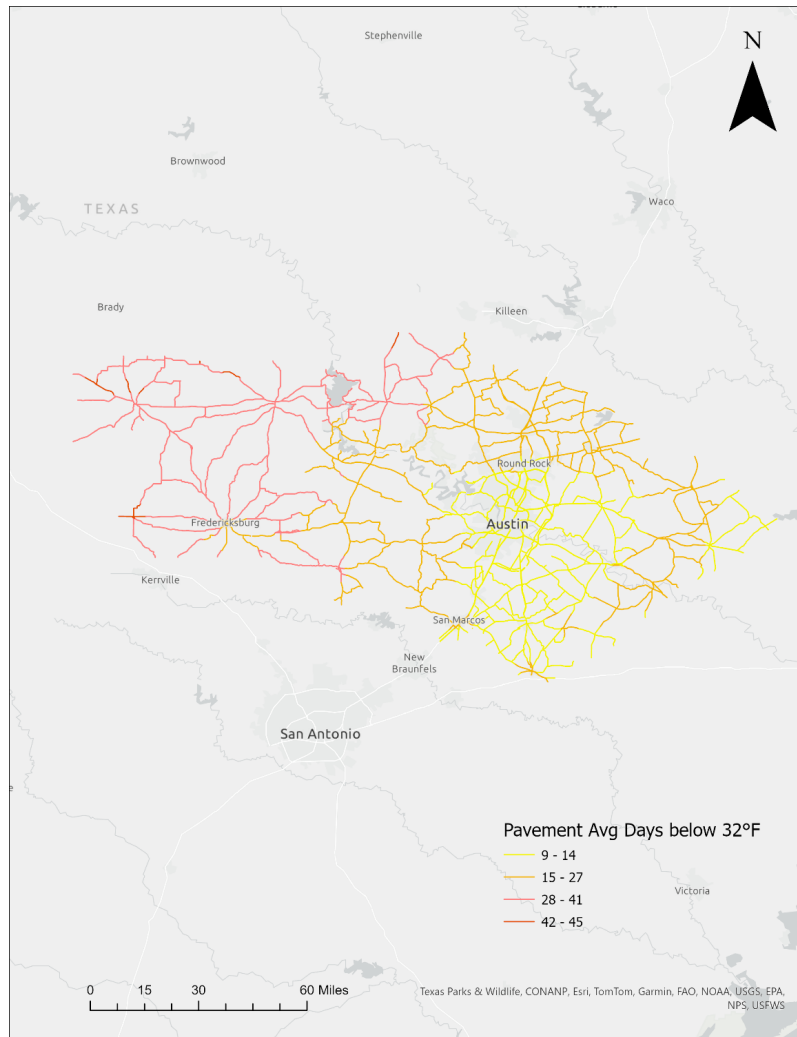


Fig. A.8.7: Pavement Average Days Below 32°F

This map illustrates the average number of days that pavement temperatures fall below 32°F, broken down into several temperature ranges: 9–14°F, 15–27°F, 28–41°F, and 42–45°F. These data points are generated through a spatial join between Loca2’s temperature data and Texas roadway centerline data. This helps understand where freezing conditions may affect the pavement and road safety.

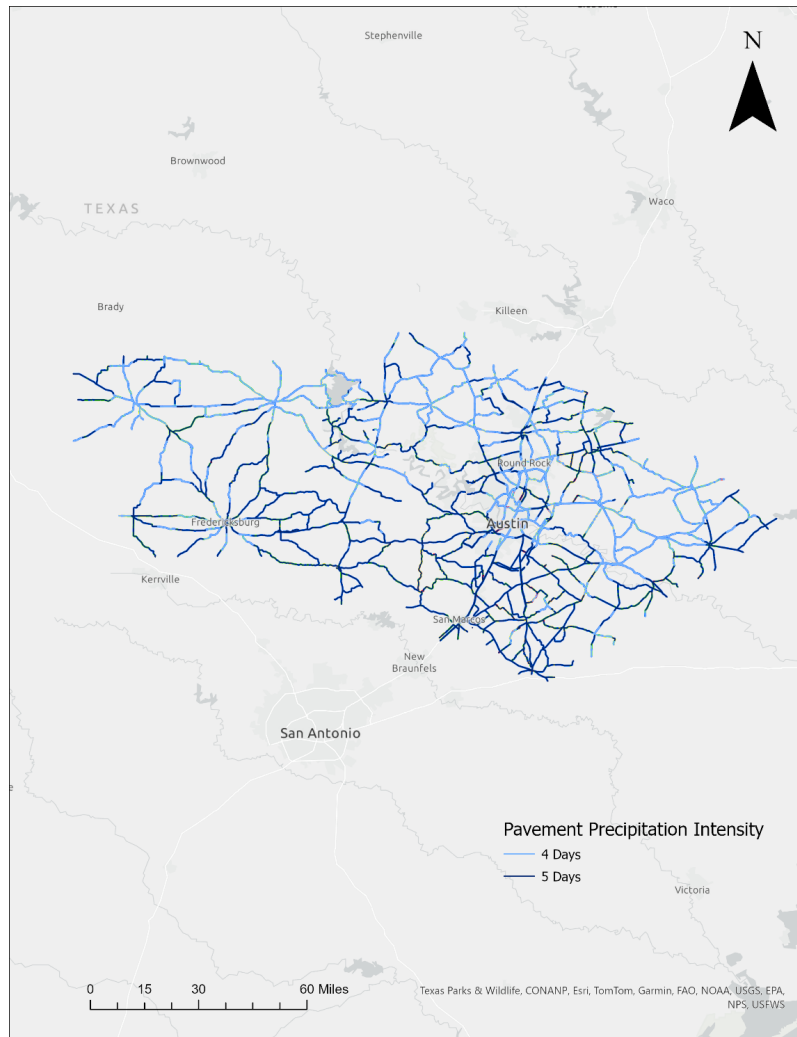


Fig. A.8.8: Pavement Precipitation Intensity

This map shows precipitation intensity along Texas roadways, categorized into areas with 4 days and 5 days of significant precipitation. The precipitation intensity data are derived from the Loca2 database and spatially joined with the roadway infrastructure dataset. This highlights where roadways are likely to experience the heaviest precipitation, informing maintenance and flood management strategies.

Appendix B

Resilience Toolbox User Manual

B.1 Purpose and Overview

The Resilience Toolbox provides an automated workflow for computing and mapping hazard-specific resilience indices for Texas transportation assets, particularly bridges/culverts and pavements/roadways, directly within ArcGIS Pro. Starting from a user-selected feature layer, the tool reads the embedded vulnerability and exposure attributes and links them with external asset condition information from the bridge inspection file or the pavement performance dataset. Using the resilience methodology described in Chapter 3, it then derives hazard-specific robustness and resilience measures for each asset and writes these values back into a GIS feature class that is usable for mapping, querying, and reporting.

The workflow is intentionally non-destructive: the original input layer remains unchanged, and all calculations are performed on a copy. This copy can be updated repeatedly—each time you run the tool for a different hazard, the corresponding resilience field is added to the same output feature class. As a result, you build a single, consolidated layer that contains resilience metrics for multiple hazards rather than managing several separate datasets.

B.2 System Requirements

This toolbox is designed to run entirely inside ArcGIS Pro, using the standard `arcgispro-py3` Python environment. No additional Python packages are required beyond what ships with ArcGIS Pro, so it can be deployed on any workstation where ArcGIS Pro is already installed and configured.

Behind the scenes, the workflow is driven by a small set of Python scripts. The main entry point is `TxDOT_ResilienceTool.py`, which acts as the script-tool wrapper called by ArcGIS Pro. This wrapper handles communication with the map layer, parameter inputs, and the creation or updating of the output feature class. The actual resilience logic is split into specialized modules: `cal_bridge_resilience.py` contains the formulas and processing steps

for bridge and culvert resilience. At the same time, `calculate_pavement_resilience 1.py` computes pavement resilience for extreme heat and extreme cold, and pavement resilience under inland flooding is handled by `calculate_pavement_resilience_Inland_flooding.py`. These scripts encapsulate the methodological choices documented previously in the report.

The tool expects TxDOT-derived GIS layers as inputs. For bridges, the input feature class must include a unique bridge identifier, such as `BRDG_ID`, along with vulnerability and rating fields such as `V_Ext_Heat`, `V_Ext_Cold_Vuln`, `V_Inland_Flood`, and corresponding rating attributes where available, plus the other standard attributes provided in the TxDOT resiliency layers. For roadways, the input feature class must contain a segment identifier, such as `Line_Seg_ID`, and hazard/vulnerability attributes for the relevant climate stressors, including extreme heat, extreme cold, inland flood, and related hazards.

In addition to the GIS layers, the tool requires a single asset data file parameter that is interpreted based on the selected asset type. When the user chooses Bridge as the asset type, this parameter should point to the TxDOT bridge condition Excel file, for example `TX_Bridge_Data.xlsx`, which provides inspection-based condition ratings. When the asset type is Pavement, the same parameter is instead expected to reference the pavement performance dataset in CSV format, for example `FY16_25_CS_0-7233_202511171432.csv`. The toolbox automatically routes this file to the appropriate computation path depending on whether bridges or pavements are being processed.

B.3 Installation and Setup

B.3.1 Place the Scripts

Before using the toolbox, you should first organize all the Python scripts in a single, consistent working directory. A typical setup is to create a project folder, such as:

```
C:\TxDOT\ResilienceToolbox\
```

Within this folder, place all the resilience-related scripts that the tool relies on. In most cases, this will include:

- `TxDOT_ResilienceTool.py` – the main script that ArcGIS Pro calls when you run the Calculate Resilience tool.
- `cal_bridge_resilience.py` – the module that implements the bridge and culvert resilience calculations.
- `calculate_pavement_resilience 1.py` – the script that computes pavement resilience for extreme heat and extreme cold.

- `calculate_pavement_resilience_Inland_flooding.py` – the script that computes pavement resilience for inland flooding.

Keeping all these files together in the same folder makes it easier to maintain the toolbox, update paths in the script tool properties, and ensure that ArcGIS Pro can consistently locate the required Python modules during execution.

B.3.2 Configure Script Paths

Before you run the toolbox, you need to make sure the main script knows where your resilience calculation scripts are stored. Open `TxDOT_ResilienceTool.py` in your preferred editor, for example VS Code or Notepad++, and look at the configuration section near the top of the file. You will see three lines that define the paths to the pavement and bridge scripts, like:

- `PAV_HEAT_COLD_SCRIPT = r"...\\calculate_pavement_resilience 1.py"`
- `PAV_FLOOD_SCRIPT = r"...\\calculate_pavement_resilience_Inland_flooding.py"`
- `BRIDGE_SCRIPT = r"...\\cal_bridge_resilience.py"`

Replace the ... in each line with the full, correct path to where those scripts live on your machine, for example your `TAM\\bridge analysis` folder. Make sure the filenames match exactly, including spaces and capitalization. Once you have updated all three paths, save `TxDOT_ResilienceTool.py`. The toolbox will then be able to locate and execute the underlying resilience scripts when you run the Calculate Resilience tool in ArcGIS Pro.

B.3.3 Add the Toolbox to ArcGIS Pro

To use the TxDOT Resilience Toolbox inside ArcGIS Pro, you first need to add the toolbox to your project. Start by opening ArcGIS Pro and making sure the Catalog pane is visible. You can turn it on from the View tab if needed. In the Catalog pane, right-click the Toolboxes node and choose Add Toolbox.

Navigate to the folder where you store your toolbox file, for example `TxDOT_Resilience.tbx` in your project directory, select it, and click OK. Once added, the toolbox will appear under Toolboxes in the Catalog pane. Expanding it should reveal the Calculate Resilience script tool, which you can then open and configure to run bridge or pavement resilience analyses directly from your map.

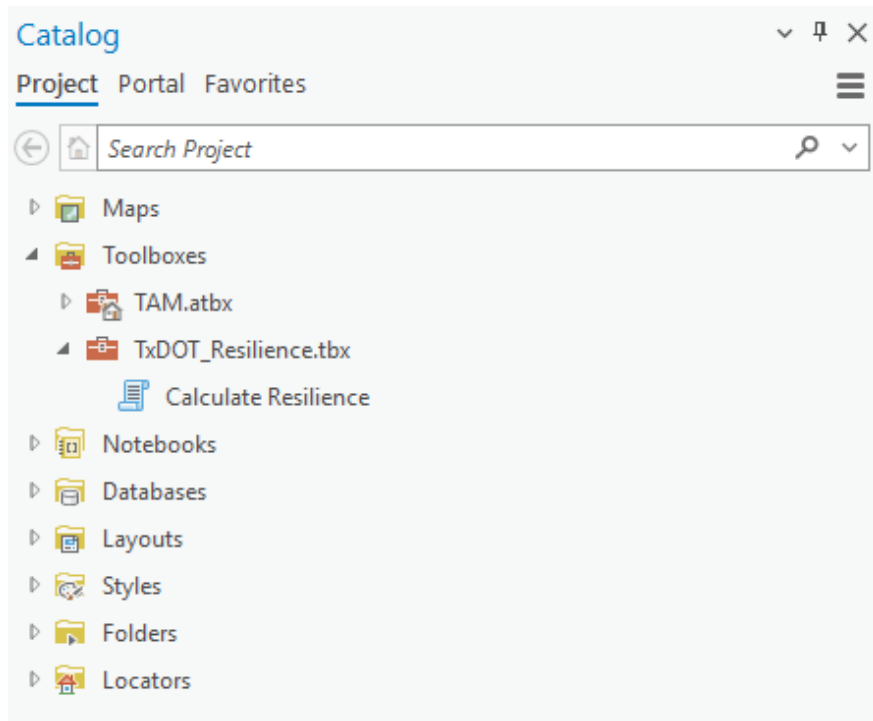


Fig. B.3.1: ArcGIS Pro Catalog pane showing the TxDOT Resilience Toolbox added under Toolboxes.

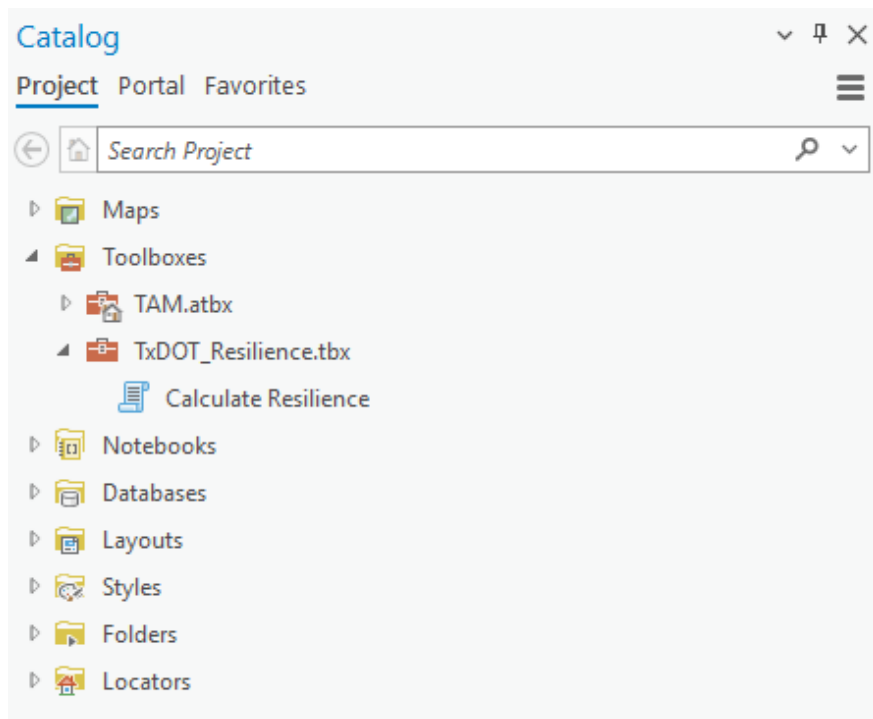


Fig. B.3.2: Calculate Resilience script tool displayed inside the TxDOT Resilience Toolbox in ArcGIS Pro.

B.4 Input Data Preparation

B.4.1 Bridge Assets

For bridge and culvert runs, the input feature layer should be a TxDOT resiliency layer representing bridge and culvert assets. This layer must include a unique identifier field, `BRDG_ID`, which is used to link each GIS feature to its corresponding record in the bridge condition dataset. In addition, the layer should carry the hazard and vulnerability attributes needed for robustness calculation—for example `V_Ext_Heat`, `V_Ext_Cold_Vuln`, `V_Inland_Flood`, and any related rating fields in the original TxDOT statewide resiliency data.

On the asset side, the Asset Data file, when the asset type is set to Bridge, should be the TxDOT bridge condition Excel file. This file must contain `STRUCTURE_NUMBER_008`, which is used to join with `BRDG_ID`, along with the deck, superstructure, and substructure condition ratings that feed into the normalized average condition index. Any additional fields referenced inside `cal_bridge_resilience.py`, such as inspection dates or other condition-derived metrics, should also be present so that the script can compute the full robustness and resilience scores without manual intervention.

B.4.2 Pavement / Roadway Assets

For pavement analysis, the input feature layer should represent individual roadway segments. Each segment needs a unique identifier, stored in the `Line_Seg_ID` field, so that the tool can reliably join computed resilience values back to the GIS layer. The layer should also include the hazard and vulnerability attributes for extreme heat, extreme cold, and inland flooding, consistent with the fields defined in your resilience framework, such as the vulnerability ratings and exposure scores used to derive robustness.

The Asset Data file for pavement runs is the TxDOT pavement dataset in CSV format, such as `FY16_25_CS_0-7233_202511171432.csv`. This file contains the detailed performance and structural information needed to compute pavement functionality and weighting factors, including TRM milepoint fields, IRI scores, distress or utilization measures, and traffic-related variables, for example, AADT, lanes, and speed. During execution, the tool combines these asset-level attributes with the hazard and vulnerability information from the roadway feature layer to calculate hazard-specific robustness and resilience for each roadway segment.

B.5 Using the “Calculate Resilience” Tool

B.5.1 Parameter Overview

When you open the Calculate Resilience script tool in ArcGIS Pro, you will be prompted to provide a small set of parameters that tell the tool what type of asset you are analyzing,

which hazard you are interested in, and where to read/write data.

Asset Type

This is a dropdown that lets you specify whether you are working with bridges or pavements/roadways.

- Options: Bridge, Pavement

Your choice here controls which resilience logic is used and how the Asset Data file is interpreted.

Hazard

This dropdown defines the specific hazard scenario for which resilience will be calculated.

- Typical options: Extreme Heat, Extreme Cold, Inland Flooding

The selected hazard is used to pick the appropriate vulnerability field(s) and to label the resulting resilience field, for example `resilience_extreme_heat`.

Input Layer

This parameter points to the feature layer in your map that contains the assets you want to analyze:

- For bridges, this will be your bridge/culvert layer.
- For pavements, this will be your roadway segment layer.

Asset Data

This is a single-file parameter that the tool interprets differently based on the asset type:

- If Asset type = Bridge, you supply the TxDOT bridge condition Excel file, for example `TX_Bridge_Data.xlsx`.
- If Asset type = Pavement, you supply the pavement CSV file, for example `FY16_25_CS_0-7233_202511171432.csv`.

The tool uses this file to pull in detailed condition, performance, and structural attributes needed for the resilience calculations.

Output_Features

Finally, you specify the output feature class where the results will be stored.

- This is usually a feature class inside a file or enterprise geodatabase, for example `TAM.gdb\Bridges_and_Culverts_Resilience`.
- On the first run, the tool creates this feature class by copying the input; on subsequent runs, it updates this same feature class with additional resilience fields for new hazards.

B.5.2 First Run vs. Subsequent Runs

The first time you run the tool for a given asset layer, for any hazard, the script takes your selected Input Layer and creates a brand-new feature class in the location you specified as `Output_Features`. This copy becomes your working “resilience layer,” and all future calculations for that asset type and layer will be written back into this same feature class.

On subsequent runs, if you point the tool to the same `Output_Features` feature class, it will no longer make another copy of the input. Instead, it simply adds new resilience fields for the selected hazard, for example, `resilience_extreme_heat` or `resilience_inland_flood`, and updates the rows in place based on the existing IDs. Previously calculated resilience values for other hazards are preserved.

In practice, this means you build up one integrated resilience layer over time, where each feature can store multiple hazard-specific resilience indices side by side, ready for mapping, comparison, and multi-hazard analysis.

B.5.3 Step-by-Step: Bridge Resilience

To compute resilience for bridges and culverts, start by opening the Calculate Resilience tool in ArcGIS Pro. In the parameter panel, set Asset type to Bridge and choose the relevant Hazard, for example Extreme Heat, Extreme Cold, or Inland Flooding. Next, select your bridge feature class, for example `Bridges_and_Culverts`, as the Input Layer, and point the Asset Data parameter to the TxDOT bridge condition Excel file, for example `TX_Bridge_Data.xlsx`. Finally, specify a name and location for `Output_Features`, such as `TAM.gdb\Bridges_and_Culverts_Resilience`, and click Run.

Behind the scenes, the tool first creates a working copy of your bridge layer in the specified output feature class on the first run. It then reads all attribute fields, excluding geometry, into a pandas DataFrame and passes this information to `cal_bridge_resilience.py`. That script converts the TxDOT vulnerability scores into hazard-specific robustness, combines them with the normalized average condition from the bridge Excel, and computes an intermediate robustness term.

Using this combined measure, it then evaluates resilience from the assumed recovery curve. The resulting resilience values are reshaped so that each bridge has a single row with dedicated fields for each hazard—typically `resilience_extreme_heat`, `resilience_extreme_cold`, and `resilience_inland_flood`. The tool creates any missing fields in the output feature class and updates the corresponding `BRDG_ID` records, so your final layer is immediately ready for mapping, querying, and further analysis.

To add another hazard later, for example Inland Flooding, rerun the tool with:

- Same Asset type, same Input Layer, same Output_Features
- Different Hazard value

The tool will add only the new hazard field, preserving existing resilience fields.

B.5.4 Step-by-Step: Pavement Resilience

To compute resilience for roadway segments, you will use the Calculate Resilience tool with the asset type set to Pavement:

1. Open the Calculate Resilience tool in ArcGIS Pro.
2. Fill in the parameters as follows:
 - Asset type: Pavement
 - Hazard: Extreme Heat, Extreme Cold, or Inland Flooding
 - Input Layer: your roadway resilience layer, for example `Roadways_ExtremeHeat_ExtremeCold_Hurricanes`
 - Asset Data: the pavement CSV file, for example `FY16_25_CS_0-7233_202511171432.csv`
 - Output_Features: the name of the output feature class, such as `TAM.gdb\Roadways_Resilience`
3. Click Run.

What the Tool Does Internally for Pavements

When you run the tool for pavements, the following steps occur behind the scenes.

Output Feature Class Management

On the very first run, for a given output name, the tool makes a copy of the input roadway layer and saves it as the output feature class. On subsequent runs targeting the same output feature class, the tool reuses this existing layer and simply adds or updates resilience fields instead of making a new copy.

Reading Attributes and Pavement Data

The tool reads relevant attributes from the output feature class, such as segment IDs and hazard/vulnerability fields, and loads the pavement CSV, which contains condition scores, IRI, distress measures, and traffic information.

Converting Vulnerability to Robustness

The pavement scripts first transform TxDOT’s hazard vulnerability scores into a robustness value for each segment and hazard:

- The original vulnerability scores are mapped to a normalized range between 20% and 100% to produce a vulnerability percentage.
- This percentage is then converted to a fraction, v , between 0 and 1.
- Robustness for the selected hazard is calculated using the transformation “one minus v , divided by 0.80,” and then clipped to stay between 0.05 and 0.99.

Intuitively, lower vulnerability, smaller v , yields higher robustness.

Computing Functional Performance

The tool then evaluates how well each segment is performing before the hazard, using two components:

- A condition-based term, defined as the condition score divided by 100.
- A ride-based term, based on the International Roughness Index, IRI, comparing the segment’s average IRI to a “good” IRI threshold.

These two components are averaged, 50% condition and 50% ride, to produce a single relative functionality measure, F_{rel} , for each segment.

Weight Factor from Distress, Trend, Criticality, and Pavement Type

Next, a weight factor is computed to capture additional influences:

- Distress utilization, how much of the allowable distress has been “used up,”
- Performance trend over time,
- Traffic and network criticality, and
- Pavement thickness/type.

These four pieces are combined into a single weight, ω , using fixed coefficients, so that segments with better trends, lower distress, and higher criticality can have their resilience adjusted appropriately.

Base and Weighted Resilience per Hazard

For the selected hazard, the pavement scripts then:

- Compute a base resilience, defined as the average of relative functionality, `F_rel`, and robustness. This represents the fundamental resilience before considering the weight factor.
- Adjust this base value with the weight factor, nudging resilience up or down depending on how functionality compares to robustness, for example, high functionality and high criticality can increase resilience.

Aggregating to Roadway Segments

The results are aggregated by `Line_Seg_ID`, so that each roadway segment receives a single resilience value for the chosen hazard. The output table returned to the toolbox includes:

- `Line_Seg_ID`
- The hazard-specific resilience measure, such as `res_w_Ex_Heat`, `res_w_Ex_Cold`, or `res_w_Inland_Flood`.

Writing Results Back to the GIS Layer

Finally, the toolbox:

- Adds the resilience field for the selected hazard to the output feature class if it does not already exist.
- Updates each segment's attributes by matching on `Line_Seg_ID`. Existing resilience fields for other hazards are preserved.

In many cases, some segments may still have missing or null resilience values, e.g., condition or pavement data are unavailable or IDs do not match. You can use a definition query in ArcGIS Pro, e.g., `res_w_Ex_Heat IS NOT NULL`, to display only the segments where both robustness and condition data are available, and a valid resilience value could be computed.

As with bridges, rerun for another hazard using the same output feature class to accumulate multiple resilience fields in one layer.

B.6 Output Fields and Naming Conventions

After the tool runs successfully, the output feature class will contain a set of new fields that store the resilience results. The exact fields you see depend on the asset type, bridge vs. pavement, and the hazards you have already processed.

For bridges and culverts, each feature is identified by the `BRDG_ID` field, which serves as the join key between the GIS layer and the bridge condition file. The tool then creates hazard-specific resilience fields such as:

- `resilience_extreme_heat` – resilience of the bridge under extreme heat
- `resilience_extreme_cold` – resilience of the bridge under extreme cold
- `resilience_inland_flood` – resilience of the bridge under inland flooding

For pavements/roadways, each segment is identified by `Line_Seg_ID`. The tool adds weighted resilience indices for each hazard, for example:

- `res_w_Ex_Heat` – weighted resilience under extreme heat
- `res_w_Ex_Cold` – weighted resilience under extreme cold
- `res_w_Inland_Flood` – weighted resilience under inland flooding

Depending on the version of the scripts, you may also see intermediate fields that support interpretation and QA, such as `F_rel_mean`, `robust_Ex_Heat_mean`, or similar summary variables. These represent average functionality and robustness metrics used in the final resilience calculation.

All resilience values are normalized between 0 and 1, where values closer to 1 indicate higher resilience, better ability to maintain and recover functionality under the specified hazard, and values closer to 0 indicate lower resilience.

B.7 Mapping and Analysis

Once the tool has populated the resilience fields in your output layer, you can immediately visualize the results in ArcGIS Pro.

First, open the Symbology for the resilience layer and switch the renderer to Graduated Colors. Choose the appropriate resilience field as the Value, for example `res_w_Ex_Heat` or `resilience_extreme_heat`, depending on your naming convention. This tells ArcGIS Pro to color each segment based on its resilience score.

Next, define a classification scheme that makes sense for your analysis. A common choice is 5–7 classes with explicit text labels such as Very Low, Low, Moderate, High, and Very High

resilience. Adjust the class breaks and symbology so that the categories are distinguishable by more than color alone. Use a readable legend and, where practical, combine differences in lightness, line width, symbol pattern, or other visual cues with the category labels. This allows low- and high-resilience segments to remain distinguishable for users who cannot reliably perceive color differences.

Finally, to focus only on segments with valid resilience values, apply a definition query to exclude nulls. For example, you can use:

```
res_w_Ex_Heat IS NOT NULL
```

or the corresponding resilience field you are mapping. This ensures that only segments with computed resilience scores are displayed, giving you a clean, interpretable resilience map.

B.8 Best Practices and Troubleshooting

B.8.1 Best Practices

To keep your workflow organized and repeatable, it helps to follow a few best practices when using the TxDOT Resilience Toolbox.

First, use a consistent output feature class for each asset type. For example, you might maintain one dedicated resilience layer for bridges and another for roadways. Each time you run the tool for a new hazard, point to the same output feature class so that new resilience fields are simply added rather than creating multiple, fragmented copies.

Second, store your asset data files, the bridge condition Excel file and the pavement CSV, in a stable project data folder. Avoid moving these files, changing their names, or renaming key ID fields such as **BRDG_ID**, **STRUCTURE_NUMBER_008**, or **Line_Seg_ID**. Keeping these files and field names consistent ensures the tool can reliably match GIS features to asset records during every run.

Finally, document which hazards have been computed for each layer. You can do this in the layer's metadata, in your project notes, or directly on map layouts and figures, for example labeling maps as "Roadway Resilience – Extreme Heat and Inland Flooding." This makes it clear to anyone using the project which resilience indices are present and which hazards still need to be evaluated.

B.8.2 Common Errors

Missing **BRDG_ID** Field

If you see an error like "BRDG_ID field not found," it means the tool cannot locate the unique bridge identifier it needs to join the resilience results back to the map layer. Check your bridge/culvert layer in ArcGIS Pro and confirm that it contains a field named **BRDG_ID**,

and that this field uses the same IDs as the **STRUCTURE_NUMBER_008** field in the TxDOT bridge Excel file. If the names or formats do not match, the join will fail and resilience values cannot be written back.

Missing Line_Seg_ID Field

An error such as “Line_Seg_ID not found” indicates a similar problem on the roadway side. The tool expects your roadway layer to have a **Line_Seg_ID** field that matches the segment IDs used in the pavement resilience output. If the field is missing, renamed, or uses a different ID convention, the tool cannot update the correct segments. Verify that your roadway feature class includes **Line_Seg_ID** and that it aligns with the IDs in your pavement CSV.

Null or Missing Resilience Values

If resilience fields are created but many rows contain NULL values, this usually points to one of two issues:

- Missing or incomplete asset data, e.g., no condition information in the bridge or pavement input files for certain IDs.
- Unmatched identifiers between the GIS layer and the asset data, for example a bridge exists in the map but not in the Excel, or vice versa.

These records can be excluded from maps using a simple definition query in ArcGIS Pro, for example **res_w_Ex_Heat IS NOT NULL**, so that only segments with valid resilience estimates appear in your final visualization.