# Establish TxDOT Transportation Resilience Planning Scorecard and Best Practices: Technical Report

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16. Abstract

With a focus on the transportation infrastructure in Texas, this research report: (a) highlights the gaps and challenges in assessing resilience in road networks, (b) provides an overview of metrics and tools for assessing road network vulnerability and resilience, and (c) introduces foundational information and methods to systematically incorporate resilience in transportation infrastructure planning and project development. The sets of information and methods include: (a) the vulnerability and criticality assessment metrics for the state road network, (b) a transportation resilience scorecard for operationalizing resilience into the planning process, and (c) transportation resilience best practices and measures.

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This research was sponsored by the Texas Department of Transportation (TxDOT) and the Federal Highway Administration (FHWA). The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of FHWA or TxDOT. This report does not constitute a standard, specification, or regulation.

This report summarizes the outcomes of the 0-7079 research project and does not include any TXDOT policy and requirement. The information provided are recommendations only based on the conducted research.

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# CHAPTER 1. INTRODUCTION

More frequent extreme weather events and natural hazards call for improving the resilience of the nation's transportation infrastructure. For example, Hurricane Harvey brought into focus important lessons regarding the need to improve the resilience of transportation infrastructure systems. Future scenarios of extreme weather events portend significant impacts on Texas road infrastructure. For example, rainfall and flooding in May 2015 caused roadway damages costing $20 million to repair. The impacts of Harvey's flooding in 2017 have been even more significant and yet to be quantified. Development and implementation of resilience strategies and measures for road infrastructure is imperative for the Texas Department of Transportation (TxDOT) to minimize risks and disruptions in future extreme events. Currently, TxDOT does not have procedures and tools for identifying vulnerable road transportation assets and for evaluating the extent to which state transportation plans affect vulnerability to extreme weather events. Although cooperative research projects and others have produced a wealth of resilience-related studies, a state-specific study and resilience scorecard is imperative for TxDOT to establish its road resilience practices and tools to effectively integrate resiliency into transportation planning and to implement resiliency best practices to mitigate the impacts of future disasters. The outcomes of this research project also address the directives of the recent Federal Highway Bill's requirements for improving disaster resilience in road networks.

The recent Federal Highway Bill has specified requirements for improving disaster resilience. In particular, the State of Texas has experienced a growing number of hurricanes and flooding events impacting its transportation infrastructure over the past two decades. In order to better integrate and operationalize resiliency in transportation planning for the Receiving Agency, this project will create foundational knowledge and tools for planning and decision making. Accordingly, this project: (1) evaluated the current state of practice, needs, gaps, and priorities related to transportation resilience through surveying various state and local stakeholders, (2) employed analytical and data-driven methods to implement vulnerability and resilience assessments on the state road networks, (3) developed a transportation resilience scorecard to inform current and future transportation resilience planning efforts, (4) identified transportation resilience best practices and measures to objectively improve transportation resiliency, (5) presented research outcomes in a guide document for the Receiving Agency and other local transportation agencies, and (6) provided transportation resilience training through workshops and webinars.

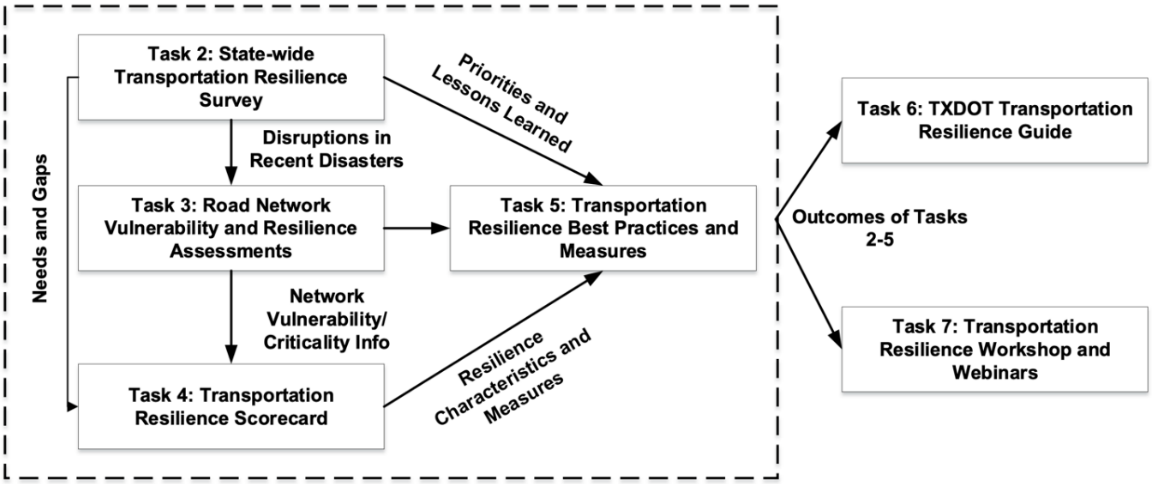

**Figure 1.1. Overview of the Research Processes of the Project.**

This project is the first research conducted on transportation resilience sponsored by the Receiving Agency; hence, the Performing Agency had an ambitious work plan to build foundational information and tools needed to enhance the resilience of state transportation infrastructure. The scope of this research project is road infrastructure networks; nevertheless, the outcomes are informative for other elements of transportation systems. The project supervisor is highly qualified to lead the scope of work and has a proven track record and expertise on infrastructure resilience methods and concepts.

This research report presents the methodologies and research processes conducted in this project, with a focus on data collection and analytical approaches. First, the researchers implemented state-wide transportation resilience interviews and surveys to provide an understanding of the hazards and threats in districts/regions; the state of practice in incorporating resilience; the processes needed for resilience incorporation; and the tools, metrics, and data needed for incorporating resilience. The interviews the researchers conducted were with professionals involved in planning and project development. The online survey was developed based on knowledge gained from the interviews to deepen the understanding of resilience in transportation planning. This research report will show the details of designing the interview protocols and constructing the online survey, as well as the selection processes of survey respondents and interviewees from various organizations across the state of Texas to ensure that the findings reflect different and diverse perspectives on the subject of resilience in transportation planning and project development.

Second, recognizing the needs and gaps from the interviews and surveys, the researchers developed a multi-dimensional resilience assessment tool to evaluate the vulnerability and criticality of the state road networks. In order to incorporate the resilience of road networks to a variety of the events in the state, an extensive literature review was conducted to identify the essential dimensionalities of resilience, such as flooding and hurricanes, and disrupted access to critical facilities in the districts. Integrating the insights from the interviews and surveys, the researchers proposed and implemented quantitative metrics to classify the criticality of road segments for understanding the system-level resilience of road networks, including the metrics for road network connectivity, vulnerability to flood events, access to critical facilities, and cascading impacts of road failures. The researchers collected data from various data sources such as 100- and 500-year floodplain data from the National Flood Hazard Layer (NFHL), facilities location data from the Homeland Infrastructure Foundation Level data repository, and energy sector data and evacuation route data from TxDOT. The researchers also developed two integrative metrics to provide an overall assessment of the criticality for road segments. This research report will provide the details about the analytical methods used to develop the metrics and the approaches the researchers adopted to calculate and visualize the criticality scores.

Third, based on the information gathered during the interviews and survey, the researchers developed a transportation resilience scorecard to provide a self-assessment tool for the TxDOT planning divisions and MPOs to examine the extent to which they incorporate resilience practices in their planning and project development processes. The research approach included three steps. The first two steps were to identify resilience practices to be included in the scorecard. The first step was to identify five dimensions of operationalizing resilience into transportation planning and project development. The next step was to conduct a systematic literature review to identify resilience practices related to the five dimensions identified in the first step. The third step was to conduct interviews to examine the applicability of resilience practices in the context of TxDOT transportation planning and project development. The reseachers also provided the use case to guide the users for assessment of the extent to which these practices are implemented in their organizations and systematically operationalize resilience in transportation planning.

Finally, the researchers developed transportation resilience best practices and measures for state organizations to improve the resilience of the state transportation systems. The main output of this task was a checklist that allows project planners and engineers to assess the status of the incorporation of resilience in projects during the project development phase. The research approach included two steps. The first step was to establish a project-level checklist for the evaluation of the alignment of projects with resilience considerations and requirements. In this step, the researchers first performed a literature review to identify resilience practices and requirements that need to be considered during the project development phase as well as practices that have been recorded by standards and guidelines. Then, the researchers summarized these practices under 14 items in a checklist. For each item, the researchers also incorporated example practices with references that help users to learn and adopt proper practices during the project development phase. The second step was to identify metrics and measures for resilience assessment from the literature, including scientific literature as well as standards and guidelines related to resilience assessment.

# CHAPTER 2. LITERATURE REVIEW

## 2.1 RESILIENCE CONCEPTS AND TRANSPORTATION RESILIENCE

Resilience includes the ability of transportation agencies to adapt state transportation infrastructure and assets to changing conditions. For transportation resilience, the American Association of State Road and Transportation Officials' (AASHTO) standing committee on research defines resilience as "the ability of the system to recover and regain functionality after a major disruption or disaster" (USDOT, 2014). The AASHTO Transportation Research Board (TRB) transportation and security summit then defines transportation resilience as "the ability of a system to provide and maintain an acceptable level of service or functionality in the face of major shocks or disruptions to normal operations" (AASHTO, 2016). Federal Road Administration Order 5520 (2014) uses the resilience definition of "the ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions" (USDOT, 2014). Murray-tuite (2006) defines resilience as "a characteristic that enables the system to compensate for losses and allows the system to function even when infrastructure is damaged or destroyed. Freckleton et al. (2012) characterizes transportation resilience as having multiple aspects, including (a) the ability to maintain its normal level of services or return to that level in a timely manner (Heaslip et al., 2009), (b) the ability to compensate for losses to allow functionality, even when that system is damaged or destroyed (Battelle, 2007), (c) the ability to manage unexpected situations without complete failure (Litman, 2008), and (d) the ability to absorb the consequence of disruption and maintain freight mobility (Wan et al., 2018). Figure 2.1 shows the resilience curve of system performance. In the pre-disruption phase, the system operates reliably with small oscillations. When the perturbation occurs, the system performance declines to minimum required performance and continues to decrease until it reaches its nadir. This point is considered the robustness of the system. To recover from the disruption, system accessibility and functionality will be rebuilt.

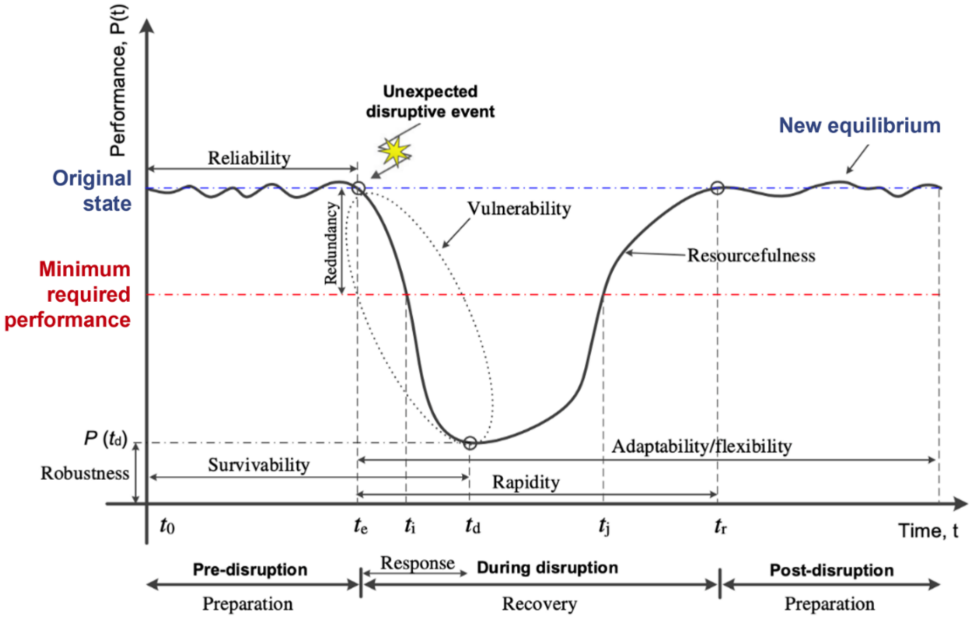

**Figure 2.1. System Resilience Curve. Adapted from Wan et al. (2018).**

Roads and bridges are typically engineered to withstand a certain set of conditions (Henry and Emmanuel Ramirez-Marquez, 2012). Older structures, however, may have been designed before modern standards were in place, or conditions may have changed. For instance, streamflow may increase outside of the parameters for which a culvert or bridge was designed due to rapid residential and commercial development in a watershed and associated increases in impervious surfaces. Precipitation patterns may have changed since the road was designed. Improving resilience when planning, designing, maintaining, and repairing transportation assets may yield cost savings in the long term through reduced repair costs, improved safety, and reduced travel disruption. The Federal Highway Administration (FHWA) statutes and regulations require state departments of transportation (DOTs) and metropolitan planning organizations (MPOs) to consider resilience in the transportation planning process and to include resilience considerations in asset management plans. Agencies have developed differing definitions to improve transportation resilience. For example, Minnesota DOT (2017) includes “reducing vulnerability and ensuring redundancy and reliability to meet essential travel needs” in its resilience definition. Wisconsin DOT (2009) emphasizes that a resilient transportation system needs “to quickly respond to unexpected conditions and return to its usual operational state.” Similarly, Tennessee DOT (2015) specifies “the ability of the transportation system to withstand and recover from incidents.” The United States Department of Transportation (USDOT) (2014) defines transportation resilience as the ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and rapidly recover from adverse events (National Research Council, 2012). To achieve rapid recovery, Oregon DOT points out in its seismic report that “it requires government continuity, resilient physical infrastructure, and business continuity.” Colorado DOT defines resilience as the “the ability of communities to rebound, positively adapt to, or thrive amidst changing conditions or challenges—including disasters and climate change—and maintain quality of life, healthy growth, durable systems, and conservation of resources for present and future generations" (Flannery et al., 2018). In general, transportation resilience is "the ability to adapt to, recover from, and respond to—and bounce back quickly from—(1) threats to physical infrastructure and operations and (2) threats of cybersecurity, terrorism, and all hazards" (Weilant et al., 2019).

## 2.2 CURRENT KNOWLEDGE AND PRACTICES IN TRANSPORTATION RESILIENCE

Dix et al. (2018) conducted a survey and found 25 out of 52 state DOTs (two states have two DOTs) and 41 out of the 101 selected MPOs incorporated resilience into their transportation plans. Of these, 25 state DOTs that had resilience in their plans, 17 states explicitly listed resilience as a goal. For example, Arkansas DOT (2016) stated plans for "improv[ing] statewide safety by funding projects reducing fatal and serious injury crashes, reducing vulnerability (the magnitude of impact on the system due to events such as major traffic incidents, flooding, lane closures, bridge failures, and seismic activity), and improving resiliency of the system (the ability of the system to recover from these events)." Colorado DOT (2015) aimed to "improve the resiliency and redundancy of the transportation system to address the potential effects of extreme weather and economic adversity, emergency management, and security." Hawaii DOT (2014) focused on promoting "long-term resiliency, relative to hazard mitigation, namely global climate change, with considerations to reducing contributions to climate change from transportation facilities and reducing the future impacts of climate change on the transportation system" and to "improve the resiliency of the state through the transportation system." Informed by lessons learned from Hurricanes Lee, Irene, and Sandy, in 2013, FHWA advised agencies on how to incorporate resilience into transportation systems through their asset management plans, including:

- Conduct a risk assessment of the state's transportation infrastructure.
- Strengthen the existing transportation networks.
- Protect transit system and tunnels against severe flooding.
- Strategically expand transportation networks to create redundancy in the system.
- Develop enhanced guidelines, standards, policies, and procedures (Flannery et al., 2018).

The American Society of Mechanical Engineers (ASME) (2009) published a framework for critical infrastructure assessment, including transportation. The framework comprises a seven-step process to analyze and mitigate risks from potential terrorist attacks on critical infrastructure assets, including:

- Asset characterization and screening.
- Threat characterization.
- Consequence analysis.

- Vulnerability analysis.
- Threat assessment.
- Risk assessment.
- Risk management.

Weilant et al. (2019) developed a conceptual framework for transportation planning organizations to use for achieving a more resilient transportation system. The logic model framework uses the following structure:

- Input (i.e., what it has, includes multi-modal infrastructure, skilled workforce, partnership, and data and information).
- Activities (i.e., what it does, includes targeted and prioritized changes to transportation infrastructure, collaboration, and coordination among partners).
- Outputs (i.e., what it achieves, includes access to critical social and economic systems, movement of goods and people).
- Outcomes (i.e., observed or desired changes, includes equity of access and movement, normally functioning infrastructures).
- Other system outcomes (i.e., observed or desired changes, includes social system, economic system, and environmental system wellbeing).

Francis and Bekera (2014) developed a framework to incorporate resilience into decision making. The framework contains five components, including system identification, vulnerability analysis, resilience objective setting, stakeholder engagement, and resilience capacities.

Globally, the New Zealand Transportation Agency developed and maintained a framework to measure the resilience of transportation infrastructure based on the New Zealand Treasury's National Infrastructure Plan. The framework measures a range of resilience scores including robustness, redundancy, safe to fail, change readiness, network, and leadership and culture. These scores will eventually be combined into an overall agency resilience score (New Zealand Transport Agency, 2014). The European Union–funded projects such as INTACT (2018) and RESILENS (2018) developed methods and tools that can help advance the resilience of critical infrastructure. The United Kingdom–funded Adaptation and Resilience in the Context of Change (ARCC) network (ARCC, 2018) provided policymakers and practitioners evidence on resilience and adaptation in the built environment. Japan also established the national resilience initiative (National Resilience Promotion Office, 2015) aimed at building resilience in critical energy, water, transport, and other lifeline infrastructures. Australia also created a critical infrastructure resilience strategy to ensure continued operation of critical infrastructure in facing disruptions (Australian Government, 2015).

## 2.3 NETWORK METHODS FOR TRANSPORTATION RESILIENCE

Resilience is closely tied to the concept of risk, since improving resilience can reduce risk by reducing vulnerability to and potential consequences of an attack or natural event. Risk comprises four elements: hazards, exposure, vulnerability, and consequence (Flannery et al., 2018). The National Academy of Sciences (2012) defined risk as “the potential for adverse effects from the occurrence of a particular hazardous event, which is derived from the combination of physical hazards, the exposure, and vulnerabilities.” The National Infrastructure Protection Plan defined risk as the “potential for an unwanted outcome resulting from an event or occurrence, as determined by its likelihood and the associated consequences” (U.S. Department of Homeland Security, 2004). The Federal Emergency Management Agency (FEMA) (2014) defined risk as the likelihood that a threat will harm an asset with certain consequences. Resilience metrics enable transportation agencies to use what they have learned from these risk analyses to measure the resilience of the transportation system (Flannery et al., 2018). Sharma et al. (2018) suggested measuring resilience using vulnerability, severity of consequences, and time to recover from the disruptions. Weilant et al. (2019) summarized four main themes related to resilience, including

- Reducing the likelihood of the system being impacted by the disaster.
- Increasing the ability of a system to absorb a disturbance.
- Increasing the system’s adaptability while maintain the functions facing a disruption.
- Quickly recovering from the disruption to return to normal functioning (can be different from the pre-event level).

These themes can be translated to capacities that are essential for a system to achieve resilience: (a) absorptive capacity, (b) restorative capacity, and (c) adaptive capacity (Norris et al., 2008). As risk disparity is receiving more attention, equity or equitable access is also incorporated into resilience (Nicholls, 2001). Consider the post-disaster network access to critical facilities. Dong et al. (2019, 2020) proposed the concept of robust components to measure communities’ risk disparity in terms of losing access to hospitals in both earthquake and flooding scenarios using a network topology analysis approach. Gao et al. (2016) uses a single metric to measure the resilience of the multidimensional complex networks. The author found that a resilience system is (a) densely connected in the system, (b) highly heterogeneous in the connections, and (c) relative symmetric. Using a percolation approach, Dong et al. 2020 measured the resilience of different cities’ and states’ road network in the face of random failure using the giant component metrics. This topological metric enables the ranking of different road networks based on the derived resilience score. Weilant et al. (2019) summarized the resilience measurement process into an absorptive capacity, restorative capacity, equitable access, and adaptive capacity (AREA) approach.. Bruneau et al. (2003) proposed that resilience should be measured in terms of robustness, redundancy, resourcefulness, and rapidity, combined with technical, organizational, social, and economical dimensions (Davis et al., 2018; Flannery et al., 2018; Reggiani, 2013).

Weilant et al., (2019) suggested using an AREA approach to inspect resilience from absorptive capacity, restorative capacity, equitable access, and adaptive capacity. Murray-tuite (2006) suggested that a resilience transportation system has ten properties, including redundancy, diversity, efficiency, autonomous components, strength, adaptability, collaboration, mobility, safety, and the ability to recover quickly. Table 2.1 presents a summary of resilience characteristics. Da Silva and Morera (2014) suggested a resilience system should equip the following seven qualities:

- Reflective (i.e., has mechanism for continuous evolvement).
- Robust (i.e., can anticipate potential failures and make provisions).
- Redundant (i.e., has spare capacity to accommodate changes).
- Flexible (i.e., can adapt and evolve).
- Resourceful (i.e., has different ways to achieve the goals).
- Inclusive (i.e., promotes community engagement).
- Integrated (i.e., promotes consistency by pursuing integration and alignment between systems).

**Table 2.1. Components of Infrastructure Resilience.**

| Component | Definition | Reference |
|---|---|---|
| Robustness | The ability of a system to withstand or absorb disturbances without significant degradation of performance in the face of disruption. | (Faturechi and Miller-Hooks, 2015; Flannery et al., 2018; Wan et al., 2018) |
| Redundancy | The extent to which a component is substitutable in a system. In transportation, it commonly means the existence of optional routes between origins and destinations. | (Fiksel, 2003; Haimes, 2009; Wan et al., 2018) |
| Resourcefulness | The ability to diagnose the problem and the availability of the resources to restore system performance. | (Flannery et al., 2018; Francis and Bekera, 2014; Reggiani, 2013) |
| Rapidity | The ability to quickly restore the normal or improved system functionality. | (Adams et al., 2012; Flannery et al., 2018; Wan et al., 2018) |
| Reliability | The probability that a system remains operative in the face of disruptions. | (Faturechi and Miller-Hooks, 2015) |
| Vulnerability | The susceptibility and physical sensitivity of the system to damages or disruption. | (Blockley et al., 2012; Wan et al., 2018) |
| Adaptability | The ability to respond to new disruptions resulting from the dynamic nature of complex systems. | (Fiksel, 2003; Wan et al., 2018) |

| | | |
|---|---|---|
| Absorptive capacity | The ability of the system to absorb the disturbances and maintain functionality. | (Bergström et al., 2015; Francis and Bekera, 2014; Lundberg and Johansson, 2015) |
| Restorative capacity | The system's ability to quickly recover from the shock. | (Flannery et al., 2018; Hickford et al., 2018) |
| Equitable access | The ability of the system to provide access across communities in the post-disruption scenario. | (Hickford et al., 2018; Nicholls, 2001) |
| Adaptive capacity | The ability of the system to change the response to disruptions to maintain normal functionality. | (Francis and Bekera, 2014; Hickford et al., 2018) |

Methods proposed to model interdependence of urban systems (Guidotti et al., 2016; Johansson and Hassel, 2009; Tabassum et al., 2018) can be classified into six categories (Ouyang, 2014). The empirical approach relies largely on empirical data and expert judgements. The agent-based bottom-up approach captures the individual autonomous agents' complex interactions but suffers from agents' behavior assumptions and calibration difficulties. The system dynamics–based approach utilizes a top-down method to understand the behavior of the system as a whole. Its application is constrained, however, as component-level dynamics are missing, and relevant data are limited. The economic theory-based approach uses the "household" and "producer" perspective to model the interaction between systems. The network-based approach views the urban system as networks where nodes are the system entities and links are the connections and intersections among them. Despite the low fidelity, they are great at modeling the aggregated effect.

## 2.4 KNOWLEDGE GAPS FOR RESILIENCE PRACTICES IN TRANSPORTATION PLANNING

There are a few challenges towards integrating resilience into transportation planning. First, a systematic vulnerability assessment is lacking. Texas' extensive system of roads and bridges provides a high level of mobility with 313,228 miles of public road and 53,875 bridges. TxDOT, a branch of the Texas Division of Emergency Management, is responsible for keeping the transportation systems working in case of emergencies and ensuring other emergency operations function. Many MPOs and state DOTs expressed the need for "more information or research on specific climate impacts, vulnerability assessments, and flood or sea-level rise modeling to better inform their understanding of how climate change will affect them and how they can respond" (Dix et al., 2018). However, regular inspections are not necessarily looking for vulnerabilities related to extreme events such as Hurricane Harvey. Weilant et al. (2019) recommend including human and equipment assets data, to consider a wider array of hazards and determine whether they are system-wide, and to acknowledge the interaction of the criticality and exposure of the assets in resilience assessment. Therefore, to establish a comprehensive plan for identifying mitigation policies, strategies, or investments in the transportation system, systematic vulnerability assessment (Dehghani et al., 2013; Maltinti et al., 2012; Murray and Grubesic, 2007; Yan et al., 2017) and critical infrastructure prioritization for protection are needed.

Second, resilience is not only about the vulnerability of the system to disruptions but also how disruptions in one network can cascade or spill over to other networks; modern infrastructures are interdependent (Guidotti et al., 2016; Johansson and Hassel, 2009; Ouyang, 2014). In normal daily operation, these interdependencies can have a positive impact on the urban system and improve the efficiency of the system. However, once one of the infrastructure systems are disrupted, the failure can propagate to its connected counterparts and result in widespread failure. Therefore, it is important to understand the criticality of different transportation infrastructures and their interdependencies with other infrastructures. For example, communities rely on transportation networks to access different infrastructure services. In turn, many infrastructure services need transportation to reach damaged sites for retrofitting and maintaining their assets. Moreover, communities (e.g., socially vulnerable neighborhoods) have different levels of needs relying on infrastructure services. Such interdependencies with critical infrastructure prioritization for protection ought to be considered when conducting a system-wide vulnerability assessment. Therefore, the mobility impact due to the disruption of the investigated infrastructure, such as the increased mileage traveled or travel time, degradation of road capacity, speed drop, etc., and the accessibility impact due to the road disruption, including community access to critical facilities and neighborhood connectivity, should be included in the vulnerability assessment.

Third, transportation system resilience extends beyond the infrastructure itself. Resilience of the transportation system is driven by stakeholders who often have their own values, norms, and priorities in terms of making resilience plans (Farahmand et al., 2020). For example, some organizations have recognized the importance of resilience in transportation planning but lack guidelines for the implementation. Others may need a vulnerability assessment framework to start evaluating their managed properties. All these require a state-wide stakeholder survey to identify the needs and gaps in resilience operationalization, to engage stakeholders and decision makers in prioritizing the resilience enhancement actions, and to determine the format of a useful toolkit for transportation agencies to integrate resilience into the transportation planning process.

Fourth, transportation and hazard mitigation plans can often contradict each other and result in adverse impacts on transportation system resilience. Over the years, the focus of infrastructure resilience has shifted from understanding the ability of infrastructure to recover from or resist disruptions before they occur (Flannery et al., 2018) to improving the resilience and reliability of the transportation system and reducing adverse impacts from natural hazards. Government and relevant agencies develop plans to retrofit or rebuild vulnerable assets in flood zone areas to ensure the region’s roadways are resilient to flooding. Among all the strategies focusing on improving transportation system resilience, transportation planning plays a critical role in guiding infrastructure development in hazard-vulnerable regions. Communities often create or adopt a network of independent plans, each of which focuses on addressing a specific resilience issue of the region. These plans, however, are often fragmented and poorly integrated (Berke et al., 2015) and can potentially increase the communities' vulnerability to hazards. Therefore, the combined effect of the network of plans on transportation resilience should be thoroughly investigated. Berke et al. (2015) developed a resilience scorecard that allows planners to assess the degree of coordination among plans to hazards. Inspired by Berke's resilience scorecard, the researchers developed a transportation-specific scorecard with the goal of improving transportation resilience planning for TxDOT. Rather than assessing the integration of the network of plans, the introduced transportation-specific scorecard focuses on evaluating state and regional transportation plans to examine the extent to which they improve redundancy, reduce vulnerability, account for system interdependencies.

# CHAPTER 3. RESEARCH APPROACH

## 3.1 TASK 1 DEVELOPMENT OF INTERVIEWS

The interview protocol design, based on a literature review, addressed questions related to resilience planning and project development in the transportation infrastructure system. The interview protocol was examined by the research team and the study oversight team. A snowball sampling method identified target interviewees. Data were collected from semi-structured interviews with 24 experienced staff from national, state, regional, and local jurisdictions. The interview data were analyzed to provide a better understanding of current practices, challenges related to the implementation of resilience, and desired tools to enable agencies to consider incorporating resilience measures into the transportation projects' planning and development.

The interviewees were from a range of organizations including, TxDOT, MPOs, FHWA, and the North Central Texas Council of Governments (NCTCOG). In total, 24 professionals were interviewed, with nine interviewees from TxDOT districts, eleven from MPOs, three from FHWA, and one from NCTCOG. The interviewees were selected based on their organizations, roles, and locations. These professionals served in roles such as district engineer, planner, and designer and were selected from urban and rural areas dealing with different hazard types across Texas. The sample provided sufficient diversity of perspectives to allow for the examination of the current state of practice for incorporating resilience from different points of view and to explore the challenges in incorporating resilience across districts and organizations. The list of interview questions can be found in the Appendix.

## 3.2 TASK 2 STATE-WIDE SURVEY

The survey focused mainly on addressing the following question categories:

- What hazards and threats cause disruptions to transportation infrastructure systems in various districts/regions in the State of Texas?
- What is the current state of practice in incorporating resilience in planning and project development of transportation infrastructure systems?
- What are the challenges, needs, and gaps in incorporating resilience?
- What are the characteristics and attributes of the tools, information, metrics, and data needed for the incorporation of resilience?

Figure 3.1 shows the qualitative research method employed to identify the current practices, challenges, and tools required to implement resiliency in the planning process, including the in-depth interviews and a survey that were conducted. Based on the knowledge from interviews and the literature review, the team constructed and deployed an online survey. The findings from the interviews informed the development of the survey questions. Survey respondents included a broader range of organizations and professionals in the transportation domain to examine the resilience incorporation in planning and project development. For example, interviewees counted and described different challenges that their organizations encounter for the incorporation of resilience. A list of different challenges based on the findings of the interviews was identified and included in the survey to further examine these challenges based on the perspective of broader professionals. A total of 58 responses were received (out of 195 invitations), which included responses from 19 out of 25 districts and 14 out of 23 MPOs in Texas. The survey questions can be found in the Appendix.

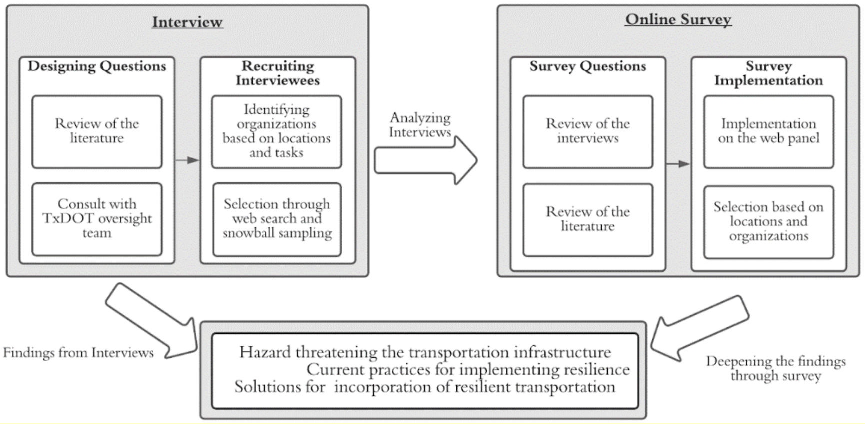

**Figure 3.1. Research Approach for Conducting the Statewide Transportation Resilience Survey.**

Figure 3.2a shows the spatial/geographic distribution of the responses to the online survey. As shown in Figure 3.2b, approximately 50 percent of the responses were from TxDOT and consisted mostly of responses from TxDOT planning, design, and maintenance departments. Of the remaining responses, 30 percent were from MPOs, Houston-Galveston Area Council (H-GAC), Brazos Valley Council of Governments (BVCOG), and New Mexico Department of Transportation (NMDOT).

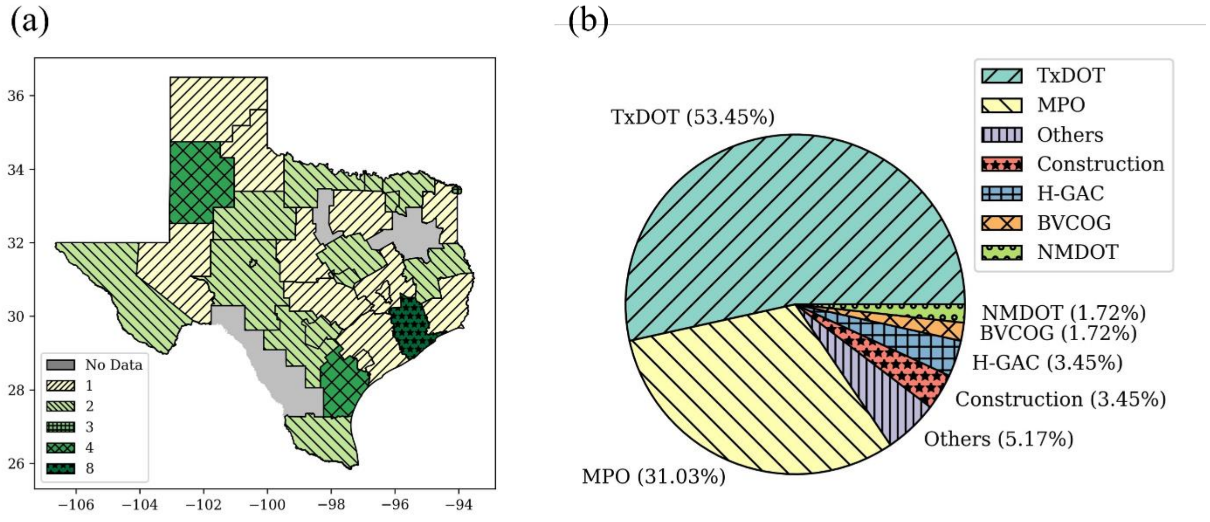

**Figure 3.2. Survey Respondents' Distribution; (a) Districts' and MPOs' Response Count (b) Distribution of Responses Based on Organization.**

### 3.2.1 Hazards Threatening the Transportation Infrastructure System in Texas

Interviews and results from the survey both revealed that extreme events and floods are the main threats to transportation infrastructure systems. Figure 3.3 and Figure 3.4 show the common hazards in the State of Texas as specified by the survey respondents. The respondents specified flooding, extreme weather events, such as hurricanes and storms, and extreme cold events as major hazards affecting transportation infrastructure in Texas. Furthermore, flooding seems to be a major concern in the majority areas in Texas. The need for updated flood maps and climate projection models for planning and project development of transportation infrastructure systems was mentioned repeatedly in interviews. Nonetheless, some guidelines and frameworks for climate adaptive planning and design for transportation infrastructure systems exist, such as the NCHRP[1] guide and FHWA vulnerability assessment and adaptation framework[2].

Furthermore, it is worth mentioning that while the general theme of the different hazard types was focused on the natural and climate-related hazards, human-induced hazards pose risks to transportation infrastructure systems. Interviewees repeatedly mentioned the impact of accidents and damage due to the low clearances of the underway. Other human-induced threats, such as cyberattacks, were mentioned by the interviewees among common hazards that may threaten transportation infrastructure systems, such as disruption to traffic signals and message signs. The consideration of human-induced hazards, however, is outside of the scope of this study.

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[1] http://onlinepubs.trb.org/onlinepubs/nchrp/docs/NCHRP1561DesignPracticesGuide.pdf

[2] https://www.fhwa.dot.gov/environment/sustainability/resilience/adaptation_framework/climate_adaptation.pdf

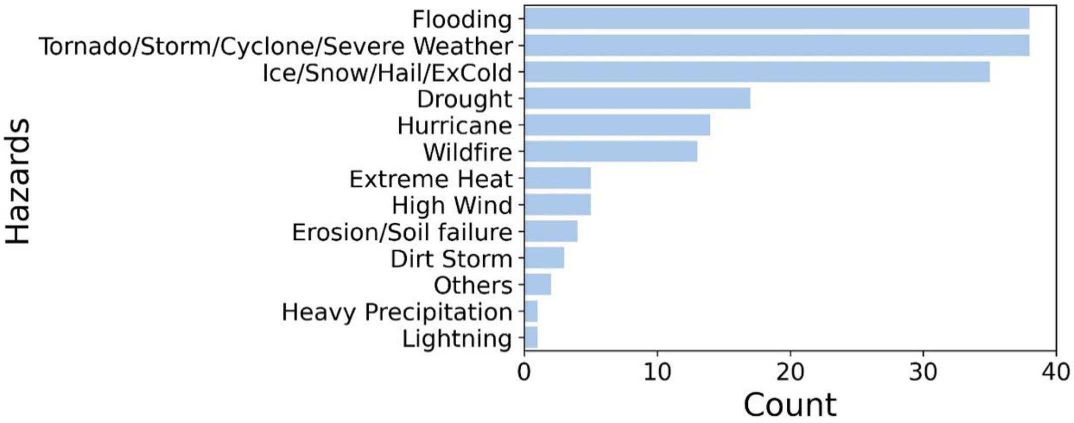

Figure 3.3. Hazard Count Based on Responses from All Districts.

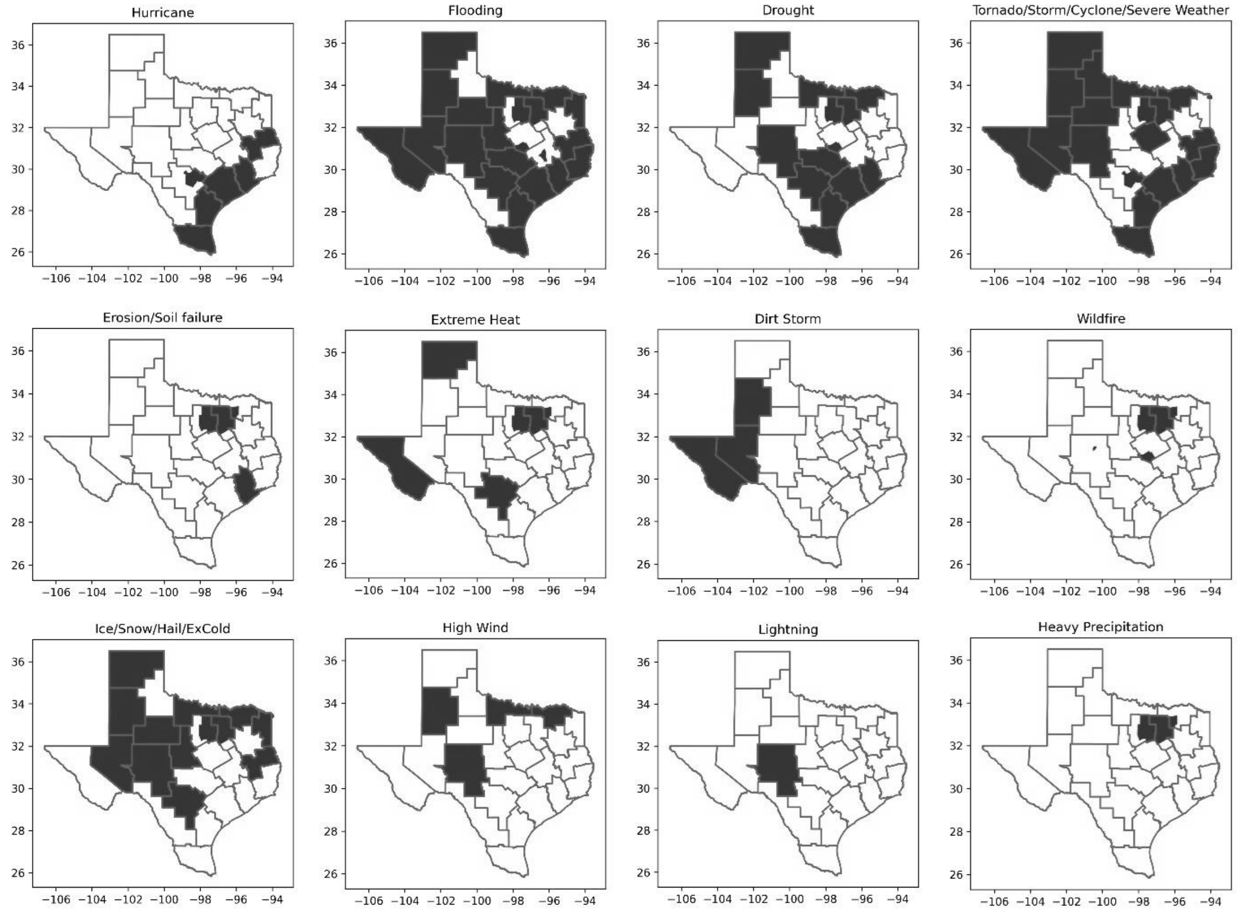

Figure 3.4. Natural Hazards of Concern by Respondents from Various Districts.

The presence and distribution of a variety of hazards posing threats to the transportation infrastructure system call for establishing the multi-hazard planning perspective. Results presented in Figure 3.4 indicate flooding and extreme weather events are the main threats of concern for the majority of districts. Hence, resilience assessments and best practices should focus primarily on these two hazards within a multi-hazard approach to resilience planning.

Severe weather events, such as tornados and storms, are prevalent throughout the state. Other hazards that impact transportation infrastructure in certain districts include dirt storms, extreme heat, and wildfires.

Respondents were asked to select the type of damage that the hazards in the region caused to the road infrastructure and the severity of the damages during recent events (Figure 3.5). It is clear that road inundation, road damage (e.g., potholes and cracking), and bridge scour are the predominant types of damage. Debris flow into rivers and streams is another source of damage to transportation infrastructure, particularly bridges. Also, some districts/areas have experienced complete slope failure, also called landslides. Some districts also mentioned frequent sinking of roads due to the presence of high-plasticity soil (e.g., road belts near the Wichita River). Hence, adequate geotechnical investigations to identify areas that are susceptible to sinkholes or slope failures are essential to assess resilience based on soil characteristics. These disruptions highlight the need for project-specific hazard considerations. One interviewee also mentioned that there is a need for resilience assessment for specific individual projects. Figure 3.5b shows the extent of impact of the damages on a five-point scale (i.e., 5 representing the highest level of impact, indicating damage to multiple roads and bridges, inundation of multiple road sections, and significant loss of access, and 1 representing no impact, indicating minimal physical damage to roads and bridges and no significant inundation and loss of access). The responses indicate that the coastal, central, and western parts of Texas seem to have a higher intensity impact of hazards compared to other regions.

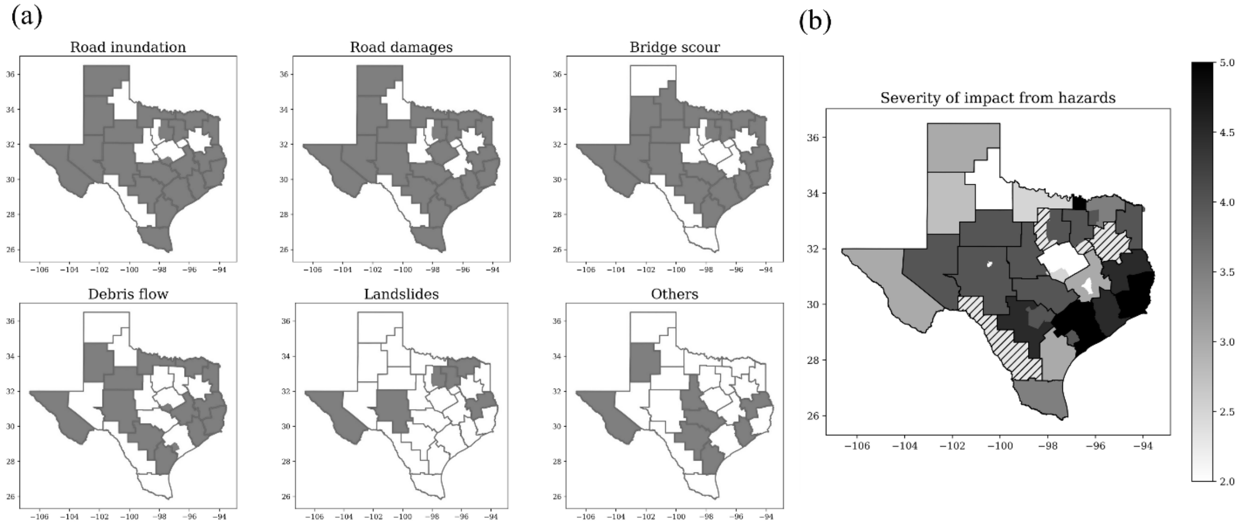

**Figure 3.5. Types of Road Infrastructure Damages (a) and Their Severity (b).**

### 3.2.2 Current State of Practice in Incorporation of Resilience

The research team examined the current state of practice related to resilience planning within TxDOT districts/departments and MPOs. Most interviewees mentioned that there is a significant need for the incorporation of resilience practices and methods in planning and project development practices; however, results indicate that resilience is not formally considered in the current transportation planning and project development. Most interviewees acknowledged that their organizations or institutions should consider resilience in transportation project planning, since they have noticed the severe impacts from the recent extreme weather events such as floods (e.g., Houston-Galveston area), wildfires (e.g., capital area of Austin), and storms (e.g., Atlanta District of northeast Texas). For instance, the Houston-Galveston area experienced severe impacts from Hurricane Harvey in 2017, with an inundation of large sections of the road network. These hazards were considered to some extent in their existing transportation project plans; however, there is a lack of assessment frameworks and tools to systematically assess road network vulnerability to inform planning and project prioritization decisions. Promisingly, local efforts are underway to improve the resiliency of transportation infrastructure. For example, the Odessa area has utilized design codes and performed geotechnical investigations to incorporate resilience in their project development processes. Their focus is to explore the geotechnical factors vulnerable to flood damage to seek solutions to proactively prevent the damage. The San Antonio area also considered resilience with a focus on enhancing the structural design of bridges to withstand future flooding and extreme weather events. These anecdotal examples show some local efforts and assessments; however, to operationalize resilience in transportation planning and project development, there is a need for statewide guidelines and practical tools to be used uniformly and consistently by districts and planning organizations across the state.

#### *3.2.2.1 Resilience Practices Vary in Rural and Metropolitan Areas*

A difference exists between rural areas and metropolitan areas in the manner by which they prioritize resilience. Interviewees from the non-metropolitan Rio Grande Valley area and the Waco and Atlanta districts have focused on traffic control and safety plans to reduce congestion and traffic incidents. It is observed that some rural areas have not considered resilience as a priority in transportation planning. Even though interviewees from rural areas such as the Pharr District and San Angelo District have realized the severe hazard impacts and necessity of incorporating resilience into transportation project planning processes, they are confronted with the issue of limited resources, such as the lack of design professionals with corresponding design experiences. In the rural areas, employing experienced transportation planners with solid design and disaster experiences remains a challenge since their new employees are recent university graduates without rich work experiences.

On the other hand, metropolitan districts seem to be more conscientious about incorporating resilience into their planning and project development practices. The metropolitan area of the Austin District has taken steps to consider resilience, such as a post-event assessment after major disaster events, identification of flood-prone areas, evaluation of road network redundancy, and consideration of soil conditions in frequently flooded areas. In another example, the Houston-Galveston area has created a vulnerability and criticality evaluation index system for evaluating road networks[3], which can support the prioritization of resilience investments for transportation planning. Compared with rural areas, metropolitan areas, including Austin, Houston, and San Antonio areas, have more financial and human resources to enable consideration and implementation of the resilience concept into transportation planning, even though in an informal way.

### *3.2.2.2 The Role of TxDOT and Coordination with MPOs for Incorporating Resilience*

MPOs rely on TxDOT's support for implementing resilience; however, neither TxDOT districts nor MPOs have formal guidelines for incorporating resilience into project development and planning. The interview results indicate that MPOs from different regions are aware of the need to incorporate resilience. For example, the interviewees from the Rio Grande Valley and San Antonio areas have indicated the lack of formal guidelines for incorporating resilience into transportation project planning. They also noted the need of a resilience checklist tool with essential scoring criteria for project evaluation and selection. The Corpus Christi area has used the regional travel model for assessing redundancies, although their model has some limitations related to insufficient fine-grained traffic data in resolution and time. The metropolitan area of Austin has employed some steps to incorporate resilience for project scoring, such as redundancy assessment and analysis of soil conditions. Although MPOs are aware of the significance of resilience in transportation planning, challenges still exist, such as lack of data support for implementing their methods and the need for a formal framework for considering resilience for transportation planning.

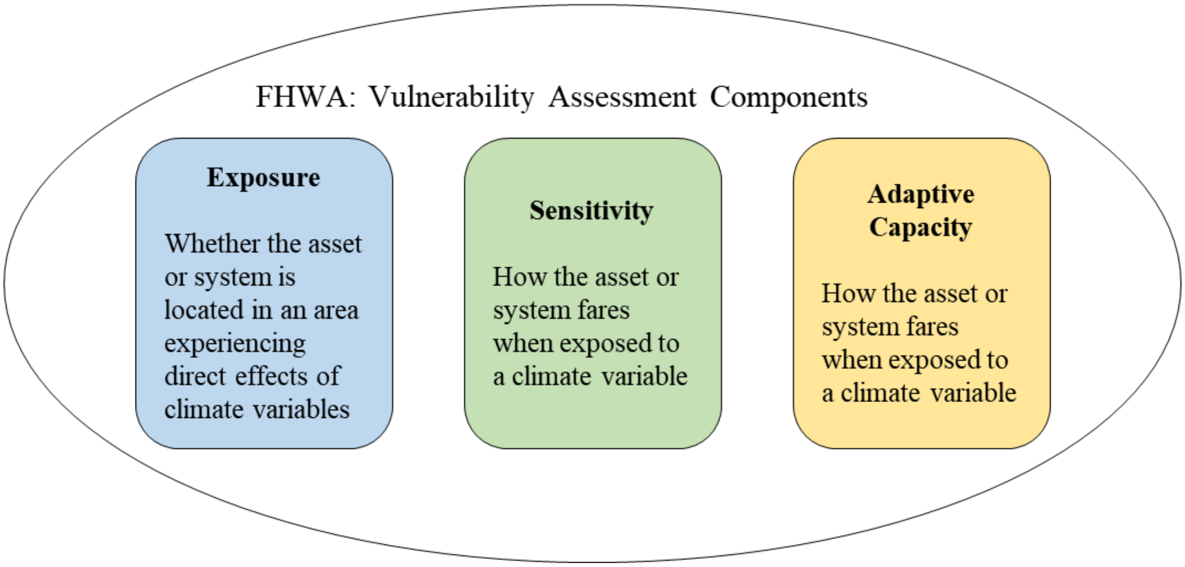

**Figure 3.6. FHWA Vulnerability Framework[4].**

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[3] https://www.arcgis.com/apps/MapSeries/index.html?appid=deae412562ab461ead3a1f0908ab22ee

[4] https://www.fhwa.dot.gov/environment/sustainability/resilience/adaptation_framework/index.cfm

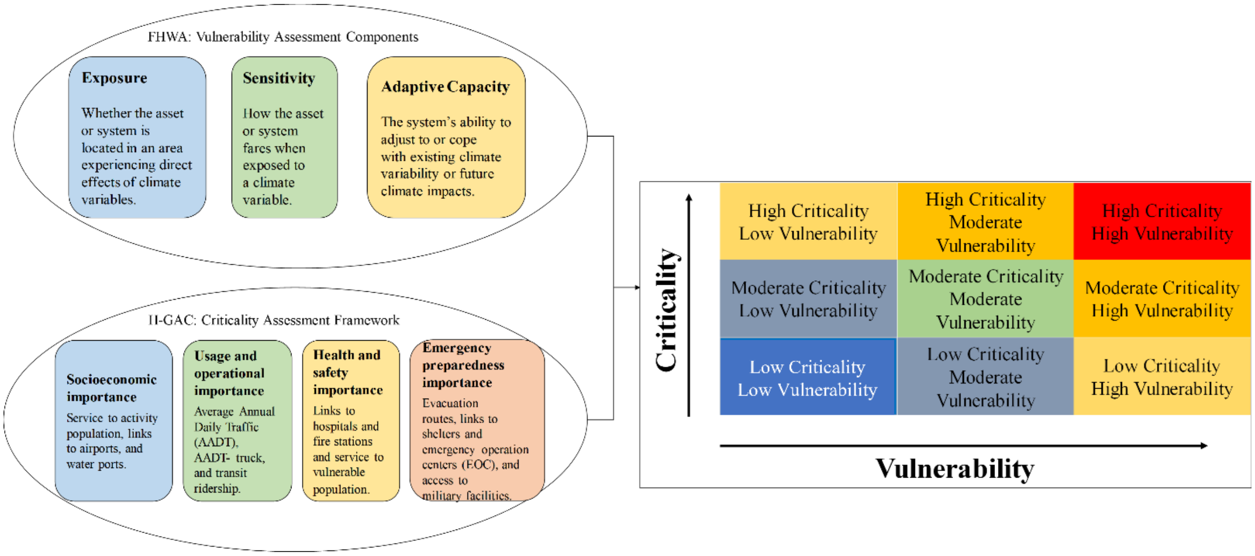

**Figure 3.7. H-GAC Multi-criteria Vulnerability-Criticality Assessment Framework (Adapted from H-GAC Resilience Program Report[5] ).**

### *3.2.2.3 Inconsistent Use of Existing Tools and Approaches for Incorporating Resilience*

Although tools and frameworks for incorporating resilience have been developed by various federal and state organizations, their adoption varies across districts and other jurisdictions. The current approaches for incorporating resilience can be divided into three categories: design, planning, and project selection. In terms of design, geotechnical investigation to identify potential hazards, design codes, and structural design considerations (e.g., elevating bridges) have been proposed and implemented by local TxDOT entities. The San Antonio and Odessa districts have implemented these design methods to incorporate resilience into transportation project planning after experiencing severe inundation. The planning approaches include consideration of flood maps, redundancy assessment for evacuation roads, FHWA vulnerability framework (Figure 3.6), multi-criteria vulnerability-criticality assessment in the Houston-Galveston area (Figure 3.7), and identification of frequent human- and natural disaster–caused hazards. Existing vulnerability frameworks, such as the Houston-Galveston area vulnerability and criticality evaluation index system, were developed after severe flooding impacted the transportation system. For the project selection approach, TxDOT institutions included open-ended questions related to resilience in the call for projects. The respondents specified the need for project scoring tools/checklists to assist with better incorporation of resilience during project development stages.

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[5] https://www.h-gac.com/getmedia/4a9d1f74-a43c-4279-8f82-f11da502e1e8/H-GAC-Resiliency-Pilot-Program-Final-Report.pdf

### *3.2.2.4 Multidimensional Resilience Assessment*

Resilience planning, by its nature, comprises the assessment of vulnerability and critical infrastructure, determination of redundancies, and evaluation of interdependencies with other systems and the resulting cascading failures; thus, a comprehensive resilience assessment must be multidimensional. This section introduces the multidimensional resilience assessment framework reflected in the interview and survey process (Figure 3.8). In addition to vulnerability and criticality as indicated in the FHWA vulnerability and H-GAC multi-criteria vulnerability-criticality assessment frameworks, the researchers identified four more dimensions for the resilience assessment of transportation projects, including interdependency, redundancy, cost-benefit analysis, and social-economic impact assessment.

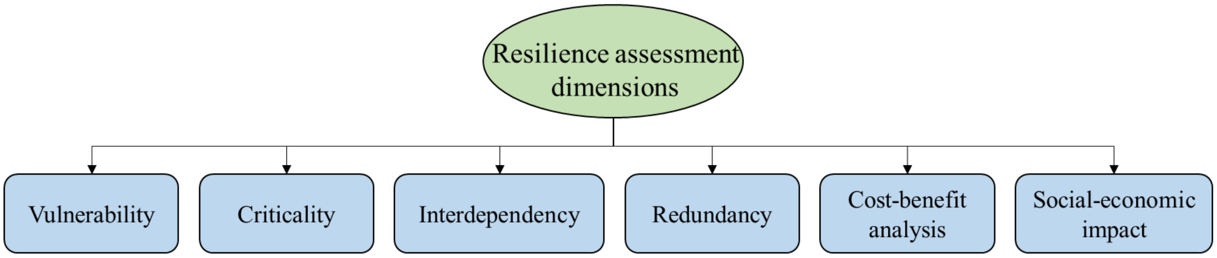

**Figure 3.8. Multidimensional Resilience Assessment Framework.**

To be specific, vulnerability refers to the extent to which a transportation asset is susceptible to sustaining damage from hazards, including climatic hazards. Vulnerability is a function of exposure, sensitivity, and adaptive capacity (FHWA Vulnerability Framework in Figure3.6.). Criticality measures which transportation assets are crucial to the region's routine functions and economic activities. Infrastructures now perform as a system of systems, exhibiting complex interdependencies that make critical functions vulnerable to cascade failure. For instance, failures of road links due to flooding can impact the accessibility of hospitals. Accordingly, interdependency is considered a critical dimension of resilience assessment. Redundancy here refers to the existence of alternative paths in case a certain path is not passable due to a disruption. This dimension can reflect the road network's response capacity to deal with disasters. A cost-benefit analysis refers to the process of comparing the projected or estimated costs and benefits (or opportunities) associated with a project decision to determine whether it makes sense from a business perspective[6]. For resilience enhancing projects, the challenge is to quantify the benefits (e.g., prevented costs or public safety) given the uncertainty of future natural hazards. The last dimension is a social-economic impact assessment mentioned by the interviewees. This dimension refers to the impact of incorporating resilience on people's daily life and social and economic development.

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[6] https://online.hbs.edu/blog/post/cost-benefit-analysis

### *3.2.2.5 Implementation Levels of Resilience Practices*

Based on the review of the literature, the research team identified 47 resilience practices in the infrastructure systems. In the survey, the respondents were asked to rate, on a five-point scale, the extent to which these resilience practices are implemented in their districts/organizations. Then, the research team calculated the aggregated score of each resilience practice and normalized the score by the number of survey participants. Therefore, the normalized score of each resilience practice represents its overall implementation level for the survey respondents. (Please see the Appendix for responses to questions Q11 to Q13.)

## 3.2.3 Process for Incorporating Resilience

Based on the findings of the interviews and survey responses, a process is needed for the systematic consideration of resilience in transportation planning and project development (Figure 3.9). These necessary components for a systemic resilience program include: (a) proper policy and procedures for encouraging proactive resilience planning, (b) adequate funding and financing for considering resilience, (c) knowledgeable and dedicated staff for incorporation of resilience, (d) within- and cross-organizational coordination and information sharing, and (e) suitable tools, metrics, and data. The following sub-section describes the existing challenges with the adoption of a systemic program.

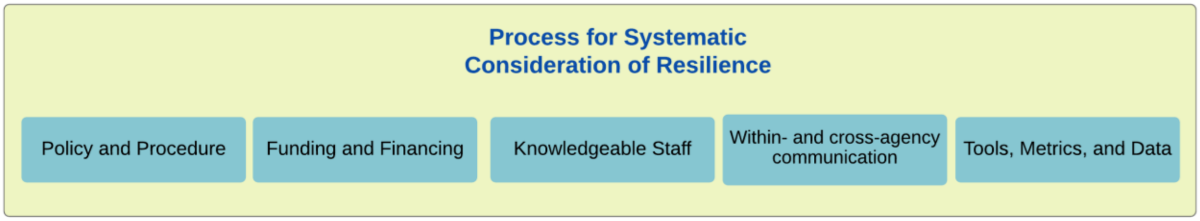

**Figure 3.9. Elements Needed for Systematic Consideration of Resilience in Planning and Project Development of Transportation Infrastructure System.**

Figure 3.10 summarizes the survey results from respondents from districts and MPOs regarding challenges inherent in incorporating transportation planning and project development. The most pressing issue is financial constraints. Financial limitations were highlighted consistently in all interviews conducted by the team; some areas struggled to find funding even for routine projects. Moreover, survey respondents mentioned that they lack the manpower and the resources to implement required assessments and would need targeted funds for the purpose of incorporating resilience.

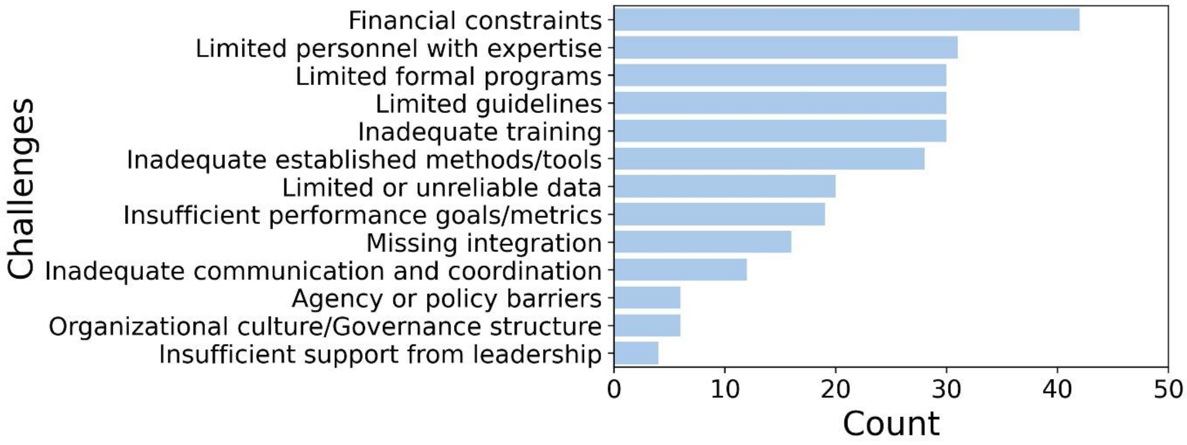

**Figure 3.10. Challenges Related to Incorporating Resilience.**

### *3.2.3.1 Proper Funding and Financing Are Needed to Enable Organizations to Incorporate Resilience and to Encourage Proactive Actions*

Inadequate resources is a major challenge in incorporating resilience in transportation planning and project development. Resources needed include funding, especially of costs related to data management. Resources, however, are not distributed equitably. Generally, less densely populated areas are more severely challenged with the lack of project funding than more densely populated areas. Therefore, although organizations in these areas are aware that resilience is an important aspect of the planning process, they are unable to prioritize it. This information suggests that an adequate amount of resources should be allocated for those smaller areas to make them capable of enjoying the long-term benefits of incorporating resilience. Another challenge with funding, as one of the respondents mentioned, is "*funding resilience requires diverting funds from other areas, and no one wants to give up their funding.*"

The financing of resilience-enhancing projects seems to be another major challenge. In fact, the existing funding scheme does not incentivize proactive resilience investment. This observation was acknowledged when a participant mentioned that "there will be a flow of cash when the area is affected by a hazard, so why would we prioritize resilience instead of using the money for other projects and wait until the area is affected to fund the resilience project." The current financing approach incentivizes a reactive approach rather than a proactive approach. Hence, there is a need to implement appropriate funding and financing schemes to finance resilience-enhancing projects. The U.S. Government Accountability Office recognized this issue and published a Disaster Resilience Framework outlining the federal opportunities to facilitate and promote resilience to natural hazards[7, 8]. Incorporating resilience requires proactive planning for

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[7] https://www.gao.gov/assets/files.gao.gov/assets/gao-20-100sp.pdf

[8] https://www.gao.gov/assets/gao-21-561t.pdf

identifying the vulnerabilities of the systems and developing mitigation strategies by reducing the impact or improving the restoration capacity.

#### *3.2.3.2 Knowledgeable Staff and Education on Transportation Resilience Are Needed for Better Incorporation of Resilience in Planning and Project Development*

Since resilience is a relatively new concept in the transportation domain, some organizations consider the lack of skilled and knowledgeable personnel a barrier to incorporating resilience. They believe that their organization needs education for defining resilience and how it could be implemented into their plans and project development activities. Some organizations' perspective of resilience is closer to safety and risk management, which may not necessarily capture the dimensions of resilience. This trend was apparent, especially in smaller organizations, which also stated that their organization needs to develop a definition of resilience. These results also suggest that, in addition to webinars and guides for training the personnel, tools developed for the incorporation of resilience should be designed to be used by organizations with different levels of expertise and size.

Initiatives and formal focus groups, such as the State of Texas Resiliency Working Group lead by the Association of Texas Metropolitan Planning Organization and the Texas A&M Transportation Institute, are effective in promoting resilience education and support for the incorporation of resilience in transportation infrastructure systems. Such groups and initiatives could contribute to resilience enhancement by knowledge exchange, communicating lessons learned, and by informing about the frameworks and guides that organizations could use to incorporate resilience in their plans and project development. Furthermore, periodic webinars, workshops, and similar events are needed to better inform planners about the long-term benefits of resilience incorporation and approaches to implementation customized to their capabilities.

Furthermore, some areas have made progress in developing tools and approaches for considering resilience in transportation planning. These organizations could share their findings to help others in planning for future events. Thus, collaborating and sharing the lessons learned through initiatives and working groups would highly benefit everyone in addressing such challenges. Workshops, groups, and resilience champions could play a vital role in developing a community for enabling resilience incorporation.

#### *3.2.3.3 Measuring the Benefits of Resilience Could Greatly Improve the Transportation Resilience Practice*

The MPOs stated that they face a major difficulty in communicating the benefits of resilience to their board. While resilience seems to provide long-term benefits to the organization and enhances public safety and welfare, there is no standard way to measure its benefits; therefore, some board members fail to recognize the incorporation of resilience as a priority. Thus, standard methods and metrics for quantifying the benefits of resilience investments could enable communication of the social and economic benefits of incorporation of resilience to encourage more resilience investments in the projects. As mentioned by the respondents, the implementation of resilience is sometimes challenging, since some departments are limited to planning and have no governmental authority or power. An interviewee mentioned that it is believed that investing in projects that lead to the development of quick and visible benefits seem to be preferred over those that bring about hidden long-term benefits which may not largely be appreciated by the public.

#### *3.2.3.4 Efficient Communication and Collaboration within and across Organizations Is Needed for Transportation Resilience Planning*

Various organizations face challenges obtaining relevant documents (e.g., hazard mitigation plans) from other organizations. For example, a respondent mentioned that when attempting to check the most recent hazard mitigation and development plans, the responsible organization was not open to sharing that information. In another example, data needed to analyze the impact hazardous events could have on road sections were unobtainable. While some of this information is available, obtaining the information seems to be a challenge. Therefore, proper coordination and information sharing management would highly benefit the organizations in the incorporation of resilience.

#### *3.2.3.5 Implementing and Developing Certain Tools, Metrics, and Data Could Highly Assist In Incorporating Resilience*

The development and maintenance of data and models for considering resilience were major challenges. Proper data are needed for conducting vulnerability assessments, determining redundancies, and evaluating interdependencies with other infrastructure systems. Maintaining data, however, is challenging, since not all organizations have the capabilities and resources to afford data management. Models, such as flood risk models, are sometimes outdated; there is a need for new methods for evaluating vulnerabilities. For example, respondents mentioned that flood maps and hydrological models need to be updated to account for recent changes and trends of hazards in the areas. In addition, as acknowledged by most interviewees, there is a need for new tools and methods for assessing vulnerable and critical road sections and bridges, as well as for evaluating cascading failures. The next section discusses tools, data, and metrics that could be used to better incorporate resilience in the planning and project development of transportation infrastructure systems.

### 3.2.4 Tools Needed to Incorporate Resilience

The interviewees and survey respondents described the characteristics of tools that would enable them to better incorporate resilience into their planning activities. As mentioned by several interviewees, resilience is a multi-dimensional assessment. It includes the assessment of vulnerability, specification of critical infrastructure, determination of the required redundancies, and evaluation of interdependencies with other systems and the resulting cascading failures.

Thus, there is a need for tools that enable assessing resilience from different aspects. For example, one interviewee mentioned that it is important to consider how vulnerable the system is to the hazard, and the system should also have redundancy to recover quickly from the potential damages. Another interviewee stated social vulnerability as an essential aspect of resilience. The tools used for resilience assessment must consider the summation of social, technical, and economic aspects.

In terms of the desired tools and information, the responses ranged from a standard guide, which includes resilience objectives, dimensions, and metrics, to a scorecard for rating the extent of organizational implementation of resilience practices. Findings from the interviews and the survey highlighted the need for tools for: (a) assessing organizational implementation of resilience practices to help different organizations assess and improve their capabilities for resilience planning and project development, (b) resilience assessments for regional planning and project prioritization, and (c) project-level evaluation of resilience considerations.

#### *3.2.4.1 Multidimensional Tools Are Needed for a Comprehensive Organizational Assessment and Inclusion of Resilience*

The interviewees frequently cited a scorecard to be an effective tool for assessing the implementation levels of and identifying the gaps in the organizational-level practices. As an interviewee mentioned, there is a need for ways to assess the progress, rather than qualitatively assess resilience, for being able to evaluate and prioritize resources; hence, a scorecard would be very beneficial in the incorporation of resilience at the organizational level.

#### *3.2.4.2 Resilience Assessment Maps Are Highly Effective for Transportation Planning and Prioritization*

Strongly cited as tools for enabling the incorporation of resilience into project planning, maps are effective for analyzing the spatial distribution of transportation systems' vulnerability and criticality. Maps are useful for understanding the extent to which the transportation infrastructure systems are exposed to the threats. The interviewees also mentioned, however, that there is a need for ways to consider the future changes in the vulnerability maps and to facilitate their update in light of changes in the climatic patterns.

Criticality of road segments is also an important aspect of resilience assessment. Access to critical facilities, cascading failures, providing emergency services, road volume demand, and social-economic impacts are examples of ways to evaluate the criticality of the transportation systems. A road section may not be highly vulnerable to a hazard (e.g., flooding); however, it might be critical in terms of providing access to other critical facilities (e.g., hospitals or power substations).

#### *3.2.4.3 Checklists and Cost-Benefit Analysis Frameworks Are Highly Beneficial for Better Incorporation of Resilience into Transportation Project Development*

Checklists and flowcharts are helpful to ensure that various key resilience considerations are accounted for during project development and planning. Interviewees mentioned that a checklist or flowchart could greatly help them to ensure that several resilience considerations are addressed in the project and assist them in the project development. These considerations include, but are not limited to, the use of the latest flood maps, evaluations of hazards such as sinkholes and landslides, reduction of vulnerability, and enhancement of redundancy.

Cost-benefit analysis is an important step in justifying resilience-enhancing investments. Current approaches for determining the benefits of resilience investments in infrastructure focus mainly on reduced costs due to assessing vulnerabilities and avoiding disruptions. These benefits would become apparent in the long term. The cost of resilience implementation depends on the different alternatives for resilience investments. These strategies include using alternative designs (e.g., expanded drainage capacity or elevating bridges), adding redundancy, and enhancing flood resilience. However, it is worth mentioning that calculation of the benefits and avoided cost is not always straightforward. For example, the future benefits of resilience investments could vary based on the intensity of future extreme weather events. Thus, prediction of the future climate scenarios becomes very important in devising a cost-benefit approach for resilience incorporation of transportation infrastructure systems.

### 3.2.5 Data and Metrics for Multidimensional Resilience Assessment

Metrics and data are needed to enable the incorporation of resilience into planning and project development of transportation infrastructure systems. The researchers asked participants in the interviews about the metrics needed for tracking resilience of transportation systems and the data required for determination of these metrics. Survey responses were examined to elicit a list of useful data and measures which the respondents believed would be beneficial in the incorporation of resilience in planning and project development. Interviewees specified certain data and approaches for measuring resilience to be helpful in the incorporation of resilience into planning and project development.

#### *3.2.5.1 Key Data for Resilience Assessment*

From the interviews and survey, the researchers identified five types of key data required for resilience assessment: (a) updated flood maps, (b) updated climate projections, (c) road/bridge conditions, (d) impact/damage data, and (e) criticality of road segments. Figure 3.11 illustrates examples of these required data and how they can be used for implementing the multidimensional resilience assessment. Different data and metrics are needed for considering the various dimensions of resilience as mentioned in the overview of Question 2 responses.

These data and metrics would enable comprehensive resilience assessment for transportation infrastructure systems.

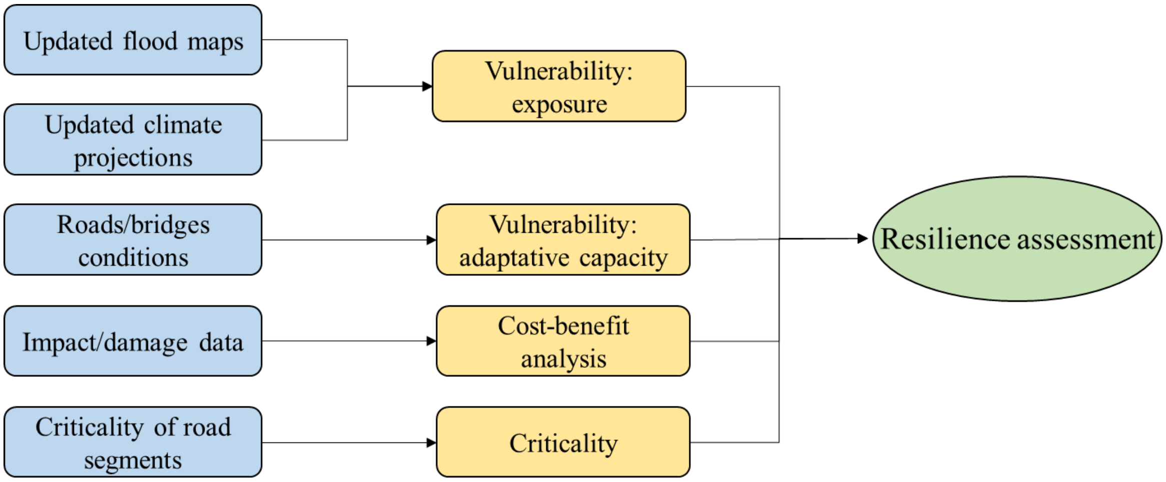


**Figure 3.11. Essential Data for Transportation Project Resilience Assessment as Reflected in Interviews and Survey Responses.**

Specifically, updated flood maps and climate projections refer to flood exposure data, characteristics of watersheds adjacent to road sections, and changes in watershed conditions that can impact vulnerability of the road sections. These data inform the planners of the systemic physical vulnerability to hazards. In addition, some interviewees noted the importance of data related to the condition of roads and bridges, such as the state of erosion and scouring. Based on climate trends, identification of areas that are at risk of this type of hazard should be updated. For example, the repeated occurrence of floods in an area requires the flood maps to reflect the up-to-date estimation of flood probability. These data help define the adaptive capacity of transportation infrastructure systems and further support the vulnerability assessment. Also, the impact/damage data highly benefits the resilience assessment. Documentation of the previous events and damages have been cited by interviewees as proper references for impact assessment data. The number of roads shut down due to a hazard, duration of the interruption, and repair cost data are among examples of the data cited by the interviewees as essential pieces of data for impact assessment. Including impact data in life cycle cost-benefit assessments enables communication of the benefits of resilience incorporation to stakeholders as well supporting resilience assessments.

Furthermore, interviewees mentioned information necessary to inform about the criticality of the road segments, which refers to the importance of the road segment in the ability of the road network to provide service with minimum disruption (e.g., extent to which the road segment contributes to the redundancy of the system). An interviewee mentioned that in their area, one bridge is the sole access to reach a destination; therefore, the bridge is an essential component of their transportation infrastructure system. Such information is highly valuable in resilience assessment. Moreover, roads that provide emergency services for evacuation are critical during hazard events since the failure of those sections could be a significant consequence on the residents. Interviewees highlighted data that could support assessment criticality of roads and further the assessment of resilience of the transportation system. For example, district-wide traffic data, street network connectivity, and as-built and elevation data of the road sectors were mentioned to be useful for assessing the criticality of road segments and predicting the impacts of future events.

#### *3.2.5.2 Key Metrics for Resilience Assessment*

Based on the inputs from the interviews and the review of the literature, the researchers identified resilience measures used by organizations for resilience characterization or have been proposed by scholarly articles as proper metrics for resilience assessment in transportation networks. The researchers assessed the list of measures and grouped similar measures to provide a short list of measures to be included in the survey. Finally, the researchers narrowed the list of resilience measures to 20. The survey was then implemented to investigate: (a) What existing metrics and methods are used for measuring resilience and related concepts in transportation networks? (b) What desired measures can help organizations better characterize the state of resilience of the transportation network? In accordance with the multidimensional resilience assessment framework introduced in Figure 3.11, the researchers included measures that captured the dimensions of resilience. For example, the researchers included roads/bridges condition, road capacity, and hours of congestion as measures of vulnerability, alternative routes as a measure of redundancy, road criticality as a measure of criticality, and total number of stormwater projects as a measure of interdependency. It enables the identification of dimensions of resilience that are currently considered for characterization of resilience. Moreover, dimensions can be recognized that are currently not considered in resilience assessment, but practitioners highlight the need for their incorporation.

Results show a mix of measures among organizations; however, the level of adoption varies. Some measures are more frequently used, while other measures have not been adopted by a majority of participating organizations. Road condition, road capacity, and hours of congestion are more frequently used. These component-level measures are primarily used for other purposes, such as repair and maintenance (i.e., roads/bridges condition) and traffic analysis (i.e., hours of congestion). Since these three measures are related to the vulnerability dimension, the researchers inferred this dimension serves as a proxy for the resilience measurement. Road criticality is the fourth most frequently used measure, which often considers system-level properties of a transportation network for quantification of the criticality dimension. Considering alternative routes as a measure of redundancy, results indicate that certain dimensions of resilience are primarily focused on resilience characterization in transportation networks. In contrast, certain dimensions, such as cost-benefit analysis and social-economic dimensions, are not currently prioritized in resilience characterization. For example, the researchers found that funding adequacy is the least frequently used measure stated by the participants. This indicates that the funding is often excluded from the assessment of resilience in projects and plans, which may reveal a lack of systematic approach for considering budgeting for resilience considerations in planning and project development practices. Moreover, measures related to short-term recovery and response phases of a hazard (e.g., restoration rapidity, accessibility, and area under the curve) are amongst the least frequently used measures. This indicates the need for a framework to quantify the short-term impacts of the hazard in the analysis.

The researchers asked participants their opinion regarding the usefulness of each measure. Participants could select one of three options (i.e., not useful, potentially useful, and must have/very useful). The responses to this question could reveal what type of measures, if available, help organizations better understand the state of resilience in the transportation network. Also, it can indicate which properties and dimensions of resilience are believed to be of great importance from practitioners' perspectives. The score was assigned by giving a weight to each option (0 = not useful, 1 = potentially useful, 2 = must have/very useful) and averaging the responses.

Results indicated that the measures with a high score are often the most frequently used. For example, road condition, road capacity, and criticality are among the top five measures, with the highest score and the top five measures based on the current use of the measure in organizations; however, some differences exist between the currently used measures and the measures perceived to be useful. For example, the total number of stormwater improvement projects is a measure generally perceived as very useful (score = 1.37) but is only used in the organizations of less than 36 percent of participants. This indicates the need for incorporation of interdependency between flood control infrastructure and road network in resilience characterization. Similarly, resilience funding adequacy (score = 1.40) is considered as a measure of resilience in transportation planning and project development practices in 14 percent of participants' organizations, although it is recognized as one of the most useful measures for resilience assessment. The annual percentage of routine culvert inspection completed is among the measures that are perceived to be highly important for resilience assessment by participants. Time to start restoration (score = 1.19) and restoration capacity (score = 1.22) are among the lowest scored measures. These measures are mainly important for emergency response, but planners and designers should also take them into consideration during planning and project development, particularly when considering the social-economic impact dimension of resilience. Moreover, the researchers concluded that accessibility, as a system-level measure that focuses on the serviceability of the transportation network, is neither among currently used measures nor must-have measures based on participants' opinions.

## 3.3 TASK 3 ROAD VULNERABILITY ASSESSMENT

This study implemented quantitative and computational research methods for the resilience assessment of road networks. As shown in Figure 3.3, the research approach first identified quantitative metrics for the resilience assessment of road networks. With those metrics, the researchers then incorporated additional information, such as evacuation routes, to understand the criticality of road networks. Lastly, all of the results and information were integrated into a geographic information system–based map for practical usage. In this section, the authors briefly outline how the quantitative metrics are calculated for road networks; further specific discussions can be found in the sections devoted to these metrics.

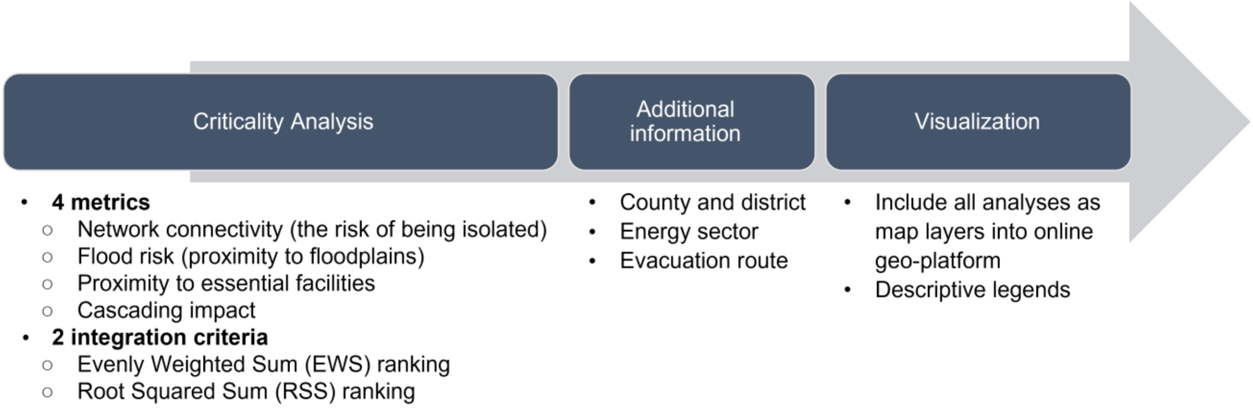


**Figure 3.12. Research Approach for Conducting the Vulnerability and Resilience Assessment of State Road Infrastructure Networks.**

First, the researchers evaluated the criticality of individual road segments for the connectivity of the road network, a characteristic that is particularly important in disasters. For example, residents rely on connected roads to evacuate, and first responders need to access impacted areas to save lives and protect properties. During disasters, fragmented networks may isolate areas, block transportation resources, and create traffic congestion. In addition, disruptions or floodwaters on road networks may spread over time. Measures considering static road network failures only may fail to capture the interconnections of road segments and consequent impacts of flood propagation. Hence, in this task, the researchers adopted percolation analysis to simulate how road failures spread from one road segment to another and the extent to which failures of road networks influence their connectivity. In the case study, the researchers collected road network data from the TxDOT roadway inventory On-System dataset updated on August 8, 2021, to perform these analyses and compute this criticality metric for road segments. This dataset includes details about the geometries of the road segments, road types, speed limits, and names of the roads. Also, the data include both highways and streets in urban and rural areas in Texas.

The second metric is the criticality of road segments to disaster impacts, which, in this study, are caused by flooding. The area of the case study, the state of Texas, especially South Texas, is prone to extreme events, such as flooding and hurricanes. Determining the criticality of road segments during flooding events is important for planning and prioritization in response to the disruptive impacts of flooding. Hence, the researchers collected 100- and 500-year floodplain data, which are the most recent nationwide extract of the NFHL for Texas. The NFHL dataset was obtained by FEMA for examining road exposure to flooding. The data include flood map panel boundaries, flood hazard zone boundaries, and other information related to flood control zones and areas. Using this data, the researchers identified the areas of flood zones and calculated the proximity of road networks to the nearest flood zones. Based on the proximity, the researchers classified the distance into five categories representing the level of criticality of the road segments to flood.

Third, the researchers analyzed the criticality of road segments based on the impacts of road disruption on access to critical facilities such as hospitals and fire stations and critical infrastructure networks such as gas lines and oil pipelines. One essential role of the road networks is to transport resources and provide public services. Accessing critical facilities is thus an important component of road network resilience assessment. The researchers implemented two metrics to evaluate the criticality of road segments based on the interdependencies, measured based on distance buffers, between road segments and facilities. In particular, one metric is measured using the proximity of road segments to critical facilities, while another metric is measured based on the closeness to critical infrastructure networks. The researchers collected facility location data from Homeland Infrastructure Foundation Level Data (HIFLD) in the ArcGIS data repository, as well as energy sector data and evacuation route data from TxDOT, which included information of facility types and corresponding locations. The researchers then extracted the location information for each of the critical facilities, such as electrical substations; power plants; hospitals; national shelter facilities; seaports; petroleum, oil, and lubricant (POL) terminals; fire stations; and police stations, as well as for each of the critical infrastructure networks, such as railroad networks, transmission lines, gas lines, hydrocarbon gas lines, and oil pipelines, which are essential for resiliency. Disruption in access to these facilities and infrastructure networks can exacerbate the impacts faced by communities during and in the aftermath of disasters.

Finally, it is important to evaluate the overall criticality by considering all dimensions of the resilience of road networks. To this end, the researchers devised two integration approaches to show the overall criticality of the road segments. The first method was to rank overall criticality based on the evenly weighted sum of all individual criticality metrics of each road segment. The second approach was based on the root squared sum ranking, by which the overall criticality score is calculated by taking the square root of the sum of squares of individual metrics. In the case study, the researchers computed the integrated criticality metrics for all road segments in Texas. The results for all metrics—including four individual and two integrated metrics—can be mapped onto GIS-based maps for visualization and to provide opportunities for further incorporation with the other resilience dimensions or critical considerations. Detailed information for each metric, including individual and integrated metrics, is discussed in the following sections.

### 3.3.1 Connectivity of Road Segments

The TxDOT Roadway Inventory shapefile updated on August 8, 2021, was the only dataset utilized in this part of the analysis. The network topology solely determined the network connectivity. The original road network file contained multiple lanes and complicated intersections. To perform the network analysis, the original road network file needed to be simplified. Multiple lanes on the same road were merged into a single central line if they were close enough to each other. The simplified road network was then transformed into a topological network model where all intersections and road segments are represented as nodes and links (Figure 3.13).

The connectivity of road segments is determined by the percolation analysis performed on the road network. The percolation analysis is an analytical technique that helps to understand to what extent a road segment contributes to the network's overall connectivity. The procedure for the percolation analysis is to remove nodes and links based on certain criteria and measure metrics that describe the change in network structure after being disturbed. When the more critical road segments are perturbed, they are more likely to cause more significant disconnection in the network.

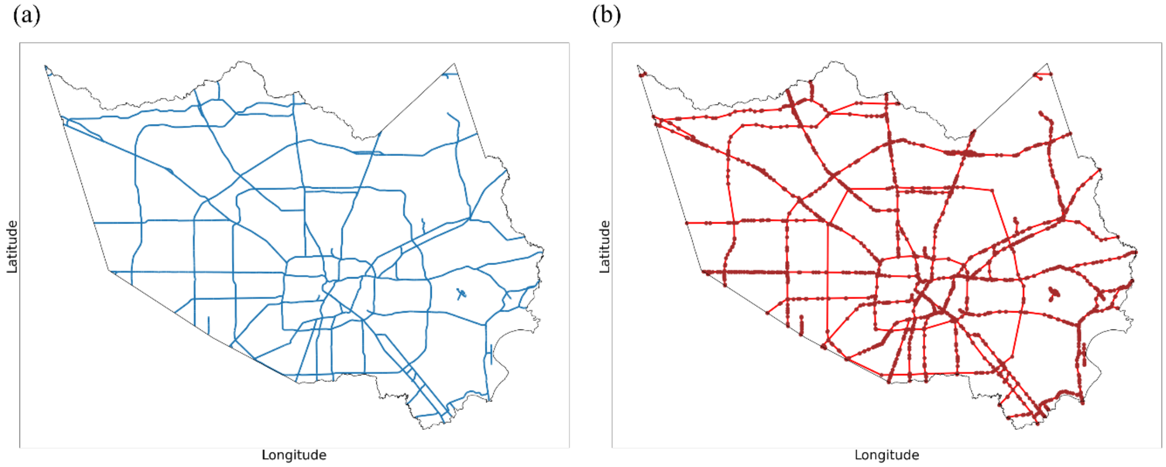


**Figure 3.13. Transforming Original Road Network to Network Topology Model (Example Illustration for Harris County, Texas). (a) Original Road Network and (b) Network Topology Generated from Original Road Network.**

While natural hazards like flooding perturb the road network, some of the components within the network may fail and other parts of the network could be disconnected and isolated. The percolation analysis mimics this process by sequentially removing the nodes in the topological network. Several standard criteria exist that rank the criticality of the components within the network and include node attributes such as degree, weighted degree, link betweenness, and size of the giant component. Figure 3.14 shows an example of removing failure links and recording the size of the giant component to understand the impact of perturbations of road networks. To obtain the worst scenario, the researchers applied the "node degree" link removal strategy for simulation. That is, this study identified failure links by removing nodes in the topological network from those with high degrees (i.e., the number of connections to that node) to low degrees. In the real-world situation, it is unlikely that all the nodes with higher degrees all fail at the early stage. During each removal stage in this analysis, essential characteristics were recorded, including the proportion of isolated links and critical transitions. Figure 3.15 depicts the steps for computing this metric. Figure 3.16 shows the five stages of failure at 20 percent increments (no failure, 20 percent failure, 40 percent failure, 60 percent failure, and lastly 80 percent failure). Critical transitions can be good indicators when assigning criticality levels to road segments, but they do not always exist. The road segments are grouped into five criticality levels. The first 20 percent of isolated road segments are assigned level 1 and the last 20 percent as level 5.

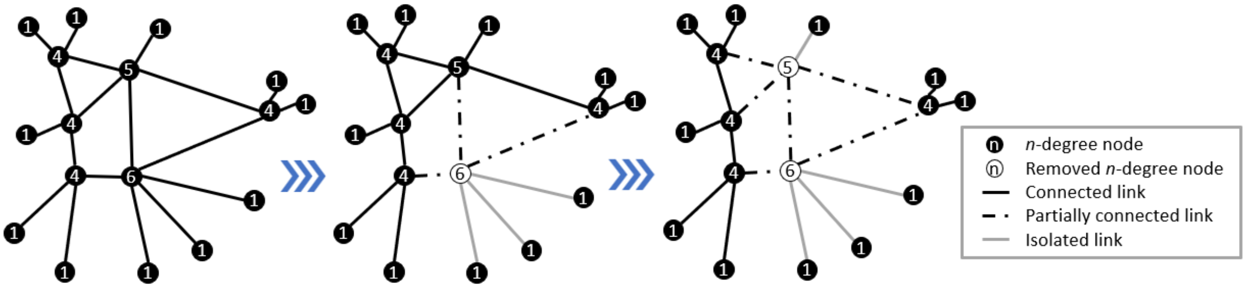


**Figure 3.14. Example of Percolation Analysis by Removing Failure Links and Recording Size of the Giant Component.**

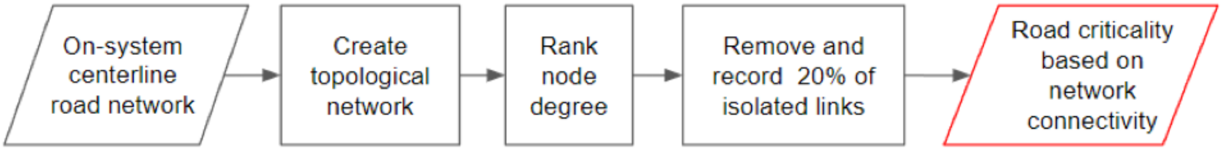


**Figure 3.15. Steps for Evaluating Criticality of Road Segments Based on Network Connectivity.**

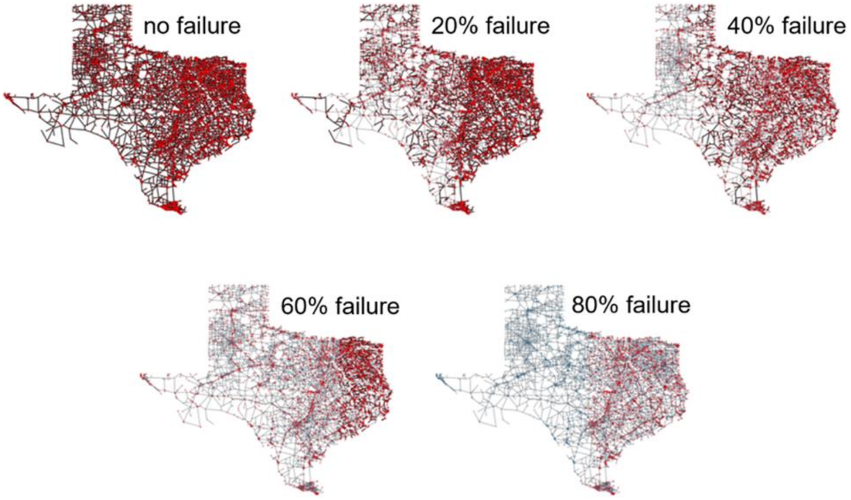


**Figure 3.16. Remaining Links at Five Stages of Failure after Removing 20 Percent of Nodes.**

### 3.3.2 Vulnerability to Flooding

From the survey results in Task 2 of the project, researchers found flooding is the most prominent hazard of concern for TxDOT districts and MPOs. Therefore, this component of the analysis particularly focused on the exposure to flood hazards determined by the proximity of road segments to floodplains. The NFHL provided by FEMA that can be acquired on DATA.GOV website is the most comprehensive floodplain data source. However, floodplain data are only available for some districts, including the largest urban areas in Texas, and missing in some of the northwestern counties in Texas (as shown in Figure 3.17). FEMA flood zones are geographic areas that FEMA has defined according to varying levels of flood risk. Each zone reflects the severity or type of flooding in the area. Based on the definition of flood zones, the researchers distinguished the 100-year floodplain, 500-year floodplain, and the others. Each of the 100-year and 500-year floodplains consists of several subcategories. The 100-year floodplain means there is a 1 percent annual flooding probability and is identified as high risk, while the 500-year floodplain means there is a 0.2 percent annual flooding probability and moderate risk. Regions located outside the 500-year floodplain will be identified as minimal risk or unknown risk. Flash floods are not considered in this analysis.

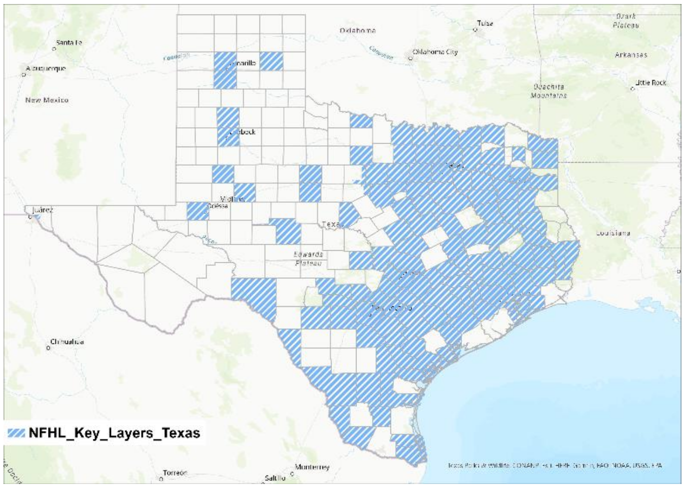


**Figure 3.17. Floodplain Data Availability in Texas.**

The criticality level of the road segments is determined based on their proximity to floodplains. ArcGIS is used to perform geo-processing tasks, including: (a) identifying road segments whose midpoints are located in the 100-year floodplain and the 500-year floodplain, and (b) calculating the distances from the midpoint of the rest of the road segments to the boundary of the 500-year floodplain. Then, the researchers determined each of the road segments belonging to one of the five criticality levels. Figure 3.18 is an example of assigning criticality levels in central Houston. Figure 3.19 shows the framework for computing this metric. The roads with their midpoint located in the 100-year floodplain are assigned to level 1. The roads with their midpoint located between the 100- and 500-year floodplain are assigned to level 2. Level 3 covers the road segments 0 to 200 meters (about 656 feet) away from the 500-year floodplain. Level 4 covers the road segments 200 to 400 meters (about 1,312 feet) away from the 500-year floodplain. Level 5 covers the road segments over 400 meters away from the 500-year floodplain.

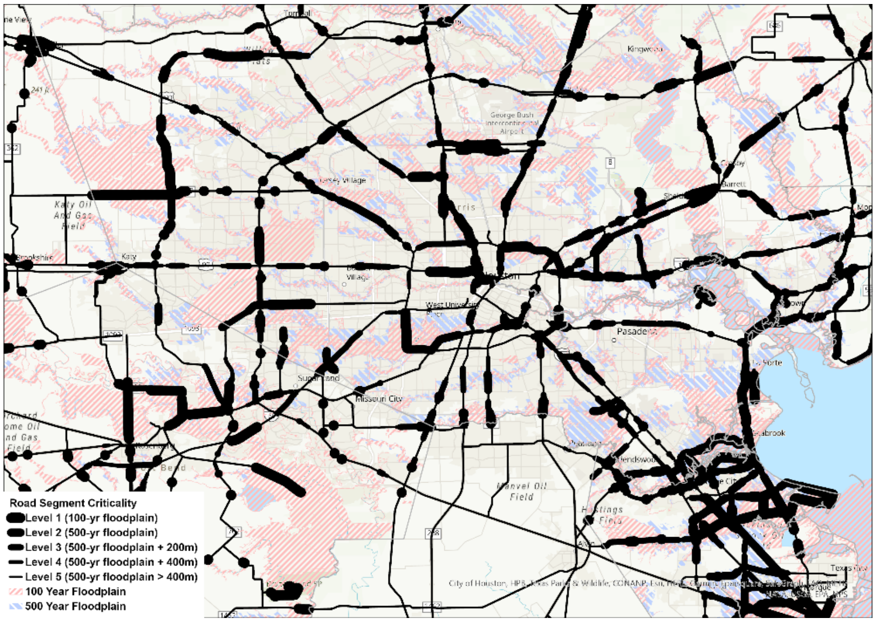


Figure 3.18. Definition of the 'Vulnerability to Extreme Events' Metric.

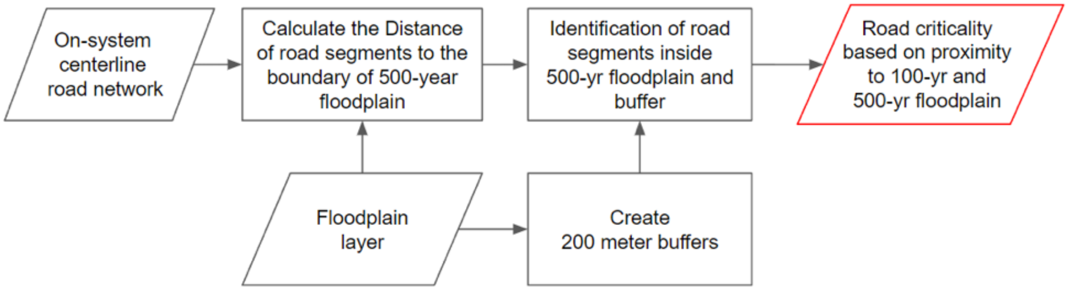
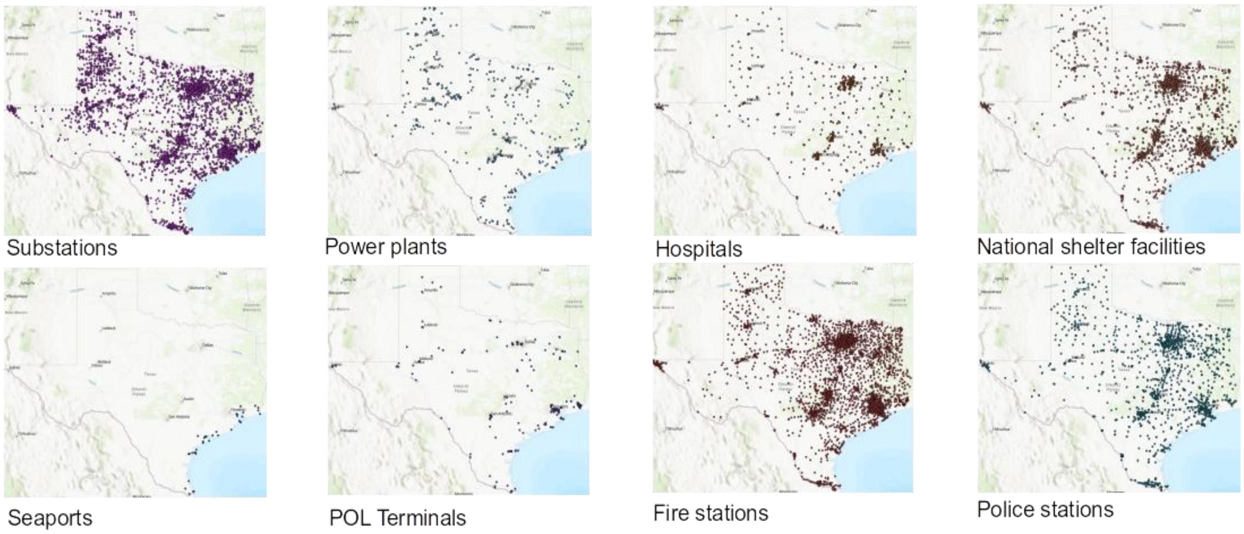


Figure 3.19. Steps for Evaluating Criticality of Road Segments Based on Proximity to Flooding Areas.

### 3.3.3 Proximity to Essential Facilities

The previous two metrics evaluated criticality of road segments based on network connectivity and vulnerability to flooding. Essential facilities, however, play an important role during and in the aftermath of disasters; thus, road segments that are close to those essential facilities become critical because of the need to transport resources and provide public services. This section evaluates the criticality of road segments based on their importance to provide accessibility to critical infrastructures.

The researchers collected location-based data of eight categories of critical facilities, which are electrical substations, power plants, hospitals, national shelter facilities, seaports, POL terminals, fire stations, and police stations, from HIFLD and ArcGIS open data portal. The data consist of latitude and longitude coordinates of the respective critical facilities. Each of these facilities are important to maintain critical functions in the state such as electricity, safety, health, and disaster relief. Access to critical infrastructures, especially during disruptions caused by disasters or other factors, is paramount for resiliency. Figure 3.20 shows the spatial distribution of the critical facilities in the State of Texas. Aggregating all the facilities together, the researchers collected location information for around 15,000 critical facilities.



Substations

Power plants

Hospitals

National shelter facilities

Seaports

POL Terminals

Fire stations

Police stations

**Figure 3.20. Spatial Distribution of the Eight Categories of Critical Facilities in the State of Texas.**

In order to evaluate the criticality of road segments in the road network, the researchers implemented the steps shown in Figure 3.21. The idea was to evaluate how many critical facilities a road segment provides direct access to. The researchers took the centerline of the on-system road network, calculated a 2000-meter (about 1.24 miles) buffer around it, and identified the number of critical facilities that lie in this buffer. There were two reasons for doing this. The first reason was to get an estimated number of the critical facilities that are distributed in close proximity to the road network. The second reason was to shortlist facilities to be used for computing the criticality measure. A buffer value of 2000 meters was selected because on average more than 80 percent of the critical facilities lie in this buffer range. Moreover, the researchers assumed that if a facility is within a 2000-meter proximity of a road network it could be considered as spatially co-located (co-location interdependency).

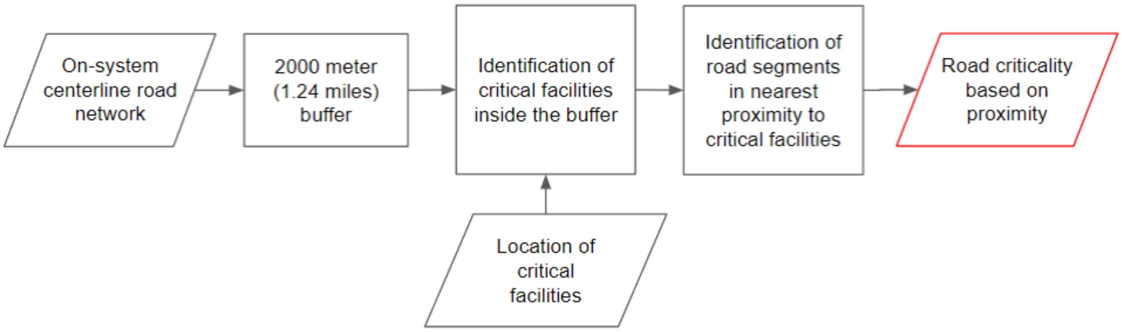


**Figure 3.21. Steps for Evaluating Criticality of Road Segments Based on Proximity to Critical Facilities.**

After extracting the information of all the critical facilities that lie in close proximity to the road network, the researchers computed the criticality measure by counting the number of facilities that lie in the proximity of each road segment to evaluate the importance of each link. These road segments were taken as the road links in the On-System centerline TxDOT road inventory shapefile, where each row in the centerline data corresponded to a road segment. The researchers then assigned a criticality score from Level 1 (L1) to Level 5 (L5). L1 is the most critical level for road segments, and L5 is the least critical level, based on the criticality measure. For example, if a road segment had more than 10 critical facilities in its nearest proximity, it was assigned a score of L1; if it had 5–10 facilities, it was assigned to L2; if it had 2–5 facilities, it was assigned to L3; if it had only one facility, it was assigned to L4, and if the road segment did not have any facility in its nearest proximity, it was assigned a score of L5. The criticality levels of L1 and L2 mean that a road segment is critical to maintaining accessibility to critical infrastructure in the vicinity, whereas L4 and L5 imply that there are none or less significant numbers of critical infrastructure in the nearest proximity to the road segment.

### 3.3.4 Cascading Impact of Critical Facility Network

The criticality metric proposed in the previous section, proximity to essential facilities, evaluated the criticality of road segments based on the locations of critical infrastructures that can be demonstrated as points on maps. Some critical infrastructures, however, such as the electrical power grid, railroad, and oil pipeline, are unable to be captured by the metric of proximity to essential facilities because they are spatially distributed as networks instead of single location attributes. For this reason, the researchers calculated the criticality of road segments according to their closeness to critical infrastructure networks to understand the criticality related to cascading impacts. Figure 3.22 demonstrates how the researchers calculated the criticality score based on the cascading impact of critical facility networks. Figure 3.23 shows the approach used in the previous metric for comparison where the criticality score is based on proximity to essential facilities.

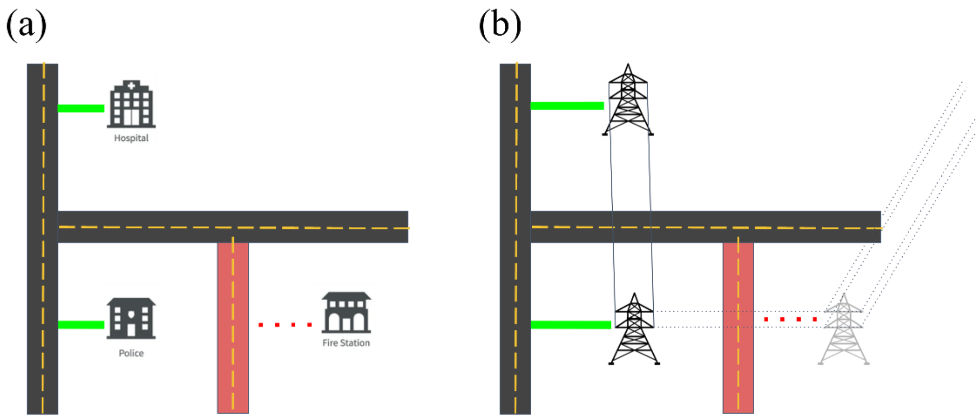


**Figure 3.22. Schematic of Assessing Criticality of Road Segments Based on (a) Critical Facility Networks and (b) Critical Facilities.**

The researchers collected critical facility network data for five critical facilities, which are railroad networks, transmission lines, natural gas pipelines, hydrocarbon gas liquids pipelines, and crude oil pipelines. These datasets were acquired from sources such as HIFLD and ArcGIS open data portal. The researchers simplified the facility networks into a node and link network model using two steps: (1) A buffer was created between 100 and 500 meters for each facility network and merged overlapping features. This was done to ensure that multiple parallel lines in the network could be merged. (2) Centerlines for the buffered networks were computed, merging some parallel lines into one and simplifying some intersections where multiple nodes were combined into one. Figure 3.23 shows the application of this method for Harris County for illustration. Figure 3.23 (row 1) shows the approximation of converting facility networks into nodes and edges. Figure 3.23 (row 2) shows superimposed simplified facility networks with the road network in Harris County.

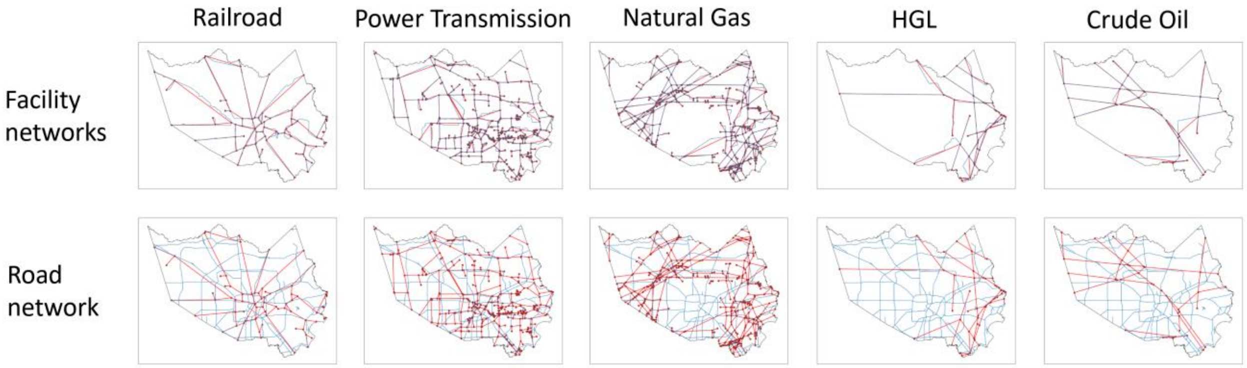


**Figure 3.23. Example of the Facility Networks and Road Network in Harris County. Row 1: Facility Networks Simplified to Node-Edge Networks. Row 2: Mapping of Simplified Facility Networks with Road Network.**

To compute the criticality scores based on cascading impacts, the researchers adopted a similar approach in which they used facility network nodes as proxy to determine interdependency of the facility network with the Texas road network. Figure 3.24 shows the analysis steps used to compute this metric. Based on the criticality measure (i.e., counts of critical facility nodes), the researchers assigned a criticality score from Level 1 (L1) to Level 5 (L5), L1 meaning the most critical level for road segments and L5 the least critical level. For example, if a road segment had more than 10 critical facilities nodes in its nearest proximity, it was assigned a score of L1; if it had 5–10 facilities nodes, it was assigned to L2; if it had 2–5 facilities nodes, it was assigned to L3; if it had only one facility nodes, it was assigned to L4, and if the road segment did not have any facility nodes in its nearest proximity, it was assigned a score of L5.

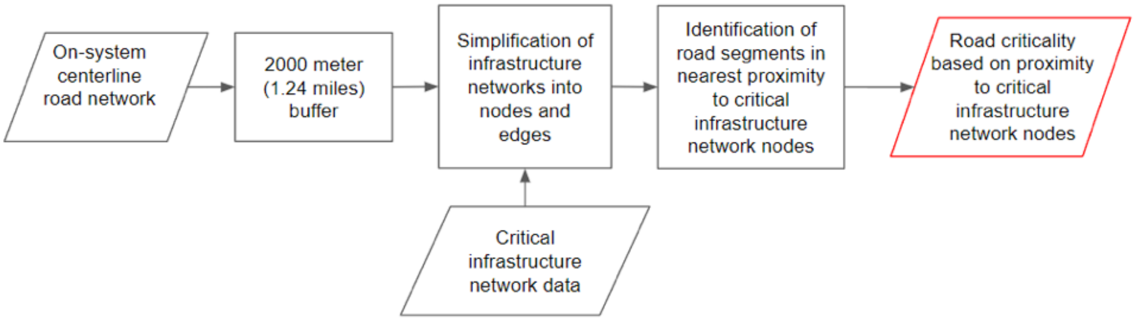


**Figure 3.24. Steps for Evaluating the Criticality of Road Segments Based on Proximity to Facility Networks.**

### 3.3.5 Integrated Criticality Metric

After developing and calculating the four criticality metrics, the integrated criticality metric that merges the four metrics together was calculated to help decision-makers understand the overall criticality of every road segment within the road network system. While every criticality metric provides unique insight, a single integrated metric that comprises all information from different dimensions can be informative as well. In this section, the authors introduce two approaches to calculate metrics for the overall criticality scores and present the results of the integrated metrics. In addition, the authors compare the results of the two integrated criticality metrics and discuss the findings based on the comparison.

To understand the overall criticality of each road segments in the Texas road network, the researchers calculated two integrated criticality metrics, which are based on an evenly weighted sum (EWS) ranking and root squared sum (RSS) ranking. The equations for EWS and RSS ranking calculation methods are:

$$EWS_{RS} = \sum Level_{RS,CA}$$

$$RSS_{RS} = \sqrt{\sum {Level_{RS,CA}}^2}$$

Where, $EWS_{RS}$ and $RSS_{RS}$ are the ranking values for each road segment and $Level_{RS,CA}$ are the criticality levels of each road segment and all criticality aspects examined in Task 3. For instance, if a road segment has a criticality level of 3 for connectivity, 2 for vulnerability to flooding, 4 for proximity to essential facilities, and 4 for cascading impact, the EWS ranking value of this road segment will be 13, whereas the RSS ranking value will be about 6.71. After having the ranking values for all road segments, these values were reclassified into five levels and assigned an integrated criticality level to each road segment. The classification method divides the range of all ranking values (i.e., maximum subtracts minimum of ranking values of all road segments) into five equal intervals, representing five classes. The Level 1 (L1) category includes the most critical segments in the network and is the highest 20 percent of the ranking values. The class of the Level 5 (L5) category includes the least critical segments in the network and is the lowest 20 percent of the ranking values.

## 3.4 TASK 4 TRANSPORTATION RESILIENCE SCORECARD

The objective of Task 4 was to develop a transportation resilience scorecard to provide transportation planning groups with a self-assessment tool to objectively evaluate the extent of implementation of resilience practices and identify the gaps associated with the consideration of resilience in transportation planning and project development (Figure 3.25). Accordingly, relevant resilience programs could be developed to systematically operationalize resilience in the planning of transportation infrastructure projects. Moreover, the resilience practices covered in the resilience scorecard require the involvement of various divisions within TxDOT, such as policy, planning, construction, operation and maintenance, and asset management. Thus, different districts and MPOs can use the resilience scorecard to facilitate communication and enhance cooperation in operationalizing resilience in their transportation infrastructure plans and projects. The resilience practices identified for the creation of the scorecard primarily focus on planning and project development. Resilience practices related to emergency response are not considered because they are outside the scope of this study.

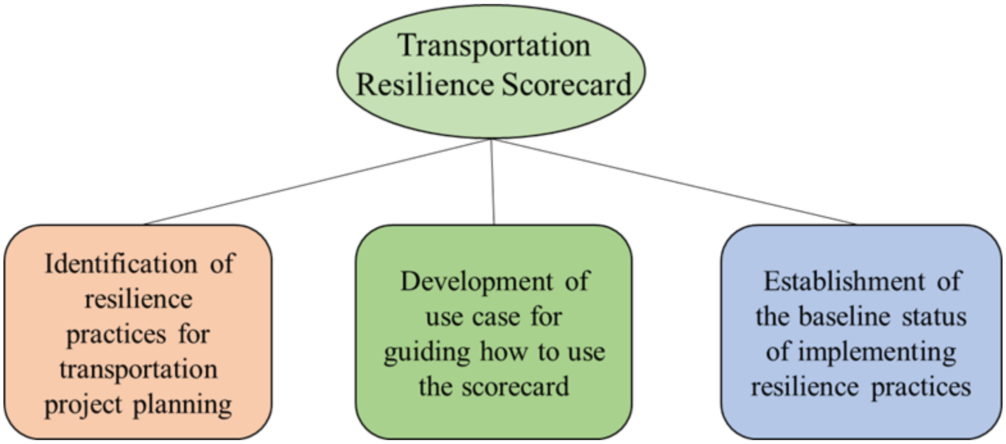


**Figure 3.25. Development of the Transportation Resilience Scorecard for Implementation at the Organizational Level.**

Three steps were implemented to develop the resilience scorecard (Figure 3.26). The first step was to incorporate different types of resilience characteristics into the scorecard by developing resilience practices. The researchers focused on six dimensions of enhancing resilience practices including resilience-focused organization, hazard and exposure assessment, impact assessment, vulnerability and risk assessment, emergency response, and resilience enhancement. The characteristics captured cover the entire cycle for an organization to prepare, assess, respond, and recover from disruptive events. Both the organizational and technical domains of resilience were incorporated in the practices.

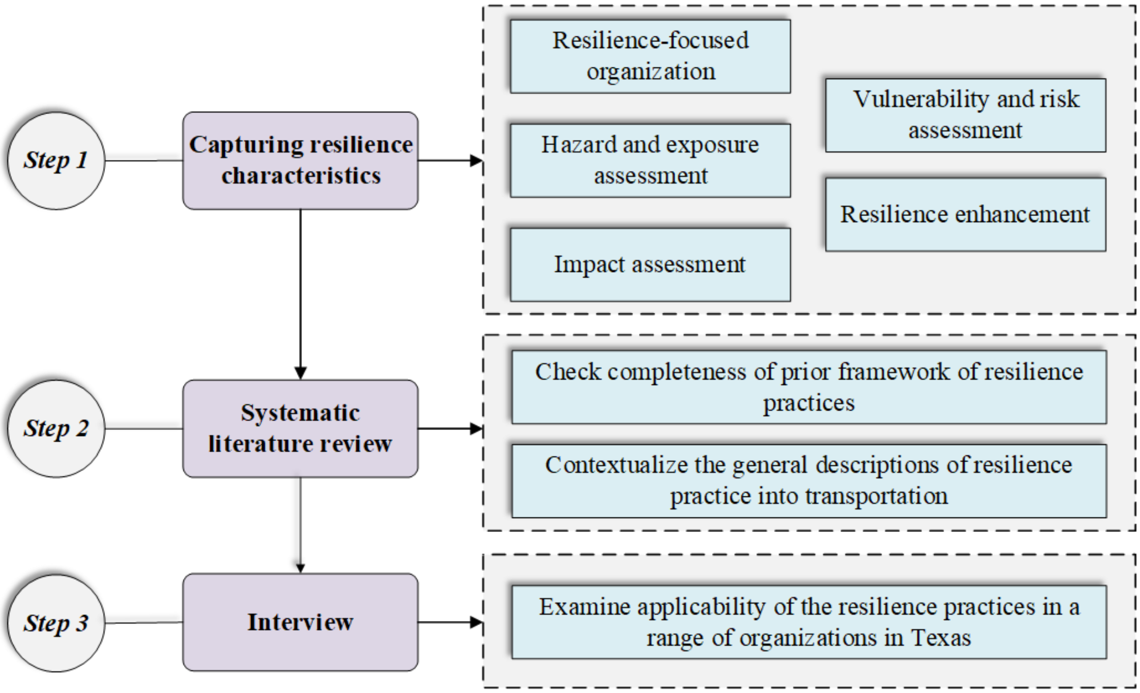


**Figure 3.26. Steps for Developing Resilience Scorecard.**

The next step was to conduct a systematic literature review to find potential practices that might not be covered at the first step. No additional resilience practices were identified from the literature review, which illustrates that the resilience practices developed in step 1 were quite systematic and complete. Since the resilience practices identified in the first step were applicable to general lifeline systems, the researchers made adjustments according to literature focusing on transportation to make the practices more specific to the context of the transportation department. For example, cascading effects can have different meanings according to the context where it is referred to. In power systems, it may refer to the large-scale power outage caused by the dysfunctionality of one node in the power grid. While in the context of transportation, cascading effect could refer to delayed delivery of relief resources or loss of access to critical facilities due to the damage of one road. Thus, the researchers specified cascading effect as "essential road segments within a transportation system" in practice and developed how to incorporate potential cascading failure in planning accordingly.

The third step was to conduct interviews to examine the applicability of resilience practices in a range of organizations in Texas. The interviews were conducted by using the snowball sampling method. Interviewees were from TxDOT, MPOs, FHWA, and NCTCOG. The interviews provided sufficient diversity of perspectives to examine the current state of practice for incorporating resilience. Modifications of resilience practices were made according to the results of the interviews to make sure they could be used across different districts and organizations.

## 3.5 TASK 5 RESILIENCE MEASURES AND BEST PRACTICES

The objective of Task 5 was twofold: (1) establishing a checklist for the assessment of the alignment of transportation projects with resilience requirements during the project development phase and providing a list of practices to guide improving project alignment with resilience objectives and (2) identifying key measures and metrics for resilience assessment (Figure 3.27). Accordingly, different stakeholders such as MPOs and project engineers can use the checklist to objectively evaluate the status of resilience consideration during project development, identify gaps and missing practices, and devise practices to ensure the incorporation of resilience. The checklist items include a list of resilience practices that need to be considered for project development ranging from multi-hazard quantitative risk and vulnerability assessment to cost-benefit analysis. Different stakeholders in project development can adopt the checklist as a resource to identify best practices for improving resilience incorporation in the transportation project development.

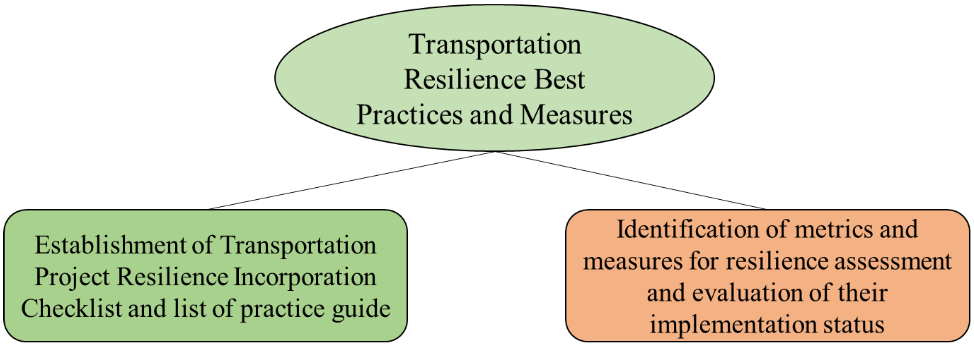


**Figure 3.27. Two Main Components of Task 5.**

The primary goal of the checklist presented in this task (i.e., Project Resilience Incorporation Checklist) is to assess the extent to which individual projects are aligned with resiliency requirements during the project development phase. The checklist serves as a resource that allows stakeholders in the project development phase to be aware of the requirements for incorporating different aspects of resiliency and have an understanding of the level of incorporation of these requirements in the existing project development practices such as design basis, cost-benefit analysis, risk quantification, and alternative selections.

In addition to the checklist, this task aimed to develop a system of measures for resilience assessment in transportation planning and project development. To do so, the researchers employed the results of the survey in Task 2 to identify measures that were needed for comprehensive resilience assessment. The survey included a specific question regarding the extent to which different measures are employed by different organizations involved in transportation planning and project development to characterize resilience. A subsequent question explored the perception of the participant regarding resilience measures that are useful for characterization of resilience (refer to Appendix). For this purpose, the researchers prepared a list of 20 measures that are currently used in organizations, have been mentioned by the participants in the interviews, or can be found in the transportation resilience literature. The list includes a variety of measures that characterize different aspects of resilience. For example, the researchers included roads/bridges condition, road capacity, and hours of congestion as measures of vulnerability, alternative routes as a measure of redundancy, road criticality as a measure of criticality, and total number of stormwater projects as a measure of interdependency.

Task 5 included two steps (Figure 3.28). Step 1 was to establish a project-level checklist for the evaluation of the alignment of projects with resilience considerations and requirements. In this step, the researchers performed a literature review to identify resilience practices and requirements that needed to be considered during the project development phase as well as practices that had been recorded by standards and guidelines. Then, the researchers summarized these practices under 14 items in a checklist. For each item, they also incorporated example practices with references that help users to learn and adopt proper practices during the project development phase.

Step 2 was to identify metrics and measures for the resilience assessment from the literature, including scientific literature as well as standards and guidelines related to the resilience assessment. First, the researchers performed a comprehensive literature review to collect different resilience metrics and measures. Then they categorized them into four groups: road-level functionality measures, recovery assessment measures, disruption extent/impact assessment, and other measures. In each category, the researchers included five measures and examined the status of their implementation, as well as the perception of their usefulness in different transportation organizations in Texas through the state-wide survey, explained in Task 2. The results from the survey provide insight into the measurement of resilience, needs, gaps, and the resilience dimensions that have been neglected in the current practices for resilience assessment.

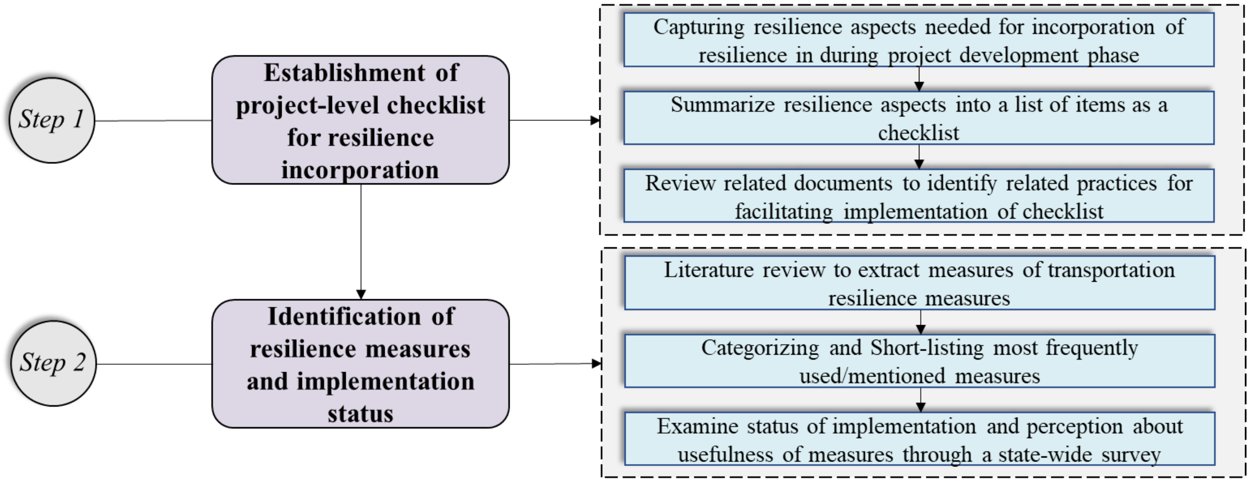


**Figure 3.28. Research Steps for Establishing Resilience Measures and Practices.**

## 3.6 TASK 6 DEVELOPMENT OF TRANSPORTATION RESILIENCE GUIDE

The research team prepares a Transportation Resilience Guide that documents the entire research effort, as a stand-alone document suitable for consideration and adoption by the Receiving Agency and other state and local agencies. The content of the guide includes the vulnerability and criticality assessments, evaluation of infrastructure interdependencies, the description of transportation resilience scorecard and its implementation, and the transportation resilience best practices and measures. The guide facilitates the widespread dissemination of findings of this study to the leadership at the state and local agencies. The guide provides the Receiving Agency, state and local agencies, and other stakeholders with the information needed to operationalize resilience in transportation planning.

## 3.7 TASK 7 WORKSHOP AND TRAINING WEBINARS

Education and outreach are critical components to ensuring transportation resiliency. When various functions and stakeholders understand the risks specific to their transportation systems, they can work closely with their organizations, armed with knowledge and tools, to develop specific programs/strategies that increase the resilience of transportations systems for unexpected events and emergencies. In this task, the researchers conducted transportation resilience training through webinars to demonstrate project findings and outcomes. They invited various Receiving Agency divisions, as well as other state and local agencies (e.g., MPOs, Texas Department of Public Safety, cities, and counties).

In the three resilience-training webinars, the researchers presented and discussed transportation vulnerability, criticality, and interdependency analyses and maps. They also presented an overview of the transportation resilience scorecard along with transportation resilience measures. Webinars are convenient, low-cost, and efficient training opportunities that can reach out to a diverse audience. In these webinars, the researchers:

- Educated the participants regarding resilience concepts, methods, and measures.
- Brought awareness of the importance of operationalizing resilience into transportation planning.
- Disseminated the findings and knowledge gained from the implemented research activities.

The information about the attendances and feedbacks on the webinars are shown in Figure 3.29.

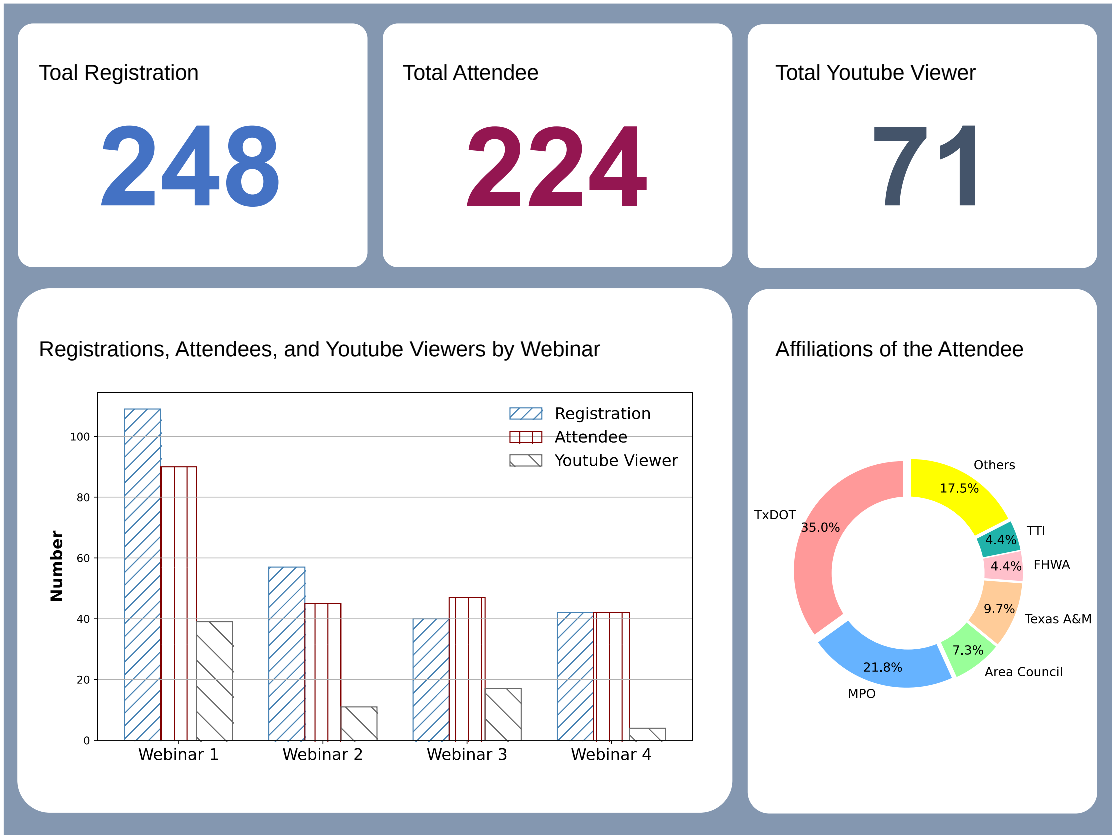


**Figure 3.29. Number of Registrations, Attendees, YouTube Viewers, and the Affiliations of Attendees in Three Resilience-Training Webinars.**

# APPENDIX

## 1. Interview and Survey

Note: A-interview; B-survey; C=figure/graph

### A-Interview Questions:

*Introduction:*

This interview is part of the tasks related to the TxDOT research project entitled "Establish TxDOT Transportation Resilience Planning Scorecard and Best Practices", project number #0-7079. This study is focused on resilience planning and practices (not emergency management and evacuation planning).

We are gathering information related to the needs and gaps in resilience planning and practices of the transportation infrastructure system and project development through interviews with practice professionals such as you. The questions are focused on the resilience of transportation infrastructure systems. In this interview, resilience is defined as the capacity of the transportation infrastructure system to absorb severe shocks and return to a desired state of operations.

*Interview Questions:*

Introductory question

*Question 1.* What aspects of planning department's tasks intersect with resilience planning and practices in project development?

Risks and challenges

*Question 2.* Please describe the major risks and challenges including flooding, erosion, rock fall, and snow related to transportation infrastructure system.

Current resilience plans and practices

*Question 3.* Describe the current plans and practices for assessing and implementing resilience throughout the planning and project development process.

If not available, there is a federal statue for incorporating resiliency, is the planning department interested in incorporating resilience in the planning and project development process?

*(Optional):* What tools and methods would be desired for TxDOT to enable resilience planning and implementation?

Measures and Data:

*Question 4.* What specific measures (quantitative and qualitative) are used to assess the resilience of transportation infrastructure systems after a shock and how the data is collected. (e.g., related to asset management)

*(Optional):* What specific measures are desired for tracking the resilience in transportation infrastructure systems? What data, if become available, would enable better assessment of resilience?

Plan evaluation:

*Question 5:* How is resilience defined and incorporated into transportation planning and project development.

*Question 6:* What specific methods and procedures would be desired to incorporate resilience in transportation infrastructure plans and project development?

Interdependence:

*Question 7:* Transportation infrastructure can be interdependent with other infrastructure systems such as storm water drainage, electricity, natural gas, etc. Describe the extent to which the interdependencies of infrastructure systems with transportation infrastructure are considered in plans and project development.

Challenges for implementing resilience plans and practices:

*Question 8.* What are the current challenges in planning for and implementing resilience?

*Question 9.* Thinking about the next five to ten years, what new procedures, tools, and data would be needed for improving resilience during planning and project development of transportation infrastructure systems?

Closing questions:

Is there anything else we should consider for understanding the current practices for transportation resilience and planning?

Please recommend others we could talk with to inform our study.

**B- Survey Questions:**

*Introduction*

This section talks about the background of the respondent. The following sections have 11 questions and will ask information regarding hazards and recent events, state of resilience practices, and desired measures.

Q1 Please select the appropriate district/MPO represented in this response?

▼ Abilene Others

Q2 Please specify the type of organization.

- TxDOT - Planning
- TxDOT - Design
- TxDOT - Maintenance
- MPO
- FHWA
- H-GAC
- Others ________________________________________

Q3 Please specify the position of the respondent and type the responsibilities in the comment box.

- Engineer
- Planner
- Project manager
- Others ________________________________________________
-
- Responsibilities
- ________________________________________________________________

State of resilience practices

This section aims to capture to what extent the resilience practices are employed and implemented in the transportation planning and the project development process in the affiliated organization/agency; and the challenges and barriers for that.

Q4 What is perceived to be the greatest challenges for the organization to incorporate resilience into transportation planning? (select all that apply)

- Limited formal programs related to transportation resiliency
- Inadequate established methods/tools for measuring resilience
- Limited guidelines for resilience assessment
- Insufficient performance goals/metrics for risk and resilience management
- Limited or unreliable data
- Missing integration with the current workflow and business processes for transportation planning and project development
- Limited personnel with expertise
- Inadequate training related to resilience assessment
- Agency or policy barriers
- Insufficient support from leadership
- Financial constraints
- Organizational culture/Governance structure
- Inadequate communication and coordination with other agencies
- Others (please specify) ________________________________________________

**C- Figures/Graphs:**

This section aims at exploring the current and desired resilience measures needed in transportation planning and project development process.

Q5 The following table lists various measures and metrics identified from the literature or suggested by organizations involved in transportation resilience planning and assessment. The table has the name of the measures and their description in the square bracket. For each measure, please indicate whether the measure or a derivative of it are currently being used in the organization. Also, irrespective of whether these measures are currently used or not, what is the perceived usefulness of each measure to be used? At the end of the table there are some blank comment boxes, kindly fill them with any additional measures that the respondent thinks will be useful.

*The respondents were asked to select whether the following measures are currently used or not and also to rate the potential usefulness in terms of – Not useful, potentially useful, and Must have/very useful*

1. Valuation of Assets Within Flood Zones [The monetary value of transportation network assets (e.g., roads and bridges) located within a defined flood zone such as a 100-year floodplain]
2. The Total Number of Stormwater Improvement Projects [Number of the projects under implementation and previously implemented to improve stormwater runoff collection and avoid road flooding]
3. Road Criticality [A measure of the criticality based on the extent to which the functionality of the road is crucial to the functionality of the road network as a system, and the significance of the failure of the road for system's ability to provide normal service]
4. Percentage of Roads/Bridges in Poor or Fair Condition [Percentage of roads/bridges in the area that have "poor" or "fair" condition based on federal or state grading standards in which different hazards that may reduce the residual life of the road/bridge such as erosion and pavement deterioration]
5. Area Under the Curve [The area under the resilience curve that shows system functionality versus time, from hazard event start time to the time that road network returns to normal operation. A higher area under the curve indicates the system experienced less functionality loss and/or the system bounced backed to normal condition faster. The expected system functionality is determined using simulation models.]
6. Road Capacity [The estimated annual daily capacity of a road as the measure of road importance]
7. Alternative Routes [The quantity of the available alternative paths including alternative routes and available transportation modes between the road and specific zones]
8. Variation of Commute Time [Percentage of roads with annual daily variance of commute time higher than a defined threshold]
9. Clearance Time [Expected time to clear road surface of the hazard-related debris after hazard impact]
10. Organizational Resilience Adoption [The percentage of agencies involved in the disaster preparedness for the region/assets that have adopted resilience planning]
11. Resilience Funding Adequacy [The extent to which the cost of resilience incorporation is considered in the project funding during planning and project development]
12. Road Monitoring Measure [A metric that shows the extent of monitoring the condition of the assets. For example, the annual percentage of routine culvert inspection completed.]

13. Resource Availability [Metrics that show the availability of resources required for restoring the condition of damaged facilities and roads such as counts of available construction equipment or workers in the region]
14. Transportation expansion [Percentage of planned facility miles completed]
15. Information diffusion metric [Time required for contact all community residents to inform them about crucial information of disruption]
16. Hours of congestion [Average monthly/daily hours that the road experiences congestion during normal condition]
17. Accessibility [Number of walkable destinations within walking and biking distance of the road]
18. Restoration rapidity [The average construction project time for road restoration projects in the region]
19. Time to start restoration [The expected time between a hazard event start and the time a restoration/response project can be started]
20. Relocation rate [The expected rate of relocation in aftermath of a hazard event that defines the rate of traffic volume increase after a hazard event]

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