Developing a Resilient Texas Metropolitan Transportation System

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Introduction

The Fixing America's Surface Transportation (FAST, 2015) Act requires transportation agencies *"to take resilience into consideration during the transportation planning processes. The updated metropolitan and statewide transportation planning regulations include a requirement that the metropolitan transportation plan assess capital investment and other strategies that reduce vulnerability of the existing transportation infrastructure to natural disasters."*

In a preceding study entitled "Developing a Resilient Texas Transportation System", the participating stakeholders recommended that the Texas Department of Transportation (TxDOT) host resiliency workshops to ensure coordination, and to share lessons learned and best practices with the Metropolitan Planning Organizations (MPOs). Several Texas MPOs have participated or are participating in FHWA pilot case studies aiming to enhance the resiliency of regional transportation systems (i.e., the Capital Area Metropolitan Planning Organization [CAMPO], the North Central Texas Council of Governments, the Houston-Galveston Area Council, and Corpus Christi MPO). The stakeholders noted that resiliency workshops provide a venue for these MPOs to share important lessons learned that could provide guidance to other Texas MPOs that are planning for resiliency.

In an effort to identify and share resiliency planning lessons learned, this study (a) surveyed U.S. MPOs, (b) summarized the efforts of the Texas MPOs that have participated in a number of Federal Highway Administration (FHWA) pilot case studies, as well as the findings of a number of TxDOT funded studies to enhance the resiliency of regional transportation systems, and (c) hosted a workshop with local agency partners to enhance the planning efforts for ensuring resiliency of regional transportation systems to extreme weather events. This report summarizes the results and findings of the study effort.

Defining Resiliency, Identifying Goals, Objectives, Performance Measures, and Assigning Roles and Responsibilities

The study team developed and administered a web-based survey to U.S. Metropolitan Planning Organizations (MPOs) to gain insight into how MPOs:

- Determined/defined a resilient transportation system.
- Determined the resiliency goals for the regional transportation system (RTS)?
- Determined resiliency metrics to measure progress towards achieving resiliency goals?
- Identified vulnerable elements of their RTS.

The study team also asked MPOs about the:

- Data/tools used to identify risk and vulnerable transportation system elements/corridors.
- Data/tools used/needed to understand consequences of disruptive events.
- Strategies/options to promote resiliency of the transportation system.

This section of the report documents the study approach and analysis conducted.

Study Approach

The study team developed a web-based survey in Qualtrics. Contact information were compiled for the 404 MPO Executive Directors or MPO transportation contacts. Individual emails with a link to the web-based survey were sent to about half of the MPO contacts between February 10 and February 23, 2019. Preliminary responses were reviewed the last week in February to determine if responses received are valid and if any wording changes to the survey are needed. No changes were deemed necessary to the questions. The remaining MPO contacts were emailed between March 3 and March 18, 2019. A reminder email was sent to all MPO contacts April 26 to ask those that have not responded to complete the survey. A total of 57 surveys were completed (see Figure 1).

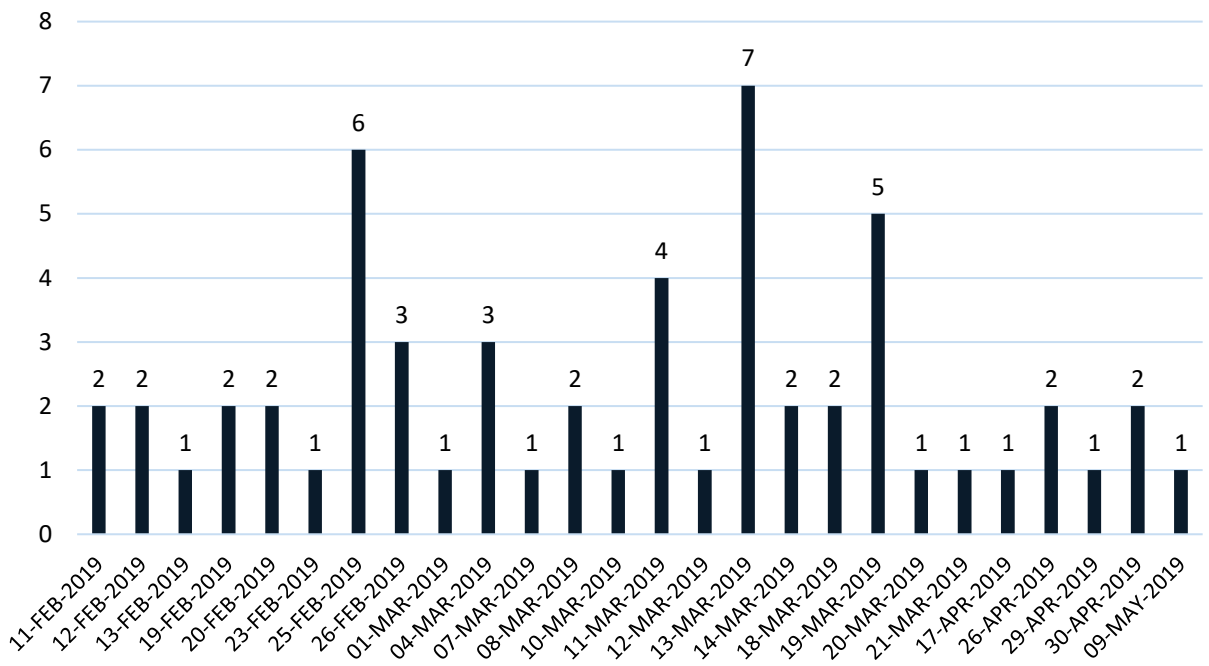
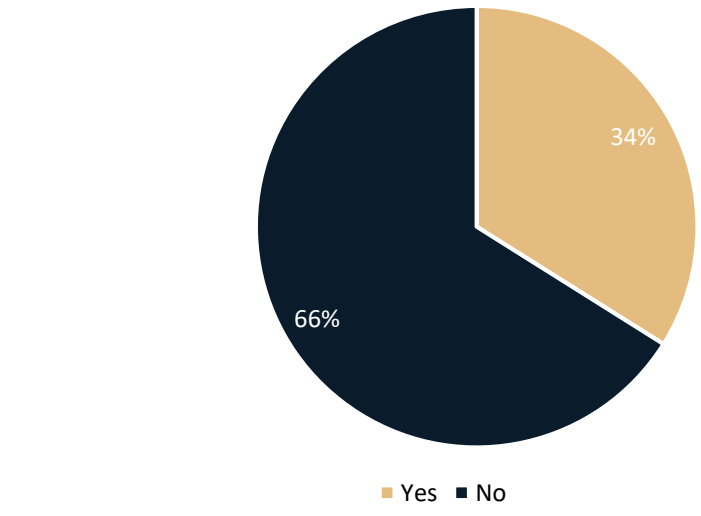


Figure 1. Survey Completion by Date

Survey Results

Two-thirds of the respondents reported that their MPO had not defined resiliency for their RTS (see Figure 2).



Number of Respondents: 56

Figure 2. Has MPO Defined Resiliency?

MPOs that had defined resiliency were asked to provide the definition that had been adopted by their MPO. Nineteen different responses were provided. After reviewing these responses, it was determined that 12 were actual definitions, with the balance being references to other documents, goals, performance measures, or project prioritization metrics. The definitions are provided in Table 1.

Table 1. Resiliency Definitions

Resiliency Definitions
Climate adaptation and resiliency planning, as it relates to transportation assets, seeks to identify infrastructure vulnerable to disruption because of changing climate, determine the risks and consequences of current climate trends, and propose investment priorities to ameliorate identified risks.
An ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions.
The ability of the transportation system to recover and regain functionality after a major disruption or disaster.
The capacity of individuals, communities, institutions, businesses, and systems within a region to plan, sustain, adapt, recover, improve and grow collaboratively - regardless of what kind of chronic stresses and acute shocks they experience - through specific actions and implementation strategies geared to address specific vulnerabilities.
The ability to react, act, and recover from possible disruptions to the system.
The ability to maintain a system with good reliability and plans to quickly restore service or react to unexpected disruptions in level of service.
The ability of the transportation system to respond to, recover from and support local, state, and federal efforts to recover from significant events regardless of source.
The ability of our transportation network to rebound (and how quickly) from shocks and stressors.
The ability for the transportation system, as well as its providers and users, to anticipate, prepare for, and adapt to changing conditions and also withstand, respond to, and recover rapidly from disruptions.
Strategies to reduce the vulnerability of existing transportation infrastructure to natural disasters.
The ability to continue to function at an acceptable level of efficiency in the face of disruptive or unexpected conditions.
The ability to prepare for changing conditions and withstand, respond to, and recover from disruptions.

MPOs that had not defined resiliency were asked why not. Figure 3 shows that half (50 percent) of these MPOs are in the process of defining resiliency. Fourteen percent reported that defining resiliency was on their radar, but was not a priority, and eight percent reported that, while their organization has not formally defined resiliency, their Metropolitan Transportation Plan (MTP) includes resiliency elements.

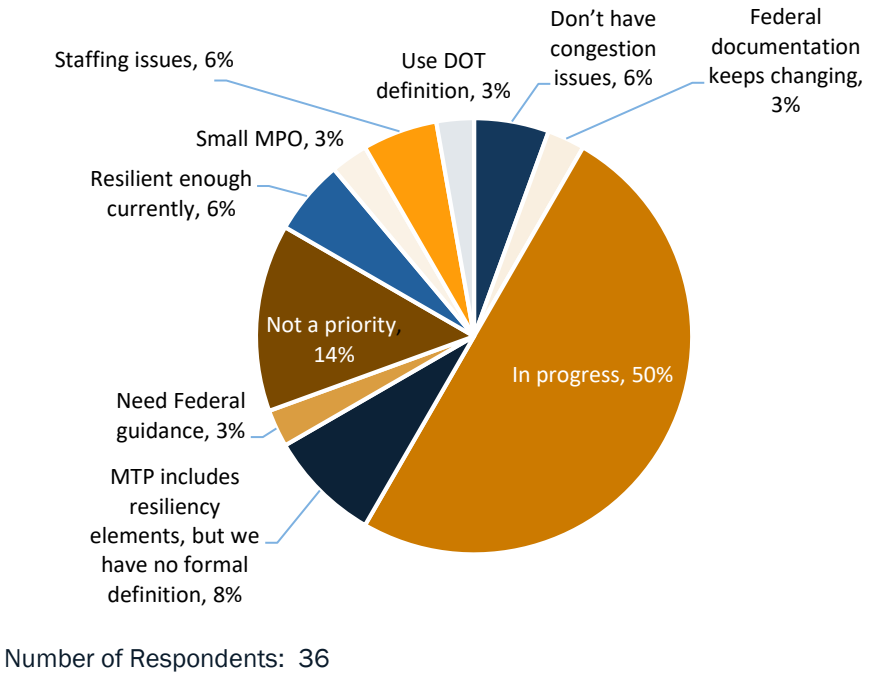


Figure 3. Reasons Resiliency Has Not Been Defined

Seventy percent of respondents reported that their MPO had not defined resiliency goals (see Figure 4).

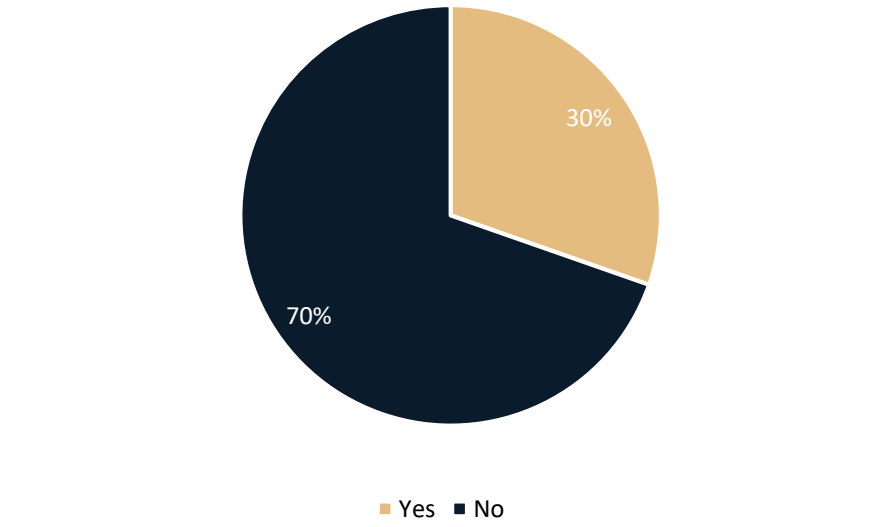


Figure 4. Has MPO Defined Resiliency Goals? (n=56)

MPOs that had defined resiliency goals were asked to provide the goals that had been adopted by their MPO. Fifteen different responses were provided. After reviewing these responses, it was determined that 11 were actual goals. The goals are presented in Table 2.

Table 2. Resiliency Goals

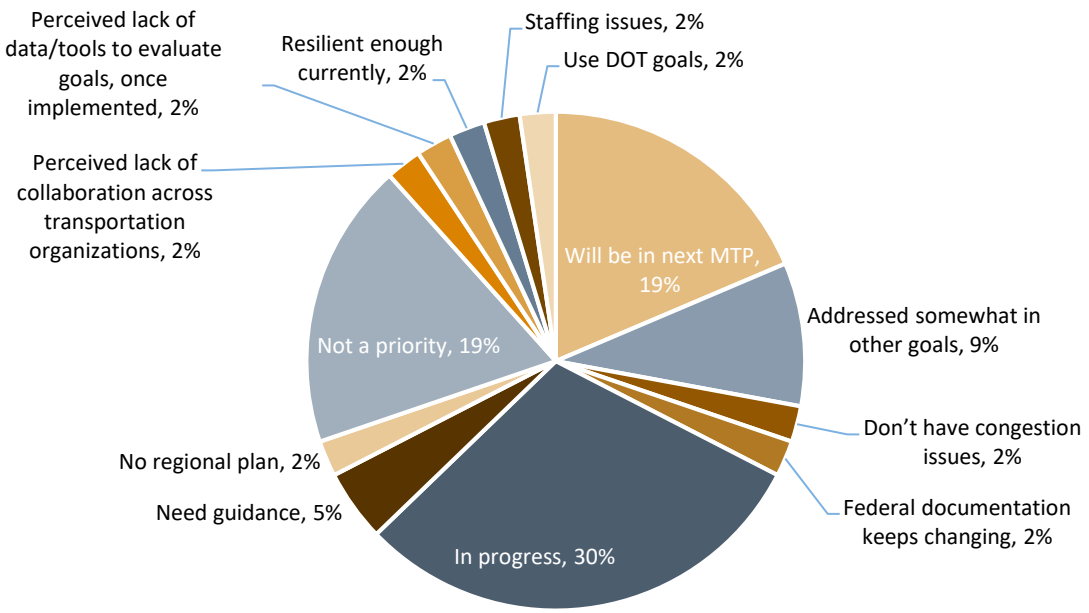
Resiliency Goals
The Long-Range Transportation Plan (LRTP) identifies preparing for the impacts of climate change (both mitigation, or reducing the severity of climate change impacts, and adaptation, or changing the design of transportation assets to lessen expected impacts of climate change on them) as one of six "Emerging Issues and Opportunities" to plan for. In addition, our LRTP includes the following recommendation: Adapt the design of transportation infrastructure to integrate security and resiliency considerations.
• Operate, manage, and maintain a safe and reliable transportation system. • Maintain existing and future transportation facilities in good condition. • Improve transportation system performance and reliability. • Improve transportation safety and security.
Increase the ability of local and regional stakeholders to implement resiliency and climate adaptation strategies across disciplines.
Improve the transportation system's stability/resiliency in the event of climate change, emergencies, or disasters.
Improve the resiliency and reliability of the transportation system and reduce or mitigate stormwater impacts of surface transportation.
• Improve resilience of the transportation network to weather events and climate change. • Adapt vulnerable transportation infrastructure to be responsive to weather events and climate change. • Improve stormwater management in transportation projects. • Improve the operational response to weather events to ensure mobility.
• Maintain acceptable levels of congestion. • Increase trail usage. • Increase transit ridership. • Decrease drive alone to work trips. • Increase biking and walking as [a] mode to work. • Encourage Park-and-Ride locations. • Convert JTS [Janesville Transit System] bus fleet to Compressed Natural Gas (CNG).
Equip, manage, and operate the transportation system to be multimodal and interconnected.
Ensure that our transportation network is: • Adequately maintained. • Providing an adequate level of service. • Designed to withstand natural hazards and changing future conditions. • Offering adequate access within the urban area and connections to rural areas. • Supporting economic development.

Resiliency Goals

Goal: Safety and reliability that meet the future needs of the region and can withstand potential natural hazards. This goal is supported by meeting the following objectives:

- Identification and planning for the congested corridors of the region.
- State of Good Repair projects carried out through the STIP/TIP process and local road projects.
- Identification of critical infrastructure in potentially flooded areas.
- Carry out a regional Community Rating System assistance program to enable our member towns to leverage the National Flood Insurance program to decrease flooding liability.
- Adoption of Connecticut Department of Transportation (CTDOT) performance measures, which allow us to identify and prioritize projects which will result in a sustainable and resilient transportation system.
- Commitment to the Municipal Separate Storm Sewer System (MS4) permitting process and the reduction of connected impervious surface on both local and state roadways through sound engineering, technical assistance, and coordination.
- Leadership in regional emergency preparedness.
- Providing assistance to towns in accessing funding for infrastructure and programs.
- Develop effective safety management strategies.
- Conduct studies on new technology to increase infrastructure resiliency.
- Work with local groups to identify vulnerabilities in emergency management.
- Continued development of the area's Emergency Operations Center (EOC).
- Recognize the potential for damage to the transportation network such as flooded roadways, bridge damage, and accelerated pavement deterioration.

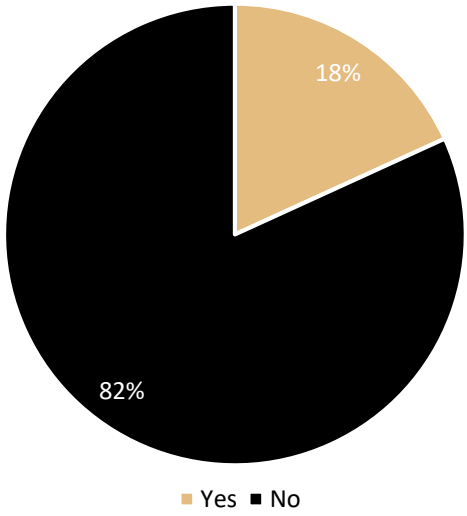
MPOs that had not defined resiliency goals were asked why not. Figure 5 shows that nearly half (49 percent) of the MPOs are in the process of defining goals (30 percent) and/or plan to include these goals in the next MTP (19 percent). Nearly one in five respondents (19 percent) said that defining goals is not a priority for their MPO.



Number of Respondents: 43

Figure 5. Reasons Resiliency Goals Have Not Been Defined

Eighty-two percent of respondents reported their MPO does not have defined resiliency metrics (see Figure 6).



Number of Respondents: 55

Figure 6. Has MPO Defined Resiliency Metrics?

MPOs that had defined resiliency metrics were asked to provide the metrics that had been adopted by their MPO. Ten MPOs provided a response, of which five provided metrics. The balance referenced other documents or listed goals or performance measures instead of resiliency metrics. The provided metrics are presented in Table 3.

Table 3. Metrics Developed to Track Progress Toward Achieving Resiliency Goals

Resiliency Metrics	
Annual average concentration of $PM_{2.5}$ in the county	Miles of roadway that include bike lanes
Annual hours of delay per auto commuter	Number of assets vulnerable to sea level rise
Average commute time	Number of projects permanently inundated by Mean Sea Level (MSL) + 5 inches
Average proportion of household income devoted to housing and transportation costs	Percentage of pavements/bridges in good/poor condition
Canopy coverage in targeted activity centers/coverage	Percentage of adults who are physically active
Collisions	Percentage of bridges rated as deficient
Fatalities	Percentage of metro employees within 1/4 mile of transit route
Greenhouse Gas (GHG) emissions reductions	Percentage of metro employees within 1/4 mile of trail system
Hours of delay	Percentage of pavement measured at fair or better
Injury rates	Percentage of roadway miles that do NOT include sidewalks
Level of service (LOS) C or better during peak hours	Percentage of shared-use paths in good condition
Metro area housing units per acre	Percentage of workers commuting via walking, biking, or using transit or rideshare
Metro area vehicle miles traveled (VMT) per capita	Seatbelt usage

MPOs that had not defined resiliency metrics were asked why not. One-fourth (26 percent) of the respondents said that the MPO is in the process of defining resiliency metrics. Fifteen percent said that defining resiliency metrics is not a priority for the MPO, while 13 percent suggest these metrics will be in the next MTP and/or indicate that MPOs need federal guidance on developing these metrics (see Figure 7).

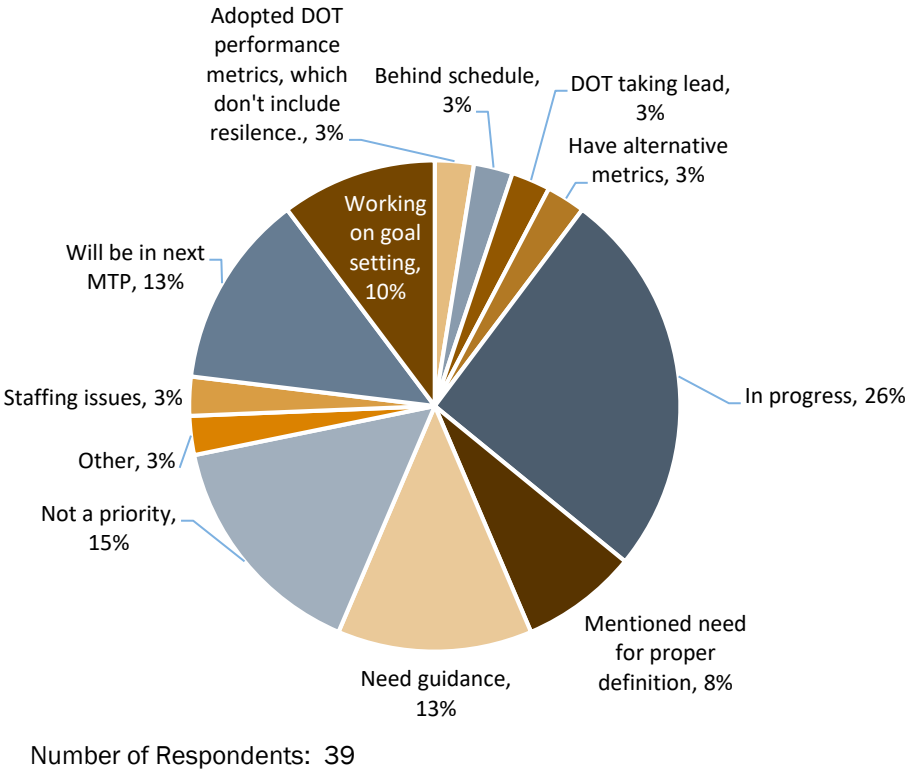


Figure 7. Reasons MPO Has Not Defined Resiliency Metrics

When asked if their MPO had assessed the vulnerability of their RTS to climate change and extreme weather events, a slight majority (54 percent) of respondents replied yes (see Figure 8).

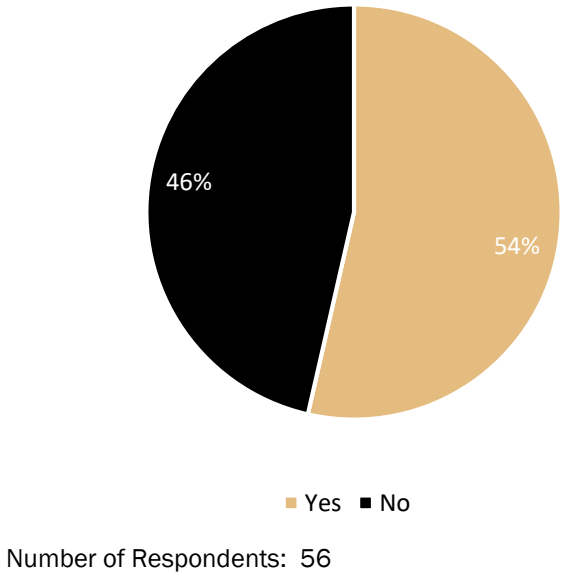


Figure 8. Has MPO Assessed Climate Change Vulnerability?

The nearly half of respondents (46 percent) representing MPOs that had not assessed the vulnerability of their RTS to climate change and extreme weather events were asked why their MPOs had not. Three of ten (30 percent) MPOs are in the assessment process. Approximately one-fourth (26 percent) of MPOs are dealing with staffing issues (15 percent) and/or funding issues (11 percent) that are preventing the assessment (see Figure 9).

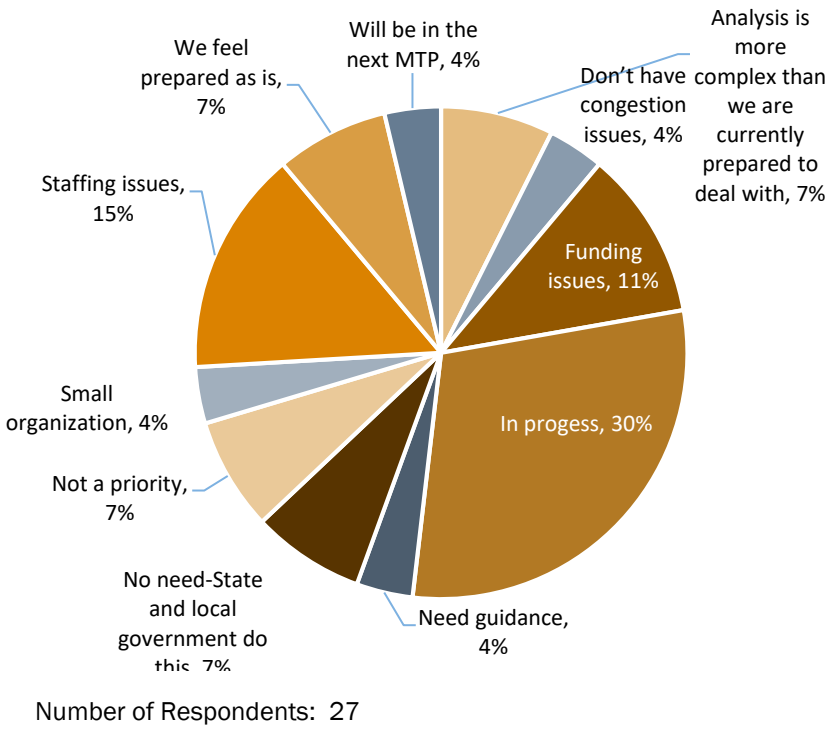
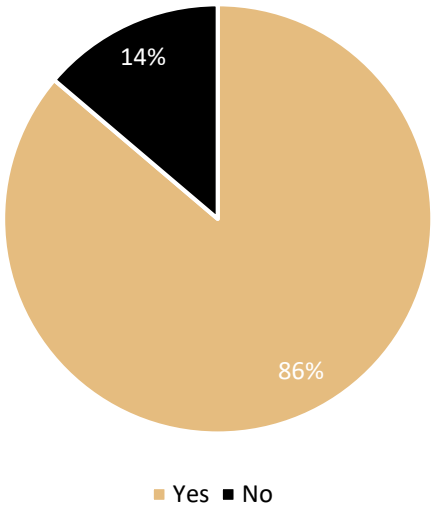


Figure 9. Reasons MPOs Have Not Assessed Climate Change Vulnerability

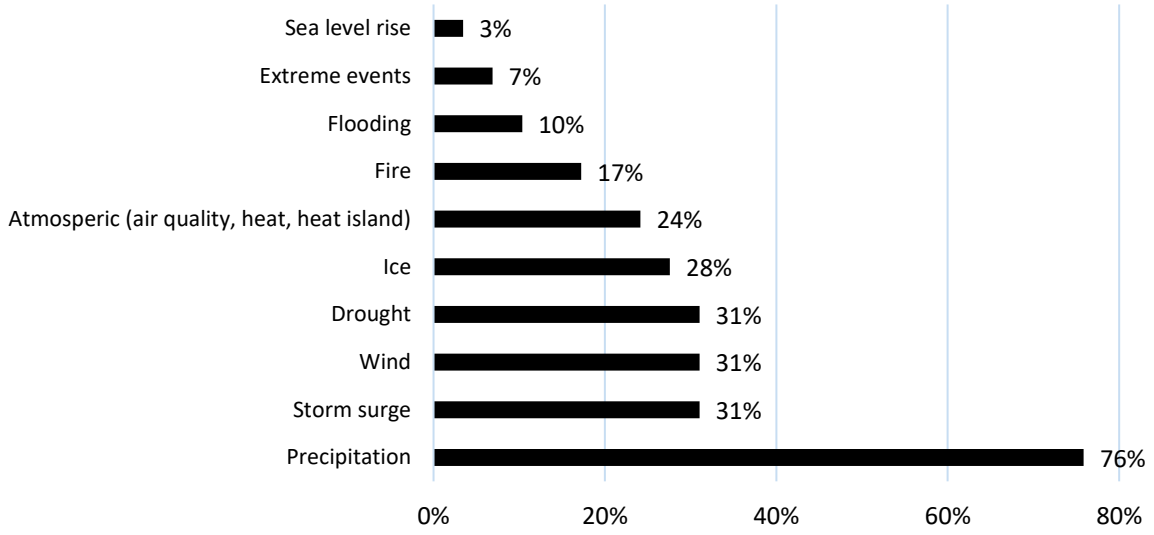
Respondents representing MPOs that had assessed the vulnerability of their RTS to climate change and extreme weather events were asked if their MPO had identified and characterized climate factors that might impact their RTS. More than eight of ten (86 percent) of these MPOs reported yes (see Figure 10).



Number of Respondents: 29

Figure 10. Has MPO Identified/Characterized Climate Factors?

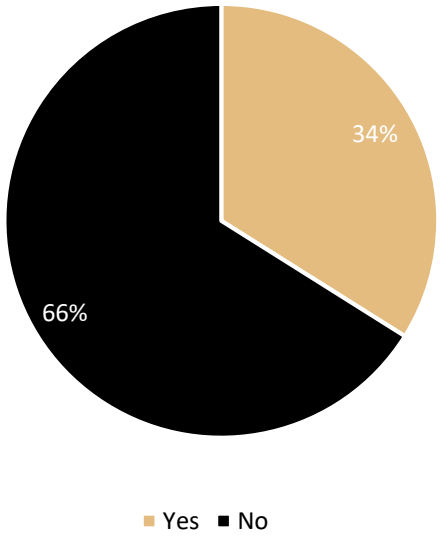
Approximately three-fourths (76 percent) of respondents reported that precipitation was a climate factor of concern. Flooding (10 percent), extreme events (seven percent) and sea level rise (three percent) were the climate factors of least concern to those that have assessed the vulnerability of their RTS to climate change and extreme weather events (see Figure 11).



Number of Respondents: 29

Figure 11. Climate Factors of Concern

When respondents were asked if their MPOs had assessed the risks/likelihood of extreme weather events occurring, one-third (34 percent) reported that they had done so (see Figure 12).



Number of Respondents: 56

Figure 12. Has MPO Assessed Risk/Likelihood of Extreme Weather Event?

The one-third of respondents working for MPOs who had assessed the risks/likelihood of extreme weather events occurring were asked to identify elements of their RTS that had been identified as vulnerable. Figure 13 shows that all these MPOs (100 percent) identified highway corridors as vulnerable, with a majority identifying bridges (95 percent), road connectors (84 percent), and rail infrastructure (79 percent) as vulnerable. Non-motorized infrastructure and land ports-of-entry were deemed vulnerable by the smallest percentage of respondents (11 percent).

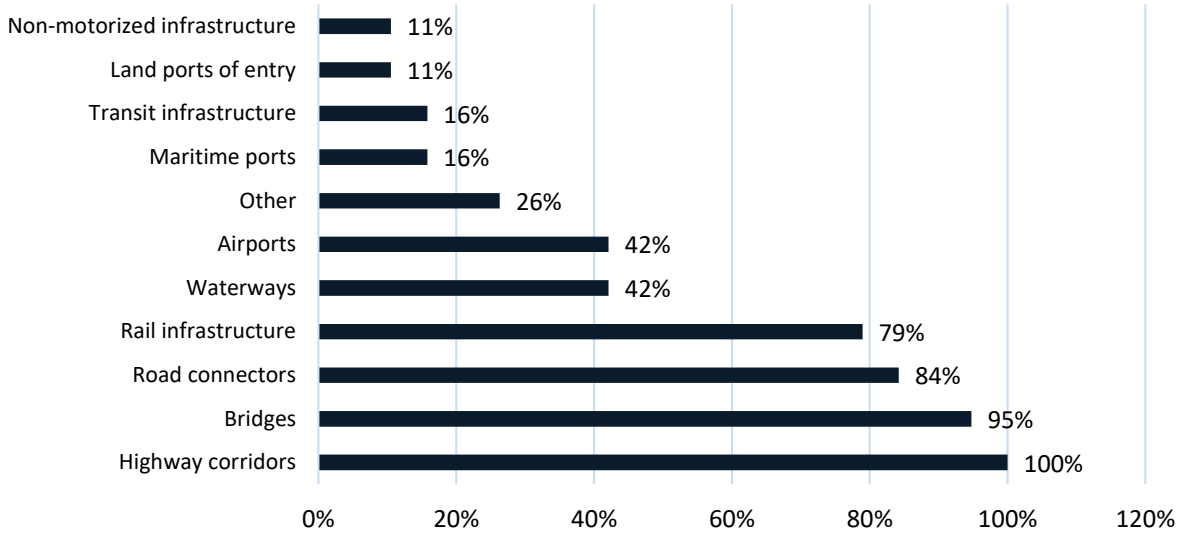


Figure 13. RTS Elements Vulnerable to Extreme Weather Events

The two-thirds of respondents representing MPOs that had not assessed the risks/likelihood of extreme weather events occurring were asked why their MPOs had not. Approximately one-fourth (23 percent) of respondents reported that the MPO was reliant on another agency (e.g., State DOTs) for this information. Nineteen percent of respondents stated that this task was in progress, and 16 percent stated staffing issues were preventing MPOs from moving forward with this assessment (see Figure 14).

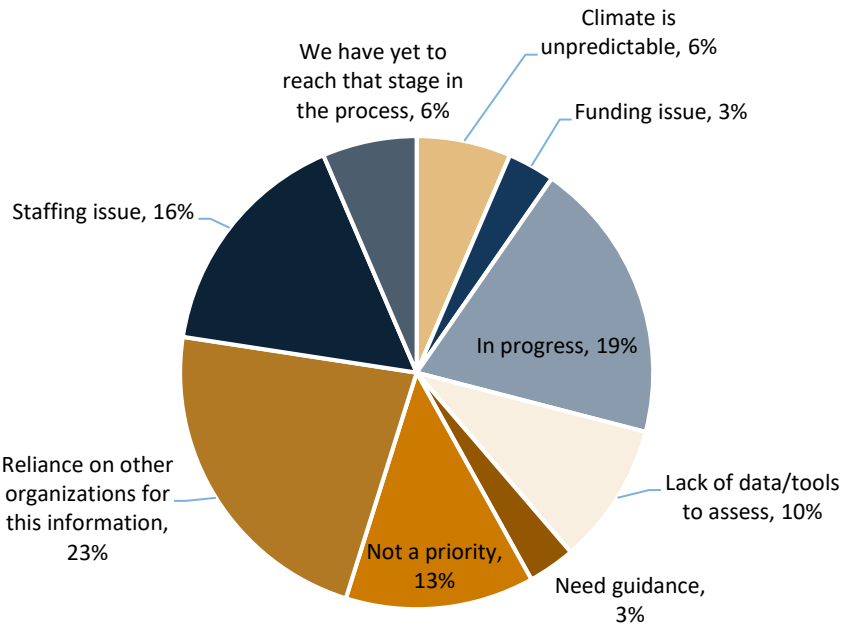
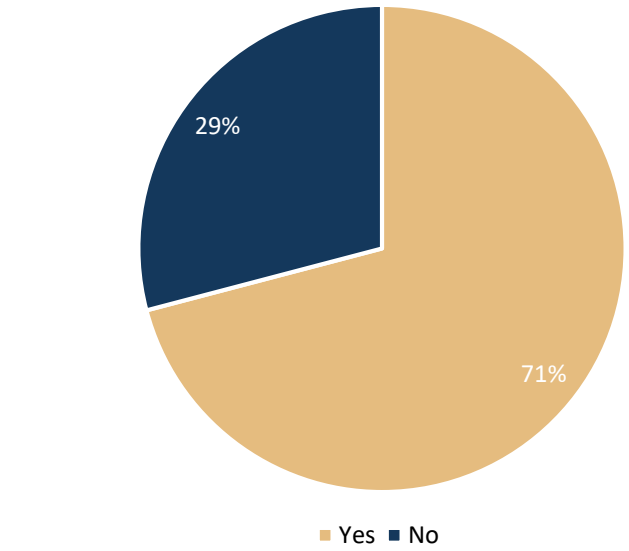


Figure 14. Reasons MPOs Have Not Assessed Risk/Likelihood of Extreme Weather Events

Seven of ten respondents (71 percent) reported that their MPO had identified the critical elements of their RTS (see Figure 15).



Number of Respondents: 55

Figure 15. Has MPO Identified RTS Critical Elements?

Respondents representing MPOs that had not identified the critical elements of their RTS were asked why not. Figure 16 shows that most (73 percent of respondents) are in the process of doing so. Two MPOs (18 percent) reported that this task is not a priority and one MPO (9 percent) reported that the responsibility for this task lied elsewhere, such as a State DOT.

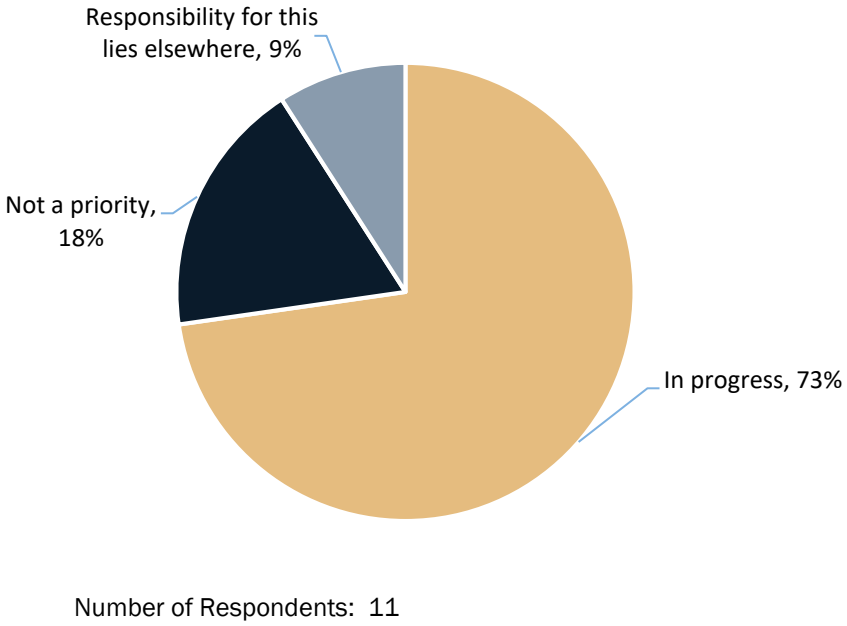
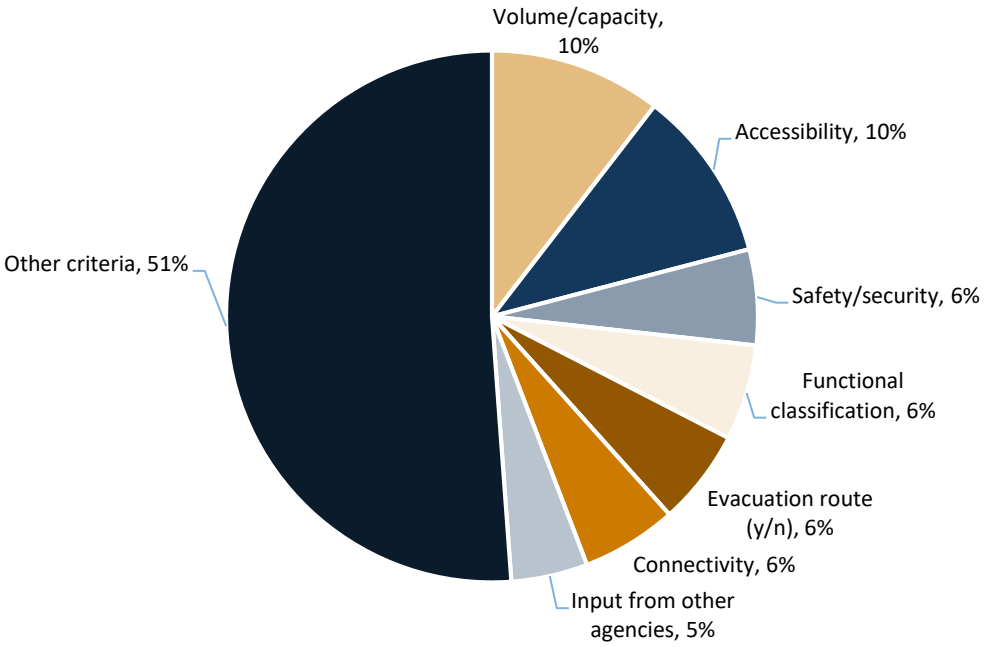


Figure 16. Reason MPOs Have Not Identified RTS Critical Elements

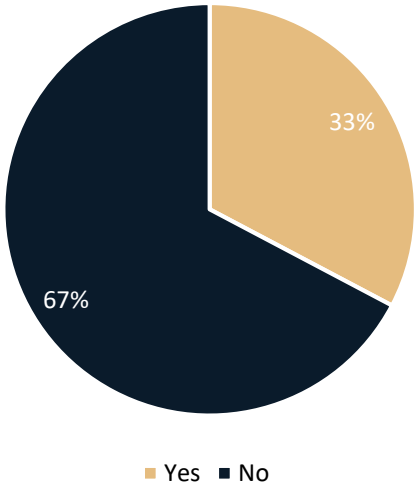
MPOs reporting that they had identified RTS critical elements were asked to specify the criteria used to determine criticality. The most often mentioned criteria were volume/capacity (10 percent) and accessibility (10 percent). Safety/security, functional classification, being an evacuation route, and connectivity each comprised 6 percent of responses. Other criteria were comprised of responses that were only mentioned one time. These included criteria such as travel time reliability, transit ridership, and pavement rating (see Figure 17).



Number of Responses: 86

Figure 17. Criteria Used to Determine Criticality

One-third of respondents reported that the MPOs they represented had determined how the RTS will respond to an extreme weather event (see Figure 18).



Number of Respondents: 55

Figure 18. Has MPO Determined Extreme Weather Event Response?

Respondents representing MPOs that had not determined how their RTS would respond to an extreme weather event were asked why this determination had not been made. One-third of responses (33 percent) indicated that this process is in progress, while three of ten responses (30 percent) indicated that other agency partners are working on this.

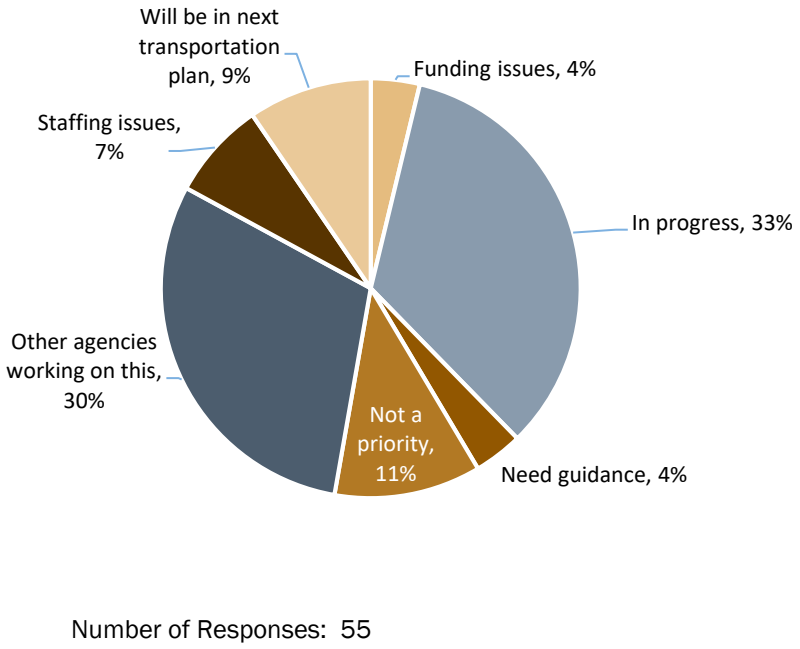
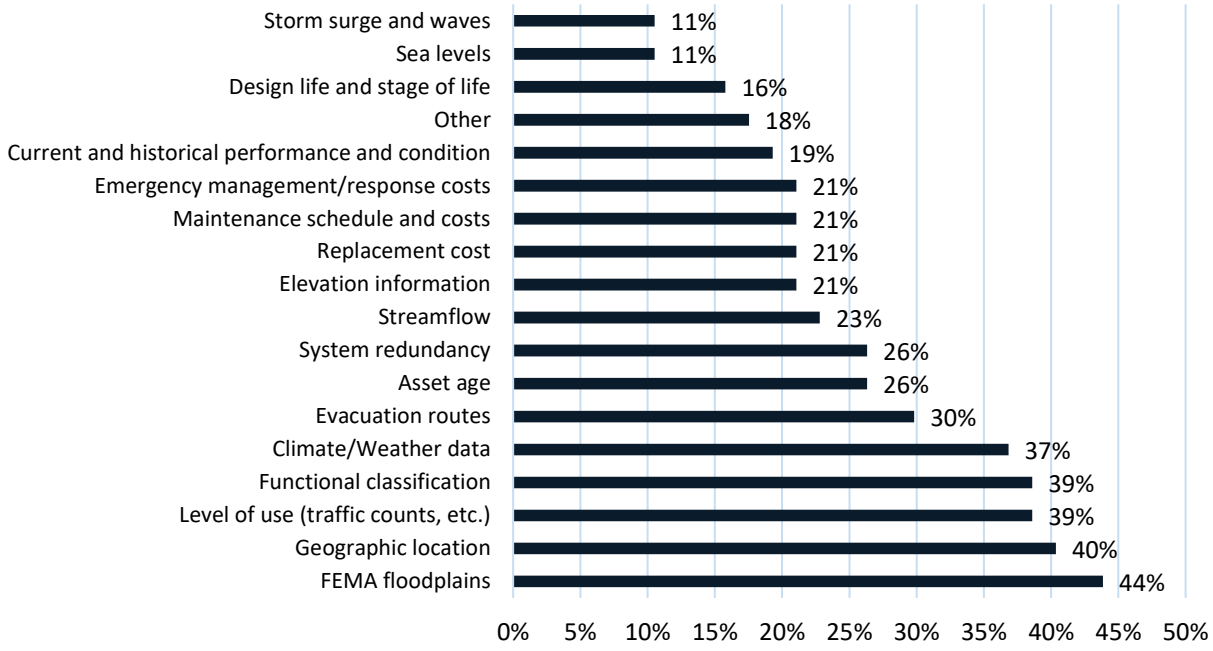


Figure 19. Reason MPOs Have Not Determined Extreme Weather Event Response

Figure 20 presents the data used by MPOs to identify risk and vulnerable transportation system elements, as well as the consequences of extreme events. At least four of ten MPOs use either FEMA floodplain data (44 percent) or geographic location data (40 percent). Level of use data and functional classification data are each used by 39 percent of MPOs, while climate/weather data is used by 37 percent of MPOs. Oceanic data (sea level, storm surge, and wave data) is used by 22 percent of MPOs (see Figure 20).



Number of Respondents: 57

Figure 20. Data Used to Assess Impact of Extreme Weather Events

Figure 21 presents a summary of additional data needed by MPOs to identify risk, vulnerability, and the consequences of extreme events to their transportation system. The most often mentioned response was hydrological data (25 percent), followed by weather data (15 percent), and financial data (13 percent) (see Figure 21).

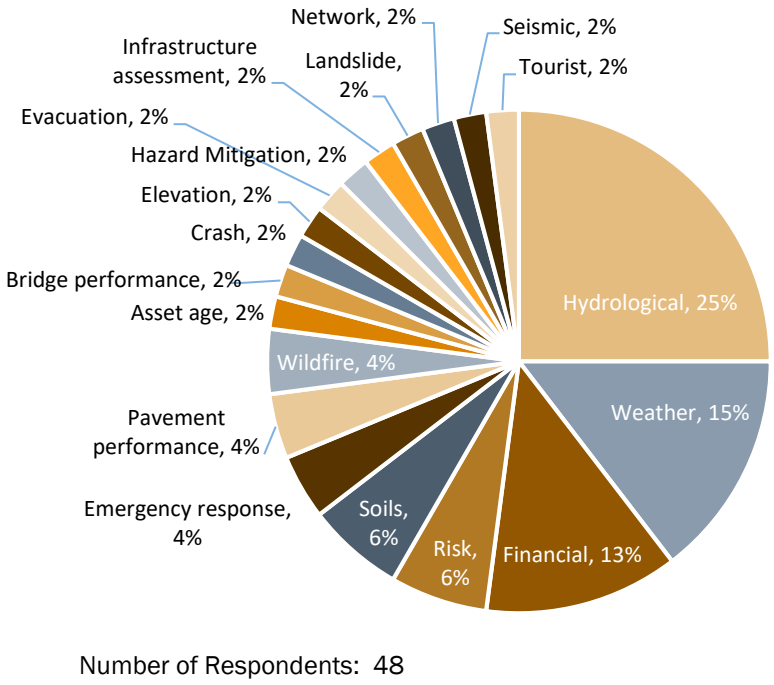


Figure 21. Additional Data Needed to Assess Impact of Extreme Events

When respondents were asked what tools their MPOs use to identify risk, vulnerable transportation system elements, and the consequences of extreme events, a majority (58 percent), stated their MPOs use Geographic Information Systems (GIS). Tools mentioned in other included cli-MATE, CoSMoS, CalFIRE, HAZUS, and the Sea Level Scenario Sketch Planning Tool (see Figure 22).

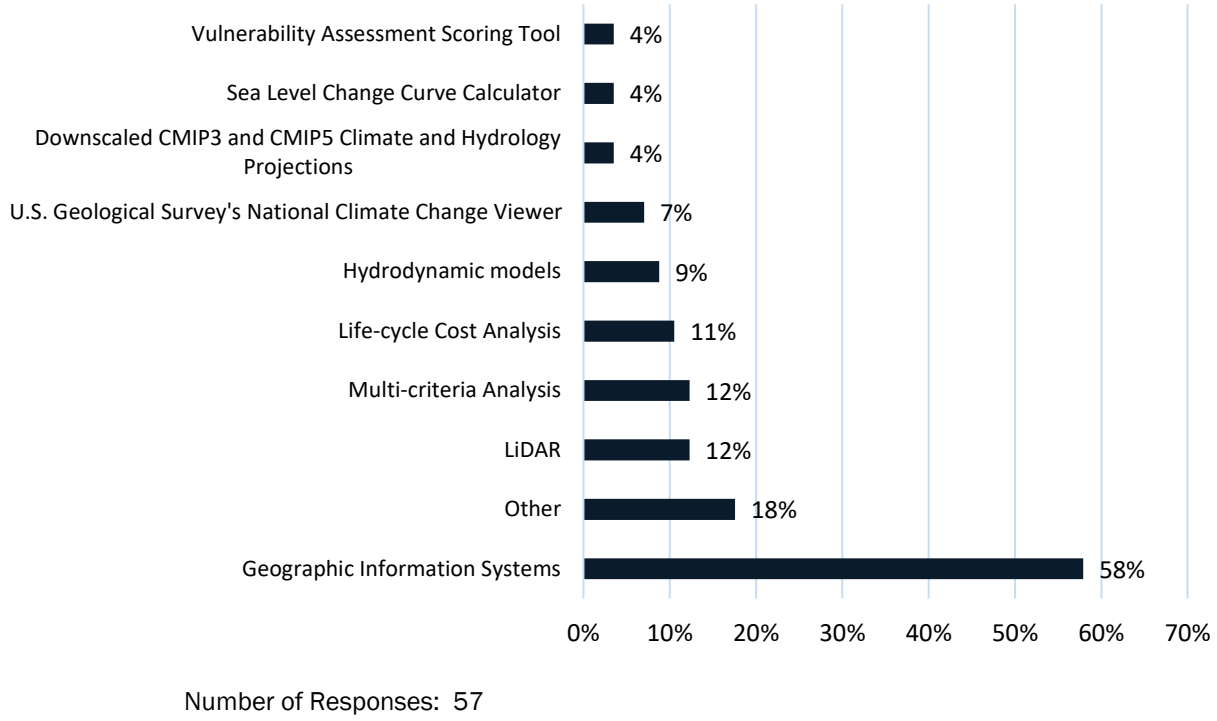


Figure 22. Tools Used to Assess Impact of Extreme Weather Events

Table 4 presents a summary of additional tools needed by MPOs to identify risk, vulnerability, and the consequences of extreme events to their transportation system. The most often mentioned responses were risk mapping tools (two responses) and technical training (two responses). The remaining responses represented a wide variety of needs.

Table 4. Additional Tools Needed to Assess Impact of Extreme Weather Events

Tool	Frequency Mentioned
Risk mapping tools	2
Technical training	2
Emergency traffic planning tool to model different scenarios	1
Hazard cost	1
Hydrological risk tools	1
Improved HAZUS	1
Lifecycle cost analysis	1
Linking TDM outputs with rainfall data	1
More funding	1

Tool	Frequency Mentioned
More staff	1
Pavement/bridge deterioration models	1
Regional incorporation of Vulnerability Assessment Scoring Tool (VAST)	1
State DOT guidance	1
Tools that facilitate multimodal analysis	1
Training on how we can help better coordinate this task	1
Weather risk	1
Wildfire risk	1
Total	19

Survey Conclusions

While the survey analyses are characterized by a small sample size (i.e., 14 percent of the MPOs responded), the data presented in Figure 23 shows how prepared the sample of MPOs are with regard to resiliency. Figure 23 shows:

- One in three (33 percent) MPOs have defined resiliency.
- About one in five (19 percent) MPOs have defined resiliency and identified resiliency goals.
- About one in ten (12 percent) MPOs have defined resiliency, identified resiliency goals, and developed resiliency metrics to measure progress toward these goals.

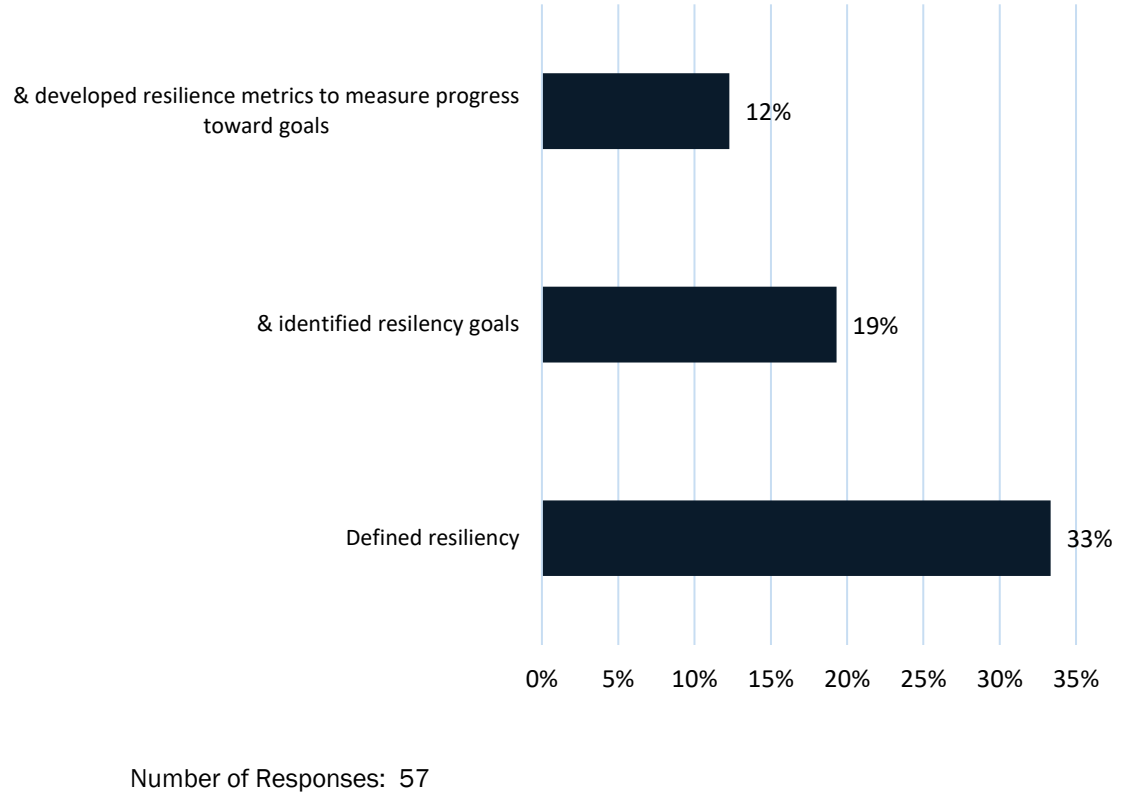


Figure 23. Resiliency Planning Efforts

While many respondents reported that their MPO is actively engaged in resiliency planning efforts, some reported that it is not a priority, either because the MPO is too small or the MPO does not have adequate resources (staff and or funding) to take on this responsibility. Some comments also suggest that resiliency has not been made a priority, because the MPO is relying on other organizations (mostly State DOTs) and or resiliency is being informally touched on in other parts of the MTP or planning process. Lastly, some MPOs feel that resiliency is a moving target and MPO planning efforts would benefit from increased federal guidance on the topic.

Some comments extracted from the survey that speak to these issues are presented below.

- *We don't have the resources to do this type of work in a way that would result in a more meaningful or robust actions to improve resiliency. Given the work, we have done to date and the challenges of the data, analysis tools and wide range of possible results, I would expect our updated plan will include broad language and policies suggesting owners of the transportation system should include this type of planning and analysis. Also, the regional plan may include suggested actions/strategies but measure when and how those actions could make a significant difference is beyond our current resources.*

- *We are a staff of two individuals. Major efforts are difficult for us to accomplish without additional tools.*
- *We are a small MPO (130k population) and currently have only two FTEs. However, as stated previously, we plan to address resiliency in a meaningful way in the near future. This will include a fulsome discussion in our upcoming 2045 RTP.*
- *Small agencies have significant challenges, in both budgetary and staff related in defining, measuring, and developing resiliency plans.*
- *Data sharing from the Federal government to states to MPO is not occurring.*
- *The MPO is part of a larger regional organization, and many of the efforts fall outside of MPO efforts.*

When it comes to preparedness for extreme weather events, Figure 24 shows:

- Slightly more than four of ten (44 percent) MPOs have identified and characterized climate factors that might impact the RTS and assessed vulnerability of the RTS to climate change/extreme weather events.
- One in three (33 percent) MPOs have (1) identified and characterized climate factors that might impact the RTS and assessed vulnerability of the RTS to climate change/extreme weather events, and (2) identified critical elements of their RTS.
- About one in five (18 percent) MPOs have (1) identified and characterized climate factors that might impact the RTS and assessed vulnerability of the RTS to climate change/extreme weather events, (2) identified critical elements of their RTS, and (3) determined how their RTS will respond to an extreme weather event.
- About one in ten (11 percent) MPOs have (1) identified and characterized climate factors that might impact the RTS and assessed vulnerability of the RTS to climate change/extreme weather events, (2) identified critical elements of their RTS, (3) determined how their RTS will respond to an extreme weather event, and (4) determined the risks/likelihood of extreme weather events occurring.

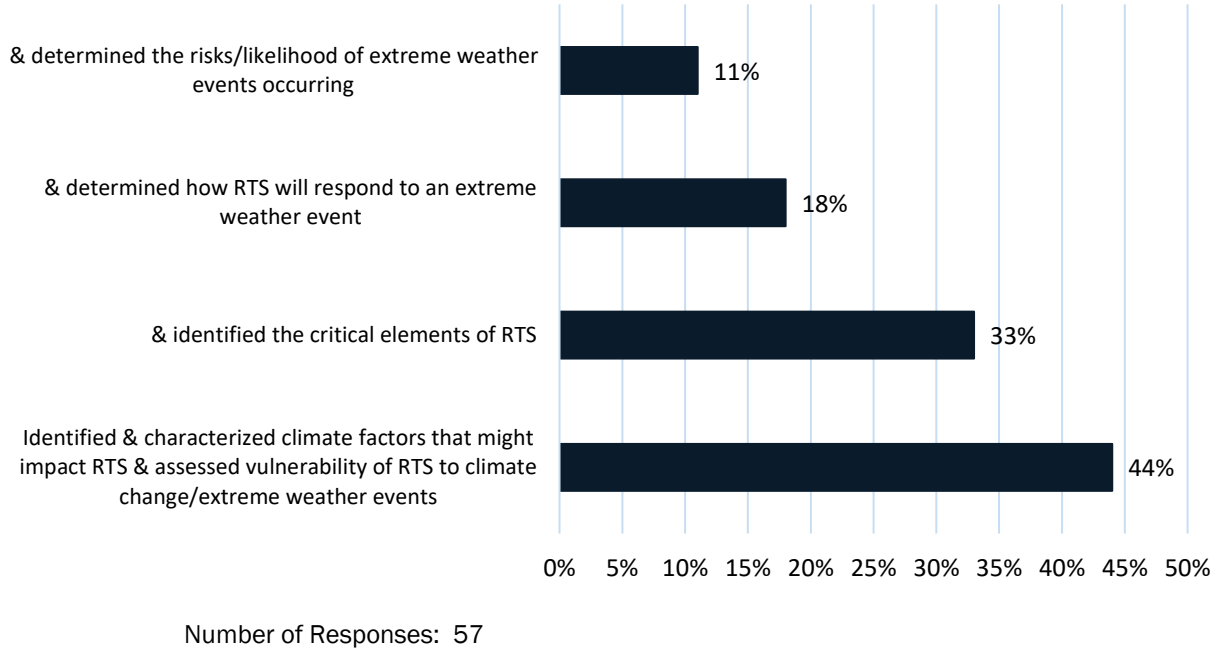


Figure 24. Extreme Weather Event Preparedness

Reasons for not being more prepared for extreme weather events were similar to the responses for not planning for resiliency: the tasks are in progress, the MPO is too small and/or lacks adequate staffing, the MPO relies on other organizations for these tasks, and/or it is not a priority.

Precipitation was mentioned by three of four (76 percent) MPOs as a climate factor of concern. This is not surprising as this survey was administered during the wettest 12 months in recorded U.S. history.[i] Given this high level of concern with precipitation, the most often mentioned type of data used to assess the impact of extreme weather events was FEMA floodplain data. The most often mentioned additional data needed to help assess the impact of extreme weather events was hydrological data, followed by weather data. Storm surge, wind, and drought were ranked less of a priority, mentioned by 31 percent of respondents each.

Highway corridors, bridges, road connectors, and rail infrastructure were the RTS elements identified as most vulnerable to extreme weather events, with GIS identified by most respondents as the tool used to assess the impact of extreme weather events on this infrastructure components.

Resiliency Study Lessons Learned

Two Texas MPOs (Capital Area Metropolitan Planning Organization [CAMPO], North Central Texas Council of Governments [NCTCOG]) have participated and two Texas MPOs (Houston Galveston Area Council [HGAC], and the Corpus Christi MPO) are participating in FHWA pilot case studies aiming to enhance the resiliency of regional transportation systems. In addition, several other TxDOT and MPO studies have been identified that addresses the topic resiliency. This section of the document provides available summary information for these studies and highlights lessons learned that can provide guidance to other Texas MPOs in planning for resiliency.

Central Texas Extreme Weather and Climate Change Vulnerability

CAMPO and the City of Austin's Office of Sustainability released the *"Central Texas Extreme Weather and Climate Change Vulnerability Assessment of Regional Transportation Infrastructure,"* study in 2015.[ii] The study analyzed the vulnerability of a limited list of transportation assets within the CAMPO region to extreme weather and climate.

How was resiliency defined?

Resiliency was not explicitly defined. However, given the context, resiliency can be interpreted as the ability to withstand the effects of extreme weather and climate.

What infrastructure/modes were considered?

The study considered the following transportation assets:

- Roadways
- Bridges
- Rail

What were the objectives?

The main objectives of the study were:

- To assess the potential vulnerability of a limited number of critical transportation assets in the CAMPO region to the effects of extreme weather and climate.
- To highlight lessons learned in the process.
- To outline potential next steps toward enhancing the resiliency of the region's transportation infrastructure.

What did they do?

The study developed three climate scenarios, plausible in the year 2040, and assessed the vulnerability of a limited number of critical transportation assets given these climate scenarios.

What did the study try to measure?

The study aimed to measure:

- The Soil Plasticity Index and moisture.
- Changes in precipitation and temperature.
- Risk of flooding, drought, extreme heat/cold and wildfires.
- Freight traffic density and Annual Average Daily Traffic (AADT).
- Adaptive capacity ratings based on each asset's criticality to the region and likelihood of exposure.

What data/tools did they use?

The study used data from CAMPO, the City of Austin, and their planning partners to create a geospatial database using GIS. The study used the following data related to transportation:

- Overview of RTS, i.e., roadways and bridges, rail, public transit, and airports.
- Current and future congestion.
- Freight corridors.
- Activity Centers.
- Population and employment density.

The study used the following climate data:

- Projection for 2041-2060 produced by Patricola and Cook (2013).[iii]
- Climate simulation: Weather Research and Forecasting (WRF) Regional Climate Model (RCM), developed by the National Center for Atmospheric Research (NCAR) and partners.

The study also used VAST for the vulnerability assessment.

Finally, the study conducted interviews with staff from the following stakeholder agencies:

- TxDOT.
- City of Austin Public Works Department.
- City of Austin Homeland Security and Emergency Management.
- City of Austin Fire Department.

- Capital Metro.
- Austin-Bergstrom International Airport.

What challenges were experienced?

Some challenges this study noted were: local roads have greater sensitivity to extreme weather events and other non-climate factors can amplify the impact of climate change, but there is less information available on these factors.

What was the outcome?

Central Texas is predicted to be warmer by approximately 2.7 degrees by the middle of the 21st century than it is now. Extreme heat events are expected to increase, as are drought conditions, and extreme precipitation events.

Preliminary risk ratings for each of the nine critical assets evaluated were presented to focus groups of state, regional, and local experts and officials. The results were adjusted based on stakeholder feedback. To justify investments to manage these risks, more in-depth evaluation would need to be conducted.

What were the lessons learned?

The study identified the following lessons learned:

- Partnerships with municipalities and coordination across sectors are important for resiliency planning.
- The nature of inland extreme weather and climate challenges may differ from those faced by coastal communities.
- Critical assets may not be the most vulnerable assets.
- Growth and other non-climate stressors can significantly influence extreme weather impacts on the transportation system.

What are the recommendations for next steps?

The study recommended more collaboration among CAMPO, City of Austin, and FHWA Texas Division Office. In addition, it was recommended that extreme weather considerations were included in the 2040 LRTP. The study also recommended that the region monitor pavement conditions and communicate with the public about road conditions.

More specific recommendations for using the results of the study to increase the resiliency of the Central Texas transportation network were:

- Build on and expand the scope of collaboration to include forming partnerships among MPOs, state DOTs, and municipalities and forming an Extreme Weather Resilience Working Group.

- Incorporate flooding, drought, extreme heat, and wildfire risks into asset management frameworks and into emergency response plans, particularly at the Y at Oak Hill, Loop 360/RM 2222, and FM 1431 at Brushy Creek.
- Expand the assessment to selected city and county roads and/or extend the assessment time horizon to consider end-of-century impacts.
- Evaluate and implement adaptation options, including improving or widening the shoulders of roads.

North Central Texas Council of Governments

The North Central Texas Council of Governments (NCTCOG) and the FHWA funded the *"Climate Change/Extreme Weather Vulnerability Risk Assessment for Transportation Infrastructure in Dallas and Tarrant Counties"* in 2015.[iv] The study assessed how extreme weather events in the future could affect the transportation infrastructure of Dallas and Tarrant counties.

How was resiliency defined?

Resiliency was not explicitly defined. Given the context, resiliency can be interpreted as a lack of vulnerability of transportation infrastructure to extreme weather and climate change.

What infrastructure/modes were considered?

The following modes were included - overlaid with FEMA flood maps – in the vulnerability assessment matrix:

- Highways.
- Rail.
- Air.

What were the objectives?

The objectives of the study were to:

- Assess how extreme weather events could affect the transportation infrastructure of Dallas and Tarrant counties in the future.
- Allow transportation planners to adapt and prepare future transportation infrastructure for extreme weather events.
- Protect and enhance taxpayer investments in transportation infrastructure.

What did they do?

The study conducted three major tasks in the climate impact vulnerability assessment:

- Compiled historical climate data and projected future climate conditions for the Dallas-Fort Worth (DFW) Metropolitan Area.
- The North Central Texas (NCT) criticality assessment team developed an asset inventory of existing and future transportation infrastructure in Dallas and Tarrant Counties that included roads, passenger rail, and aviation facilities.
- Evaluated the vulnerability of transportation infrastructure in Dallas and Tarrant Counties to risks from extreme weather events and climate change.

What did the study try to measure?

The study assessed:

- Temperature, precipitation, wildfire, and flood risk.
- Population growth, vehicle hours spent in delay (daily), increased travel time due to congestion, current capacity (number of lanes), and annual average daily traffic (AADT).
- Pavement design, traffic loads, soil conditions, weather/precipitation patterns, and maintenance schedules.

What data/tools did they use?

The study gathered climate and weather data from 1900 to 2010. For the vulnerability assessment, transportation data were overlaid with FEMA flood maps and University of Texas at Arlington (UTA) temperature maps. The study developed a GIS data inventory with location maps of current and future transportation assets. NCTCOG's LRTP was used to incorporate projected infrastructure expansions. AADT and passenger rail ridership data were also considered.

The study identified transportation assets located within the FEMA 100-year floodplain and created a risk assessment based on the criticality of the transportation assets and the likelihood of extreme weather impacts.

What challenges were experienced?

The study mentioned that critical infrastructure in the floodplain may or may not be directly exposed to flooding, but that the study team did not have the time to evaluate each facility individually. It was also noted that climate change was only one factor that affected road performance and that the study team did not evaluate any other factors.

What was the outcome?

The study concluded that by the end of the 21st century, it was likely that more extreme storms and higher precipitation will result in service disruption and infrastructure damage.

These weather events will also likely result in more flooding, especially in the Spring. Furthermore, it was considered likely that multiple infrastructure assets will be at risk of heat damage, especially during the Summer.

What are the recommendations for next steps?

The study recommended that future work be conducted to allow for a more accurate and comprehensive vulnerability assessment of North Central Texas transportation assets. Specifically, the study recommended:

- More precise forecasts of extreme precipitation and temperature to determine runoff risks.
- Tracking weather- associated damage to infrastructure to inform future infrastructure construction projects.
- More data collection and analysis to identify particular impacts resulting from weather events.

The study also recommended the development of several new rail corridors by 2035.

Gulf Coast

The U.S. Climate Change Science Program and the Subcommittee on Global Change Research released *"Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: Gulf Coast Study, Phase I"* in 2008.[v] The study addresses how changes in weather could affect the transportation infrastructure of the U.S. Gulf Coast between Galveston, Texas and Mobile, Alabama. This was Phase 1 of a multi-phase study.

How was resiliency defined?

Resiliency is not explicitly defined. In this context, resiliency can be interpreted as the ability of the transportation system to withstand the risks of climate change and ensure the safety of the transportation system.

What infrastructure/modes were considered?

The following modes were included in the study:

- Highways.
- Transit.
- Freight and Passenger Rail.
- Maritime.
- Air.
- Pipelines.

What were the objectives?

The primary objectives of Phase I were:

- To collect data needed to characterize the region – its physiography and hydrology, land use and land cover, past and projected climate, current population and trends, and transportation infrastructure.
- To demonstrate an approach for assessing risks and vulnerability of transportation modes at regional and local scales.

The ultimate goal was to provide transportation planners and managers with knowledge and tools to better understand the risk, strategies, and trade-offs involved in transportation planning, investment, design, and operational decisions.

What did they do?

The study team used historical trends and plausible future climate scenarios to examine the potential effects of climate change on transportation modes within the Gulf Coast Region.

What did the study try to measure?

The study team aimed to measure:

- The destructive potential of hurricanes, storm activity, temperature, precipitation, sea level rise, and wind speed.
- Road structure, socioeconomic conditions of an area, and various system level factors, such as repair and replacement costs, modal capacity, and whether a road is an evacuation route or not.

What data/tools did they use?

Two types of data were used: climate data and transportation data. The study team used the following sources by data type:

- Climate data:
    - United States Climate Division Datasets (CDD)
    - United States Historical Climate Network (USHCN)
    - National Center for Atmospheric Research (NCAR)
    - National Oceanic and Atmospheric Administration's (NOAA) Sea, Lake and Overland Surges from Hurricanes (SLOSH) model
- Transportation data
    - Federal Highway Association (FHWA)
    - American Public Transportation Association (APTA)
    - National Transit Database (NTD)
    - Bureau of Transportation Statistics (BTS)

- U.S. Army Corps of Engineers (USACE)
- U.S. DOT, Pipeline and Hazardous Materials Safety Administration (PHMSA)

What challenges were experienced?

This study noted a lack of references or other studies that attempted *"to quantify the estimated costs, benefits, or effects on performance resulting from climate change; more commonly, they identified potential impacts without a quantitative assessment".* There was therefore a lack of materials to reference and inform the quantification of the costs, benefits, and transportation performance impacts of climate change.

What was the outcome?

The study reported the following expected climate changes for the Gulf Coast in the next 50 to 100 years: (a) increased temperatures, (b) changing precipitation patterns, and (c) more intense storms. Sea levels are expected to rise globally due to the warming of ocean temperatures and melting of polar ice sheets. In the Gulf Coast, land surface is also expected to sink. The effects of these changes on transportation are predicted to be as follows:

- **Warming temperatures:** increase in cost of transportation construction, maintenance, and operations.
- **More frequent extreme precipitation events:** disruption of transportation networks, flooding, and visibility problems.
- **Rising sea levels:** existing infrastructure will be more prone to inundation.
- **Increased storm intensity:** more service disruption and infrastructure damage.

What are the recommendations for next steps?

The study recommended that:

- Transportation infrastructure be replaced and designed to withstand higher intensity storms.
- Agencies need to incorporate longer-term climate change effects into planning processes.
- Planners need new tools to address the uncertainties in climate change projections.
- This study be replicated in other areas of the country to help determine the possible impacts of climate change on transportation infrastructure and services in other areas.
- The effects of climate change on freight transport demand, demographic change, and emergency management be identified.
- Materials be developed to help withstand higher temperatures.
- A study be conducted to investigate how land use development and environmental management affect the magnitude of climate change impacts.

The Texas Department of Transportation (TxDOT) Statewide Freight Resiliency Plan

TxDOT released the *"Statewide Freight Resiliency Plan, Stage 1: Prepare the Freight System"* in 2011.[vi] This report was prepared to provide a framework for identifying key freight infrastructure corridors to ensure that the Texas freight transportation network is resilient.

How was resiliency defined?

The report defines resiliency for the freight transportation system as *"the ability for the system to absorb the consequences of disruptions, to reduce the impacts of disruptions and maintain freight mobility."*[vii]

What infrastructure/modes were considered?

The following freight modes were included in the study:

- Highways.
- Rail.
- Marine.
- Air.
- Pipeline.

What were the objectives?

The objective of the resiliency plan, as stated in the report, is:

"To assess the resilience of the strategic freight system in Texas when an event of extended duration limits freight mobility, resulting in prioritized infrastructure enhancements to keep freight moving."

Three study goals were developed by TxDOT with support from the Texas Statewide Freight Resiliency (SFR) Plan Advisory Committee.

1. To have a freight transportation system prepared to keep freight moving during an event.
2. To have a responsive framework to address shipper and carrier needs as an event occurs, and to recover the freight transportation system as quickly as possible.
3. To have a flexible, relevant plan that is used to improve freight mobility in Texas.

What did they do?

The study assessed the preparedness of the freight system to respond to an event. The study team completed the following tasks:

- Conducted a literature review.
- Interviewed key stakeholders.

- Interviewed other organizations that developed similar resiliency plans.
- Identified the freight system using the transportation system network and economic data.
- Assessed physical and capacity constraints.
- Analyzed institutional and supply chain needs.

What data/tools did they use?

The freight system was identified using population, employment, and commodity flow data. Resiliency was determined using a risk management procedure. The study team also identified all federally-declared disasters in Texas, such as floods and hurricanes, from 1953 to 2010. The study team used data from the Texas Hazard Mitigation Package to develop maps of the geographic location of the areas vulnerable to disasters. Finally, the study team used the State of Texas Hazard Mitigation Plan to obtain information on historic occurrences and mitigation actions that were implemented.[viii]

What was the outcome?

The study team assessed the resiliency of ten primary highway freight corridors, as well as the overall statewide highway system. The study team also assessed the overall resiliency of the rail network. For the marine, air, and pipeline modes, the study team developed short case studies on the approaches of these modes to past events.

The Texas highway system was found to be robust and redundant. All other modes (rail, air, maritime, and pipeline) were deemed highly resilient.

The study team developed four strategies for advancing a resilient freight transportation system as follows:

1. Support planning for a resilient, well-maintained freight transportation network.
2. Prioritize infrastructure enhancements to improve the freight resiliency of Texas highways.
3. Improve access to data, information, and people needed for effective resiliency planning.
4. Communicate before, during, and after events.

What are the recommendations for next steps?

The study focused on identifying and assessing Texas's freight transportation corridors and providing the context and purpose for resiliency planning in Texas. It was recommended that implementation strategies be covered in a Stage 2 of the Statewide Freight Resiliency Plan. The goal of Stage 2 is to develop a responsive framework for addressing shipper and carrier needs as an event occurs and to recover the freight transportation system as quickly as possible.[ix]

North Texas: Temperature and Precipitation Impacts to Pavements on Expansive Soils

FHWA released a study entitled *"Temperature and Precipitation Impacts to Pavements on Expansive Soils: Proposed State Highway 170 in North Texas"* in 2015.[x] The study explores the impacts of environmental conditions on pavements. The environment can affect pavement and result in rutting, cracking, and heaving. This affects the structural performance of the pavement, the riding comfort, and the safety of the road. Pavements are expensive to repair, while structural issues can present safety issues. Pavement design approaches usually take climate factors into consideration, but this is typically based on historical weather data and does not consider future climate change.

How was resiliency defined?

Resiliency is not explicitly defined. However, given the context, resiliency can be interpreted as pavements that are adequately prepared for projected changes in precipitation and temperature.

What infrastructure/modes were considered?

The study focused on the impact of environmental conditions on rigid and flexible pavements built on expansive soils.

What were the objectives?

The main objectives of the study were:

- To evaluate the potential impacts of projected changes in precipitation and temperature on pavement performance.
- To analyze whether current pavement design adequately prepares pavement for projected changes in precipitation and temperature during the expected life of the road.
- To study the effect of variations in precipitation and temperature due to climate change on the performance of flexible and rigid pavements on expansive soil.
- To investigate the options for mitigating the risks and adapt to climate change.

What did they do?

The study was designed to address gaps in past assessments of the impact of environmental conditions on pavements. This included the following elements:

- Considering climate information, specifically changes in temperature and moisture.
- Considering changes in temperature and precipitation patterns and soil moisture conditions.
- Combining historical climate data with projected future climate changes.
- Considering secondary impacts of climate stressors.

- Incorporating climate change into design practices.
- Identifying phased adaptation strategies.
- Accounting for climate change uncertainty and the cost of adaptation.

Mechanistic-empirical pavement performance prediction models were used to estimate pavement performance. This estimated pavement performance was evaluated against future projections of precipitation and temperature. More specifically, the study evaluated:

- Changes in the Thornthwaite Moisture Index (TMI) and the associated impacts on soil support conditions.
- Changes in the shrink-swell potential of soils that would contribute to loss in pavement smoothness.
- Changes in the performance grade requirements of asphalt binder and the dynamic modulus of asphalt concrete mixtures due to changes in temperature.
- Resulting changes in pavement distresses. For flexible pavements, (1) load-related fatigue cracking, (2) subgrade rutting, and (3) AC rutting were considered. For rigid pavements, the punchout potential of continuously reinforced concrete pavements (CRCP) was investigated.

What data/tools did they use?

Mechanistic-empirical pavement performance prediction models were used to estimate pavement performance. Both flexible and rigid pavement were considered. The data and information used by the study team included:

- Pavement designs using TxDOT-approved design methods.
- Historical climate data.
- Inputs for typical materials and design parameters.
- Forecasted traffic.

What was the outcome?

The study team predicted that temperatures will increase, and moisture will decrease during the 21st century. This is expected to lead to a modest increase in distress on pavement. The study team compiled the following recommendations:

- Develop adaptation options, such as improved drainage and use other remedial measures, such as geotextiles or mulch on the shoulders to reduce the infiltration of moisture into the subgrade and thereby prevent base erosion.
- Assess the performance of the identified adaptation options.
- Conduct an economic analysis of each adaptation option.
- Evaluate additional option that go beyond proven strategies that TxDOT routinely uses.
- Select a course of action and develop a Facility Management Plan.

Asset Management, Extreme Weather, and Proxy Indicators Pilot Final Report

FHWA selected TxDOT to pilot the development of an extreme weather event risk framework. The TxDOT Houston District was used as the case study to develop the framework for understanding and integrating extreme weather risk into asset management. TTI conducted the research. The final report was published in February 2019.

How was resiliency defined?

Resiliency was not explicitly defined.

What infrastructure/modes were considered?

The study considered the following transportation assets:

- State-maintained roads in TxDOT's Houston District.

What were the objectives?

The main objectives of the study were:

- To develop a risk assessment framework to understand flood risk and the potential impact on the Houston state-maintained network.
- To characterize flood risk in Houston to provide better inputs for pavement engineers to estimate the damage caused by these events.
- To provide a data-driven approach to identify mitigation strategies and prioritize investment decisions.

What did they do?

This study team conducted a literature review to identify the climate factors of concern to TxDOT's Houston District. In addition, the study team conducted a workshop to focus the pilot effort on the climate factor of most concern to stakeholders. Based on the input received, the researchers focused on characterizing inland flooding and its impact on Houston's road infrastructure. The study team reviewed data resources and information potentially useful for characterizing flooding in Houston. The study team translated spatial information of 100- and 500-year flood zones into a spatial view of inundation characterized by flood height and analyzed Light Detection and Ranging (LiDAR) data to provide information on the elevation of road infrastructure (pavements) in Houston. The study team calculated the potential impacts of flooding on Houston's pavement infrastructure, the potential loss in service life, and disruption impacts (road closures due to flooding). Finally, the study team identified potential mitigation measures and investment priorities to increase the resiliency of Texas's road system to flooding in Houston and potential proxy indicators that the agency can track in the future.

What did the study try to measure?

The study aimed to measure:

- Flooding risk in Houston.
- Pavement impacts associated with different flooding scenarios.

What data/tools did they use?

The study team used the following data/tools:

- FEMA floodplains.
- LIDAR data.
- Pavement deterioration simulations.
- Traffic volumes.
- Road topography data.

What challenges were experienced?

Some challenges this study noted were:

- A lack of robust models prevented the evaluation of the impact of flooding on other distresses or the evaluation of alternative measures (e.g., more frequent maintenance of culverts, improved drainage, addition of shoulders, or roadside vegetation/stabilization) on the pavement service life given a flooding event.
- No tools currently exist to conduct a robust analysis of the inundation impacts of measures to increase the resiliency of pavements to flooding: flood defenses, higher flood walls, levees, and additional pumping stations; the creation of wetlands and marsh rehabilitation; and green infrastructure to deal with rainfall events and to capture storm water.

What was the outcome?

The study team concluded that 75 percent of the state-maintained lane-miles are at minimal risk from flooding. However, 12 percent of the state-maintained lane-miles in Harris County are at risk of flooding in the case of 100-year events. Even small amounts of surface water on the roadway places drivers at a safety risk from, for example, hydroplaning. Water depths of between four and 20 inches are likely to limit visibility of lanes, road boundaries, and the road surface, while depths of greater than 20 inches are likely to be impassable even to emergency response vehicles.

What were the lessons learned?

The study identified the following lessons learned:

- Thinner pavement structures, particularly those without treated subgrades and less than two inches asphalt are particularly vulnerable to flooding. Strengthening unbound layers such as subgrades and base materials with stabilization techniques helps mitigate pavement damage caused by flooding. If thinner pavement sections are furthermore heavily trafficked during flood response, immediate pavement damage should be expected that will likely require immediate reconstruction

- Most of the impacts will lead to disruptions in travel rather than chronic damage to the pavement.

The results of this study also added to the understanding of the long-term impacts of flooding events on the serviceability of flexible pavements. The results can be employed in lifecycle plan analysis and resiliency assessment of pavement networks to extreme weather events in the update of the TxDOT Transportation Asset Management Plan (TAMP).

What are the recommendations for next steps?

Specific recommendations for using the results of the study to increase the resiliency of the transportation network were:

- Develop sampling methods that use subsurface measurements to infer pavement performance over the entire network.
- Improve risk assessment of the extreme weather event threats to the agency's assets. The work can be extended to develop a resiliency index for the state-maintained system in terms of both potential infrastructure damage and disruptive impacts. Such a resiliency index can ultimately be used to inform and prioritize investment decisions.
- Improved results could be obtained by working with the original hydrological models, which explicitly translate rainfall frequencies and intensities into flood depth maps.
- While transportation engineers may be predominately concerned about the impacts of flooding on roads, road surfaces also alter the topography of an area and play an important role in determining the nature of surface water flow. This requires improved collaboration among climatologists, hydrologists, pavement engineers and other transportation domain specialists.
- Further work is needed to convert rutting impacts into the distress and condition scores used in TxDOT's Pavement Analyst because the condition score is the performance measure used by the agency in evaluating maintenance measures and managing its assets. Besides rutting, water inundation can also lead to stripping of asphalt concrete layers, creating the potholing effect often seen after heavy rain events. More robust tools are needed to simulate this impact.

- A lack of robust models prevented the evaluation of alternative measures (e.g., more frequent maintenance of culverts, improved drainage and hydrological solutions, or addition of shoulders or roadside vegetation/stabilization) on the pavement service life given a flooding event.
- Investigate the potential disruptive effects of flooding and the significant cost of elevating impacted roads. Additional work is needed to understand the routing decisions and the impact of road closures of the state-maintained network that result in the diversion of traffic onto roads with weaker pavement structures in cities and counties.

Resiliency in Regional Transportation Plans

TTI hosted a one-day workshop on *"Addressing Resiliency in Regional Transportation Plans"* on June 26, 2019 at the NCTCOG offices in Arlington. The Workshop comprised several 15-minute presentations by FHWA, TTI, and Texas MPOs on planning for resilient transportation systems, as well as the challenges experienced.

The workshop comprised three sessions. During the first morning session, the FHWA and researchers from TTI shared information on addressing resiliency in the planning process, developing a resilient Texas transportation system, and the findings from the national MPO survey. The second morning session focused on incorporating resiliency in regional transportation planning documents given an assessment of climate factors that are of concern to inland areas (e.g., extreme heat, droughts, inland flooding, ice storms, etc.). NCTCOG, CAMPO, and Texarkana MPO shared lessons learned from their FHWA pilot studies and resiliency efforts, as well as challenges experienced. The afternoon session focused on incorporating resiliency in regional transportation planning documents given an assessment of climate factors that are of concern to coastal areas (e.g., sea level rise, storm surge, hurricanes, etc.). Lamar University, H-GAC, and Corpus Christi MPO shared lessons learned from their FHWA pilot studies and resiliency assessments, as well as challenges experienced.

The workshop concluded with stakeholders participating in four small group discussions for 20 minutes to share any comments on (a) data sources/tools for identifying vulnerable RTS elements, (b) strategies/options to promote resiliency of the transportation system, and (c) challenges/issues experienced in incorporating resiliency in regional transportation plans.

Fifty-seven transportation planners and subject matter experts attended the workshop. This section of the report summarizes the information presented at the workshop.

Addressing Resiliency in the Transportation Planning Process (Kirk Fauver, FHWA)

Mr. Fauver started his presentation by observing that the FHWA has partake in workshops on the topic of resiliency in Texas since 2017. The first workshop was hosted in Austin in 2017, followed by the workshop in College Station in 2018, and then today's workshop in Arlington.

The FHWA defines resiliency as the *"capacity to anticipate, prepare, adapt, and recover rapidly from disruptions."* Resiliency activities are deemed important because extreme weather events (e.g., hurricanes, floods, wildfires, drought, tornadoes) are causing billions of dollars in damage to the economy, as well as result in large costs to repair infrastructure. Recent examples include Hurricane Maria (Puerto Rico), Hurricane Harvey, Hurricane Sandy, the Missouri River Flood (I-680 Iowa), and the Lotto Canyon Fire that impacted Highway 1 in California.

Mr. Fauver pointed out that resiliency activities need to be considered in both system planning and project design. Federal law (FAST Act) requires that state-wide transportation plans address the resiliency and reliability of the state transportation system. Specifically, the law requires that state's LRTPs address emergency relief and disaster preparedness. Section 40.3249(f)(7) requires that the LRTPs address the vulnerability of existing transportation infrastructures to natural disasters. The FAST Act also requires that Metropolitan Transportation Plans (MTPs) consider resiliency. Transportation planners are therefore required to prioritize capital investments to reduce vulnerability to natural disasters. Finally, the FAST Act requires that state DOTs consider resiliency goals by periodically evaluating emergency relief events and facility requirements in their asset management plans. Asset management plans require the development and maintenance of risk management and lifecycle plans that consider the impact of natural disasters on infrastructure. Project design requires looking at construction procedures to enhance resiliency through mitigation and adaptation. In the DOTs' risk-based asset management plans, DOTs are required to evaluate alternatives to facilities that require repeated repairs. Resiliency, however, also pertains to traffic operations and emergency response/recovery efforts. Mr. Fauver pointed out that extreme weather resiliency projects are eligible for FHWA Surface Transportation Program (STP) funds.

Mr. Fauver concluded by pointing workshop attendees to several federal resiliency resources as follows:

- Guidebook that will be forthcoming in the summer addressing resiliency within asset management covering pilot projects in Arizona, Kentucky, Texas, Maryland, New Jersey, and Massachusetts.
- Project level engineering case studies covering bridges, slope stability, forest fires, and pavement analysis from across the country.
- Methods incorporating resiliency into emergency response with instructions on how to conduct traffic operations and emergency response during extreme weather events.
- Vulnerability Assessment and Adaptation Framework (VAST) 3rd Edition covered in this and prior workshops. The VAST tool is an Excel Spreadsheet tool, available online, that transportation planners can use in the development of their LRTPs.
- 2nd International Conference on Resilience to Natural Hazards and Extreme Weather Events that will be held in November in Washington DC.

Developing a Resilient Texas Transportation System (Jolanda Prozzi, TTI)

Ms. Prozzi provided an overview of a resiliency study that TTI conducted for TxDOT. The objectives of the study were:

- To host a resiliency forum on the state-of-the-practice in resiliency research at Texas state universities to inform resiliency planning activities.
- To outline a framework for planning a resilient Texas transportation system.

Ms. Prozzi outlined a five-step planning framework for transportation resiliency in her presentation. The first step in this framework is to define resiliency for transportation. The FHWA definition requires planners to address short- and long-term trends, as well as plan transportation systems that can recover from extreme weather events. Ms. Prozzi highlighted that forum participants defined a resilient transportation system that are robust, reliable, and rapid to recover from major disruptions.

The second step is to identify resiliency goals and objectives. The literature revealed that some DOTs developed standalone goals for resiliency, while others adapted existing planning goals to include aspects of resiliency. Given the latter, it can be argued that TxDOT can adapt the asset management goal to include resiliency. Similarly, goals pertaining to mobility, reliability, and connectivity can be adapted to include resiliency components.

The third step is to identify performance measures that can be used to track progress towards achieving resiliency goals. The literature seems to focus on impact and redundancy measures. Example impact measures include infrastructure resiliency measures (e.g., lane-miles of critical highways that can withstand an extreme flooding event) and operational performance measures (e.g., operational at reduced capacity for less than x days). Redundancy measures typically include number of reliable routes and available multimodal options.

The fourth step is to assess the vulnerability of the transportation system. Vulnerability assessments require:

- **Identifying and categorizing extreme weather events.** TxDOT's Environmental Affairs Division provided climate projections for Texas that could potentially impact the state's transportation system. TxDOT has also identified climate stressors for each of Texas's 254 counties.
- **Determining extreme event probability and risk.** This step requires transportation planners to partner with other agencies, such as the state climatologist, that have experience working with weather and climate data and use climate projections.
- **Identifying vulnerable transportation system elements.** This involves overlaying weather risk data with transportation assets. TxDOT's Asset Management Plan overlaid floodplain information with the National Highway System (NHS) and identified the potentially vulnerable infrastructure as the infrastructure in the floodplain.
- **Estimating impact of extreme events on vulnerable infrastructure.** The impact on the infrastructure (e.g., how the infrastructure will respond to an extreme weather event) is largely a function of the asset age, condition, physical attributes, and maintenance schedules.
- **Identifying the critical transportation assets.** These are typically assets that the region cannot afford to fail. Criteria for determining criticality include: level of use (current and future), critical commerce or commuter corridors, functional classification, and replacement cost.

The fifth step include identifying and prioritizing adaptation, mitigation, and recovery measures to increase the resiliency of the transportation system, such as building/rebuilding assets to withstand anticipated environmental conditions, site new facilities outside floodplains or reconstruct at-risk highways to consider more conservative flood frequency event assumptions. Prioritization methods are typically founded in economic theory (i.e., multi-attribute criteria analysis or lifecycle cost analysis). The method is usually determined by the data available.

Ms. Prozzi concluded her presentation by sharing the recommendations from the 2018 Transportation Resiliency Forum in College station:

- TxDOT should create a Texas Resiliency Workgroup that coordinates and provides input on the development of a Texas Transportation Resiliency Framework, but also share data, tools, and innovative approaches to ensure a resilient transportation system.
- TxDOT should include resiliency goals, performance measures, and metrics in the performance-based planning process used for project prioritization in the Unified Transportation Program (UTP).
- TxDOT should lead the development of a resiliency data clearinghouse and share the data with local partners to ensure confidence that the data they use are robust and vetted.
- TxDOT should continue and support ongoing resiliency workshops to share lessons learned, best practices, and challenges in planning for resiliency.
- TxDOT should develop a scenario planning tool for "what if" analysis (e.g., what happens if flood risks increase or given different assumptions about climate change).

Resiliency Best Practices: Results from the Metropolitan Planning Organization Survey (Chris Simek, TTI)

TTI administered a survey to MPOs to determine how these planning agencies are responding to federal resiliency requirements. Fifty-seven MPOs provided complete responses to the web-based survey that was administered over a three-month period between February and April 2019. Mr. Simek reviewed the highlights of the survey results with workshop participants as follows:

- Only 33 percent of the survey respondents have defined resiliency. Of the 66 percent of the respondents that indicated that they have not defined resiliency, about 50 percent reported that they were in the process of defining resiliency; 10 percent indicated that it was on their radar, but not a priority; while another 10 percent indicated that they have not defined resiliency in their LRTP, but that their plan included resiliency elements.
- About 33 percent of the survey respondents have adopted resiliency goals. Of the 66 percent of the respondents that have not identified resiliency goals, 30 percent reported that they are in the process of establishing resiliency goals, 20 percent reported that the

MPO will include resiliency goals in the next MTP, and 20 percent reported that defining resiliency goals are on the MPO radar, but not currently a priority.

- About 20 percent of the survey respondents defined resiliency metrics to monitor progress towards achieving resiliency goals. Of the 80 percent of the respondents that have not defined resiliency metrics, about one in four stated it is a work in progress, 15 percent stated it was on their radar but not a priority, 13 percent stated it will be in the next MTP, and 13 percent stated more federal guidance is needed.
- Only 12 percent of the survey respondents reported that they have defined resiliency, resiliency goals, and associated performance metrics.
- About 44 percent of the respondents identified climate and weather factors and assessed how vulnerable their transportation system was to these factors, 70 percent of the respondents identified the critical elements of their RTS, 33 percent identified responses to extreme weather events, and 33 percent assessed the likelihood of an extreme event occurring. However, only about one in ten (11 percent) MPOs have (1) identified and characterized climate factors that might impact their RTS and assessed the vulnerability of their transportation system to climate change/extreme weather events, (2) identified critical elements of their RTS, (3) determined how their transportation system will respond to extreme weather events, and (4) determined the risks/likelihood of extreme weather events occurring. Overwhelmingly, MPOs focused on the vulnerability of the highway and rail infrastructure components of the RTS.
- About 76 percent of survey respondents identified precipitation as the climate factor of most significant concern. As such, the most common type of data used to assess the impact of extreme weather events were FEMA floodplain data. The most needed data to assess the impact of extreme weather events were reported to be hydrological data.

Incorporating Resiliency in Regional Transportation Plans in North Central Texas (Jeff Neal, NCTCOG)

Mr. Jeff Neal reported that NCTCOG's focus in terms of resiliency planning is how to effectively incorporate resiliency into how the region establishes investment priorities. Mr. Neal noted that the planned distribution of funding for transportation projects in the Dallas-Fort Worth region as included in NCTCOG's 2045 MTP is primarily focused on maximizing the performance of the existing transportation system. Mr. Neal noted that although resiliency pertains to both the planning and design of the transportation system, transportation resiliency can be best measured in the context of asset management.

The FAST Act requires setting targets and measuring the performance of the National Highway System (NHS) in terms of meeting those targets. Mr. Neal reviewed Texas's and NCTCOG's 2018 baseline conditions and 2022 targets for the NHS pavement and bridge conditions. TxDOT collects data for only the on-system NHS (i.e., the TxDOT state-maintained elements of the NHS) in the NCTCOG region, which represent a very small percentage of the NHS system in the region. NCTCOG therefore established the 2018 baseline conditions and 2022 targets for the entire NHS network (i.e., on-system interstates, on-system non-

interstate freeways, off-system toll roads, on-system arterials, and off-system arterials) in the region. Mr. Neal remarked that asset resiliency and vulnerability to extreme weather events will be affected by whether MPOs consider the off-system components of the NHS in their regions. Regional resiliency performance goals, targets, and measures will be affected whether the off-system NHS roads are included (and if they are prioritized for Category 2 funding) as these roads are critical to the region. The challenge for MPOs is how to assess the performance of pavements and bridges on the off-system NHS (i.e., the components of the system that TxDOT is not responsible for).

The bottom-line for NCTCOG is that system needs currently outweigh the resources available to the local governments – even before any resiliency investments are considered. For example, Mr. Neal showed that to maintain the pavement condition in the City of Dallas at the current 77 percent of the network of 11,775 lane-miles in good condition – which is 10 percent less than the target of 87 percent overall pavement network condition target - an additional $1.6 billion will be required over the next 10 years. Many cities within the NCTCOG region are reporting that pavement degradation rates are increasing.

NCTCOG conducted a vulnerability assessment of the region's transportation system to extreme weather impacts in 2015. The vulnerability assessment revealed a large variation in the climate/weather factors of concern in the region. Specifically, it was noted that eight of the 10 warmest years in the Dallas-Fort Worth region occurred since 1998. NCTCOG considered various scenarios in the region's vulnerability assessment. For example, the "Business-as-Usual" emissions scenario translated into substantial temperature increases and reductions in soil moisture by 2100. The scenario also translated into lower annual rainfall, but fewer storms of greater intensity. Any infrastructure impacts will also be magnified because of the region's soil properties. A large share of the region has soils with high shrink-swell rates. NCTCOG reported that significant future temperature increases will accelerate pavement degradation and result in greater cracking, rutting, joint failures, and utility breaches. Furthermore, many critical roadway segments are in the 100-year flood plain. NCTCOG also pointed out that substantial data needs remain. Data on elevation, materials, design, event detection, mitigation effects are needed to assess overall vulnerability and how to plan for resiliency.

Mr. Neal concluded his presentation by sharing information about various initiatives that NCTCOG has initiated. NCTCOG has implemented the North Texas SHARE program to determine the region's transportation infrastructure needs (as well as solutions) through collaboration and through cooperative purchasing programs with procured private vendors. NCTCOG's Public Works Council has also developed construction standards to promote the use of "green infrastructure" and to increase the emphasis on asset/stormwater management. An important resiliency goal for the region is integrating regional transportation and stormwater management to ensure comprehensive, collaborative planning to dissolve silos and improve on the *"delivery of consolidated, adaptive infrastructure before expected population growth, urban development distribution/intensity,*

and expected levels of service make addressing these issues more difficult and costly". NCTCOG is leading a working group comprising policy and technical partners in the region, as well as Dallas, Denton, Ellis, Johnson, Parker, Tarrant, and Wise counties in conducting the $10 million *"Integrated Regional Transportation and Stormwater Management Study".* Mr. Neal pointed to a 2017 *"Natural Hazard Mitigation Saves"* Report that stated a $5 to $7 return on every dollar invested to alleviate riverine flooding risks.

Incorporating Resiliency in Regional Transportation Plans in Austin Region (Kelly Porter, CAMPO)

CAMPO examines resiliency from an environmental, economic, and social perspective. In 2014, CAMPO and the City of Austin's Office of Sustainability (the fiscal agent) were recipients of a FHWA grant to analyze the vulnerability of critical infrastructure in the CAMPO region to extreme weather and climate change. CAMPO identified 10 critical assets and the climate factors of concern: flooding, drought, extreme heat, wildfire, and extreme cold and ice. A climate risk rating was developed for each asset (see Table 5). From Table 5, it is evident that the Red Capital MetroRail line is vulnerable to flooding as it crosses Boggy Creek.

Table 5: CAMPO Critical Asset Risk Rating

ID	Asset	Flooding	Drought	Heat	Wildfire	Extreme Cold
2	MetroRail Red Line at Boggy Creek	Moderate-High	Inconclusive	Moderate	None	Low-Moderate
3	SH 71E at SH 21	High	Moderate-High	Low-Moderate	Moderate-High	Low-Moderate
4	I-35 at Onion Creek Parkway	Low	None	None	Moderate-High	Low-Moderate
5	US 290W/SH 71 - Y at Oak Hill	Moderate	Moderate	None	High	Low
6	Loop 360/RM 2222	Moderate	Moderate	None	High	Low-Moderate
7	FM 1431 at Brushy Creek/Spanish Oak Creek	None	Moderate	Low	Moderate-High	Low
8	US 281 and SH 29 Intersection	Moderate-High	Low	Low	Moderate	Low
9	US 183 north of Lockhart	Low-Moderate	High	Low-Moderate	Moderate-High	Low-Moderate
10	SH 80 (San Marcos Highway) at the Blanco River	Moderate	Low	Low	Moderate	Low

Mr. Porter noted that CAMPO's 2045 Transportation Plan (currently in progress) will include a resiliency goal. CAMPO has embarked on a locally driven approach to long-term planning (termed "Platinum Planning) that considers: the environment, economic development, equity, mixed use, multi-modal transportation, and housing. Pertaining to resiliency, a key criterion for transportation project development is land suitability and therefore considering

the environmental and social criteria of land suitability in transportation project development decisions. Mr. Porter pointed out that the land suitability and vulnerability analysis will allow for the identification of areas that may be of concern when locating transportation projects. For example, CAMPO will be examining an abandoned rail line in Austin in a land suitability study to determine if the ROW provides for a viable transportation project. Similarly, a land suitability study could result in certain land-use restrictions for former dump sites or at former gas stations. Finally, flood plains or highly elastic soils may present high quality farmland but may not be ideal for building roads. Soil plasticity is particularly relevant to determining infrastructure lifecycle costs. CAMPO is also expanding its vulnerability assessment beyond infrastructure to include environmental justice and Title VI communities. CAMPO is therefore assessing evacuation options and access for, for example, low income, non-white, school-aged, limited English proficiency, and zero car households.

In conclusion, Mr. Porter highlighted various regional transportation studies that CAMPO is leading in partnership with local governments:

- "2045 Regional Arterials Plan" considers improvements to evacuation routes, system redundancy, and roadway design and materials. The study revealed that wildfires in heavily populated areas of Bastrop leave emergency responders with only one way in and residents with only one way out. The Plan also looks at connectivity as a redundancy measure for minor arterials to serve as an alternative if major arterials are impacted by extreme events. CAMPO worked with local governments to identify their existing and planned network (included in the Transportation Improvement Program), as well as their desired network given population projections for the region. CAMPO developed several scenarios considering different levels of transportation investments to visualize the impact on vehicle miles traveled, vehicle hours traveled, and network speed.
- 2018 Regional Incident Management Plan and 2045 Regional Active Transportation Plan present data analysis that can aid decision making when evaluating project submittals to CAMPO.
- 2045 Regional Transit Plan has been drafted and will be available in 2019.

Incorporating Resiliency in Regional Transportation Plans in Texarkana Region (Rea Donna Jones, Texarkana MPO)

The Texarkana MPO defines resiliency as (a) reducing the vulnerability of the RTS and the communities that reside within the region to chronic and acute stressors by ensuring redundancy and reliability to meet essential travel needs and (b) implementing a resilient transportation system that can quickly respond to unexpected conditions and return to a sustainable state of performance. Resiliency in Texarkana is more than just transportation system resiliency. It is about making the entire community resilient.

Ms. Jones noted that Texarkana has limited funds to address all needs in the region. The region has substantial passenger and freight volumes and wanted to consider transit, pedestrian, and bicycle investments within the resiliency discussion. Priorities therefore had to be established in the 2045 MTP. In its Plan Review and Needs assessment, the MPO started off by identifying historical acute stressors, such as floods, tornadoes, earthquakes, fires, major transportation incidents (e.g., crashes and spills), and other transportation related events. The historical knowledge was supplemented with predictions about acute stressor changes in the future (e.g., climate change) as documented in the research literature. The MPO also identified the chronic stressors through a review of its current plans and multimodal needs analysis. Chronic stressors that emerged included:

- Growth pattern and population changes.
- Challenges faced by Environmental Justice Communities.
- Housing and transportation costs.
- Chronic and incident related congestion.
- Poor travel time reliability.
- Environmental factors (such as, soil conditions, heat, rain/drought cycles).
- Increasing maintenance needs.
- Lack of funding.

The approach allowed the MPO to assess vulnerabilities and identify gaps (e.g., high need pedestrian facility areas, and high need transit areas). The MPO subsequently identified existing assets that support resiliency to the identified chronic and acute stressors. These included, the MPO's

- Diverse economic portfolio.
- Diverse multimodal options.
- Current Transportation Systems Management and Operations strategies.
- Existing maintenance plans for ensuring roads and transit are in a state-of-good repair.
- Coordination and planning efforts with the Regional Office of Emergency Preparedness to ensure both short- and long-term recovery (e.g., Continuity of Operations Plans and Emergency Operations Plans).

This allowed the MPO to, for example, assess the current infrastructure condition in areas of sprawl or low auto ownership neighborhoods and identify neighborhoods with high emergency response times or where more elderly populations without access to automobiles reside in recovery and evacuation planning. The vulnerability assessment is therefore connected to land use, economic development, and other planning and engagement activities.

Ms. Jones remarked that the MTP is a suitable vehicle for addressing resiliency assessment needs, given its outreach and engagement as well as systematic prioritization and program planning efforts involving multiple regional stakeholders. For the MTP, the MPO draws on

performance-based planning and programming data to evaluate quantifiable measures for prioritizing projects that are critical for resiliency from a community and transportation network perspective. Texarkana's Project Prioritization Assessment includes 12 evaluation criteria following the FAST Act Planning Factors, but the process also allows for the consideration of local values through criteria weighting. The 12 evaluation criteria are:

- Improve safety and security.
- Improve quality of life.
- Reduce congestion.
- Improve multimodal access.
- Increase multimodal connections.
- Support land use and economic development goals.
- Promote efficient system management and operations.
- Preserve rights-of-way (ROW).
- Protect the environment.
- Increase multi-modal options and energy conservation.
- Improve resiliency and reliability.
- Enhance travel and tourism.

Examples of improvements to system resiliency and reliability (as well as reduce stormwater impacts) include:

- Increasing connections, especially for evacuation and recovery.
- Improvements in system condition (state of good repair).
- Projects with drainage design extending and incorporating outfall beyond the immediate ROW.
- Leveraging existing drainage infrastructure and discouraging growth in areas necessitating intensive drainage design.

Ms. Jones concluded by saying that "Resilience is not just a condition it's a state of mind".

Enhancing Freight Transportation System Resiliency Through the Application of Strategic Asset Management Methodology (Erik Stromberg, Lamar University)

Mr. Stromberg introduced the curriculum of the Center for Advances in Port Management at Lamar University. Technically the curriculum focuses on the first three weeks after a storm event and what is required to return to normal operations.

Mr. Stromberg defined strategic asset management as a data-driven risk-based process that links an organization's (or system's) assets to its strategic and business goals: "*coordinated activity of and organization to realize value from assets.*" (ISO 55000). Success is derived through the engagement of the entire organization (or system). Mr. Stromberg recommended a US Army Corps of Engineers study by Katherine Chambers entitled

"Understanding Marine Transportation System Resilience – An Overview of Activities from the 2017 Hurricane Season" as a good resource for developing tiered resiliency outcomes and metrics. Mr. Stromberg remarked that planners only need as much information as decision-makers require to make informed decisions about system assets and how to ensure operational recovery faster.

Mr. Stromberg reviewed the Strategic Asset Management Methodology with participants by outlining it in the context of a proposed Sabine-Neches Waterway port and transportation system resiliency study. In principle, the methodology applies asset management concepts to identify critical assets and processes. The outcome of the Sabine-Neches Waterway (SNWW) resiliency study would be the "*identification through a data-driven, risk-based process, critical infrastructure projects and process improvements necessary to enhance the resiliency of the SNWW, ports and terminals, and the connecting freight transportation systems".* The study team will engage public and private owners, users, customers, and stakeholders. The study team will follow the ISO 55000 process, which entails:

- Defining system goals and objectives.
- Conducting a literature review, documenting both best practices and lessons learned.
- Identifying risks.
- Identifying critical assets and processes.
- Assessing asset condition/asset lifecycle and processes (including, historical performance, dependencies/interoperability, and workarounds/redundancies).
- Defining system/asset/process required level of service (i.e., a complete depiction of what, for example, the asset need to do).
- Gap analysis.
- Assessing risk to prioritize projects/process improvements.
- Developing cost estimates.
- Developing a list of recommended process improvements and capital investments in the near term.
- Identifying continuous maintenance and operations improvements to cover gaps over the long term.

Mr. Stromberg noted that ports and waterways include an array of assets critical to system function. Most of these assets are held by the private sector, which makes a system-wide assessment critical that includes the built environment, human resources, and resiliency planning.

Mr. Stromberg highlighted some of the preliminary key issues that have been identified prior to the study:

- The need for public and private sector support. Mr. Stromberg pointed out that the success of the study will depend on the support of the Southeast Texas Waterways

Advisory Committee and all stakeholders along the SNWW, TxDOT, the Coast Guard, Oil and Gas, and Jefferson, Hardin, and Orange counties.

- Concerns about a lack of a resilient communication network and the processes relying on the network.
- Private sector supply chain and logistics concerns that result in bottlenecks across modes. For example, feed stock deliveries to plants shipping to Europe and Asia are backed up when the river backs up.
- Corporate interest and resource availability concerns. Asset management in ports entail running assets to failure, which is good from a private sector asset management perspective, but it ultimately impacts client perceptions. There is typically no excess capacity to accommodate work arounds or redundancies if one supply chain gets backed up. Also, inter-port shifting is complicated because of the facilities and investments made by individual companies at each port to accept and process freight through their customized facilities.

Mr. Stromberg concluded that ports are often not considered in regional planning efforts. They are often not presented at an MPO nor do they actively participate and share their investment needs in planning efforts.

Planning for a Resilient Houston-Galveston Region (Kristina Ronneberg, H-GAC)

Regional planning for resiliency in H-GAC involves several topic areas and activities, such as:

- The Regional Flood Management Council.
- Development of Hazard Mitigation plans.
- The 2040 regional flood management effort entitled "*Our Great Region 2040".*
- Resiliency information campaign entitled "Together against the Weather", which alerted the public of evacuation routes by zip code zones.
- Transportation.

Besides incorporating resiliency in the 2045 Regional Transportation Plan, other noteworthy transportation resiliency efforts include:

- The 2018 Call for Project workshop. Proposals included improved drainage projects, more green spaces, and diversification of supply chain routes.
- Increased coordination and reviewing the Transportation Improvement Program (TIP) processes to discuss resiliency related project set asides.
- FHWA Resiliency and Durability pilot project – the topic of the presentation.

In the wake of Hurricane Harvey, FHWA provided funding for resiliency efforts to MPOs. For the Resiliency and Durability pilot, H-GAC is using FHWA's VAST tool, a risk analysis, and economic analysis to identify the most vulnerable assets/road segments to extreme weather events in H-GAC's eight county region. The pilot will focus on the vulnerability of the region's

on-system roads and bridges to coastal and inland flooding for three-time horizons (i.e., currently, 2030 to align with the MPOs 10-year plan, and 2045 to align with the MPOs LRTP). Upon identifying the vulnerable assets, H-GAC will develop recommendations for the most vulnerable assets/road segments that need to be re-built or elevated following a cost-benefit analysis. Upon completion, H-GAC will update its publications and project selection criteria for future TIP updates.

Ms. Ronneberg reviewed the pilot project phases with the audience:

- Pilot project initiation, which entailed identifying the pilot project objectives and facilitating a stakeholder meeting.
- Data collection, which focuses on compiling the resiliency recommendations, collecting and processing climate data, and inventorying the region's transportation assets.
- Assessment, which entails identifying the critical transportation assets and conducting the vulnerability assessment, risk analysis, and economic analysis.
- Strategy recommendations, which includes development of strategy recommendations and consideration of recommendations in the LRTP and TIP project selection.
- Information dissemination, which comprises the development of the final report and case study documents, as well as knowledge exchange.

The kickoff meeting was held at H-GAC's offices on May 22, 2019. The three objectives were: (1) formalize the scope parameters, (2) receive feedback from stakeholders on the criticality methodology proposed by H-GAC, and (3) select the VAST tool indicators (i.e., indicators for exposure, sensitivity, and adaptive capacity).

H-GAC decided to focus on flooding as the climate factor of concern, because there have been more than 20 flooding events in the region in the past three years.

Ms. Ronneberg reported that is has been challenging to reach consensus on the criticality indicators and she requested the advice of NCTCOG and CAMPO. Mr. Ronneberg said that H-GAC has developed criteria for three categories: socio economic, use and operation, and health and safety (which includes evacuation routes). The agency has identified 120 critical assets that include: pipelines, electric utilities, roads, and bridges. H-GAC will use the VAST tool to prioritize five to 12 of the assets for resiliency investments.

Ms. Ronneberg remarked that the LRTP currently has general language on resiliency, but that the language will be revised and be made more specific upon the completion of the vulnerability pilot.

Ms. Ronneberg concluded her presentation by highlighting some of the challenges with resiliency and planning for transportation resiliency. Ms. Ronneberg noted that transportation resiliency is defined as *"a system's ability to continue to function at an acceptable level of efficiency in the face of disruptive or unexpected conditions."* Resiliency therefore requires redundancy to accommodate extreme events, but at the same time there

is a need to address chronic stresses. The challenge is that a large percentage of Houston's road network is currently operating at a level-of-service (LOS) F during the peak period and an even larger percentage of the system is forecasted to experience congestion (LOS F) in 2045 despite planned roadway capacity improvements.

Transportation resiliency is also impacted by land use and land use types. Ms. Ronneberg shared the example of the Cedar Bayou Initiative. It is estimated that the amount of impervious cover in Cedar Bayou will more than double (increase by 107 percent) between 2018 and 2045. An increase in impervious surface increases run off, which increases the risk of flooding, but also reduces other land use types that are better for drainage. If land use and development are not considered, it will be difficult to plan for a transportation system that is resilient to extreme events and climate change. Ms. Ronneberg also highlighted the challenges associated with jurisdictional authority and ownership. There are 12 different jurisdictions that cover the Cedar Bayou watershed and it is often challenging to determine ownership of flooding issues.

Finally, channel and drainage ditch maintenance are an important component, because if ditches and channels are not maintained it increases the risk of flooding.

Resilience and Durability to Extreme Weather Pilot Project (Robert MacDonald, Corpus Christi MPO)

The Corpus Christi MPO (CCMPO) has no resiliency department/section. Resiliency will be incorporated in everything the MPO does and reflected in all documents produced.

Mr. MacDonald reported that the FHWA provided a grant to CCMPO to conduct a resiliency pilot project in partnership with Texas A&M Corpus Christi, the City of Corpus Christi, Nueces County, and a consultant team, comprising HDR and LJA Engineering. Match funding was provided by CCMPO. The project is considered a special study: no different than a regional travel speed study. The study deliverable will be a final document.

Resiliency planning needs to (a) connect to the regional planning context, (b) be reflected in the LRTP, and (c) be considered in the projects that are prioritized in the TIP. In Corpus Christi, resiliency will be planned for and integrated into overlapping transportation objectives for roads, transit, bicycles, freight, pedestrians, aviation, and rail. The Corpus Christi Port Authority is also on board.

The FHWA pilot project is exploring options to build a more resilient segment of the Laguna Shores Road along Corpus Christi Bay. The specific road has been inundated and damaged several times in the past. The road is specifically vulnerable to erosion (e.g., the road edge has been damaged as a result), inundation, and other chronic and acute impacts from rising sea levels and coastal storm activity. Since the road needs to be rebuild currently, the City of Corpus Christi agreed that this project would be a good pilot to examine a nature-based shoreline protection feature to strengthen the road against flooding and high tides. Mr.

MacDonald shared some of the data that is being collected as part of the pilot project (i.e., vegetation type, elevation, and geotechnical boring locations). The lessons learned from this specific pilot project will be incorporated into the MPO TIP. Furthermore, the reconstruction of the two-lane Laguna Shores road elevated 5 feet above the mean sea level together with the lessons learned from the pilot project will be funded through local government bonds.

Small Group Discussion Insight

The workshop concluded with stakeholders participating in four small group discussions for 20 minutes to share any comments and provide input on (a) data sources/tools for identifying vulnerable RTS elements, (b) strategies/options to promote resiliency of the transportation system, and (c) challenges/issues experienced in incorporating resiliency in regional transportation plans.

Data Sources/Tools for Identifying Vulnerable RTS Elements

Stakeholders remarked that access to robust data is critical. Comprehensive traffic data is needed, but freight and other modal (rail, transit), land use, and socio-economic data (specifically projected growth) are also needed. For example, data from the Department of Housing and Urban Development is useful but hard to obtain.

Asset inventory data is critical. TxDOT has good pavement (i.e., highway condition), bridge, and safety data, but only for the state-maintained system. Data on local infrastructure is a challenge. Also digesting and understanding the TxDOT bridge data can be challenging. Furthermore, robust models (degradation models) to analyze the degradation or the response of the transportation infrastructure to climate change or climate stressors are largely lacking. A lack of robust inventory data for local infrastructure and a lack of robust models to analyze the impact on the transportation infrastructure make project prioritization for resiliency challenging. Similarly, data to conduct lifecycle costing is lacking.

It was also mentioned that rainfall rates have changed dramatically in some areas, which will require changes to how infrastructure is designed (e.g., which designs handle water better) and build (e.g., what materials are used). Planners will have to balance the environmental impacts with safety.

In terms of data sources and tools, stakeholders commented that:

- FEMA (i.e., floodplain) and USGS (i.e., floodgate data), as well as the US Army Core of Engineers are good data sources, but it is often a challenge to filter the data and connect to the resiliency discussion.
- Cities have had some success working with the Flood Control Districts. However, it was mentioned that although the focus has been on flooding, transportation resiliency entails more than preparing for flooding events. It also concerns, for example, extreme temperatures (that can result in roads buckling) and wildfires.

- FHWA's VAST tool has provided a framework for many funded pilot projects (including by MPOs) to conduct vulnerability assessments of their critical infrastructure.
- Local trucking companies can be a good source of data.
- Houston's TRANSSTAR is a good data source.
- Hazard mitigation plans, emergency preparedness plan, universities, cities and counties can have useful data.

Finally, communities need more than one road to enter and exit in the case of an extreme event, areas that will receive evacuees need to be prepared, and evacuees need to know where they can go. Communication, a consistent message, and a central coordination point, as well as how information is being communicated is therefore critical before, during, and after an extreme event.

Strategies/Options to Promote Resiliency of the Transportation System

Stakeholders listed the following strategies/options for promoting transportation system resiliency:

- Community support is very important in any discussion about resiliency. It is important to inform decision-makers both about the risks, but also about the opportunities that exist to mitigate risk. TxDOT's Public Involvement staff can help in communicating with the public.
- Development of Backage Roads to increase redundancy.
- Hardening components of the local road system to increase redundancy.
- Maintaining and operating the existing system to ensure resiliency.
- Retrofit vulnerable road segments that are critical to the transportation system.
- Pay attention to culvert sizing/replacement and culvert maintenance to ensure resiliency.
- Develop an inventory of culverts/stormwater system to increase the resiliency of the transportation system.
- Increase the design standards for driveways to protect the road system.

Challenges/Issues Experienced in Incorporating Resiliency in Regional Transportation Plans

Stakeholders identified the following challenges/issues:

- The need for a Resiliency Working Group to direct and guide the resiliency discussion in Texas.
- Lack of zoning (specifically in Houston) presents a challenge when planning for resiliency in regional transportation plans.
- The lack of robust data and models for vulnerability and risk assessments.
- Inadequate funding to meet existing system needs, not considering resiliency priorities.
- Communication with both internal and external stakeholders to make resiliency relevant to decision-makers (education).

- A system approach is required when planning for resiliency, but there is a lack of understanding of the system and the inter-dependencies (inter dynamics) of the system.
- A robust inventory of the transportation infrastructure and the condition of the infrastructure are required for resiliency planning, but information is not available for key components of the system (e.g., culverts).
- A common understanding and goals are required for resiliency planning.
- There is a need to integrate resiliency in documents and manuals, such as the planning and design manuals.
- There is a need to collaborate with regional emergency operations centers; identify the correct contact person.

Conclusions

In an effort to support MPOs in meeting the FAST Act requirement *"to take resilience into consideration during the transportation planning processes",* this study aimed to document and share resiliency lessons learned and best practices. The study team: (a) surveyed U.S. MPOs, (b) summarized the efforts of the Texas MPOs that have participated in a number of FHWA pilot case studies, as well as the findings of a number of TxDOT funded studies, to enhance the resiliency of regional transportation systems, and (c) hosted a workshop with local agency partners to enhance the planning efforts for ensuring resiliency of regional transportation systems to extreme weather events. The main conclusions from the study effort are summarized below.

Defining Resiliency, Identifying Goals, Objectives, Performance Measures, and Assigning Roles and Responsibilities

The study team developed a web-based survey that was administered to 404 MPO Executive Directors or MPO transportation contacts. A total of 57 surveys were completed. While the survey analyses are therefore characterized by a small sample size, the following observations were made about how prepared the sample of MPOs are with regard to resiliency:

- One in three (33 percent) MPOs have defined resiliency.
- About one in five (19 percent) MPOs have defined resiliency and identified resiliency goals.
- About one in ten (12 percent) MPOs have defined resiliency, identified resiliency goals, and developed resiliency metrics to measure progress toward these goals.

While many respondents reported that their MPO is actively engaged in resiliency planning efforts, some reported that it is not a priority, either because the MPO is too small or the MPO does not have adequate resources (staff and or funding) to take on this responsibility. Some comments also suggest that resiliency has not been made a priority, because the MPO is relying on other organizations (mostly State DOTs) and or the idea of resiliency being informally touched on in other parts of the MTP or planning process. Lastly, some MPOs feel that resiliency is a moving target and MPO planning efforts would benefit from increased federal guidance on the topic.

When it comes to preparedness for extreme weather events:

- Slightly more than four of ten (44 percent) MPOs have identified and characterized climate factors that might impact the RTS and assessed vulnerability of the RTS to climate change/extreme weather events.

- One in three (33 percent) MPOs have (1) identified and characterized climate factors that might impact the RTS and assessed vulnerability of the RTS to climate change/extreme weather events, and (2) identified critical elements of their RTS.
- About one in five (18 percent) MPOs have (1) identified and characterized climate factors that might impact the RTS and assessed vulnerability of the RTS to climate change/extreme weather events, (2) identified critical elements of their RTS, and (3) determined how their RTS will respond to an extreme weather event.
- About one in ten (11 percent) MPOs have (1) identified and characterized climate factors that might impact the RTS and assessed vulnerability of the RTS to climate change/extreme weather events, (2) identified critical elements of their RTS, (3) determined how their RTS will respond to an extreme weather event, and (4) determined the risks/likelihood of extreme weather events occurring.

Reasons for not being more prepared for extreme weather events were similar to the responses for not planning for resiliency: the tasks are in progress, the MPO is too small and/or lacks adequate staffing, the MPO relies on other organizations for these tasks, and/or it is not a priority.

Precipitation was mentioned by three of four (76 percent) MPOs as a climate factor of concern. The most often mentioned type of data used to assess the impact of extreme weather events was therefore FEMA floodplain data. The most often mentioned additional data need to help assess the impact of extreme weather events was hydrological data, followed by weather data. Storm surge, wind, and drought were ranked less of a priority, mentioned by 31 percent of respondents each.

Highway corridors, bridges, road connectors, and rail infrastructure were the RTS elements identified as most vulnerable to extreme weather events, with GIS identified by most respondents as the tool used to assess the impact of extreme weather events on this infrastructure components.

Resiliency Study Lessons Learned

Two Texas MPOs (CAMPO and NCTCOG) have participated and two Texas MPOs (H-GAC and the CCMPO) are participating in FHWA pilot case studies aiming to enhance the resiliency of regional transportation systems. In addition, several other TxDOT and MPO studies have been identified that addresses the topic of resiliency. These studies vary in terms of infrastructure/modes considered, objectives, approach and data/tools used, and therefore in terms of the challenges experienced, the outcome, and the lessons learned. The following are general observations about these efforts:

- Most studies did not identify resiliency explicitly.
- The studies attempted to assess the potential vulnerability of the transportation system or a component of the transportation system (e.g., the freight system or a specific highway) to the effects of a climate stressor or extreme weather event.
- The studies varied widely in terms of the sophistication of the approach and data utilized. In general, most studies aimed to measure the impacts of flooding, drought, extreme heat/cold, and wildfires. Only one study considered hurricanes, storm activity, sea level rise, and wind speed.
- Some key challenges identified were limited data for local roads that often have greater sensitivity to extreme weather events and limited data to quantify the costs, benefits, and transportation performance impacts of climate change.
- Some key lessons learned include the need for partnerships with local municipalities and coordination across sectors when conducting resiliency planning; critical assets may not be the most vulnerable asset and that growth and non-climate stressors can significantly influence extreme weather impacts on the transportation system.
- Some general recommendations include more collaboration among regional, local, and federal stakeholders; forming an Extreme Weather Resilience Working Group; incorporating flooding, drought, extreme heat, and wildfire risks into asset management frameworks, emergency response plans, and planning processes; evaluate and implement adaptation options including improving or widening the shoulders of roads, developing materials to help withstand higher temperatures and replacing transportation infrastructure to withstand higher intensity storms; obtain more precise forecasts of extreme precipitation and temperature to determine runoff risks, tracking weather-associated damage to infrastructure to inform future infrastructure construction projects, additional data collection and analysis to identify particular impacts resulting from weather events; and additional studies to investigate how land use development and environmental management affect the magnitude of climate change impacts.

Resiliency in Regional Transportation Plans

TTI hosted a one-day workshop on *"Addressing Resiliency in Regional Transportation Plans"* on June 26, 2019 at the NCTCOG offices in Arlington. The Workshop comprised several 15-minute presentations by FHWA, TTI, and Texas MPOs on planning for resilient transportation systems, as well as the challenges experienced. Salient findings and challenges shared during the workshop include:

- FHWA has funded various pilot projects, engineering case studies, the VAST tool, guidance documents, and conferences on resiliency to natural hazards and extreme weather events.

- A TxDOT funded study outlined a five-step planning framework for transportation resiliency that included recommendations for planning a resilient transportation system (i.e., TxDOT should create a Texas Resiliency Workgroup, TxDOT should include resiliency goals, performance measures, and metrics in its performance-based planning process, TxDOT should lead the development of a resiliency data clearinghouse, TxDOT should continue and support ongoing resiliency workshops, and TxDOT should develop a scenario planning tool for "what if" analysis).

- Some MPOs consider transportation system resiliency in the broader context of regional planning and making entire communities more resilient. The vulnerability assessment is connected to land use, economic development, and other planning and engagement activities. The MTP is therefore a suitable vehicle for addressing resiliency assessment needs, given its outreach and engagement components, as well as systematic prioritization and program planning efforts involving multiple regional stakeholders.

- A challenge for MPOs is how to assess the performance of pavements and bridges on the off-system NHS (i.e., the components of the system that TxDOT is not responsible for).

- MPO planners pointed out that resiliency requires planners to address both chronic and acute climate stressors (extreme weather events). However, transportation system needs currently outweigh the resources available to the local governments – even before any resiliency investments are considered. For example, NCTCOG showed that to maintain the pavement condition in the City of Dallas at the current 77 percent of the network of 11,775 lane-miles in good condition – which is 10 percent less than the target of 87 percent overall pavement network condition target - an additional $1.6 billion will be required over the next 10 years. Similarly, H-GAC remarked that resiliency requires redundancy to accommodate extreme events. The challenge is that a large percentage of Houston's road network is currently operating at a level-of-service (LOS) F during the peak period and an even larger percentage of the system is forecasted to experience congestion (LOS F) in 2045 despite planned roadway capacity improvements.

- Transportation resiliency is impacted by land use and land use types. An increase in impervious surface increases run off, which increases the risk of flooding, but also reduces other land use types that are better for drainage. If land use and development are not considered, it will be difficult to plan for a transportation system that is resilient to extreme events and climate change.

- Substantial data needs remain. Data on elevation, materials, design, event detection, mitigation effects (e.g., channel and drainage ditch maintenance) are needed to assess overall vulnerability and how to plan for resiliency.

- Some modes (specifically ports) are often not considered in regional planning efforts. They are often not presented at an MPO nor do they actively participate and share their investment needs in resiliency planning efforts.

Appendix A – Resiliency Survey Instrument

The Fixing America's Surface Transportation (FAST, 2015) Act requires transportation agencies to take resilience into consideration during the transportation planning processes. The updated metropolitan and statewide transportation planning regulations include a requirement that the metropolitan transportation plan assess capital investment and other strategies that reduce vulnerability of the existing transportation infrastructure to natural disasters.

This survey is an effort to identify best practices in planning for resiliency. The results of the survey will be documented and shared with local planning agencies in an effort to enhance planning for resiliency of regional transportation systems to climate change and extreme weather events. Your participation in completing this survey is very important for understanding how metropolitan planning organizations (MPOs) include resilience in the transportation planning process. Your responses will be treated confidentially and will be used solely for the purpose of this study.

Thank you in advance for your help on this important project.

It will take approximately 20 minutes to complete the survey. If you have any questions regarding the survey, please contact Jolanda Prozzi at j-prozzi@ttimail.tamu.edu.

Sincerely yours,

Jolanda Prozzi
Division Head: Environment and Air Quality
Program Manager: Environment and Planning
Texas A&M Transportation Institute

Has your MPO defined "Resilience/Resiliency" for your regional transportation system?

- ○ Yes
- ○ No

Why has your MPO not yet defined "Resilience/Resiliency" for your regional transportation system?

_____

What is the definition of "Resilience/Resiliency" for your regional transportation system?

_____

Has your MPO defined resilience goals for your regional transportation system?

- ○ Yes
- ○ No

Why has your MPO not yet defined resilience goals for your regional transportation system?

_____

What are the resilience goals for your regional transportation system?

_____

Has your MPO developed resilience metrics to measure progress towards achieving resilience goals?

- ○ Yes
- ○ No

Why has your MPO not yet developed resilience metrics to measure progress towards achieving resilience goals?

_____

What are the metrics your MPO has developed to measure progress towards achieving resilience goals?

_____

Has your MPO assessed the vulnerability of your regional transportation system to climate change and extreme weather events?

- ○ Yes
- ○ No

Why has your MPO not yet assessed the vulnerability of your regional transportation system to climate change and extreme weather events?

_____

Have you identified and characterized climate factors that might impact your regional transportation system?

- ○ Yes
- ○ No

Why have you not yet identified and characterized climate factors that might impact your regional transportation system?

_____

Please indicate the climate factors of concern:

- ☐ Storm surge
- ☐ Precipitation
- ☐ Wind
- ☐ Drought
- ☐ Ice
- ☐ Other (please specify) _____

Has your MPO determined the risks/likelihood of extreme weather events occurring?

- ○ Yes
- ○ No

Why has your MPO not yet determined the risks/likelihood of extreme weather events occurring?

_____

Which elements of your regional transportation system have you identified as vulnerable? Select all that apply.

- ☐ Highway Corridors
- ☐ Road Connectors
- ☐ Bridges
- ☐ Rail infrastructure
- ☐ Maritime Ports
- ☐ Waterways
- ☐ Land Ports of Entry
- ☐ Airports
- ☐ Other (Please specify) _____

Has your MPO identified the critical elements of your regional transportation system?

- ○ Yes
- ○ No

Why has your MPO not yet identified the critical elements of your regional transportation system?

_____

What criteria do you use to determine criticality?

_____

Has your MPO determined how the regional transportation system will respond to an extreme weather event?

- ○ Yes
- ○ No

Why has your MPO not yet determined how the regional transportation system will respond to an extreme weather event?

_____

What data did your MPO use to identify risk and vulnerable transportation system elements, as well as the consequences of extreme events? Select all that apply.

- ☐ Not Applicable
- ☐ Asset age
- ☐ Design life and stage of life
- ☐ Geographic location
- ☐ Elevation information
- ☐ Current and historical performance and condition
- ☐ Level of use (traffic counts, etc.)
- ☐ Replacement cost
- ☐ Maintenance schedule and costs
- ☐ Evacuation routes
- ☐ Emergency management/response costs

- [ ] Functional classification
- [ ] System redundancy
- [ ] Climate/Weather data (e.g., Flood history, precipitation, temperature, etc.)
- [ ] FEMA floodplains
- [ ] Sea levels
- [ ] Storm surge and waves
- [ ] Streamflow
- [ ] Other (Please specify) _____

What tools did your MPO use to identify risk and vulnerable transportation system elements, as well as the consequences of extreme events? Select all that apply.

- [ ] Not Applicable
- [ ] Geographic Information System (GIS)
- [ ] Coupled Model Intercomparison Project (CMIP)
- [ ] U.S. Geological Survey's National Climate Change Viewer
- [ ] Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections
- [ ] Sea Level Change Curve Calculator
- [ ] Digital Coast
- [ ] Hydrodynamic models
- [ ] Vulnerability Assessment Scoring Tool (VAST)
- [ ] LiDAR
- [ ] Multi-criteria Analysis

☐ Life-cycle Cost Analysis

☐ Other (Please specify) _____

What additional data does your MPO need to identify risk, vulnerability, and the consequences of extreme events to your transportation system? Please list below.

○ 1 _____

○ 2 _____

○ 3 _____

○ 4 _____

○ 5 _____

What additional tools does your MPO need to identify risk, vulnerability, and the consequences of extreme events to your transportation system? Please list below.

○ 1 _____

○ 2 _____

○ 3 _____

○ 4 _____

○ 5 _____

Please describe any strategies your MPO employs to promote resilience of the transportation system.

○ 1 _____

○ 2 _____

○ 3 _____

○ 4 _____

○ 5 _____

Is there anything else we should know about your MPO's resilience planning efforts?

_____

Could you please provide your contact information in case we need to clarify any of your answers?

- ○ Agency Name _____
- ○ Division _____
- ○ Respondent Name _____
- ○ Position _____
- ○ Email _____
- ○ Phone Number _____

Appendix B – Metropolitan Planning Organization Strategies to Promote Resilient Transportation Systems

Work with the local EMA's in the development of their Hazard Mitigation Plan.
We work closely with the transit agency and know how many and what type vehicles they have available and the replacement schedule.
We have identified critical parallel corridors to our major corridors. We are slowly making improvements to those parallel corridors so they better function during major events and/or if the major corridors are no longer functional.
We have frontage roads identified in our MTP and TIP. We only have one road in and one road out, so this is currently our only option.
We are beginning to make resilience more of a priority by making it a factor in our planning process and considering what have been non-traditional projects (e.g., blowing up beaver dams and other mitigation strategies) to improve network resilience.
Regular tracking of performance measures.
Promote leadership, education, and empowerment both in government, and public and private sectors to foster the implementation of resiliency strategies across disciplines and communities.
Plans and planning processes. Zoning and land use. Compliance and enforcement programs.
Note that the MPO is part of a larger regional organization, and many of the efforts fall outside of MPO efforts, including a dedicated flooding and resiliency program run the community development program, and a rail asset management plan that prioritizes adaptation on the part of the joint rail authority.
Look and analyze secondary routes and access.
Identify resilience as a core principle in your long-range plan.
Green and complete streets policy.
Coordinated research activities between DOT and the University on thawing permafrost and innovative road embankment design.
Consideration of natural hazards when scoping transportation projects.
Build redundancy into connections.

Work with DOT in reviewing and commenting on their alternate / emergency route system for our area.

We are always working with our local DOT District Office on scheduled maintenance of the system within our MPA as well as those that will directly impact the MPA.

Upsizing culverts and other storm drainage systems.

Testing of newly manufactured "ice breaker" equipment (local and international inventions) to create friction on roads that experience winter rain events that freeze inch+ thick ice on top of the asphalt.

Support for partner organizations in their efforts to address the issue. Ranges from supporting applicants for state and federal funding rounds to consulting with other agencies on unanticipated impacts their measures may have on the transportation network (upsizing of culverts on gravel roads leads to replacement with a structure large enough to require inspection, for example).

Participating in FHWA trainings on incorporating resilience into the transportation planning process.

Eco-Logical Action Plan.

Develop 20 specific actions that the region can take to promote resilience.

Coordinate with agencies/officials responsible for disaster risk reduction.

Information dissemination to the community is vital.

We have worked with the local university to assist us in analyzing the impacts of major events in our region.

We work closely with the city and monitor their maintenance and construction plans as well as their plans to reroute traffic during construction and maintenance.

Utilize results of corridor/system vulnerability assessments to inform infrastructure design and use of materials that are more sustainable to natural disasters.

Risk assessments related to road closures and alternate routes.

Regional green infrastructure framework - overlaid with transportation plan.

Modeling the local storm drain system's capacity to handle extreme precipitation events (i.e., 50-yr and 100-yr storm events).

Infrastructure & Construction - designing, building, and retrofitting transportation assets to improve vulnerability.

Developed a number of strategy papers around resilience and climate change.
Review the White Papers released by FHWA on Transportation Resilience.
Recognize that climate change is real.
Partner with resource agencies to identify funding sources for environmental data and analysis, incorporate expertise for determining regional vulnerabilities, and strategize on collaborate resiliency options.
Natural & Land Resource Protection - changes to natural/agricultural lands to lessen hazard impacts.
Centers and corridors focus.
Use of natural resource/land cover data as evaluation criterion for project selection.
Routing operations/maintenance activities that are important for enhancing resiliency.

Appendix C – Important to MPO Resiliency Planning Efforts

We received an FHWA climate adaptation grant to evaluate specific risks and vulnerabilities to critical transportation infrastructure in one urban watershed (population, 1M). A continuous 2-D simulation model incorporating climate projections for precipitation, coupled with an ecosystem service module to estimate benefits from upper watershed green infrastructure investments, will provide an initial basis for future planning.

We don't have the resources to do this type of work in a way that would result in a more meaningful or robust actions to improve resiliency. Given the work we have done to date and the challenges of the data, analysis tools and wide range of possible results, I would expect our updated plan will include broad language and policies suggesting owners of the transportation system should include this type of planning and analysis. Also, the regional plan may include suggested actions/strategies but measure when and how those actions could make a significant difference is beyond our current resources.

We completed a regional critical transportation infrastructure vulnerability assessment that is available on our Plans and Studies webpage: https://www.gtcmpo.org/sites/default/files/pdf/2016/5750_-_final_report.pdf The above strategies are taken from this report.

We are just getting started and should have a much more defined plan that incorporates resilience with the update of our long-range plan.

We are currently working with our CRT and a consultant to prioritize the vulnerable areas and to identify projects and/or best practices, and solutions to implement in our region. These will then be "folded in" to our Regional Transportation Plan update.

We are a staff of two individuals. Major efforts are difficult for us to accomplish without additional tools.

We are a small MPO (130k population) and currently have only two FTEs [Full Time Employees]. However, as stated previously, we plan to address resiliency in a meaningful way in the near future. This will include a fulsome discussion in our upcoming 2045 RTP.

This study, Vulnerability of Transportation Assets to Sea Level Rise, Technical Paper 164, provides some insight into our MPO's efforts to identify the vulnerability of our

transportation network to sea level rise: http://www.planning.ri.gov/documents/sea_level/2015/TP164.pdf

The State of Oregon has completed and continues to do additional planning for a future earthquake along the coast (the Cascadia Subduction Zone). We will incorporate information from that work in our plan update. Additionally, our area is at extreme risk of wildfire. Some planning has been completed, but additional work will occur over the next 2 years. We will be part of that effort and will incorporate the information in our plan.

The MPO is an active participant in a NOAA study and the scope of work for the 2045 LRTP includes coastal resiliency. We will incorporate findings from the study in the 2045 LRTP.

Small agencies have significant challenges in both budgetary and staff related in defining, measuring, and developing resilience plans.

Resiliency and climate adaptation measures are being incorporated into River to Sea TPO plans, policies and procedures.

Resilience is one of three core principles of our recently adopted plan: https://www.cmap.illinois.gov/2050/principles#Resilience1. Here is the part of the plan focused on transportation resilience: https://www.cmap.illinois.gov/2050/mobility/transportation-climate-resilience. Here is some research we did for the plan that may interest you: https://www.cmap.illinois.gov/documents/10180/517388/Climate+Resilience+Strategy+Paper.pdf/dd610883-d00f-407d-808b-484f9800a3f6. A report on flooding: https://www.cmap.illinois.gov/documents/10180/653821/FY18-0051+STORMWATER+AND+FLOODING_FINAL.pdf/42e7f8b1-c9ed-b7b5-0eeb-a03f4a51dee7

Please understand we are in the very early stages of resilience planning efforts. One of the first tasks is for the gain the trust and respect of the emergency managers and first responders, without them feeling like we are coming in and "telling them" what to do. This goes back to the "Whole Community Concept" that FEMA promoted several years ago when mitigation, not response, was a cornerstone of FEMA. Don't misunderstand, response is important, but so is mitigation, it is just not as glorified. To sum it up, we have to work together.

One of our future strategies is to incorporate a resiliency criterion in our STP-U ranking process. We are still in the very nascent stages of considering resiliency.

More discussion about resilience, please see: http://www.compassidaho.org/documents/prodserv/CIM2040_20/TechDocs/Security.pdf

We are located in a cold climate region that faces very different types of events than much of the Lower 48. Our University has a Cold Climate Research Center and has been a tremendous asset to our resilience planning efforts, and would be happy to share info with other cold climate communities.

In our state, hazard mitigation plans are required and developed at a county level, while MPOs function at the county or multi-county level. The difference in scale can create difficulties in bringing the vulnerability assessments of the hazard mitigation process into the transportation planning process.

Data sharing from the Federal government to states to MPO is not occurring, especially around wildfires, stormwater runoff risks, and detouring.

As a Council of Governments, we undertake a variety of regional initiatives, outside of transportation planning. Our Vision Statement contains a strategy for resiliency, which is proposed to be adopted by reference into the pending Metropolitan Transportation Plan (goal and objectives were included in this form. We have also recently completed the following projects that address regional resiliency: Regional hazard mitigation plan, regional Community Rating System (CRS) study and model, and critical facilities risk assessment.

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