SOUTHERN PLAINS
TRANSPORTATION CENTER

A Sustainable Performance-Based Methodology to Address the Impact of Climate Changes on the "State of Good Repair" of Transportation Infrastructure

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16. ABSTRACT

This final report documents the results of the project “A Sustainable Performance-Based Methodology to Address the Impact of Climate Changes on the “State of Good Repair” of Transportation Infrastructure”. Threats, risks, and performance measures to monitor the climate change impact on transportation infrastructure are identified; and a framework to incorporate risk assessment of infrastructure damage due to extreme climate events into TAM practices is presented. The framework includes an analytical method to quantify the impact and level of risk, and recommendations to mitigate the impact of climate change. Two case studies demonstrate the applicability of the framework and risk assessment method for a bridge and a road section. Occurrence, severity, and the Risk Priority Number (RPN) are outcomes of the model proposed to quantify the risk of damaged due to extreme climate events. The RPN can be used to prioritize funding allocation in the asset management programs.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

Acknowledgements

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A SUSTAINABLE PERFORMANCE-BASED METHODOLOGY TO ADDRESS THE IMPACT OF CLIMATE CHANGES ON THE "STATE OF GOOD REPAIR" OF TRANSPORTATION INFRASTRUCTURE

Final Report

September 2018

by

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CHAPTER 1
INTRODUCTION

1.1 PROBLEM STATEMENT

The development of strategic plans is a complex process faced by transportation agencies in order to address the short and long-term transportation infrastructure needs. As the needs and threats to infrastructure increases due to growing population, aging assets, global climate change, and budget constraints; there are new challenges to preserve the transportation infrastructure in a “State of Good Repair”.

In the 20th century, the majority of the United States territory has experienced a temperature increase ranging from 1 to 4 °F. Between 1901 and 2013, seven of the ten warmest years occurred after 1998 [1]. Regardless of whether these climatic changes are due to natural or anthropogenic activities, their impacts on the natural systems are undeniable and becoming ever more apparent. The Intergovernmental Panel on Climate Change (IPCC) indicates that by the end of this century, the average surface temperature could rise up to 7 °F [2]. Transportation infrastructure networks are more likely to be impacted more frequently by extreme rainfall, temperatures, hurricanes and floods, as well as by gradual changes in temperature and water levels. As the likelihood and intensity of climate change rises, there is a need to develop innovative strategic plans and asset management practices to mitigate the impact on the transportation infrastructure.

Strategic plans need to comply with federal and state laws to receive funding. The Moving Ahead for Progress in the 21st Century Act (MAP-21), signed on July 17, 2012 and extended until 2015, required State Departments of Transportation (DOTs) to establish performance measures in seven national performance goals: safety, infrastructure condition, congestion reduction, system reliability, freight movement and economic vitality, environmental sustainability, and reduced project delivery delays. MAP-21 also defined eight planning factors: (1) economic vitality, (2) safety, (3) security, (4) accessibility and mobility, (5) environment protection, energy conservation and quality of life, (6) integration and connectivity between modes, (7) system efficiency, and (8) preservation of existing transportation system. The Fixing America's Surface Transportation Act (FAST Act), enacted in 2015, is a five-year authorization for fiscal years 2016 to 2020 and includes additional performance measures, such as climate-related pollution from transportation [3]. Under the FAST Act, DOTs required to report ozone, carbon monoxide, and particulate matter. States that do not comply with standards for maximum allowed pollution must use a portion of federal funding on projects addressing this problem [4].

Transportation Asset Management (TAM) practices that considers the risk of damage caused by extreme climate events are vital. “Asset management is a systematic process of maintaining, upgrading, and operating physical assets cost-effectively. It combines engineering principles with sound business practices and economic theory, and it provides tools to facilitate a more organized, logical approach to decision-making” [5]. The ultimate purpose of TAM is to provide the required level of service of transportation assets in the most cost-effective manner. The occurrences of extreme weather are more frequent and severe as the global warming and climate change continue that makes the development of transportation asset management plans even more complex.

1.2. BACKGROUND

Extreme climatic events can affect transportation infrastructure in several ways. First, transportation components may deteriorate faster due to the gradual increase in temperatures, or even collapse as a result of an extreme climatic event. For example, coastal areas are expected to face the risks of sea level rise and flooding, which will result in restricted accessibility to the transportation network. In addition, the probability and severity of extreme climatic events such as heat and cold waves, greater snowfall, extreme rainfall, and strong winds are likely to increase adding more stress to the transportation assets. Therefore, maintenance, repairs, and rehabilitation activities must be performed more often [6].

To increase the resilience of transportation assets, special design requirements and improved TAM practices must be established. The primary goal is to maintain road safety, minimum mobility, and accessibility even during extreme climatic events. Efforts conducted to consider climate change effects in the TAM process are not new and relevant studies include:

(1) <u>Meyer et al. (2009) [7] Transportation Asset Management Systems and Climate Change: An Adaptive Systems Management Approach:</u> This study mentions the need to integrate climate change into TAM and proposes climate adaptation strategies, although there is not methodology to quantify the risk of failure due to the climate events.

(2) <u>FHWA (2010) [8] Regional Climate Change Effects: Useful Information for Transportation Agencies:</u> This study mentions that effects of climate change can be altered region by region from impacts of global climate change on highway infrastructure including bridges, roads, and signs. CMIP 3 is a database developed by a Working Group on Coupled Modelling (WGCM) that provides decision makers information by Region about the time horizon, and by climate variable or "climate effect" (i.e., changes in temperature, precipitation, storm activity, and sea level).

(3) <u>AASHTO (2012) [9] Integrating Extreme Weather Risk into Transportation Asset Management:</u> This study describes the major risks that affects transportation

systems due to extreme weather events such as heavy precipitation, storm surge, flooding, drought, windstorms, extreme heat, and extreme cold. It emphasizes the need for the implementation of TAM practices to tackle extreme weather events. This study proposes the idea of "risk rating" but it does not quantify the likelihood of occurrence and severity.

(4) FHWA (2012) [10] Extreme Weather Vulnerability Assessment: This FHWA report provides transportation agencies a framework to assess the vulnerability of failure of a transportation asset due to climate change events and extreme weather events. FHWA aims with this report to advance beyond the assessment stage towards the development and implementation of the framework, but concludes that additional efforts are necessary to integrate climate change adaptation strategies into TAM.

(5) NCHRP (2013) [11] Strategic Issues Facing Transportation, Volume 2: Climate Change, Extreme Weather Events, and the Highway System: This report describes TAM practices and implementation strategies in order to adapt to climate change. It covers goals, performance measures, and policies; asset vulnerability assessment; risk appraisal; project implementation strategies; and economic impact of climate adaptation strategies, but it does not explain how to quantify the risk of failure.

(6) NCHRP (2014) [12] Response to Extreme Weather Impacts on Transportation Systems: Eight cases of how extreme weather events affect infrastructure, including prolonged heat, wildfires, hurricanes, flooding, tornadoes, intense rains, tropical storms, and severe snowstorms are discussed in this report. The main objective in this study was to identify common and recurring themes in state-level responses to extreme weather events to develop a unified, accessible knowledge. This research concludes that more analytical tools are required to identify extreme weather preparedness actions, to build resilience, and to implement adaptation strategies.

(7) FHWA (2014) [13] Gulf Coast Study Phase I & II: This study was developed in two phases. The first phase focused on how climate changes could affect the transportation systems, and the second phase developed risk management tools to identify what assets to protect. The Gulf Coast study also proposed climate adaptation strategies, and a risk matrix to evaluate the effects of climate change on transportation assets.

Overall, all previous research efforts focused on identifying climatic events that may impact the transportation network but not in quantifying the risk of damage or failure to adopt climate adaptation strategies into TAM practices.

1.3. RESEARCH OBJECTIVES

This main research objective is to investigate how to incorporate risk assessment methods into TAM practices to address the impact of extreme climate events on transportation infrastructure. The specific objectives of this research are:

(1) to identify threats, risks, and performance measures to monitor climate change impact on transportation infrastructure and particularly in the Southern Plains region (NM, TX, OK, AR, and LA).

(2) to develop a framework to incorporate risk assessment of infrastructure damage due to extreme climate events into TAM practices, and criteria to prioritize funding allocation based on infrastructure resilience.

(3) to use analytical methods to quantify the level of risk and impact of extreme climatic events to preserve the transportation infrastructure in a “State of Good Repair”.
(4) to recommend practical TAM adaptation strategies to mitigate the impact of climate change.

1.4. SCOPE OF THE RESEARCH

The scope of the research is focused on how to assess the risk of potential transportation infrastructure damage due to climate events, and to develop a TAM framework with a methodology to quantify this risk. The research covers TAM technical aspects to respond efficiently to climate event threats and provides recommendations to communicate the results of the risk assessment to prioritize funding allocation. The economic impact of climate events is another important aspect of TAM, although it deserves an independent study due to the complexity of the factors involved in the process.

1.5. ORGANIZATION OF THE FINAL REPORT

This final report is organized into five chapters:
(1) **Chapter 1: Introduction** of the topic of climate change as a problem that should be addressed in TAM practices due to its impact on transportation infrastructure. The problem statement, background, objectives, and scope of the research are described in this Chapter.
(2) **Chapter 2: Body of the report** with a comprehensive literature review about the threats of climate change on the transportation network and performance measures for TAM practices. A framework for modeling climate change in TAM is presented with a methodology to quantify the risk of damage on transportation infrastructure.
(3) **Chapter 3: Analysis of a case study for bridges and pavements** that demonstrates the applicability of the framework and methodology proposed in this report to quantify the risk of failure. Case studies for a bridge and a roadway pavement section due to Hurricane Katrina are presented in this Chapter.
(4) **Chapter 4: Discussion of the climate risk assessment model** to quantify the risk of failure due to climate change. The results of a sensitivity analysis to identify the most relevant parameters in the risk assessment model are presented. TopRank and @Risk, software tools developed by Pallisade, are used for the analyses. [14].
(5) **Chapter 5: Conclusion and Recommendations** are summarized including a summary of the research findings, major contributions, and areas of future research.

CHAPTER 2
BODY OF THE REPORT
SYNTHESIS, FRAMEWORK, AND METHODOLOGY TO QUANTIFY THE IMPACT OF CLIMATE CHANGE FOR TAM

This chapter contains a synthesis of climate change threats and risk performance measures for TAM practices, a description of the framework to integrate climate change models, and the methodology to quantify their impact on transportation infrastructure.

2.1. SYNTHESIS OF CLIMATE CHANGE THREATS AND PERFORMANCE MEASURES FOR TAM PRACTICES

2.1.1. World Climate Change

According to the National Oceanic and Atmospheric Administration (NOAA), “climate change is a long-term shift in the statistics of the weather (including its averages)” [15]. It includes change in temperature, change in precipitation patterns, sea level rise, and change in winter storms patterns. As a result, droughts, flooding, dust storms, possibility of wildfires, and changes in freeze/thaw cycles are experienced worldwide. A report conducted by the IPCC displays the variations in climate in a period of 100 years. Figure 1 shows the rising temperature trend in the world, the top portion of the graph depicts an annual average increase of temperature between 1986 and 2005, and the bottom portion depicts the decadal temperature average. Figure 2 displays an increase in temperature by world location.

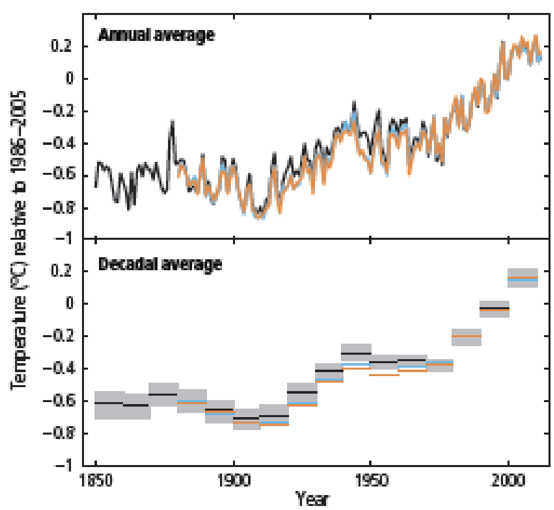


Figure 1. Globally Average Combined Land and Ocean Surface Temperature Anomaly 1850-2012 [16]

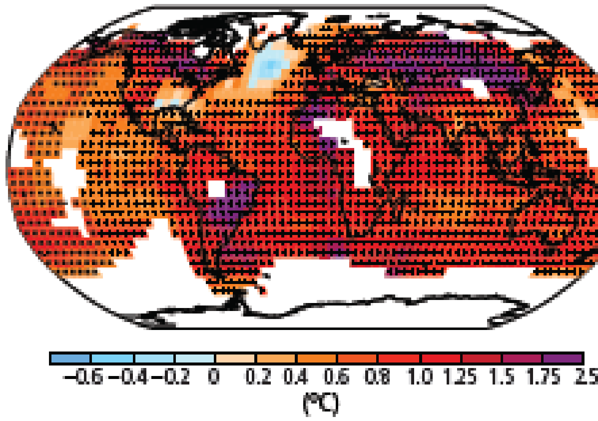


Figure 2. Change in World Surface Temperature 1901-2012 [16]

The IPCC also reported a rising trend in the sea level and a change in annual precipitation. Figure 3, illustrates an average sea level change in meters between 1986 and 2005, the different colors depicts different data sets and all of them have the same trend increasing from about -0.15 m to 0.05 m, and Figure 4 display the sea level rise and change in annual precipitation respectively.

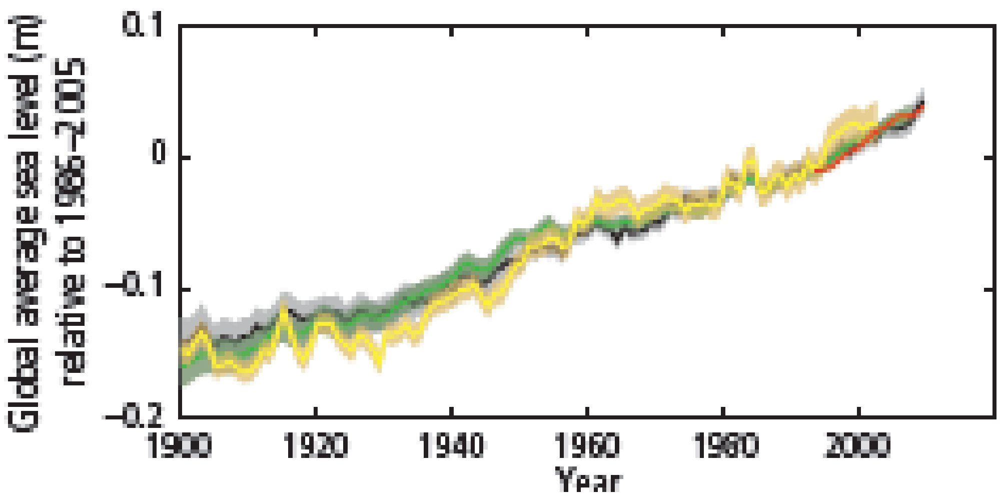


Figure 3. Global Mean Sea Level Change 1900-2010 [16]

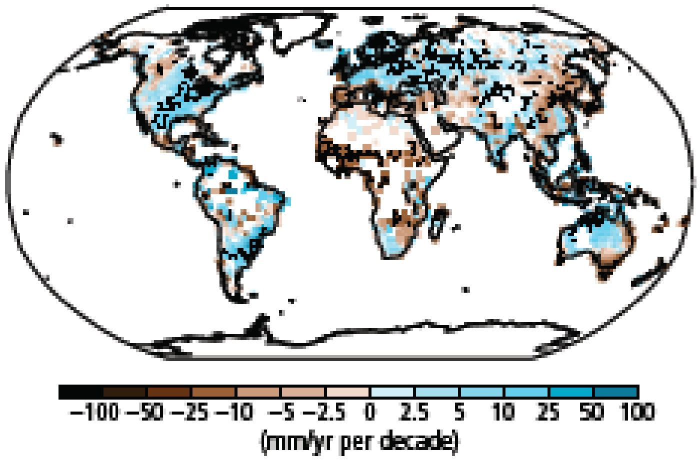


Figure 4. Change in Annual Precipitation 1951-2010 [16]

The IPCC also ran climate models to mathematically represent the Earth's climate system. These models project that the temperature, average precipitation, and average sea level will continue rising. Figures 5, 6, and 7 show IPCC's projections for temperature, precipitation, and sea level respectively. The three figures show the changes observed from 1986 to 2005 on the left, and the projected change from 2081 to 2100 on the right. From the figures, it is observed that an increase of 4-5 °C, 10 percent increase in precipitation, and a 0.5-0.6 m increase in sea level is expected by 2100 in the United States.

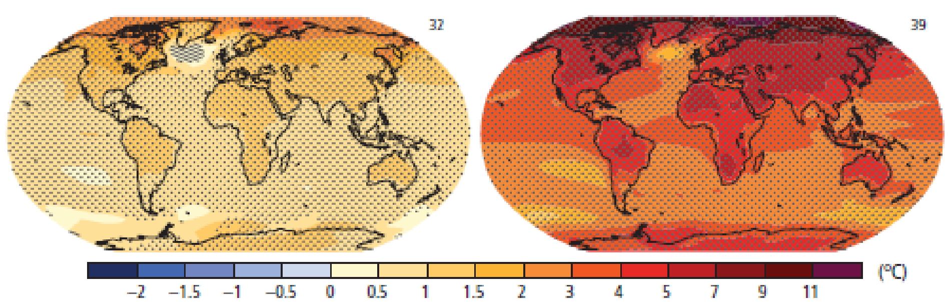


Figure 5. Change in Average Surface Temperature (1986-2005 to 2081-2100) [16]

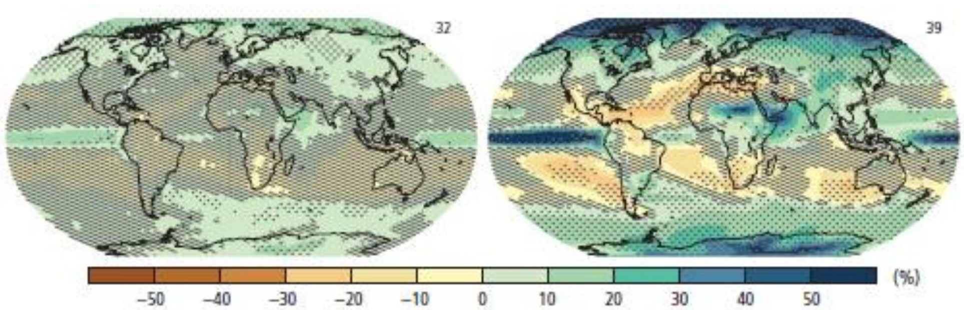


Figure 6. Change in Average Precipitation (1986-2005 to 2081-2100) [16]

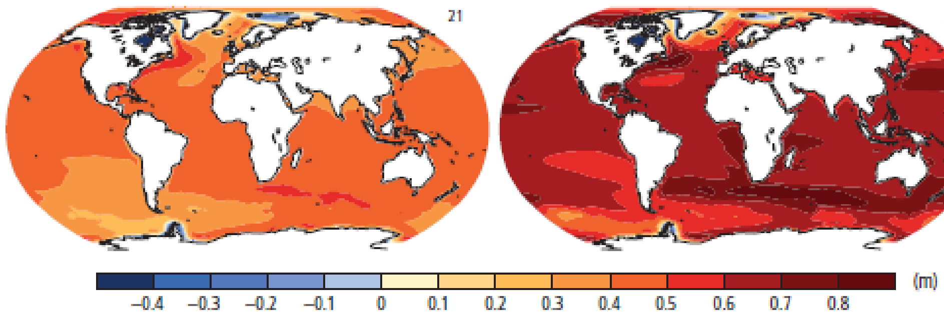


Figure 7. Change in Average Sea Level (1986-2005 to 2081-2100) [16]

2.1.2. Cause of Climate Change

According to NOAA there are two main reasons why the climate is changing: natural variability of the Earth and human-induced change. The natural variability relates to "interactions among the atmosphere, ocean, and land, as well as changes in the amount of solar radiation reaching the earth" [15]. The human-induced change is caused by "the increase in anthropogenic greenhouse gas concentrations" [15, 16]. Figure 8 shows a relationship developed by IPCC, where the mean temperature increases as a function of cumulative total global carbon dioxide (CO_2) emissions [16].

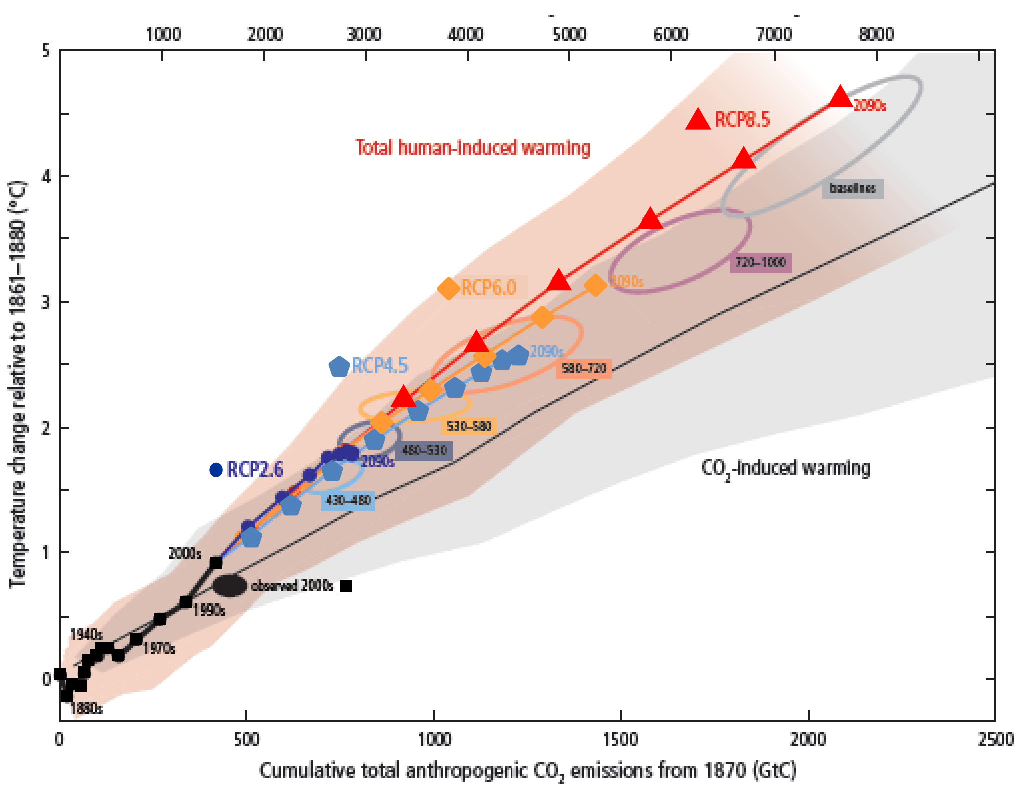


Figure 8. Cumulative Total Anthropogenic CO$_2$ Emissions from 1870 (GtC) [After 16]

2.1.3. Southern Plains Climate Change

The Southern Plains Sector of the United States consists of five states: New Mexico, Texas, Oklahoma, Arkansas, and Louisiana. The Southern Climate Impacts Planning Program (SCIPP) states that the "climate is already changing in both averages and the number and intensity of extremes" [17]. The following sections summarize climate change events experienced in these states.

2.1.3.1. New Mexico Climate Change

New Mexico is the sixth fastest warming state in the nation. According to the Union of Concerned Scientists, "the average annual temperature has increased about 0.6°F per decade since 1970 or about 2.7°F over 45 years" and "the annual temperatures in New Mexico are projected to rise another 3.5 to 8.5°F by 2100" [18]. Figure 9 shows summer temperatures for New Mexico from 1900 to 2016 with an increasing trend over time. With the increasing temperature, there was longer drought periods. The drought has broken historical records increasing the risk of wildfires in New Mexico. As for precipitation, "as the total annual precipitation decreases in places like the Southwest, the heaviest annual rainfall events may become more intense" and can lead to flash floods [18].

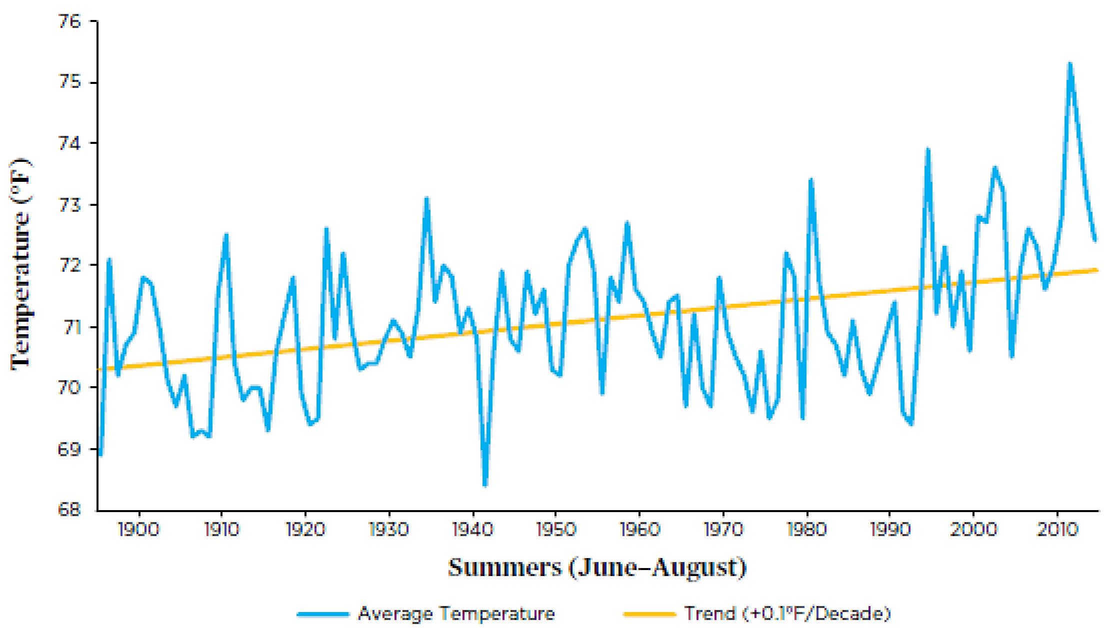


Figure 9. New Mexico Summer Temperature Increase over Time [18]

2.1.3.2. Texas Climate Change

In Texas, the temperature is "projected to increase 3-9°F by 2100" and "sea levels are expected to rise between 1 and 6 feet in the next century" [17]. Figure 10 shows the increasing trend of the sea level near Galveston, Texas. With warmer temperatures and higher sea levels, storm surges are “expected to become more frequent and more intense” and warmer temperatures lead to droughts becoming “more frequent, lasting longer and becoming more intense” [17]. In Figure 10, the middle line of the three linear lines represents the sea level trend as for the top line represents the “Higher 95% confidence interval and the bottom line represent the “Lower 95% confidence interval”. A combination of “dry periods, high temperatures, and more lightning” can result in more frequent wildfires [17]. Figure 11 shows the change in the amount of rain that Texas receives each year across the state - from an overall decrease in west Texas to an overall increase in east Texas gets come from tropical storms (NOAA).

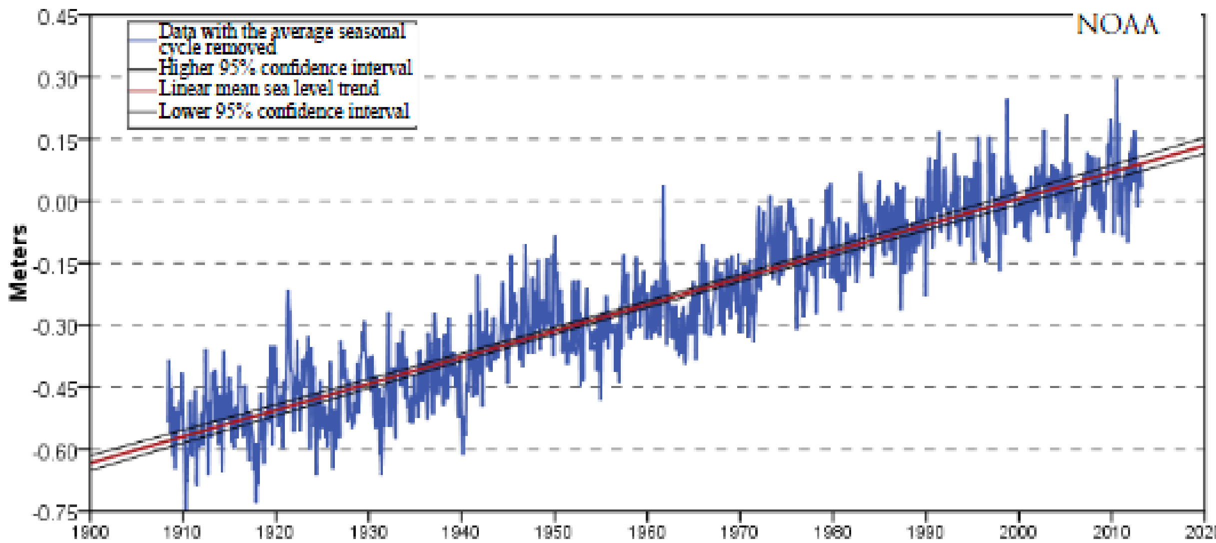


Figure 10. Sea Level Rise in Galveston, Texas [17]

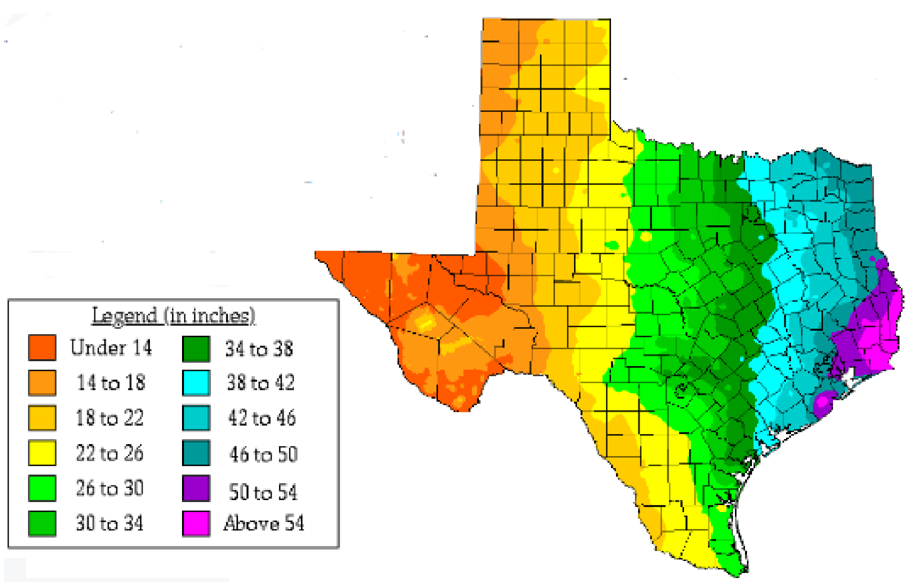


Figure 11. Annual Texas Rainfall [17]

2.1.3.3. Oklahoma Climate Change

SCIPP states that climate change acts as a treat-multiplier leading to "more intense hurricanes, heat waves, floods, droughts and extreme weather." In Oklahoma, temperatures "are projected to increase another 3-9 degrees by 2100" [19]. Figures 12 and 13 shows projected temperatures and drought severity respectively. Figure 12, displays that temperatures in the Great Plains are projected to increase significantly by the end of this century, with the northern part of the region experiencing the greatest temperature increased (NCA). Figure 13 depicts an extreme drought for most of the Oklahoma state and an exceptional drought for the part of the state that connects to the Northeast of the panhandle of Texas, except for a few exception as the Northeast and Southeast with a moderated drought. As a result, "precipitation has become more unpredictable, swinging back and forth between extreme drought and intense downpours" resulting in flooding [19]. With high drought periods, "large wildfires are expected. With high temperatures, "cold seasons are expected to be warmer and shorter, leading to fewer frost and freeze days" [19].

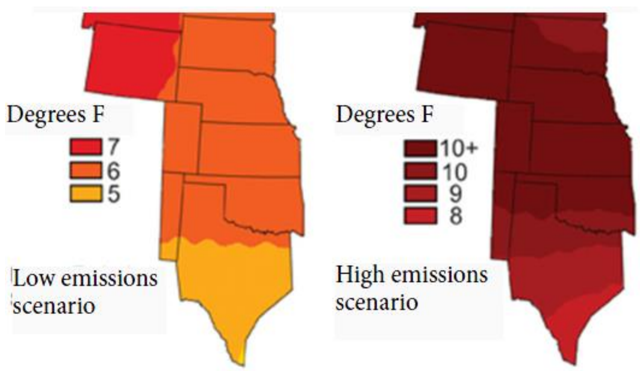


Figure 12. Summer Temperatures by 2080-2099 [19]

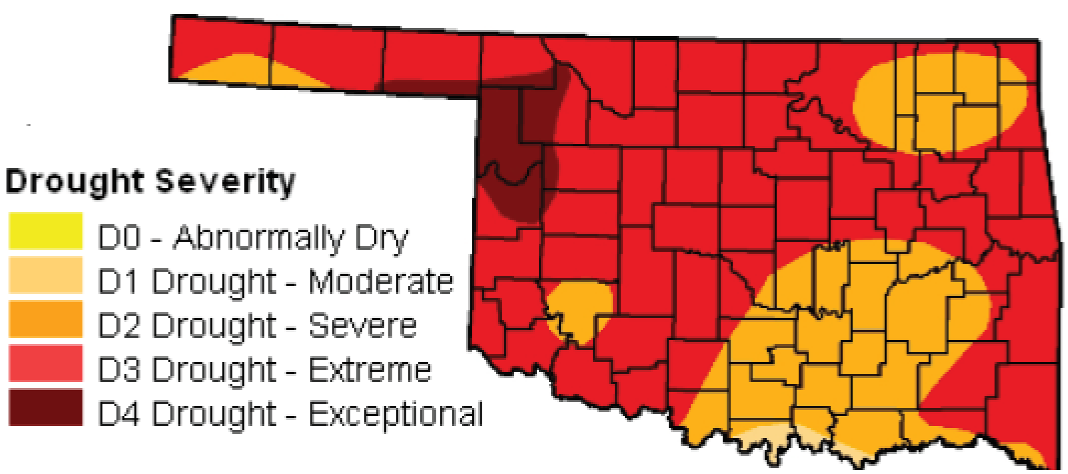


Figure 13. Drought Severity in Oklahoma [19]

2.1.3.4. Arkansas Climate Change

Arkansas "experienced a record of 87 days with temperatures above 90 degrees Fahrenheit in 2010." "Temperatures in the Southeast have risen 2 degrees" and are projected to increase 4-8 °F by 2100 [20]. Figure 14 shows the projections of temperature in the Southeast region of the United States. According to SCIPP, the precipitation in Arkansas has increased 20 to 35 percent during the fall and decreased from 5 to 25 percent during the summer. Figure 15 shows the precipitation of the Southeastern United States by season, where summer has the lowest percent change of precipitation and fall the highest. Arkansas is expected to experience heavy precipitation, wild fires, and possible flooding as a result of the droughts [20].

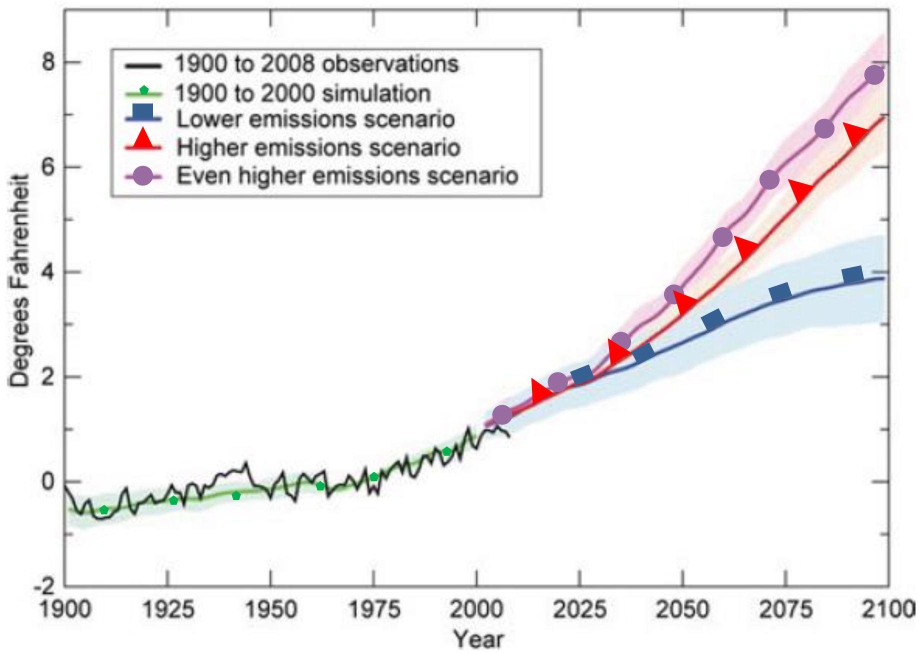


Figure 14. Temperature Rise Projection in Arkansas After [20]

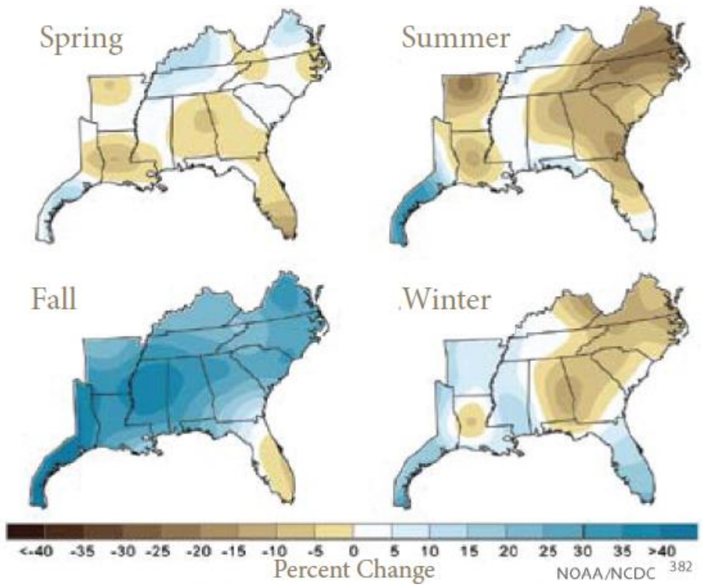


Figure 15. Precipitation by Season of Southeastern United States [8, 20]

2.1.3.5. Louisiana Climate Change

Louisiana is expected to experience climate change events similar to Texas and Arkansas. Temperatures are projected to "increase 4 to 8 degrees by 2100" [21]. Downpours are becoming more intense resulting in flash flooding during periods of drought. Sea level is also expected to rise 1 to 6 feet in the next century. Figure 16 shows the sea level rise in the Louisiana coast. Hurricane intensity and frequency is also expected to increase, and wildfires are expected to occur more frequently due to droughts [21].

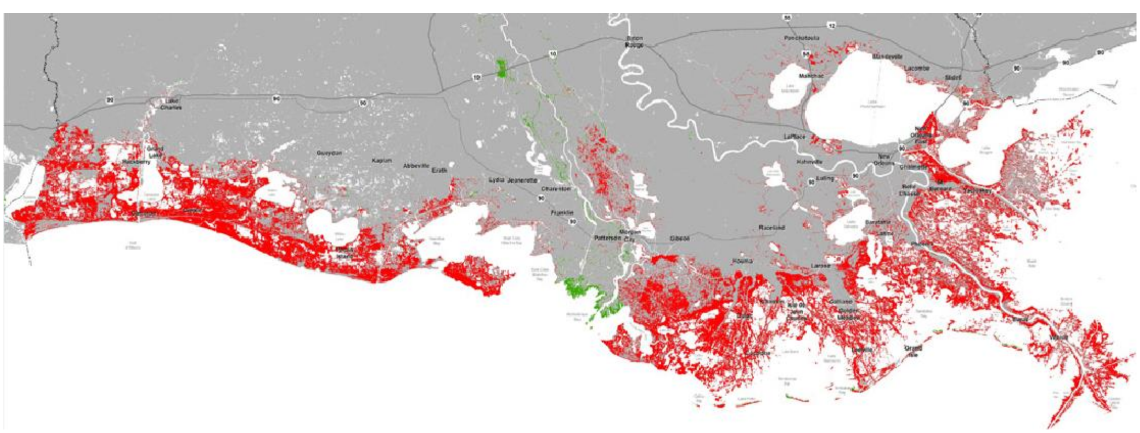


Figure 16. Sea Level Rise 1930-2012 [21]

2.1.4. How Climate Change Affects Transportation Infrastructure

Transportation infrastructure is composed of bridges, roads, rails, airports, ports and waterways. According to the American Society of Civil Engineers (ASCE), the United States Infrastructure has gone from a letter grade of "D" to a letter grade of "D^+" [22],

[23]. A “D” rating is defined as “Poor” which means that “the infrastructure is in poor to fair condition and mostly below standard, with many elements approaching the end of their service life and many systems exhibiting significant deterioration” [23].

At present, “transportation systems are designed to withstand local weather and climate; however, “due to climate change, historical climate is no longer a reliable predictor of future risk” [24]. The combination of poor to fair condition of infrastructure and climate change could result in even lower infrastructure rates in the future. A sensitivity matrix was developed by ICF International for the United States Department of Transportation to evaluate the performance of certain infrastructure and different climate stressors as a result of the FHWA Gulf Coast study [13]. According to ICF International, “sensitivity is the degree to which an asset or a system responds to a given change in climate stressor” [25]. The climate stressors studied were (1) increased temperature and extreme heat, (2) precipitation-driven inland flooding, (3) sea level rise/extreme high tides, (4) storm surge, (5) wind, (6) drought, (7) dust storms, (8) wildfires, (9) winter storms, (10) changes in freeze/thaw, and (11) permafrost thaw [25].

The next subsections describe how climate change affects main transportation assets including bridges, roads, culverts, rails, and ports and waterways. These sections also describe a number of performance measures used for each type of asset.

2.1.4.1. Bridges

For increased temperatures and extreme heat, bridges are sensitive to thermal expansion. Bridges are designed to operate at a certain temperature range, and when the temperature is outside this range, the bridge might fail. The Washington State Department of Transportation (WSDOT) uses Equation 1 to calculate the total thermal movement range [26].

$$\Delta_T=\alpha*L_{trib}*\delta T \quad (1)$$

where:

- Δ_T = Total thermal movement range
- L_{trib} = Tributary length of the structure subject to thermal variation
- α = Coefficient of thermal expansion; 0.000006 in./in./°F for concrete and 0.0000065 in./in./°F for steel
- δT = Bridge superstructure average temperature range as a function of bridge type and location

Floods can also damage bridges due to lateral forces acting on railings and pile debris on bridge decks. As for the substructure of the bridge, substantial precipitations can increase the flow velocity and flow depth of a stream or river which affects the local scour depth or depth of erosion to the bridge support. During flood conditions, when the stream elevation reaches the low chord bridge elevation “the scour depth could increase by 200%-300%. Damage to a bridge can result in the bridge being removed from service, and it can remain unserviceable until “debris is cleared and/or structures are repaired and evaluated for integrity” [25].

Extreme storms can increase the base sea level. According to ICF International, “many coastal bridges were designed to withstand erosion produced by storm surges having a 1% annual change of occurrence, as sea level increases the statistics used to design these structures change.” A higher baseline combined with a 50-year storm could “scour a bridge as severely as would the current 100-year storm surge.” Higher baselines also reduce the clearance under bridges [25, 27].

Powerful storms can create waves that stress the superstructure and the substructure of a bridge. During Hurricane Katrina, “most bridges damaged were near water” [28]. ICF International states that, “stress may damage or destroy the connection between the bridge’s superstructure and substructure, leading to the bridge span to be shifted or even unseated completely.” The storms can also damage “abutments, bent caps, and girders” [25, 28]. Figure 17 displays a bridge along the Texas coast with four shifted or unsettled spans from Hurricane Ike.

Figure 17. State Highway 87 Rollover Pass Bridge along the Texas Coast [28]

Winds are another climate stressor that affects bridges. Wind stress adds additional horizontal loadings and larger waves. High winds can also lead to dust storms which can buildup material on the bridge deck. This buildup can only retain water that is detrimental to the bridge deck and structure [25]. High winds can also spread wildfires quickly. “Infrastructure is at risk from both wildfires and any subsequent debris-flow” (Cannon and DeGraff, 2009). Post-wildfire debris flow can damage bridges by “drag, buoyancy, lateral impact or burial" resulting in "bridges displaced, lifted off their foundations, or damaged from debris flow" [25, 29].

Winter precipitation has also started to change, and according to the National Research Council, there is a "tendency for increasing winter precipitation and decreasing summer precipitation as global temperatures increase" [30]. Increased precipitation can cause higher levels of soil saturation which makes the bridge more susceptible to movement [25]. With the onset of seasonal warming, the period of springtime load restrictions may be reduced in some areas resulting in longer thaw periods [30]. This change in the freeze-thaw cycle can result in damage to bridge decks and expansion in joints. "As water seeps into the pavement on the bridge deck, and accumulates in the aggregate, the cement becomes susceptible to cracking (and) over time, this cracking expands upward until it reaches the road surface" [25]. Figure 18 shows the damage to concrete from freeze-thaw. An increase in the freeze-thaw cycles causes cracks in concrete and pavement surfaces [25].

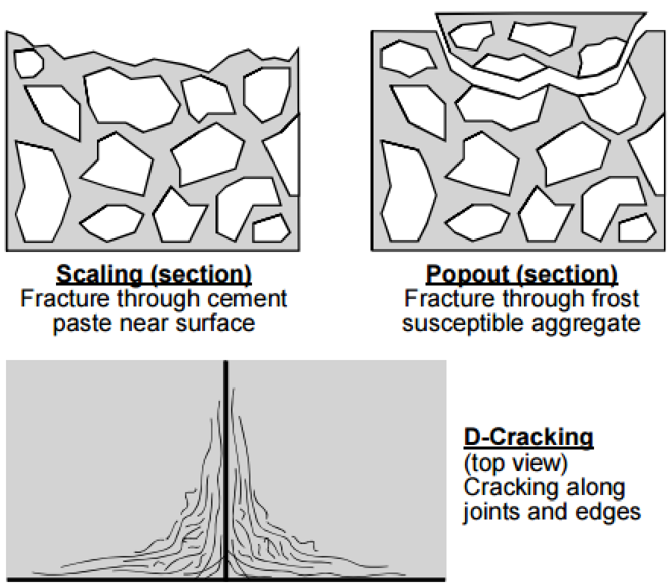


Figure 18. Forms of Freezing and Thawing Damage to Concrete [31]

The impact of these climate change events on bridges can be monitored using performance measures implemented for bridges by Department of Transportations as summarized in Table 1.

Table 1. Common Performance Measures for Bridges [32]

Performance Measure	Description
National Bridge Inventory General Condition Rating	0 (worst) – 9 (best) rating reported for deck, substructure, and superstructure condition (and for culverts long enough to be included in the NBI)
National Bridge Inventory Structural Condition Rating	Good, fair, or poor, calculated based on NBI condition and appraisal ratings
National Bridge Inventory (NBI) Structurally Deficient (SD) / Functionally Obsolete (FO) Status	Calculated based on NBI data. A bridge that is Structurally Deficient (SD) has a condition rating of 4 or less for either the deck, superstructure, or substructure (or culvert in the case of NBI-length culverts). Such bridges require rehabilitation, but are not necessarily unsafe. A bridge that is FO fails to meet current functional standards for deck geometry, load-carrying capacity, clearances and/or approach roadway alignment.
Sufficiency Rating (SR)	"0 (worst) –100 (best) scale based on four factors reflecting ability to remain in service": structural adequacy and safety, serviceability and functional obsolescence, essentiality for public use, and special reductions. Calculated based on NBI data.
Element condition	Conditions for individual elements (e.g., the NBE) are summarized by percent of element quantity by state, typically with four condition states defined for an element.

2.1.4.2. Roads and Culverts

Rutting and shoving are often the result of sustained high temperature that cause asphalt concrete pavement to soften [25]. A report prepared for the Department of Transport in the United Kingdom, "research has found that the majority of rutting in the asphalt surfacing occurs on a few days of the year, when the temperature of the road surfacing exceeds 45°C" [33]. In July 2006, damage to rural highways of Leicestershire, England occurred due to high temperatures. "Around 80km of these roads were damaged by the high temperatures" [33].

Precipitation falling as rain rather than snow leads to immediate runoff and increases the risk of floods, landslides, slope failures, and consequent damage to roadways. Rural roadways are especially affected in the winter and spring months [30]. Some of the common damage from moisture includes: surface defects, surface deformations, and cracking [25]. In paved roads, flooding can also cause pavement and embankment failure. This occurs when the water is high enough to flow over the roadway surface. During heavy precipitation events, rain can leak in under the pavement and damage the subgrade making it very sensitive to moisture levels [25]. In unpaved roads, heavy precipitation followed by flooding can cause damage rapidly. In culverts, heavy precipitation can cause debris accumulation, sedimentation, erosion, scour, piping, and conduit structural damage which can result in flooding [25].

In roads, sea level rises, "will reduce in the return of the 100-year storm flooding event" [25, 34]. This reduction is expected to lead to more flooding of roads that are already vulnerable and can exacerbate the situation by causing more frequent and serious disruptions to transportation services [25, 34]. In culverts, the sea level rise can cause the drainage systems to collapse [25].

Strom surges like Hurricane Sandy and many other hurricanes can damage roadways. Kaufman et al. stated that “Hurricane Sandy caused massive flooding of many roads and tunnels in New York and New Jersey. Roadways and tunnels in New York City that sustained significant flooding included the Brooklyn-Battery, Holland, and Midtown Tunnels and the Battery Park underpass” [25, 35]. Figure 19 shows the flooding caused by Hurricane Sandy. A similar event was observed in Texas which flooded many roadways during Hurricane Harvey in August 25, 2017.

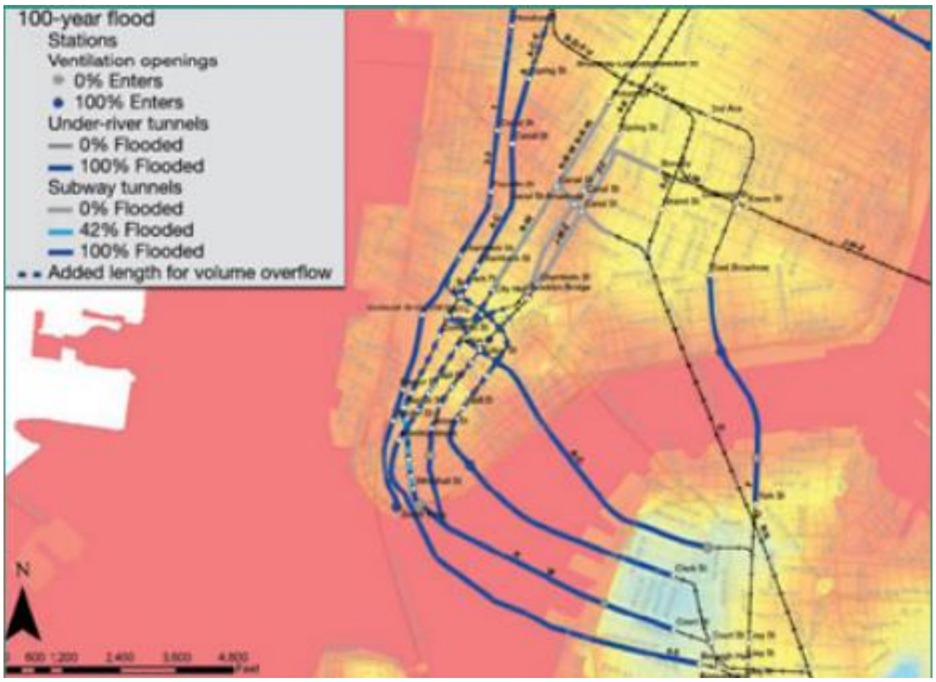


Figure 19. Flooding in New York as a Result of Hurricane Sandy [35]

Storms usually are accompanied by strong winds. Winds do not damage the physical structure directly, but they can severely disrupt road traffic and other service activities [25]. Winds can also damage trees, buildings, and other structures. In New York wind gusts and downed trees knocked power to millions during Hurricane Sandy [35]. The debris from the strong winds affects the storm water drainage system and results in flooding that affected the surrounding area [25].

In 2011, droughts caused splitting and cracking of asphalt pavements located in Texas [25, 36]. The cracks in the asphalt can be attributed to the clayey soil foundation. Clayey soils are susceptible to shrinking and swelling and during a drought, the asphalt pavement cracks. Figure 20 shows high severe cracks observed in Fort Worth, Texas in 2011.

Figure 20. Cracks in a Pavement Due to Drought in Texas [36]

Wildfires are extremely dangerous to human life, and they also affect roadways. The high heat from the wildfires can ignite road surfaces and soften the asphalt. The softening may result in rutting. The wildfires can also destroy hillslopes of vegetation and change soil properties. These changes affect the watershed hydrology and sediment-transport processes [25]. A small rainstorm after a wildfire can increase runoff eroding soil, rock, ash, and vegetative debris from the hillslopes [37]. The debris-flows applies great impulse loads on objects in their paths blocking drainage ways, and damaging structures [25]. The debris-flow can also bury roadways, as shown in Figure 21, in which a hillslope was burned by the South Canyon fire in Arizona causing a landslide that covered the roadway.

Figure 21. South Canyon Landslide in Arizona [38].

The increase in temperatures are affecting the number of freeze-thaw cycles experienced by roadways. Pavements are damaged by the melting of ice lenses as temperatures increase. First, the water in the soil rises due to capillary action and freeze creating ice lenses that heaves the pavement upward as shown in Figure 22. As the temperature increases, the ice lenses melt and the water trapped between the pavement and the frozen soil below weakens the roadway subgrade being the entire pavement structure more susceptible to traffic loads [39].

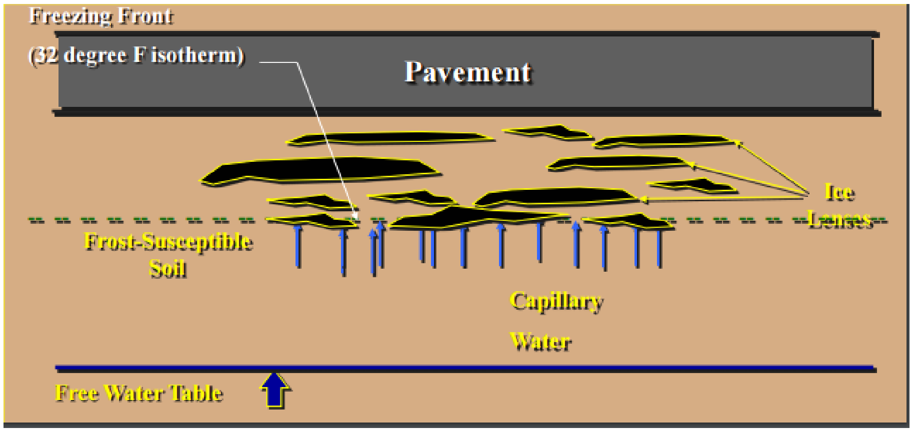


Figure 22. Pavement Heave Due to Creation of Ice Lenses [39].

Figure 23 illustrates the variation of the subgrade resilient modulus over a freeze-thaw cycle. It is observed that during freeze periods the soil gains strength, but during thaw periods, the strength decreases substantially.

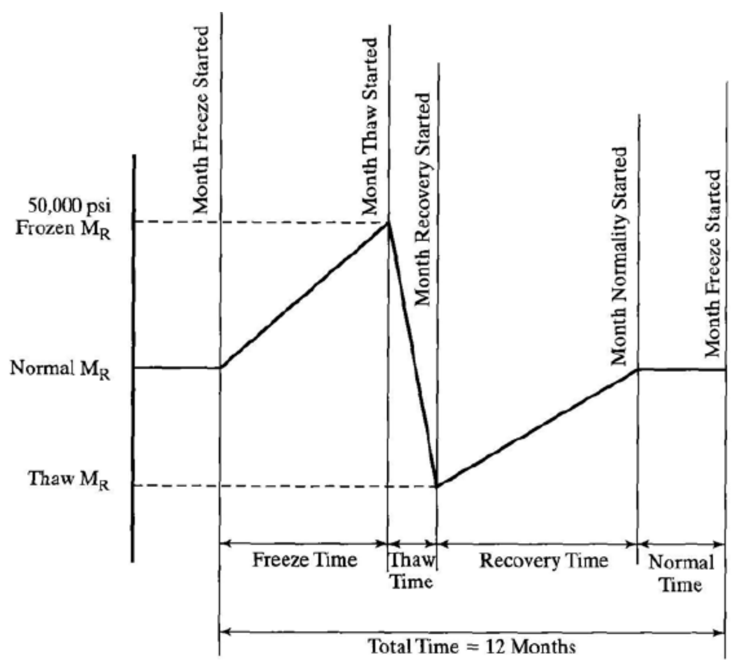


Figure 23. Subgrade Resilient Modulus Seasonal Variation [40]

The impact of these climate change events on pavements and culverts can be monitored using performance measures implemented by Department of Transportations as summarized in Tables 2 and 3 [32].

Table 2. Common Performance Measures for Pavements [32]

Performance Measure	Description
International Roughness Index (IRI)	IRI is “an index computed from a longitudinal profile measurement using a quarter-car simulation at a simulation speed of 50 mph (80 km/h)”. It is related to pavement smoothness that affects the riding comfort when traveling. DOTs are required to report the IRI to FHWA every year since 1993 as part of the HPMS data submittal.
Pavement Condition Index (PCI)	PCI is “a numerical rating of the pavement condition that ranges from 0 to 100 with 0 being the worst possible condition and 100 being the best possible condition”
Present Serviceability Index (PSI)	PSI measures the pavement “ability to serve the type of traffic which use the facility”. It ranges from 0 (collapsed road) to 5 (perfect road). It is obtained from a mathematical combination of certain physical measurements (e.g., rut depth, cracking, slope variance). This performance measure is related to the functional pavement capacity to provide a smooth ride.
Present Serviceability Rating (PSR)	PSR is “a mean rating of the serviceability of a pavement (traveled surface) established by a rating panel under controlled conditions. The accepted PSR scale for highways is 0 to 5, with 5 being excellent”. PSR is an indicator of the riding comfort of the users when traveling the roadway section.
Skid Number (SN) or Friction Number (FN)	The Friction Number (FN) or Skid Number (SN) is locked-wheel testing device, represents the average coefficient of friction measured across a test interval. The reporting SN values range from 0 to 100 (0 represents no friction and 100 complete friction). This performance measure is related to safety regulations. The National Highway Safety Act of 1996 mandates to correct excessive slipperiness.
International Friction Index (IFI)	In the early 1990s, the World Road Association (PIARC) developed the International Friction Index (IFI) in order to measure friction on roads. The IFI is composed of two numbers, the friction number (F60) and the speed number (Sp). The F60 represents the friction value of a pavement at a slip speed of 37 mph (60 km/h), and the Sp is the variation of speed and friction at speeds different than 37 mph (60 km/h).
Cracking	There are different types of cracks including longitudinal, transverse, block or map, and edge. Longitudinal cracks are “predominantly parallel to the direction of traffic.” Transverse cracks are “predominantly perpendicular to the direction of traffic.” Map or block cracks are “interconnected cracks that extend only into the upper portion of the slab.” Edge cracks are “crescent-shaped cracks or fairly continuous cracks that are located within 2 ft (0.6 m) of the pavement edge”

Table 2. Common Performance Measures for Pavements [32] (Cont'd)

Performance Measure	Description
Rutting	Rutting is "a surface depression in the wheel paths," which "stems from a permanent deformation in any of the pavement layers or subgrades, usually caused by consolidated or lateral movement of the materials due to traffic load". Rut depth is "the maximum measured perpendicular distance between the bottom surface of the straightedge and the contact area of the gauge with the pavement surface at a specific location".
Faulting	Faulting is "difference in elevation across a joint or crack". It is a common distress in jointed plain concrete pavements.
Structural Number (SN)	The SN is a function of the layers' thicknesses, structural material coefficients, and drainage coefficients. It is a number represents the pavement capacity to withstand traffic loads.
Remaining Service Life (RSL)	RSL is defined as "the time until the next rehabilitation or reconstruction event", also as the time until a condition index (or distress) trigger value is reached"

Table 3. Common Performance Measures for Culverts [32]

Performance Measure	Description
NBI Culvert Rating	0-9 rating similar to the deck, superstructure and substructure ratings for bridges
FHWA FLH Condition Rating	Good, fair, poor, critical, unknown
HydInfra Condition Rating	1 = like new, 2 = fair, 3 = poor, 4 = very poor, 0 = can't be rated
NYSDOT Condition Rating	1 = totally deteriorated, 3 = serious deterioration, 5 = minor deterioration, 7 = new condition, 8= not applicable, 9 = condition/existence unknown. Ratings of 2, 4, 6 are used to shade between 1 and 2, 3 and 5, 5 and 7.
Ohio DOT Condition Rating	Excellent, good, fair, poor, failure/critical. Culvert performance zones: satisfactory, monitored, and critical.
Western Transportation Institute Rating System	0-1-2 rating system for degree of scour, failure, corrosion, inverts, joint separation, and damage ranging from 0 (no issue), 1 (minor issue), to 2 (major issue)

2.1.4.3. Rails and Tunnels

The increase in high temperatures affect railways causing buckling when the metal in the track expands beyond the capacity of the supporting structure. If the metal cannot expand beyond their constraints, the track buckles either vertically or horizontally [25]. Figure 24 shows an example of rail buckling due to high temperatures. The high temperatures from a wildfire can cause the rail to buckle as well. ICF International states "wildfire temperatures can reach 2,000℉, while buckling can occur at rail temperatures of just over 100℉". The high temperatures can warp or melt the metal components if exposed to high temperatures [25].

High winds can also aid the progress of a wildfire. Wildfires can directly damage wooden bridges and rail ties. High velocity winds can damage rail infrastructure indirectly as a result of falling trees and other wind related debris. High winds can damage signals and crossing gates [25].

Figure 24. Example of Railroad Buckling [41]

Tunnels are a vital part of rail systems and are affected by precipitation. Underground systems are sensitive to heavy rains and storm surges that can be exacerbated by the rising of the sea level. Transits systems and stations can flood during high precipitation events. Heavy precipitation can exceed the capacity of existing pumps and flooding can cause rail sensor failure and permanent damage to the rail if the water reaches the electrified third rail [25]. As a result of Hurricane Sandy in 2012, many subway tunnels were flooded. Figure 25 displays the pumping of a New York tunnel after flooding. Inundation can wash out costal bridges and supporting infrastructure for rail systems [25]. Figure 26 shows the aftermath of a railroad bridge washed out by a hurricane flooding.

Figure 25. Flooding in a Subway Tunnel in New York City after Hurricane Sandy [53]

Figure 26. Railroad Bridge Washed Out by Hurricane Flooding [42]

The rail infrastructure is also affected by the freeze-thaw cycle and can cause damage due to the changes in the strength of the soil foundation. The impact of these climate change events on rails and tunnels can be monitored using performance measures implemented by Department of Transportations as summarized in Table 4.

Table 4. Common Performance Measures for Rails and Tunnels

Performance Measure	Description
Track Stiffness	The track stiffness is used to determine effectiveness of the rail embankment. The ballast should transfer the vertical load, maintain the track in a fixed position, provide elasticity of track and absorption of energy, ensure drainage of water, and set and level the surface of the track [43].
Q Index	The Q index is a parameter over a 200 m long track segment. The Q index ranges from 10 to 0. The larger the Q index, the better the track [44].
P Index	P Index. P index is adopted by Japanese railroads and is the ratio of the number of sampling points whose quality parameter measurements fall outside ±3 mm to the number of all sampling points in a track segment. There are two lengths of track segments over which P index is applied, 100 m and 500 m. The larger the P index, the worse the track segment in some quality aspect [44].
Track Quality Index (TQI)	The TQI is a 2nd order polynomial equation of the standard deviation σi of measurement values for a quality parameter over a track segment to assess its partial quality The overall quality assessment is achieved by averaging six partial quality indices for gauge, cross level, left (right) surface, and left (right) alignment. A larger track quality index implies the track segment has a better quality [44].
Track Geometry Index (TGI)	Track geometry index uses the measurement value space curve length for a quality parameter over a track segment to quantify the quality of the track segment. A larger TGIi indicates that the track segment has a worse quality [44].
Buckling	This occurs when the metal in the track expands beyond the capacity of the supporting infrastructure. If the metal cannot expand beyond the constraints the track will buckle either vertically or horizontally [25].
Level of Service Rating	A way to quantify how well a preservation action improves the service level is to simply provide a rating 1 to 100 as a qualitative assessment of performance of a tunnel [45].
Level of Service Score	An average rated level of service from 1 to 100 for tunnels with weighted individual ratings scaled from 1 to 5 on six tunnel level of service categories including Reliability, Safety, Security, Preservation, Quality of Service, and Environment [45].
Risk of Urgency (RBU) Score	The RBU, on a scale of 0 to 100, is calculated based on a user-input rating of 0 to 10 for urgency, where 10 indicates an action that is very urgently required and 0 indicates an action that would be beneficial, but is not necessarily urgent at the time of the analysis [45].

2.1.4.4. Ports and Waterways

Ports and waterways are major components of the transportation network and function as intermodal connectors for international and domestic trade. ICF International states that, "higher sea levels can increase the risk of chronic flooding" [25]. Flooding from heavy precipitation and storm surges are exacerbated by the higher sea levels damaging channels, piers, wharves, and berths. "While erosion can weaken supports, most channels and waterways are built to withstand erosion. However, increased erosion rates may not be adequately planned for and could this impact port support structures" [25].

High winds and changes in the freeze thaw cycle also affect ports and waterways. High winds can damage signage and build-up debris in channels. "Highway signage has to withstand winds of 125 mph but varies by location, but if equipment (like signage) falls into the channel, it has to be cleaned up before shipping can resume" [25]. Freeze-thaw can undermine the foundations of infrastructure through the weakening of soil as discussed in previous sections of this report.

The Physical Condition Rating of Critical Coastal Navigation Infrastructure rates the ports and waterways infrastructure on a scale of A to F (insignificant damage to completely degraded) [46].

2.1.5. Economic Impact

Extreme climatic events will result in severe economic losses for a region. This is a result of unbudgeted expenses that an agency will have to invest in order to return the transportation system to a working condition. A study conducted by Padgett et al. 2008, reports the bridge damage and repair costs from Hurricane Katrina. In damages only to bridges, the hurricane cost an estimated $8.15 million, $52.23 million, and $569 million in Alabama, Louisiana, and Mississippi, respectively [47].

NCHRP 750 describes a benefit cost methodology to evaluate climate change adaptation strategies. This methodology consists of eight steps: identify the highest risk infrastructure, estimate future operations and maintenance costs, estimate the agency costs of asset failure, estimate the user cost of asset failure, estimate likelihood of asset failure, calculate agency benefits of the strategy, calculate the user benefits of the strategy, and evaluate the results [11]. With this methodology an agency can determine the Benefit/Cost ratio of a mitigation strategy.

2.1.6. Transportation Infrastructure Laws

At present, there are two main national laws related to transportation infrastructure. The first law is the Moving Ahead for Progress in the 21st Century (MAP-21) signed on July

17, 2012 and MAP 21 extended until May 2015. According to the U.S. Department of Transportation (2013), “the objective of this performance and outcome-based program is for States to invest resources in projects that collectively will make progress toward the achievement of the national goals.” The seven national goals are shown in Table 5. If climate change is not considered, all these seven goals will be affected.

Table 5. MAP-21 Seven National Goals [48]

Goal Area	National Goal
Safety	To achieve a significant reduction in traffic fatalities and serious injuries on all public roads
Infrastructure Condition	To maintain the highway infrastructure asset system in a state of good repair
Congestion Reduction	To achieve a significant reduction in congestion on the National Highway System
System Reliability	To improve the efficiency of the surface transportation system
Freight Movement and Economic Vitality	To improve the national freight network, strengthen the ability of rural communities to access national and international trade markets, and support regional economic development
Environmental Sustainability	To enhance the performance of the transportation system while protecting and enhancing the natural environment
Reduced Project Delivery Delays	To reduce project costs, promote jobs and the economy, and expedite the movement of people and goods by accelerating project completion through eliminating delays in the project development and delivery process, including reducing regulatory burdens and improving agencies’ work practices

The second law is the Fixing America’s Surface Transportation (FAST) Act. This law is a “five-year legislation to improve the Nation’s surface transportation infrastructure including our roads, bridges, transit systems, and rail transportation network. The bill reforms and strengthens transportation programs, refocuses on national priorities, provides long-term certainty and more flexibility for states and local governments, streamlines project approval processes, and maintains a strong commitment to safety” [49]. The bill was enacted in December 2015 and extended until fiscal year 2020.

In October 24, 2016 the Federal Highway Administration released a rule for asset management plans that requires periodic evaluations of facilities that repeatedly need repair and reconstruction after emergency events. This rule states that: “A State shall develop a risk-based asset management plan that describes how the NHS will be managed to achieve system performance effectiveness and State DOT targets for asset condition, while managing the risks, in a financially responsible manner, at a minimum practicable cost over the life cycle of its assets” [50]. Transportation asset management and risk management practices are discussed in the next sections.

2.1.7. Transportation Asset Management

Transportation Asset Management (TAM) “is a strategic and systematic process of operating, maintaining, upgrading, and expanding physical assets effectively throughout their lifecycle. It focuses on business and engineering practices for resource allocation and utilization, with the objective of better decision making based upon quality information and well-defined objectives” [51]. The TAM process is comprised of seven components as shown in Figure 27: goals and policies, asset inventory, condition assessment and performance modeling, alternatives evaluation and program optimization, short and long-range plans, program implementation, and performance monitoring.

TAM begins identifying goals and establishing policies for maintenance, repair and rehabilitation. Goals and policies are clearly defined by the agency through a set of performance measures used to set target objectives for the transportation infrastructure network. In order to be successful, an agency must keep updated records of the asset inventory to provide reliable data for all the assets. TAM also requires performing periodical condition assessments of all the assets in the inventory and performance models to forecast the future condition. Alternatives for maintenance and rehabilitation programs are analyzed to determine the best course of action in terms of performance and resource allocation. As a result of this evaluation, short- and long-range plans are prepared to address the current and future infrastructure needs. The implementation of the program implementation follows in the management process in order to preserve the assets in the most cost-effective manner. The agency needs to monitor the asset performance and check if the assets operates as expected, and the goals are being accomplished [7].

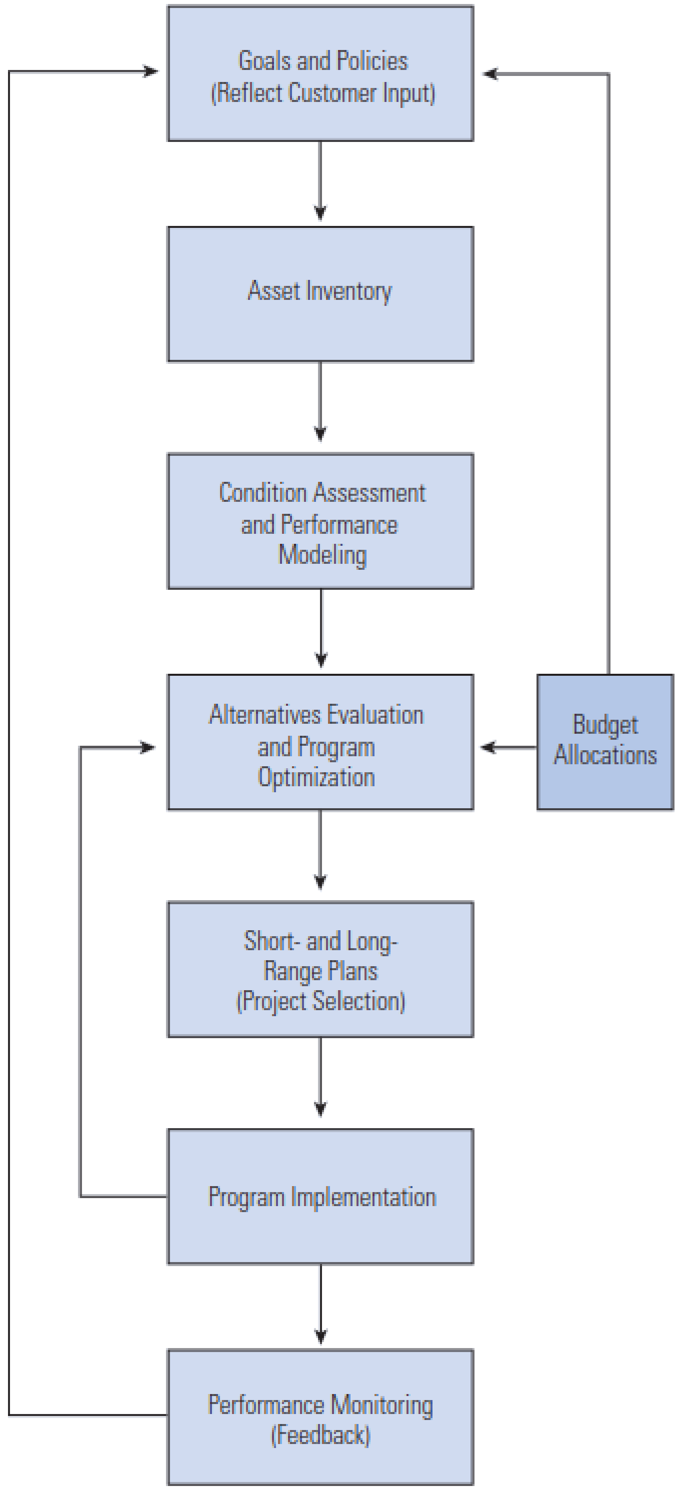


Figure 27. Transportation Asset Management Process [51]

2.2. FRAMEWORK FOR MODELING CLIMATE CHANGE IN TAM

As climate change continues to affect weather patterns, the resilience of the transportation assets becomes critical. Resilience is "the ability for an infrastructure asset to maintain a level of robustness during or after an extreme event and to return itself to a desired level of performance within the shortest possible time to minimize the impact on the community" [52]. A highly resilient asset continues to function properly under extreme circumstances, and TAM practices should consider the impact of climate change on the resilience of transportation infrastructure.

The framework for modeling climate change into TAM practices must be developed within the context of the existing goals, objectives, and performance measures used by USDOT and the state DOTs. The following subsections provides a summary for the USDOT and the five Southern Plains States.

2.2.1. Goals, Objectives, and Performance Measures used by USDOT, TxDOT, NMDOT, OkDOT, ArDOT, and DOTD

The goals, objectives, and performance measures of the states located in the Southern Planes are summarized for USDOT (2017), TxDOT (2015), NMDOT (2015), OKDOT (2014), ArDOT (2016), and DOTD (2015) in Tables 6 to 8. Appendix A lists in detail all the goals, objectives, and performance measures of the states located in the Southern Planes.

All DOTs have similar goals in the areas of Safety, Infrastructure Preservation, and Environmental Responsibility. However, they have their own objectives and performance measures. The accomplishment of the goals is compromised by the climate change impact on transportation assets.

Table 6. Summary of Objectives and Performance Measures for Safety

Agency	Objectives	Performance Measures
United States Department of Transportation [53]	• To achieve a significant reduction in traffic fatalities and serious injuries on all public roads	• Highway fatalities and serious injuries (number and rate) • Crashes involving trucks (number and rate) • Number of crashes involving pedestrians and bicyclists • Number of crashes involving transit vehicles • Number of crashes at rail crossings • Number of collisions on waterways (12-year rolling average)
Texas Department of Transportation [54]	• Improve multimodal transportation safety • Reduce fatalities and serious injuries • Improve safety of at-grade rail crossings • Eliminate conflicts between modes wherever possible • Increase bicycle and pedestrian safety through education, the design and construction of new facilities, and improvements to existing facilities • Educate the public on the dangers of high-risk driving behaviors • Coordinate with enforcement to improve • Improve incident response times	• Total Number of Fatalities and Serious Injuries • Truck Related Crashes and Fatalities • Rail Accidents • At-grade Rail Crossing Safety • Number of fatalities • Number of serious injuries • Number of fatalities/serious injuries per 100 million vehicle miles traveled • Number of fatalities/serious injuries per million population • Number of crashes between train and vehicle • Number of crashes between train and vehicle resulting in fatalities or serious injuries • Number of pedestrian and bicyclist fatalities and serious injuries • Number of pedestrian and bicyclist fatalities per million population • Number of fatal and serious injury crashes involving cell phone use • Number of fatal and serious injury crashes involving speeding • Safety belt usage rate • Number of fatal crashes due to DUI • Average incident response time/incident clearance time

Table 6. Summary of Objectives and Performance Measures for Safety (Cont'd)

Agency	Objectives	Performance Measures
New Mexico Department of Transportation [55]	• Reduce collision- related fatalities and serious injuries for all modes through data-driven, innovative, and proactive processes	• Total number of fatalities • Total fatalities per 100 million vehicle miles traveled (statewide, rural, and urban) • Total number of serious injuries • Serious injuries per 100 million VMT (statewide, rural, and urban) • Pedestrian fatalities and serious injuries (statewide, rural, and urban)* • Bicyclist fatalities and serious injuries (statewide, rural, and urban)*
Oklahoma Department of Transportation [56]	• Reduce traffic-related fatalities/serious injuries on all public roads. • Increase seat belt usage.	• Fatalities and Serious Injuries (number & rate)
Arkansas Department of Transportation [57]	• Align safety goals with the goals of the AHTD Strategic Highway Safety Plan (SHSP). • Partner with the Arkansas State Police, local governments, and federal agencies to administer comprehensive traffic safety programs related to driver, roadway, and railroad crossing safety • Partner with counties and local governments to provide training on low-cost safety applications for local roads. • Coordinate with District Engineers to identify roadways and bridges that are vulnerable to extreme weather events and other natural phenomena. Improve the resiliency of the transportation system to meet travel needs in response to extreme weather events. • Coordinate with local governments for disaster preparedness. • Work with emergency management agencies to expand emergency communications infrastructure across the state.	• Statewide number of fatalities • Statewide number of serious injuries • Fatalities/100 million VMT • Serious Injuries/100 million VMT • Statewide combined number of non-motorized fatalities and serious injuries • Roadway Clearance Time (RCT)

Table 6. Summary of Objectives and Performance Measures for Safety (Cont'd)

Agency	Objectives	Performance Measures
Arkansas Department of Transportation [57]	• Work with emergency management agencies to ensure efficient and coordinated responses to emergency and disaster events. • Identify non-interstate crash hotspots and develop recommendations that have the potential to reduce crashes.	
Louisiana Department of Transportation [58]	• Reduce the number and rate of highway-related crashes, fatalities, and serious injuries. • Reduce the number of pedestrian and bicycle crashes. • Assist modal partners in achieving safe and secure aviation, port, rail, transit, and waterway performance.	• Highway fatalities and serious injuries (number and rate) • Crashes involving trucks (number and rate) • Number of crashes involving pedestrians and bicyclists • Number of crashes involving transit vehicles • Number of crashes at rail crossings • Number of collisions on waterways (12-year rolling average)

Table 7. Summary of Objectives and Performance Measures for Infrastructure Condition

Agency	Objectives	Performance Measures
United States Department of Transportation [53]	• To maintain the highway infrastructure asset system in a state of good repair	• Percentage of pavement of the Interstate System in Good condition • Percentage of pavement of the Interstate System in Poor condition • Percentage of pavement of the non-Interstate System in Good condition • Percentage of pavement of the non-Interstate System in Poor condition
Texas Department of Transportation [54]	• Maintain and preserve multimodal assets using cost-beneficial treatments • Decrease the number of bridges that are structurally deficient, functionally obsolete, or substandard-for-load • Achieve state of good repair for pavement assets, keeping pavements smooth and pothole free • Achieve state of good repair for transit assets such that they are comfortable and reliable • Identify and mitigate risks associated with asset failure	• Percent NHS Pavement Lane-Miles in a State of Good Repair (IRI based) • Percent NHS Pavement Lane-Miles in a State of Good Repair (Condition Score based) • Percent Non-NHS Pavement Lane-Miles in a State of Good Repair (IRI based) • Percent Non-NHS Pavement Lane-Miles in a State of Good Repair (Condition Score based) • Percent Structurally Deficient NHS Bridges Deck Area

Table 7. Summary of Objectives and Performance Measures for Infrastructure Condition (Cont'd)

Agency	Objectives	Performance Measures
Texas Department of Transportation [54]	• Identify existing and new funding sources and innovative financing techniques for all modes of transportation • Build upon and regularly update the asset inventories for all transportation modes	• Count of Structurally Deficient NHS Bridges • Percent Structurally Deficient Non-NHS Bridges Deck Area • Count of Structurally Deficient Non-NHS Bridges • State of Good Repair on the Strategic Freight Network
New Mexico Department of Transportation [55]	• Develop and implement a "preservation-first" asset management strategy to ensure that NMDOT can maintain all existing and future elements of the state's multimodal transportation system in a state of good repair. • Ensure that NMDOT can affordably meet the minimum condition standards for each roadway tier by right sizing the state-owned network to provide the needed capacity to support statewide connectivity standards.	• Percent of pavement in good/fair/poor condition by tier • Percent of bridges in good/fair/poor condition by tier • Percent of transit assets in state of good repair by mode (bus, rail) • Number of pavement miles preserved by tier • Percent of airport runways rated "good" • Total maintenance expenditures and maintenance cost per capita
Oklahoma Department of Transportation [56]	• Maintain or improve the highway system in a state of good repair. • Improve state highway system* (SHS) bridge condition. • Improve transit system. • Improve and maintain transit equipment in a state of good repair. • Maintain state-owned freight rail system. • Improve ride quality on NHS roads. • Improve ride quality on entire state road system.	• Number of structurally deficient (SD) bridges on SHS • Basic Option – Avg. Int'l Roughness Index (IRI) • Advanced Option –Good/fair/poor index for IRI + rutting, cracking, faulting
Arkansas Department of Transportation [57]	• Enforce weight and size restrictions to protect roads and bridges. • Improve ride quality on NHS roads. • Follow asset management principles to optimize preservation strategies on the state highway system • Identify potential freight corridors within which special attention is given to preempt commercial vehicle bottlenecks.	• Percent of Bridge Deck Area on the NHS in Good Condition • Percent of Bridge Deck Area on the NHS in Poor Condition • Percent of Pavement on the Interstate in Good Condition • Percent of Pavement on the Non-Interstate NHS in Good Condition • Percent of Pavement on the Interstate in Poor Condition • Percent of Pavement on the Non-Interstate NHS in Poor Condition

Table 7. Summary of Objectives and Performance Measures for Infrastructure Condition (Cont'd)

Agency	Objectives	Performance Measures
Louisiana Department of Transportation [58]	• Keep Louisiana's state highway pavement, bridges, and highway related assets in good condition. • Assist modal partners in achieving state-of-good-repair for aviation, port, rail, transit, and navigable waterway infrastructure. • Assist local roadway departments in achieving state-of-good-repair for locally owned roads and streets.	• Percent of State-owned highways meeting pavement condition targets, by system tier – Interstate Highway System (IHS), National Highway System (NHS), Statewide Highway System (SHS), and Regional Highway System (RHS) • Percent of structurally deficient bridges by deck area for each tier • Percent of publicly owned airports meeting the State's standard • Percent of public transit fleets meeting applicable condition standards • Percent of locally owned NHS mileage meeting pavement condition targets • Percent of structurally deficient locally owned bridges by deck area

Table 8. Summary of Objectives and Performance Measures for Environmental Responsibility

Agency	Objectives	Performance Measures
United States Department of Transportation [53]	• To enhance the performance of the transportation system while protecting and enhancing the natural environment	• Annual Hours of Peak-Hour Excessive Delay per Capita • Percent of non-Single Occupancy Vehicle (SOV) Travel • Total Emission Reductions • Percent Change in Tailpipe CO_2 Emissions on the NHS Compared to the Calendar Year 2017 Level
Texas Department of Transportation [54]	• Manage resources responsibly and be accountable and transparent in decision-making • Identify sustainable funding sources and leverage resources wisely to maximize the value of investments and minimize negative impacts • Develop and implement a project development process that recognizes quality-of-life concerns for all system users and future generations of Texans • Link transportation planning with land use • Reduce project delivery delays	• Daily kilogram of VOC reduced by the latest annual program CMAQ projects in areas with 1 million pop. Or more (5-year average) • Daily kilogram of NOx reduced by the latest annual program CMAQ projects in areas with 1 million pop. Or more (5-year average) • Daily kilogram of CO reduced by the latest annual program CMAQ projects in areas with 1 million pop. Or more (5-year average)

Table 8. Summary of Objectives and Performance Measures for Environmental Responsibility (Cont'd)

Agency	Objectives	Performance Measures
Texas Department of Transportation [54]	• Coordinate project planning and delivery with all planning partners and stakeholders • Minimize impacts to natural, cultural, and historic resources and promote sustainability in project design and delivery	
New Mexico Department of Transportation [55]	• Transportation projects and programs respect the context within which they are built and implemented. • NMDOT seeks to improve environmental outcomes with both its transportation investments and business operations. • NMDOT celebrates and advances New Mexico economic goals in the areas of recreation and tourism.	• Stakeholder satisfaction surveys before and after development of major projects • Number of vehicle/wildlife collisions • Effectiveness of mitigation measures as defined through NEPA process
Oklahoma Department of Transportation [56]	• Minimize impacts to cultural and historic resources. • Minimize impacts to wetlands, vulnerable ecosystems, and threatened and endangered species. • Support improved water quality. • Promote use of clean fuels. • Protect existing and design new transportation infrastructure to function under changing weather conditions.	• Quantity (cubic yards or other measure of weight/volume) of litter and debris cleared from storm drains/culverts/roadsides • Clean fuels as a share of ODOT's total fleet fuel use [in gasoline gallon equivalents (GGE)]
Arkansas Department of Transportation [57]	• Identify and reduce barriers to reduce delay and improve the project delivery process. • Minimize impacts to natural, historic, and cultural resources. • Support initiatives to reduce congestion and improve air quality. • Implement context sensitive solutions in the transportation system design.	• Annual hours of peak-hour excessive delay per capita (the PHED measure) • Percent of Non-SOV travel where SOV stands for single-occupancy vehicle • Total emissions reduction
Louisiana Department of Transportation [58]	• Minimize the environmental impacts of building, maintaining, and operating Louisiana's transportation system. • Comply with all federal and state environmental regulations	• Percent of DOTD fleet converted to alternative fuels • Percent of state and local public fleets converted to alternative fuels • Acres of wetlands impacted by DOTD or DOTD-funded projects relative to investment • Number of parishes that meet NAAQS mobile source emissions standards • Place holder for any MAP-21 air quality measurement requirements

2.2.2. Framework to Integrate Climate Change Impact Analysis into TAM

Extreme climatic events have costly impacts to humans and budgets and TAM needs to incorporate climate change impact analysis as part of routine practice [12]. AASHTO (2012) and FHWA (2012) presented ideas to integrate climate change into TAM practices [9, 10]. Both reports suggest a deterministic method to identify low, medium, or high levels of risk. The AASHTO approach defines consequence categories: "insignificant, minor, significant, major, and catastrophic"; and the likelihood of occurrence for a climate event: "frequent, common, seldom, rare, and very rare" [9]. The FHWA defines a 1 to 10 scale for the consequence (least critical to critical), and a 1 to 10 impact parameter (reduced capacity to complete failure). Although both reports show the need for integrating climate change into TAM, their methodologies to determine the impact are based on expert opinion collected through a questionnaire.

Figure 28 shows a project management process for an individual asset. The process begins monitoring the current performance measures to develop the project plans. Then, forecast of the asset performance is conducted for the actions considered in the project plans. The project is then designed and delivered depending on available funding. As a result, an improved performance is expected for this asset while is being monitored over time to evaluate the effectiveness of the action. The project management process must be part of the overall TAM and should consider climate mitigation practices for the entire transportation network.

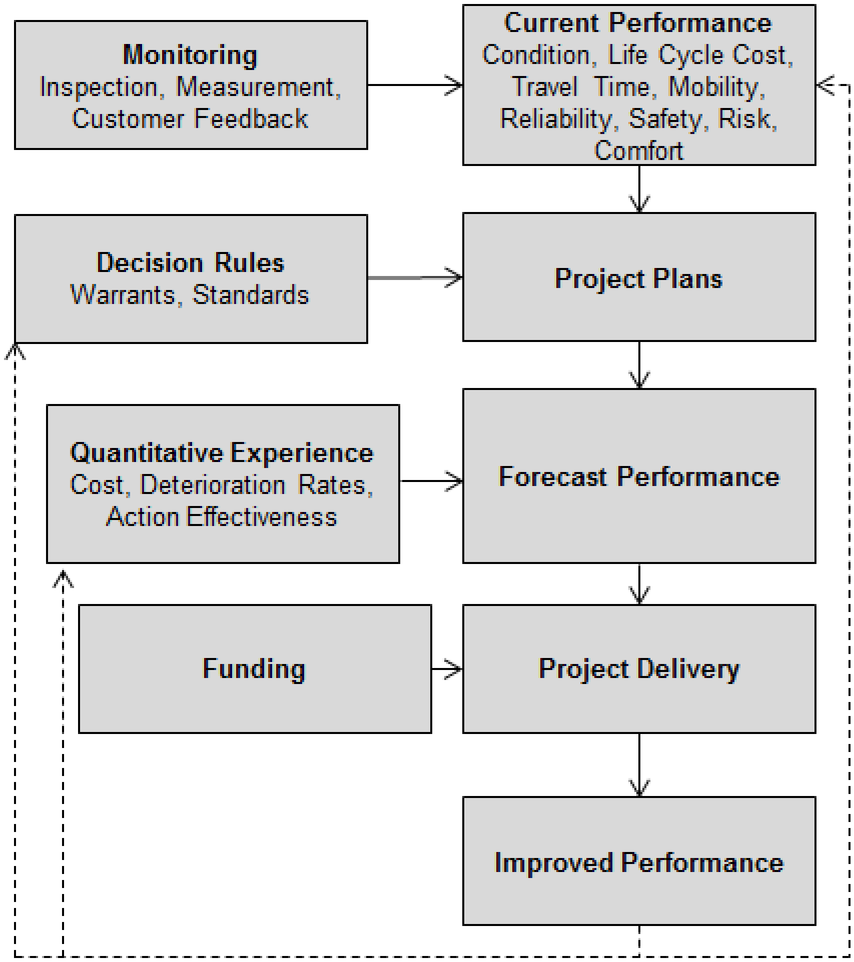


Figure 28. Project Management Process [59]

Figure 29 shows the proposed framework for integrating climate change risk assessment and impact analysis into TAM. It is based on the TAM components described by AASHTO and U.S. DOTs, and applies to the entire transportation network. The framework consists of eight main steps.

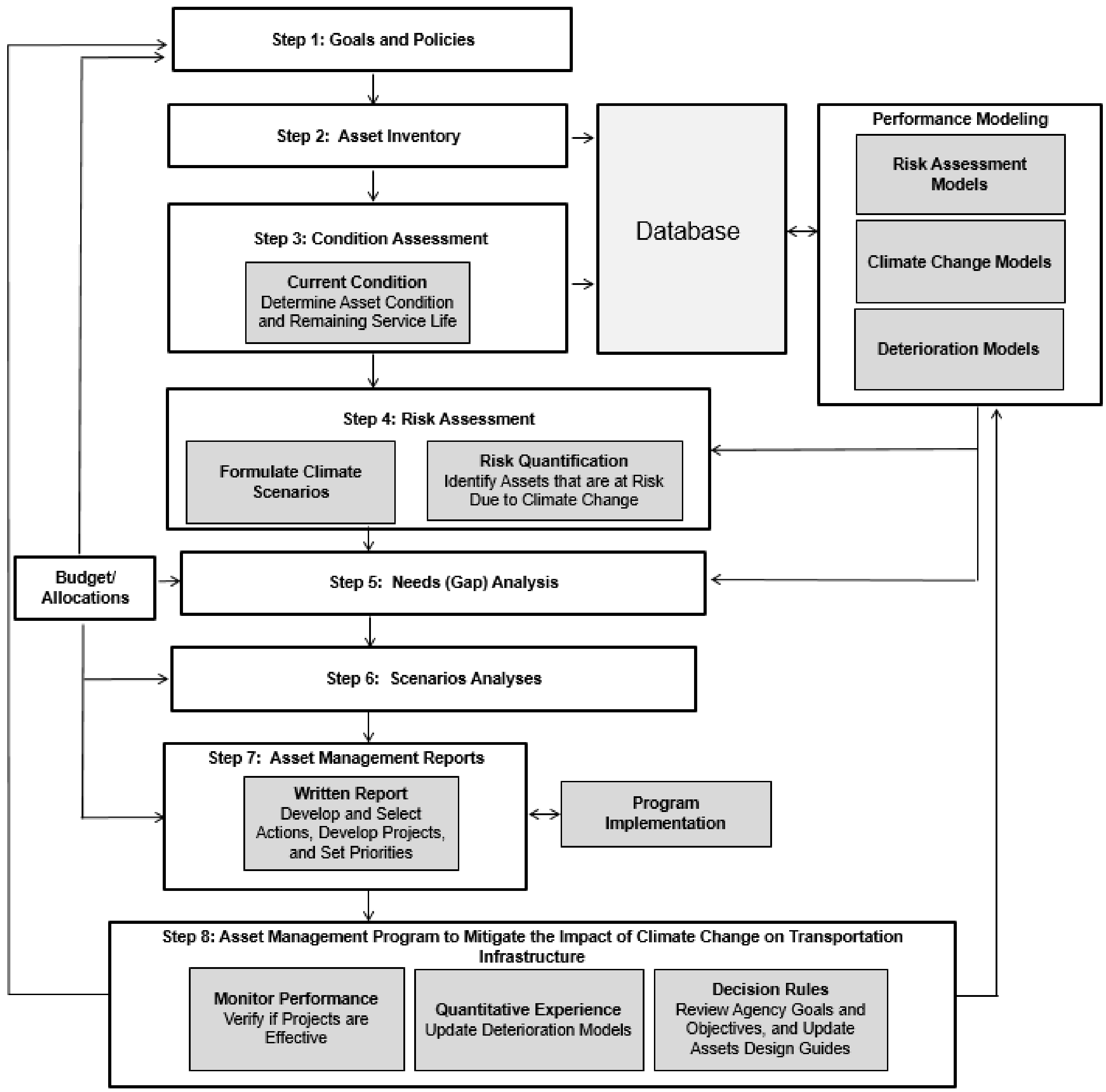


Figure 29. Framework to Integrate Climate Change Impact Analysis into TAM Practices

Step 1: Goals and Policies

In this step, agency goals and policies are identified by the agency. Goals defines the "results to be achieved" while policies express the "intentions and direction of an organization" [60]. This is an important step because without clearly identifiable goals there will be a lack of guidance and direction. Goals and policies aid in the evaluation of asset performance and facilitate the planning process. In this step, the desired level of service or asset performance throughout its life cycle must be defined. Performance measures are useful to gage the asset's conditions and monitor the progress towards achieving the goals. Climate change performance measures must be selected in this step to facilitate monitoring the progress of the goals' accomplishment. The previous section describes performance measures from different States in the Southern Plains, although not directly affected by climatic events. More specific performance measures are required to properly evaluate the effects of climatic events, for example the number of bridges at high risk.

Step 2: Asset Inventory

FHWA states that "a major component of an effective Asset Management program is the existence of an inventory of infrastructure assets by type and their condition" [61]. The inventory should include the type of asset, dimensions, location, and any other relevant information required to identify the infrastructure assets managed by the agency. "Transportation infrastructure assets are the physical elements, such as pavements, bridges, culverts, signs, pavement markings, and other roadway and roadside features that comprise the whole highway infrastructure network, from right-of-way line to right-of-way line" [61]. It is also important to collect all data related to climate change in the region. The National Oceanic and Atmospheric Administration (NOAA) developed a database with tools, as summarized in Table 9, that can help to analyze climate change scenarios [62].

Table 9. NOAA Climate Change Analysis Tools [62]

Tool Name	Climate Data	Description
The Climate Explorer	• Precipitation • Temperature	This tool evaluates precipitation and temperature data and projections by zip, city or state. This tool contains historical data and projections. https://toolkit.climate.gov/climate-explorer2/
Global Climate Change Viewer	• Precipitation • Temperature	This tool is used to visualize future temperature and precipitation changes by country. It also contains histograms and monthly temperature projections. http://regclim.coas.oregonstate.edu/gccv/
The Northwest Climate Toolbox	• Precipitation • Temperature • Wind Speeds	This tool contains historical climate variability data, future boxplot projections, and future time series for precipitation, temperature and wind speeds in the United States. https://climatetoolbox.org/
NOAA Sea Level Rise Viewer	• Sea Level Rise • Flooding	This is a visual tool to project sea level rise from 1 foot to 6 feet rise to evaluate the risk of flooding of the coasts of the United States. https://coast.noaa.gov/slr/

Table 9. NOAA Climate Change Tools [62] (Cont'd)

Tool Name	Climate Data	Description
NOAA Historical Hurricane Tracks	• Hurricane Frequency	This tool shows the path and category of past hurricanes. It can be used as a reference for the frequency of hurricanes in a period of time. https://coast.noaa.gov/hurricanes/
EPA Storm Surge Inundation Map	• Hurricane Frequency • Storm Surge	This tool contains hurricane frequency for United States' Eastern Coast and storm surge flooding data. https://epa.maps.arcgis.com/apps/MapSeries/index.html?appid=852ca645500d419e8c6761b923380663

If the information in the toolkits is insufficient or not found for a region, then data collection must be conducted to determine the return period and severity of the climatic event. Currently, the return period is calculated by dividing the number of years of historical data by the number of events occurring in that period of time. For example, if there were five Category 3 hurricanes that struck an area in a period span of 105 years, then the return period would be 1 in every 21 years. For future events, the return period must be adjusted to climate change effects that cause more intense storms that return at a faster rate.

Step 3: Condition Assessment

The condition of the assets must be evaluated periodically to identify treatment needs and budget. Frequent inspections are recommended to evaluate if an asset component is at risk of failing due to an extreme climatic event. Typically, inspections for main transportation assets including pavements, bridges, culverts, and signs are conducted once a year. Other transportation assets, pavement marking and guard rails, are inspected twice a year or when a crash occurs. Transportation assets should also be inspected right after an extreme climate event. There is a relationship between asset condition and the remaining service life. Condition is a measurement of health of an asset and the remaining service life is the time that takes an asset to go from serviceable to no longer serviceable.

Step 4: Risk Assessment

Risk assessment is "the process of quantifying the risk events documented in the preceding identification stage. Risk assessment has two aspects. The first determines the likelihood of a risk occurring (risk frequency); risks are classified along a continuum from very unlikely to very probable. The second judges the impact of the risk should it occur (consequence severity)" [63]. By combining both aspects, we can assess the level of risk due to an event as shown in Figure 30.

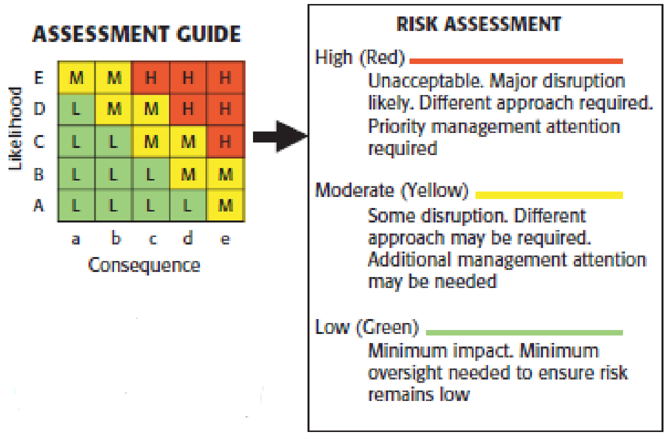


Figure 30. Risk Assessment Matrix [11]

The likelihood of a climate event to occur and severity of the damage to the assets condition is evaluated under different climate scenarios. "What If" analyses are used to assess the risk of an asset of being damaged under high, medium and low risk impact scenarios. For example, temperature change scenarios can be 8℉ increase for high, 5℉ increase for medium, and 2℉ increase for low risk of become unserviceable after an extreme climatic event.

Step 5: Perform Needs (Gap) Analysis

The Needs Analysis is also referred to as a Gap Analysis and it is conducted for each of the climate change scenarios. These analyses determine the activities and budget required to preserve the assets in a "State of Good Repair" by reducing the risk of failure due to climate change events. The risk reduction is determined by calculating the RPN from step 4. The All Needs Scenario determines the level of investment required to reduce the risk to an acceptable level under each scenario. In order to reduce risk, the entire risk management process must be considered as shown in Figure 31.

Figure 31. Risk Management Process [63]

This risk management process is proposed by FHWA for individual projects, and it can be extended to all the assets in the transportation network. The first step is to “identify and categorize risks that could affect the project and document these risks.” The second step is to “Assess/Analyze” the risk for the assets, which is “the process of quantifying the risk events documented in the preceding identification stage.” In the risk assessment process, there are two main aspects to analyze: the likelihood of the risk to occur as “very unlikely to very probable.” and the consequences in the asset condition. The third step is to “Mitigate and Plan” with the aim “to explore risk response strategies for the high-risk items identified in the qualitative and quantitative risk analysis.” There are four alternatives to manage risk: avoidance, transference, mitigation, or acceptance. Avoidance is the elimination of risk. Transference is the transfer of financial responsibility of risk by contracting out management activities. Mitigation seeks to reduce the risk or impact of the event. Acceptance is the agreeing of risk as they occur. In the fourth step, “Allocate”, risk management activities are assigned or allocated to an individual or department responsible for addressing the risk. The fifth step is to “Monitor and Control” the risk management activities. The objective is to “systematically track the identified risks, identify any new risks, effectively manage the contingency reserve, and capture lessons learned for future risk assessment and allocation efforts.” Monitor and control “must continue for the life of the project because risks are dynamic. The list of risks and associated risk management strategies will likely change as the project matures and new risks develop or anticipated risks disappear” [63].

Climate mitigation involves actions to reduce the consequences of climate change by focusing on the source (e.g. greenhouse gases), while climate adaptation seeks to be prepared to climate change threats by creating costal building defenses, modifying existing assets to be more resilient, and other actions. Table 10 summarizes climate mitigation and adaptation strategies. Some of the climate adaptation strategies are fostered by the United Nations [65].

Table 10. Climate Mitigation and Adaptation Strategies

Climate Change Stressor	Transportation Asset Affected	Mitigation and Adaptation Strategies
Increased Temperature	• Rail lines • Roads	• Use of continuous welded rail lines to prevent buckling. • Paint tracks or roads white to reduce the heat.
Increased Precipitation/Flooding	• Rail lines • Tunnels • Roads • Culverts and Drainage Systems	• Protect critical evacuation routes. • Continuously monitor water flows. • Riprap development in bridge piers and abutments. • Flood plain restrictions. • Increase in culvert capacity. • Installation of flood gates.
Sea Level Rise and Storm Surge	• Rail lines • Tunnels • Bridges • Roads	• Increase elevation of bridges, rail lines, roadways. • Relocated sections of roadways to less vulnerable to flooding. • Addition of drainage canals near coastal roads. • Increase protection of high value roads with levees, dikes, and seawalls. • Strengthen and increase height of levees, seawalls, and dikes. • Increase pumping capacity of tunnels. • Restrict vulnerable areas.
Increase in Frequency of Strong Storms	• Rail lines • Bridges • Roads	• Increase levee height and strength. • Check bridge designs to assure decks are tied to substructure. • Increase drainage capacity. • Return some coastal areas to nature. • Protect critical evacuation routes. • Decentralize systems.

These mitigation and adaptation strategies can be implemented in Southern Plains region to reduce the risk of asset failure from climate change. The strategies can help agencies think about actions to reduce risk, but the driving factor for their implementation depends on the budget of each agency. Some mitigation and adaptation strategies are expensive such as increasing the elevation of a bridge or relocating sections of roadways, while others are not, such as painting white tracks.

Step 6: Conduct Scenarios Analyses

Scenarios analyses can be formulated for different budget levels, climatic events, and risk tolerance. For example, budget scenarios analyses can be conducted for 75%, 50%, and 25% of the all needs budget. For climatic event scenarios, the analysis may consider specific climatic events such as hurricanes, flooding at different levels of magnitude. For risk tolerance, an agency may prefer to invest more funds to preserve the transportation infrastructure at a minimum risk of failure or accept moderate risk to reduce the investments in the short-term. With the results of the scenarios analysis, an agency can prioritize their available resources by focusing on risk reduction to preserve the transportation infrastructure in a “State of Good Repair”.

Step 7: Asset Management Reports and Risk Assessment

A risk assessment section describing the threats and actions to improve the resilience of the asset by reducing the risk of damage are included in the asset management reports. These actions are grouped into project categories and prioritized by asset groups. The driving factors of these projects are available budget and risk tolerance in the short and long-term. If there is residual risk with a course of action already defined, the agency has to specify how to manage the risk or improve the action. This information should assist the agencies with the implementation of the asset management program to enhance the resiliency of the entire transportation infrastructure network under extreme climatic events.

Step 8: Asset Management Program to Mitigate the Impact of Climate Change on Transportation Infrastructure

Once the level of investment is determined, the asset management program is prepared and should include the actions needed to mitigate the impact of climate change in the short and long-term planning period. Performance monitoring of the transportation assets must be conducted regularly to evaluate if the asset management program is working as expected. Asset condition is monitored to determine if the deterioration models used in the needs and scenarios analyses are reliable or needs calibration. Climate change information is also reviewed to update the climate models as needed to better predict the asset’s response. Decision rules, agency goals and objectives may also be updated to improve the asset management process in lieu of extreme climatic events.

2.3. METHODOLOGY TO QUANTIFY AND REPORT THE RISK OF ASSET FAILURE DUE TO CLIMATIC EVENTS

The methodology to quantify the risk of asset failure includes a matrix and probabilistic equations to analyze the likelihood of occurrence and severity of a climatic event; as well as recommendations on how to report the results of the analysis. The process described in this section must be conducted for each asset in the inventory.

2.3.1. Risk Analysis Matrix and Risk Quantification

A risk analysis matrix is used to identify the assets at risk of failure due to a climatic event as shown in Figure 32. Assets in the transportation network are prioritized based on this information.

Identify				Assess/Analyze					Mitigate & Plan	Allocate		Moni
Current Condition									Proposed Solutions			
Extreme Climatic Event	Asset Type	Climatic Scenarios of Potential Cause(s) of Failure	Detection Action	Occurrence (1-10)	Severity (1-10)	Current Controls	Risk Chart Result	RPN	Reccomended Action	Responsibility and Target Completion Date	Action Taken	Revis Occurr (1-1
Hurricane/ Storm Surge	I-10 Twin Span Bridge	1: 25 ft Storm Surge	Visual, Height of water	10	4	None	M	40	Rebuild with 30ft Elevation	State DOT	-	4
		2: 15 ft Storm Surge	Visual, Height of water	10	9	None	H	90	Rebuild with 30ft Elevation	State DOT	-	10
		3: 5 ft Storm Surge	Visual, Height of water	4	10	None	M	40	Rebuild with 30ft Elevation	State DOT	-	10

Figure 32. Example of a Risk Analysis Matrix

The risk analysis matrix has five sections that reflect the steps described in the risk management process: identify, assess/analyze, mitigate and plan, allocate, monitor and control.

a. Identify

Information about the extreme climatic event, asset at risk, potential cause of failure, and recommended detection actions is entered in the matrix. Examples of potential causes of failure are wildfire closure and flooding. Detection actions are recommended with the inspection method to check if the asset has failed, and it could be visual or with a monitoring device. Performance measures, as described in the previous sections, are recommended to evaluate the magnitude of the damage.

b. Assess/Analyze

Probabilistic equations quantify the risk in terms of the likelihood of occurrence and severity of the climate event. For the occurrence, the probability of the asset to experience an extreme climate event during its lifetime is modeled with a binomial distribution equation, and then multiplied by 10 to express it in a 1 – 10 number scale. Equation 2 shows the equation to calculate occurrence.

$$\text{Occurrence} = P[X \geq 1] * 10 = [1 - f_x(k)] * 10 = \left(1 - \binom{n}{k} * p^k * (1-p)^{n-k}\right) * 10 \qquad (2)$$

where:

$P[X \geq 1]$	= Probability of an asset to experience at least one extreme climate event during its service life.
n	= Remaining life or number of years for the analysis.
a	= Number of years of climatic events
b	= Number of climatic events
Rep	= Return Period is a/b
p	= 1/Rep of the extreme climate event (e.g. 1 storm in 50 years = 0.02)
k	= Number of expected extreme climate events in the analysis period.

Note that 1 – p in the equation, represents the probability of one or more extreme climate events to occur and therefore k=0.

For the severity, the probability of an asset to experience damage or failure is modeled with a cumulative standard normal distribution. The risk of failure is 1 minus the cumulative standard normal distribution. This risk of failure is multiplied by 20 minus the clearance parameter express the severity in a 1 to 10 number scale. Equation 3 shows the equation to calculate the severity.

Severity= $P[Z < 0] * \left(20 - C_p\right) = (1 - \Phi(Z)) * (20 - C_p)$=$(1 - \Phi\left(ln\left(\frac{R}{L}\right)\right)) * (20 - C_p)$ (3)

where:

P$[Z < 0]$	= Probability an asset to experience failure or damage at the time of occurrence of the extreme climate event.
$\Phi(Z)$	= Cumulative standard normal distribution
R	= Resistance parameter (e.g. height of bridge, volumetric capacity of culvert, etc.)
L	= Acting parameter or climate stressor that can cause failure (e.g. height of storm surge, flow due to heavy precipitation, etc.)
C_p	= Clearance Parameter (R - L)

The risk of failure is expressed in terms of the occurrence and severity; and the level of risk is then judged using the risk quantification chart shown in Figure 33.

Occurance										
10	M	M	M	M	H	H	H	H	H	H
9	M	M	M	M	H	H	H	H	H	H
8	L	L	M	M	M	M	H	H	H	H
7	L	L	M	M	M	M	H	H	H	H
6	L	L	L	L	M	M	M	M	H	H
5	L	L	L	L	M	M	M	M	H	H
4	L	L	L	L	L	L	M	M	M	M
3	L	L	L	L	L	L	M	M	M	M
2	L	L	L	L	L	L	L	L	M	M
1	L	L	L	L	L	L	L	L	M	M
	1	2	3	4	5	6	7	8	9	10
	Severity									

Figure 33. Level of Risk Quantification Chart

The Failure Modes and Effects Analysis (FMEA) proposes a Risk Priority Number (RPN) used to identify assets at high risk. The RPN was proposed by the University of Colorado Denver (UC Denver), and it is calculated by multiplying the likelihood of occurrence, severity, and detection. The detection factor is scaled from 1-10 (detectable to undetectable). This factor aims to measure if the risk could be detected [64]. UC Denver describes a methodology based on surveys and expert opinion to determine the occurrence, severity, and detection.

In the methodology proposed in this study, detection is replaced by significance to express the level of importance of the asset to the agency in a 1-10 scale Equation 4 shows the calculation for RPN.

$$RPN = Occurrence * Severity * Significance \quad (4)$$

Assets that are vital or places more people's lives at risk if it fails, have higher significance values than non-vital assets. For example, assets in an evacuation route are assigned a higher significance than those that are not.

c. Mitigate and Plan

Recommended actions are described in the "Mitigate and Plan" section of the risk analysis matrix. Actions can vary from inspecting the asset more frequently to reconstruction. Other mitigation and adaptation strategies were previously discussed previously in Step 5 of the framework.

d. Allocate

The implementation of the actions for an asset is then assigned/allocated to a person or group of persons responsible for the asset's preservation. This responsibility can vary between assets depending on who manages the asset. For example, highways are managed by DOTs while arterial roadways are managed by Metropolitan Planning Organizations (MPO).

e. Monitor and Control

In the last section of the risk analysis matrix, the asset is reevaluated to determine if there is a reduction of the risk due the actions recommended in the plan. Occurrence and severity are recalculated to determine the level of risk and the new RPN. The risk reduction can be measured by comparing the RPNs before and after the mitigation actions.

2.3.2. How to Report the Impact of Climate Change on Transportation Assets

Reports in TAM Practices are important to communicate the impact of climate change at different management levels: strategic, network, and project. At the strategic level, decisions on policies and funding allocation across the asset groups are made. At the network level, decisions are made on how to allocate available funds among the components of each asset group (e.g. roads, bridges) [32]. At the project level, the most-cost effective risk reduction actions are identified for each individual asset. For each individual asset component in the transportation network the following information should be added in the report:

- Asset condition
- Remaining service life
- Current risk level (risk quantification chart)
- Risk Priority Number (RPN)
- Cost to preserve or repair the asset
- Recommended Risk Reduction Action and Cost

Figures 34 and 35 show an example of a two-page Scored Card with this information.

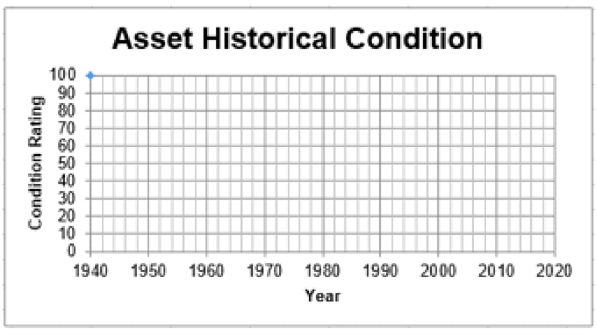
SCORECARD	
State:	
Place Name:	
County:	
Asset Type:	
Asset Location:	
Latitude:	
Longitude:	
Year Built:	
Level of Service:	
Owner:	
Asset Material Design:	
Asset Dimensions:	
Other Asset Information:	
Asset Structural Condition:	
Asset Substructure Conditions:	
Asset Rating (IRI, SR, etc.):	
Asset Climate Change Risk	
Asset RPN	
Asset Historical Condition	

Figure 34. Example of a Scorecard, Page 1

Current Condition									Proposed Solutions			Results/Revisit				Investment
Extreme Climatic Event	Asset Type	Climatic Scenarios of Potential Cause(s) of Failure	Detection Action	Occurrence (1-10)	Severity (1-10)	Current Controls	Risk Chart Result	RPN	Reccomended Action	Responsibility and Target Completion Date	Action Taken	Revisited Occurrence (1-10)	Revisited Severity (1-10)	Risk	RPN	Cost

Occurance											
	10	M	M	M	M	H	H	H	H	H	H
	9	M	M	M	M	H	H	H	H	H	H
	8	L	L	M	M	M	M	H	H	H	H
	7	L	L	M	M	M	M	H	H	H	H
	6	L	L	L	L	M	M	M	M	H	H
	5	L	L	L	L	M	M	M	M	H	H
	4	L	L	L	L	L	L	M	M	M	M
	3	L	L	L	L	L	L	M	M	M	M
	2	L	L	L	L	L	L	L	L	M	M
	1	L	L	L	L	L	L	L	L	M	M
		1	2	3	4	5	6	7	8	9	10
		Severity									

Figure 35. Example of a Scorecard, Page 2

At the network and strategic levels, performance measures to show the impact of climate change are necessary to assist agencies be aware of the assets at risk. It is recommended to add specific climate change performance measures as follows:

- Percent of transportation assets (e.g. bridges, rails, etc.) that are affected by climatic events (e.g. flooding, storm surge, etc.).
- Percent of asset components in an asset group at high, medium, or low risk based on the RPN and the Risk Quantification Chart.
- Percent of essential evacuation routes affected by a climatic event.
- Number of people affected by the climatic event.

It is critical to present these performance measures in a concise and easy to understand form. Figure 36 shows an example of how to represent this information graphically showing the percent of asset components in each asset group at different levels of risk. Figure 37 displays an example of the population at risk due to a climatic event. Data in these figures is not representative of any specific agency and it is only provided as an example. For both figures, the left would be the current condition of the assets and on the right projected results.

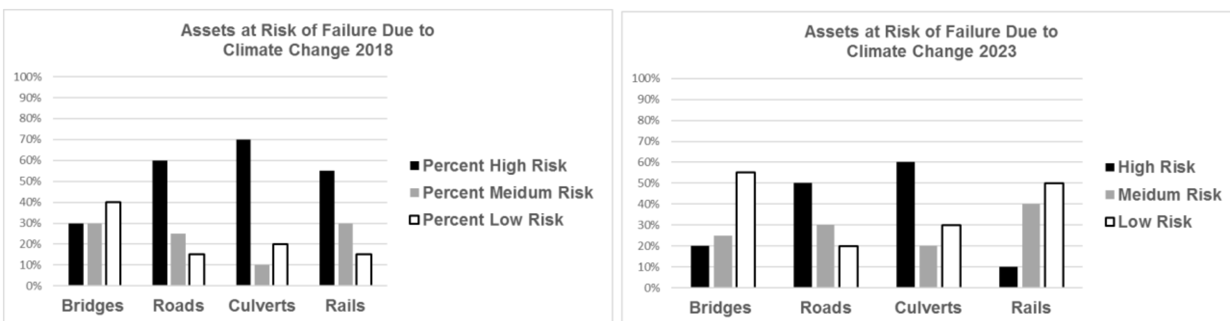


Figure 36. Assets at Risk of Failure Due to Climate Events

Figure 37. Population at Risk of Failure Due to Climate Events

These types of graphs can be used in the reports to easily show the number of assess at each risk level, consequences in the future if no actions are taken, and the benefits of the risk mitigation practices implemented by the agency. GIS maps are also recommended to visually identify the location of the assets at risk due to climate change.

As climate change continues to affect weather patterns, resilience must be embraced by TAM practices. To measure resilience, a Life Cycle Analysis (LCA) must be conducted. An extreme climatic event appears as a vertical line in the life cycle to indicate a loss of service life as shown in Figure 38.

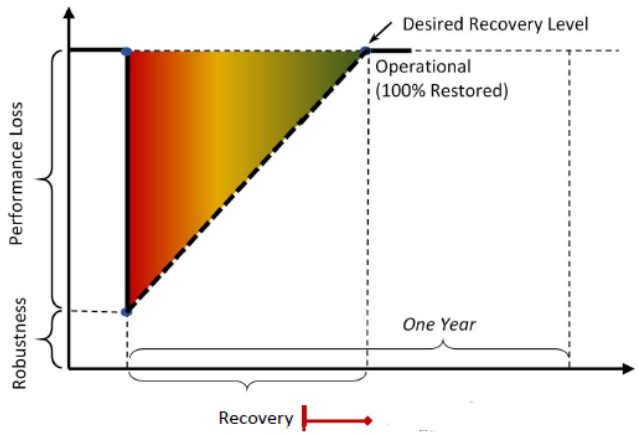


Figure 38. Asset Resilience in LCA [52]

The next sections illustrate the impact on the asset condition due to an extreme climatic event that result in the loss of service life. Condition is a measurement of asset health, and remaining service life is the time that takes an existing asset to become non-serviceable. Recommendations about the parameters required to quantify the risk, occurrence and severity, are also provided for pavements, bridges, and culverts.

2.3.2.1. Pavements

Figure 39 shows a condition deterioration curve for pavements and treatment actions. It is observed that as the pavement condition deteriorates the level of service is affected. Over time, if no maintenance is conducted, the pavement condition crosses the maintenance and rehabilitation treatment zones and then it is in need of reconstruction to reestablish its functionality. Once the pavement reaches this condition stage, its remaining life is over.

On the other hand, the service life of the pavement is extended if timely maintenance is scheduled. However, when an extreme climate event hits a region, a pavement can suffer a sharp decline in condition and becomes in need of rehabilitation or reconstruction no matter its previous condition. If no action is taken to repair the damage, then the pavement becomes unserviceable as illustrated in Figure 40.

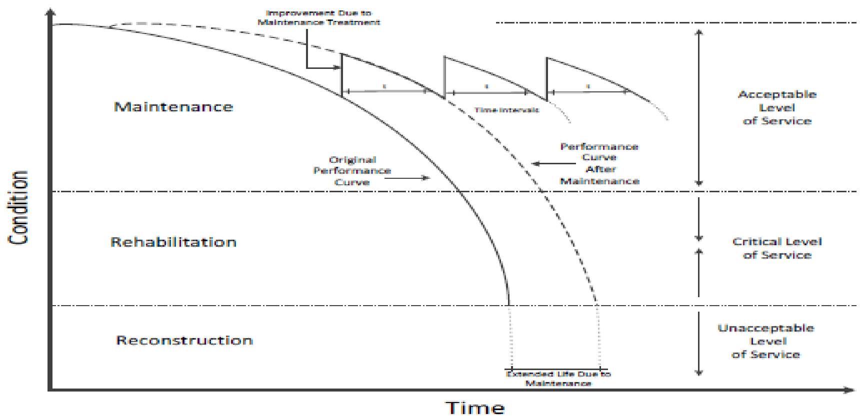


Figure 39. Pavement Condition Deterioration Curve [32]

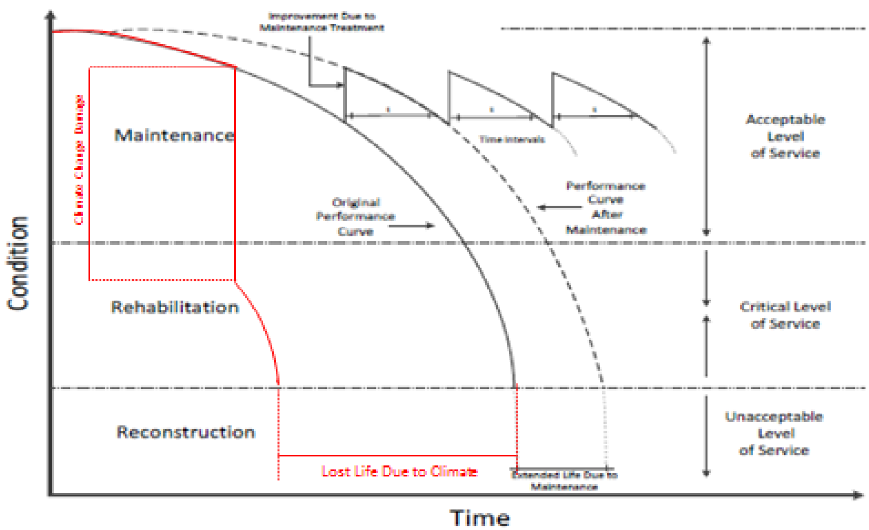


Figure 40. Pavement Condition and the Effect of Severe Climatic Events

An extreme climate event affects the entire pavement network. Figure 41 shows the percentage of pavements in very good/good, and poor/very poor conditions over time in normal working conditions. As the percentage of pavements in state of good repair decreases, the number of pavements in poor condition starts to increase. If an extreme climate event occurred in 2016, then there will be a spike on the graph as illustrated in Figure 42.

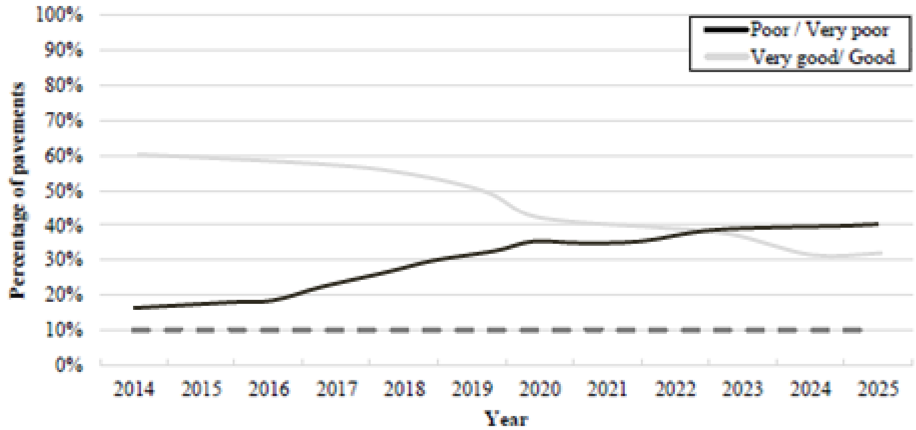


Figure 41. Projection of Pavement Condition Categories over Time in Normal Working Conditions [32]

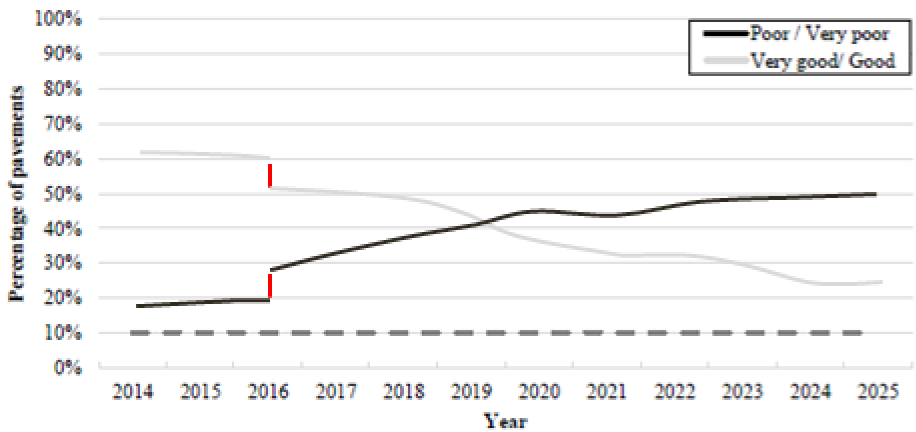


Figure 42. Projection of Pavement Condition Categories over Time affected by an Extreme Climate Event

To quantify the level of risk in terms of occurrence and severity, data should be collected for the specific climatic event that threatens the pavement network. For example, for flooding, the number of floods in a time period are needed to calculate the occurrence; and for the severity, the R parameter can be the pavement profile elevation, and the L parameter the height of the water in the flood.

2.3.2.2. Bridges and Culverts

Figure 43 shows an example of the service life trend for Timber and Gravel bridges under normal working conditions. The NBI is used by the Federal Highway Administration to evaluate the bridge condition and varies from 9 to 0 (excellent to fail condition) as described in Table 11.

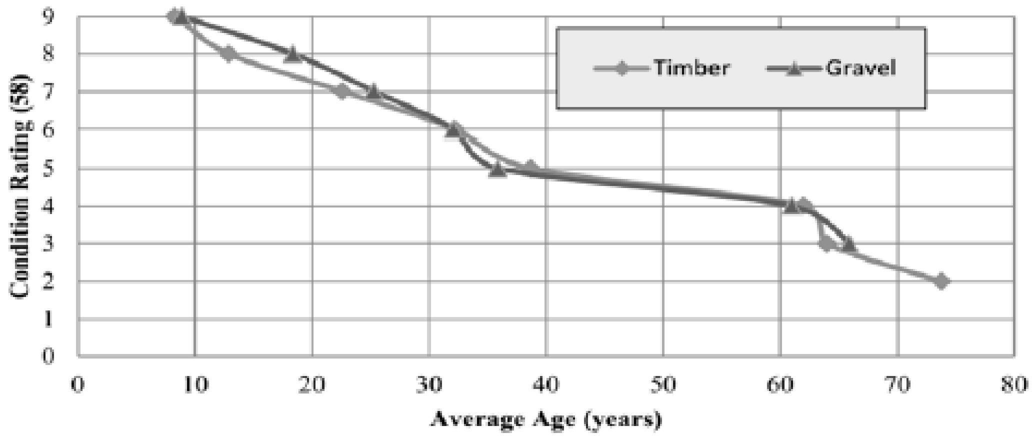


Figure 43. Bridge Deterioration Curve for Timber and Gravel Bridges in Normal Working Conditions [32]

Table 11. National Bridge Inventory General Condition Rating [66]

NBI Rating	Description	Commonly Employed Feasible Actions
9	Excellent condition.	Preventive maintenance
8	Very good condition, no problems noted.	Preventive maintenance
7	Good condition, some minor problems.	Preventive maintenance
6	Satisfactory condition, structural elements can show some minor deterioration.	Preventive maintenance and/or repairs
5	Fair condition, all primary structural elements are sound but may have some minor section loss, cracking, spalling or scour.	Preventive maintenance and/or repairs
4	Poor condition, advanced section loss, deterioration, spalling or scour.	Rehabilitation or replacement
3	Serious condition, loss of section, deterioration, spalling or scour have seriously affected primary structural elements.	Rehabilitation or replacement
2	Critical condition, advanced deterioration of primary structural elements. Unless closely monitored the bridge may have to be closed until corrective action is taken.	Rehabilitation or replacement
1	Imminent failure condition, major deterioration or section loss present in critical structural components or obvious vertical or horizontal movement affecting structure stability. Bridge is closed to traffic but corrective action may put back in light service.	Rehabilitation or replacement
0	Failed condition, out of service – beyond corrective action	Replacement

The bridge condition deterioration curve shown in Figure 43 is an example for a particular type of bridge, the NCHRP 859 research report recommends that “it is often helpful to develop different deterioration curves depending on traffic, climate, or other factors" [32]. The service life of the bridge could be interrupted by an extreme climatic event, suddenly decreasing the NBI as shown Figure 44.

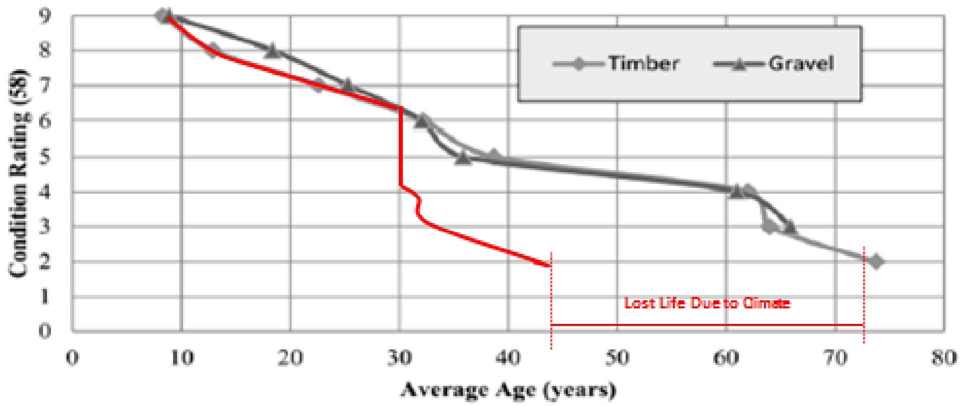


Figure 44. Bridge Deterioration Curve Affected by an Extreme Climatic Event

For bridges, climate change information should be collected for the specific climatic event under study. For example, information about the number of floods or storm surges in a time period is required for overtopping to calculate the occurrence. For severity, the R parameter can be the average height or clearance of the bridge with respects to the level of water, and the L parameter the height of the storm surge.

The risk assessment reports for culverts is similar to bridges as shown in Figure 45 by the culvert condition index over time. Due to an extreme climatic event, the culvert condition deteriorates drastically as shown in Figure 46.

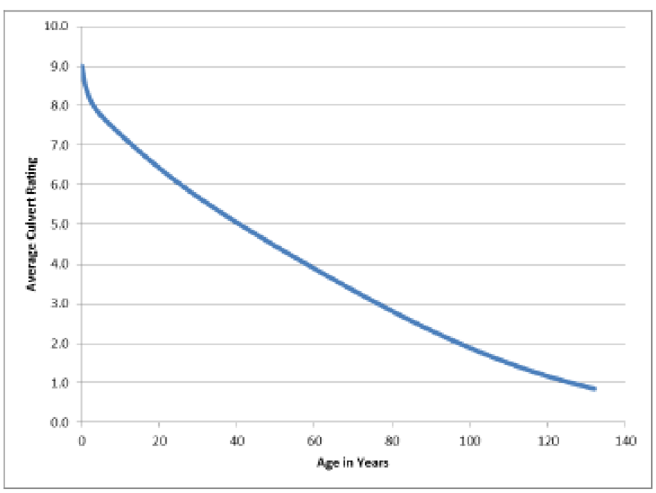


Figure 45. Culvert Condition Deterioration Curve [32]

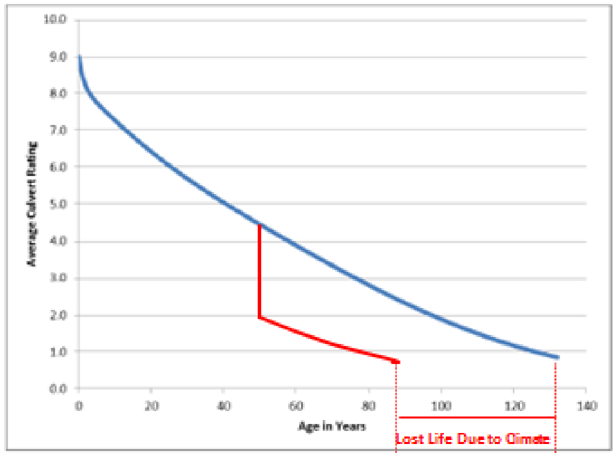


Figure 46. Culvert Deterioration Curve Affected by an Extreme Climatic Event

For culverts, climate change information about the number of floods in a time period is required to calculate the occurrence. Since a culvert is constraint by the capacity of water it can push through, then to calculate the severity the R parameter can be the current capacity of the culvert, and the L parameter the flow caused by heavy precipitation. R and L parameters can also be simplified adopting for the calculations the height of the culvert and the flood surge height respectively.

2.3.2.3. Economic Impact

Another type of reports to show the macro effects of extreme climatic events in a region are those that include economic performance measures. These economic measures are: the Current Employment Statistics (Establishment Survey), Current Population Survey (CPS) (Household Survey), Local Area Unemployment Statistics (LAUS), Job Openings and Labor Turnover Survey (JOLTS), Producer Price Indexes (PPI), Consumer Price indexes (CPI), Import and Export Price indexes (MXP), and the Employment Cost Index (ECI). Table 12 provides a brief description of these performance measures.

Table 12. Economic Performance Measures Affected by Climatic Events [67]

Performance Measure	Description
Current Employment Statistics (Establishment Survey)	The reference period of the establishment survey is the pay period that includes the 12th of the month. People are not counted as employed if they are not paid for the entire pay period that includes the 12th of the month.

Table 12. Economic Performance Measures Affected by Climatic Events [67] (Cont'd)

Performance Measure	Description
Current Population Survey (CPS) (Household Survey)	CPS is a monthly survey of households conducted by the Bureau of Census for the Bureau of Labor Statistics. It provides a comprehensive body of data on the labor force, employment, unemployment, persons not in the labor force, hours of work, earnings, and other demographic and labor force characteristics.
Local Area Unemployment Statistics (LAUS)	LAUS program produces monthly and annual employment, unemployment, and labor force data for Census regions and divisions, States, counties, metropolitan areas, and many cities, by place of residence.
Job Openings and Labor Turnover Survey (JOLTS)	The JOLTS program produces data on job openings, hires, and separations.
Producer Price Indexes (PPI)	PPI program measures the average change over time in the selling prices received by domestic producers for their output. The prices included in the PPI are from the first commercial transaction for many products and some services.
Consumer Price indexes (CPI)	CPI is a measure that examines the weighted average of prices of a basket of consumer goods and services, such as transportation, food and medical care. It is calculated by taking price changes for each item in the predetermined basket of goods and averaging them.
Import and Export Price indexes (MXP)	MCP contains data on changes in the prices of nonmilitary goods and services traded between the U.S. and the rest of the world.
Employment Cost Index (ECI)	ECI is a quarterly economic series detailing the changes in the costs of labor for businesses in the United States economy.

The economic impact of extreme climate events deserves further study based on statistical analysis. It was noted that the collection process was affected by the extreme climatic events [67]. There are also a number of interrelated factors involved in this process and performance measures to quantify the economic risk and benefits of mitigation actions; however, this study is beyond of the scope of this report.

CHAPTER 3
ANALYSIS OF A CASE STUDY
FOR BRIDGES AND PAVEMENTS

Case studies for a bridge and a road are described in this Chapter to demonstrate the applicability of the framework and methodology proposed to quantify the risk of asset damage due to extreme climatic events.

Hurricane Katrina was selected for the case studies since it significantly affected the New Orleans, Louisiana region. The hurricane made landfall in August 29, 2005 with “1800 lives lost and caused major flooding and damage that spanned more than 2000 miles along the Gulf Coast of the United States.” Levees, commercial and public buildings, roads and bridges, utility distribution systems for electric power and water, wastewater collection facilities, and vital communication networks were substantially damaged. Winds from the hurricane were estimated at “125 mph and storm surges as high as 25 feet.” Hurricane Katrina gained strength to a “Category 5 while in the Gulf of Mexico, but quickly dissipated to a Category 3 before landfall.” When Hurricane Katrina made land fall, “the wind speeds were substantially reduced before striking land, but the storm surge apparently maintained the heights associated with a Category 5“ [68].

The case studies presented in this Chapter demonstrate how the risk is quantified for individual projects. This process can be extended to all the asset components in the asset group network. At the network management level, they agency must look at all assets to fully apply the framework. Also note, that the examples look at events that have already occurred, although the method must be applied to analyze future climate threats to the infrastructure.

3.1. I-10 TWIN SPAN BRIDGE

The old I-10 Twin Span Bridge located over Lake Pontchartrain in Louisiana was selected for this case study. In 2005, this bridge was heavily damaged during Hurricane Katrina, and this study compares the risk assessment for the old I-10 Twin Span Bridge and the newly-constructed I-10 Twin Span Bridge that replaced the old bridge after Hurricane Katrina.

Step1: Bridge Goals and Policies

Since the bridge is located in Louisiana, the goals and policies of the Louisiana Department of Transportation are reviewed in this step and summarized in Table 13. The complete list of goals, objectives and performance measures are in Appendix A.

Table 13. Summary of Goals and Objectives, Louisiana DOT [58]

Goal Area	Objectives
Infrastructure Preservation and Maintenance	• Keep Louisiana's state highway pavement, bridges, and highway related assets in good condition. • Assist modal partners in achieving state-of-good-repair for aviation, port, rail, transit, and navigable waterway infrastructure.
Safety	• Reduce the number and rate of highway-related crashes, fatalities, and serious injuries. • Assist modal partners in achieving safe and secure aviation, port, rail, transit, and waterway performance.
Economic Competitiveness	• Improve the efficiency of freight transportation and the capacity of freight related infrastructure throughout Louisiana. • Improve access to intermodal facilities and the efficiency of intermodal transfers. • Provide predictable, reliable travel times throughout Louisiana. • Ensure small urban areas (5,000+ population) are well connected with one another and with large urban employment centers.
Environmental Stewardship	• Minimize the environmental impacts of building, maintaining, and operating Louisiana's transportation system. • Comply with all federal and state environmental regulations

Since these are general goals and objectives, performance measures that directly correlate climate change with asset conditions at the network level should be added. For example, the number of bridges at high, medium, or low risk of damage by an extreme climatic event. Objectives must be quantifiable to monitor the progress and very specific, for example to preserve 90 percent of the bridges in a state of good repair or at low risk.

Step 2: Bridge Asset Inventory

In this step, inventory records for all the bridges are required. This information can be found for United States bridges in a database developed by the FHWA National Bridge Inventory [69]. If the information is not available, the inventory record of the bridge should be prepared. An example of the information recommended in an inventory bridge record is shown in Figure 47.

Step 3: Bridge Condition Assessment

In this step, the current condition of the bridge is determined. This information is also stored in the National Bridges database. For our case study, Figure 47 shows the current condition of the New Twin Span Bridge in terms of the sufficiency rating. The Sufficiency Rating "is a weighted average comprised calculated by combining scores for structural adequacy and safety (55 percent weight), serviceability and functional obsolescence (30 percent weight), essentiality for public use (15 percent weight), and special reductions (6 percent weight). Sufficiency Rating ranges between 0 for entirely deficient bridge and 100 for entirely sufficient bridge" [32].

State:	LA
Place Name:	New Orleans
Country:	Orleans
NBI Structure Number:	23600000020467
Route Sign Prefix:	Interstate
Route Number:	10
Facility Carried:	I0010EB
Feature Intersected:	LAKE PONCHARTRAIN
Location:	0.1 MI EAST OF LA 11
Year Built:	2011
Record Type:	Roadway is carried ON the structure
Level of Service:	Mainline roadway
Owner:	State Highway Agency
Highway Agency District :	2
Maintenance Responsibility:	State Highway Agency
Functional Class:	Principal Arterial - Interstate, Rural
Service On Bridge:	Highway
Service Under Bridge:	Waterway
Latitude:	30 09 11 57 N
Longitude:	89 51 20 28 W
Material Design:	Steel Continuous
Design Construction:	Stringer/Multi-beam or Girder
Approach Material Design:	Prestressed concrete *
Approach Design Construction:	Mixed Types
Structure Length (m):	8,897.000
Navigation Vertical Clearance (m):	2.3
Approach Roadway Width (m):	17
Lanes on Structure:	3
Average Daily Traffic:	38520
Year of Average Daily Traffic:	2015
Design Load:	MS 18
Scour:	Bridge foundations determined to be stable for the assessed or calculated scour conditions
Bridge Railings:	Meet currently acceptable standards.
Historical Significance:	Historical Significance is not determinable at this time
# of Spans in Main Structures:	62
# of Spans in Approach Structures:	182
Structure Flared:	No flare
Transitions:	Meets currently acceptable standards.
Approach Guardrail:	Meets currently acceptable standards.
Approach Guardrail Ends:	Meets currently acceptable standards.

Navigation Control:	Navigation Control on waterway (bridge permit required)
Navigation Horizontal Control (m):	6.1
Structure Open?:	Open, no restrictions
Deck:	Good Condition
Superstructure:	Very Good Condition
Substructure:	Good Condition
Structural Evaluation:	Better than present minimum criteria
Sufficiency Rating (%):	94.4

Figure 47. Example of an Inventory Record for the I-10 Twin Span Bridge [69]

To show the effects of Hurricane Katrina on the old Twin Span Bridge, assumptions about the prior condition of the bridge were made. Originally built in 1965, the Twin Span Bridge was almost 50 years old when Hurricane Katrina made landfall. Using the bridge deterioration model described in Chapter 2, and assuming that only routine maintenance was conducted, the bridge would have been in fair condition (NBI condition rating = 5). Figure 48 shows the bridge condition before Hurricane Katrina.

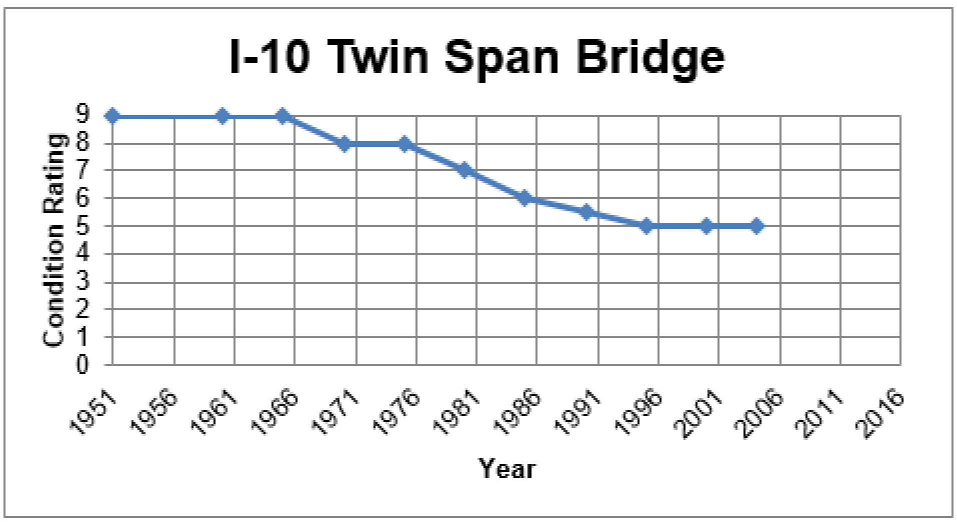


Figure 48. Condition Assessment for I-10 Twin Span Bridge before Hurricane Katrina

Step 4: Bridge Risk Assessment

In this step, climate scenarios are formulated to assess the risk of bridge failure. The climate scenarios for analysis are the storm surge, which is the most critical parameter. The following climatic impact scenarios are analyzed:

- Scenario 1: High risk impact scenario that corresponds to a Category 5 Hurricane with a storm surge of 25 ft.
- Scenario 2: Medium risk impact scenario that corresponds to a Category 3 Hurricane with a storm surge of 15 ft.

- Scenario 3: Low risk impact scenario that corresponds to a Category 1 Hurricane with a storm surge of 5 ft.

The old I-10 Twin Span Bridge had a 9 ft elevation from the surface of the water [70]. Occurrence and severity quantifies the risk of damage. For occurrence, the NOAA Historical Hurricane Tracks toolkit is used to determine the frequency of the hurricanes [62]. Appendix B includes the data used for the calculations. For severity, H_R is the clearance of the bridge deck and the water level in feet, H_L is the height of potential storm surge height in feet, and C_p is the new clearance with the storm surge. The RPN is calculated by multiplying the occurrence times the severity. Tables 14 and 15 show the complete analysis for occurrence and severity respectively.

Table 14. I-10 Twin Span Bridge Occurrence, 9 ft Clearance

Hurricane Category	Number of Events (b)	Return Period (Years)	1/Return Period	Probability P(X≥1)	Occurrence
TD	5	30.0	0.033	0.82	8
TS	40	3.8	0.267	1.00	10
H1	10	15.0	0.067	0.97	10
H2	6	25.0	0.040	0.87	9
H3	5	30.0	0.033	0.82	8
H4	1	150.0	0.007	0.28	3
H5	1	150.0	0.007	0.28	3
Number of Years of Climatic Events (a)	150				
Asset Remaining Life (n) (Years)	50				

The acronyms for the Hurricane category in Table 14 are: TD for tropical depression, TS for tropical storms, H1 for Hurricane Category 1, H2 for Hurricane Category 2, H3 for Hurricane Category 3, H4 for Hurricane Category 4, and H5 for Hurricane Category 5. The three risk impact climatic scenarios analyzed are highlighted in green. The number of years of historical data is the amount of historic data available from the first event recorded until now. The asset life was arrived under the assumption that the asset had a remaining service life of 50 years. This can also be interpreted as analyzing the asset in the next 50 years.

Table 15. I-10 Twin Span Bridge Severity, 9 ft Clearance

Storm Surge	Hr/Hsurge	z=ln(Hr/Hsurge)	Cumulative Normal Standard Probability	Probability of Failure	Clearance (Cp) (ft)	Severity Calculation	Severity
1	9.000	2.197	0.986	0.014	8	0.168	1
2	4.500	1.504	0.934	0.066	7	0.862	1
3	3.000	1.099	0.864	0.136	6	1.904	2
4	2.250	0.811	0.791	0.209	5	3.131	3
5	1.800	0.588	0.722	0.278	4	4.453	4
6	1.500	0.405	0.657	0.343	3	5.824	6

Table 15. I-10 Twin Span Bridge Severity, 9 ft Clearance (Cont'd)

Storm Surge	Hr/Hsurge	z=ln(Hr/Hsurge)	Cumulative Normal Standard Probability	Probability of Failure	Clearance (Cp) (ft)	Severity Calculation	Severity
7	1.286	0.251	0.599	0.401	2	7.214	7
8	1.125	0.118	0.547	0.453	1	8.609	9
9	1.000	0.000	0.500	0.500	0	10.000	10
10	0.900	-0.105	0.458	0.542	-1	11.381	10
11	0.818	-0.201	0.420	0.580	-2	12.749	10
12	0.750	-0.288	0.387	0.613	-3	14.104	10
13	0.692	-0.368	0.357	0.643	-4	15.443	10
14	0.643	-0.442	0.329	0.671	-5	16.767	10
15	0.600	-0.511	0.305	0.695	-6	18.077	10
16	0.563	-0.575	0.283	0.717	-7	19.372	10
17	0.529	-0.636	0.262	0.738	-8	20.653	10
18	0.500	-0.693	0.244	0.756	-9	21.921	10
19	0.474	-0.747	0.227	0.773	-10	23.176	10
20	0.450	-0.799	0.212	0.788	-11	24.419	10
21	0.429	-0.847	0.198	0.802	-12	25.651	10
22	0.409	-0.894	0.186	0.814	-13	26.872	10
23	0.391	-0.938	0.174	0.826	-14	28.082	10
24	0.375	-0.981	0.163	0.837	-15	29.283	10
25	0.360	-1.022	0.153	0.847	-16	30.475	10

Table 15 shows the also shows the three risk impact climatic scenarios that were analyzed highlighted in green. As expected, a higher storm surge results in a higher Severity. The Cp values can show when the bridge has overtopped. If the Cp is zero, the water level has reached the height of the bridge. When the Cp becomes negative, that shows how many feet the bridge has been overtopped by.

Using the values from both the occurrence and severity tables, the risk assessment matrix for each climatic scenario and potential causes of failure for the old I-10 Twin Span Bridge can be populated in Table 16 as shows.

Table 16. Risk Assessment Matrix for I-10 Twin Span Bridge

Current Conditions								
Extreme Climatic Event	Asset Type	Climatic Scenarios of Potential Cause(s) of Failure	Detection Action	Occurrence (1-10)	Severity (1-10)	Current Controls	Risk Chart Result	RPN
Hurricane/ Storm Surge	1-10 Twin Span Bridge	1: 25 ft Storm Surge	Visual, Height of Water	3	10	None	M	30
Hurricane/ Storm Surge	1-10 Twin Span Bridge	2: 15 ft Storm Surge	Visual, Height of Water	8	10	None	H	80

Table 17. Risk Assessment Matrix for I-10 Twin Span Bridge (Cont'd)

Current Conditions								
Hurricane/ Storm Surge	1-10 Twin Span Bridge	3: 5 ft Storm Surge	Visual, Height of Water	10	4	None	M	40

Step 5: Bridge Needs (Gap) Analysis

In this step, the agency identifies the actions and budget needed to repair or rebuilt the bridge. In the case of the I-10 old Twin Span Bridge, the bridge repair cost estimate was $30 million [28]. Just repairing the bridge would result in the same level of risk as before. The cost to build the new twin span bridge was estimated at $800 million [71].

For the occurrence, the new I-10 Twin Span Bridge design life changed to 100-year and the occurrence was recalculated. For the severity, H_R is the new clearance of the bridge deck and water level in feet; H_L remained as the height of potential storm surge in feet, and C_p is the new clearance for the storm surge. Tables 17 and 18 show the analysis for the occurrence and severity respectively in the new risk assessment. The RPN values are also recalculated for the actions recommended to reduce the level of risk.

Table 18. I-10 Twin Span Bridge Occurrence, 30 ft Clearance

Hurricane Category	Number of Events (b)	Return Period (Years)	1/Return Period	Probability P(X≥1)	Occurrence
TD	5	30.0	0.033	0.97	10
TS	40	3.8	0.267	1.00	10
H1	10	15.0	0.067	1.00	10
H2	6	25.0	0.040	0.98	10
H3	5	30.0	0.033	0.98	10
H4	1	150.0	0.007	0.49	5
H5	1	150.0	0.007	0.49	5
Number of Years of Climatic Events (a)	150				
Asset Remaining Life (n) (Years)	50				

Table 19. I-10 Twin Span Bridge Severity, 30 ft Clearance

Storm Surge	Hr/Hsurge	z=ln(Hr/Hsurge)	Cumulative Normal Standard Probability	Probability of Failure	Clearance (Cp) (ft)	Severity Calculation	Severity
1	30.000	3.401	1.000	0.000	29	-0.003	1
2	15.500	2.708	0.997	0.003	28	-0.027	1
3	10.000	2.303	0.989	0.011	27	-0.075	1
4	7.500	2.015	0.978	0.022	26	-0.132	1
5	6.000	1.792	0.963	0.037	25	-0.183	1
6	5.000	1.609	0.946	0.054	24	-0.215	1
7	4.286	1.455	0.927	0.073	23	-0.218	1
8	3.750	1.322	0.907	0.093	22	-0.186	1
9	3.333	1.204	0.886	0.114	21	-0.114	1
10	3.000	1.099	0.864	0.136	20	0.000	1
11	2.727	1.003	0.842	0.158	19	0.158	1
12	2.500	0.916	0.820	0.180	18	0.360	1
13	2.308	0.836	0.798	0.202	17	0.605	1
14	2.143	0.762	0.777	0.223	16	0.892	1
15	2.000	0.693	0.756	0.224	15	1.221	1
16	1.875	0.629	0.735	0.265	14	1.589	2
17	1.765	0.568	0.715	0.285	13	1.995	2
18	1.667	0.511	0.695	0.305	12	2.438	2
19	1.579	0.457	0.676	0.324	11	2.915	3
20	1.500	0.405	0.657	0.343	10	3.426	3
21	1.429	0.357	0.639	0.361	9	3.967	4
22	1.364	0.310	0.622	0.378	8	4.539	5
23	1.304	0.266	0.605	0.395	7	5.138	5
24	1.250	0.223	0.588	0.412	6	5.764	6
25	1.200	0.182	0.572	0.428	5	6.415	6

In Table 17 we see an increase of the occurrence due to the longer analysis period and Hurricane Katrina added to the table. Table 18 shows a reduction in severity due to the height of the bridge. With both the occurrence and the severity tables, the revisited risk and RPN can be tabulated as shown in Table 19. This table also shows that each scenario could require different levels of investment.

Table 20. Risk Analysis Matrix for Reevaluation of the I-10 Twin Span Bridge

Current Condition			Propose Solution			Results/ Revisit				Investment Cost
Extreme Climate Event	Asset Type	Climatic Scenarios of Potential Causes(s) of Failure	Recommended Action	Responsibility and Target Completion Date	Action Taken	Revisited Occurrence	Revisited Severity (1-10)	Risk	RPN	Cost
Hurricane/ Storm Surge	1-10 Twin Span Bridge	1: 25 ft Storm surge	Rebuild 30ft Elevation	State DOT	-	5	6	M	30	$800 Million
Hurricane/ Storm Surge	1-10 Twin Span Bridge	2: 15 ft Storm surge	Rebuild 30ft Elevation	State DOT	-	10	1	M	10	$800 Million

Table 21. Risk Analysis Matrix for Reevaluation of the I-10 Twin Span Bridge (Cont'd)

Current Condition			Propose Solution			Results/ Revisit				Investment Cost
Hurricane/ Storm Surge	1-10 Twin Span Bridge	3: 5 ft Storm surge	Rebuild 30ft Elevation	State DOT	-	10	1	M	10	$800 Million
Hurricane/ Storm Surge	1-10 Twin Span Bridge	1:25 ft Storm surge	Repair	State DOT	-	3	10	M	30	$30 Million
Hurricane/ Storm Surge	1-10 Twin Span Bridge	2:15 ft Storm surge	Repair	State DOT	-	8	10	H	80	$30 Million
Hurricane/ Storm Surge	1-10 Twin Span Bridge	3: 5 ft Storm surge	Repair	State DOT	-	10	4	M	40	$30 Million

Step 6: Bridge Scenario Analyses

In this step, the three climate risk impact scenarios are evaluated with two budget scenarios. The RPNs before and after are calculated with the occurrence and severity obtained from the analysis in step 5. Since the case study is conducted for an individual bridge, the significance is assumed to be 1 in the RPN calculations. For the I-10 Twin Span Bridge, the percent of risk reduction of each scenario is shown in Tables 20 and 21 for $800 million and $30 million budgets respectively.

Table 22. Percent of Risk Reduction for the I10 Twin Span Bridge Rebuilt, 30 ft Clearance and $800 Million Budget

Scenario	Climatic Event	RPN Before	RPN After	Risk Percent Reduction
1	H5/ 25ft Storm Surge	30	30	0%
2	H3/ 15ft Storm Surge	80	10	88%
3	H1/ 5ft Storm Surge	40	10	75%

Table 23. Percent of Risk Reduction for the I-10 Twin Span Bridge Repair, 9 ft Clearance and $30 Million Budget

Scenario	Climatic Event	RPN Before	RPN After	Risk Percent Reduction
1	H5/ 25ft Storm Surge	30	30	0%
2	H3/ 15ft Storm Surge	80	80	0%
3	H1/ 5ft Storm Surge	40	40	0%

The percent of risk reduction for rebuilding the bridge with a 30 ft clearance is 0% for a Category 5 Hurricane with a 25 ft storm surge, 88% for a Category 3 Hurricane with a 15 ft storm surge, and 75% for a Category 1 Hurricane with a 5 ft storm surge. Although there was no risk reduction for a Category 5, the severity was reduced. Table 21 shows that there is no risk reduction if the bridge is just repaired.

Step 7: Bridge Asset Management Reports

In this step, a report is prepared to communicate decision-makers the level risk for the climate scenarios. The level of risk reduction is expressed through the difference between the RPN's. Figure 49 and 50 shows the scorecard for the bridge before the landfall of Hurricane Katrina as an example of how to report an asset at risk. The rebuilt of the Twin Span Bridge cost $803 million and it was built 300 ft east of the old I-10 Twin Span Bridge [70].

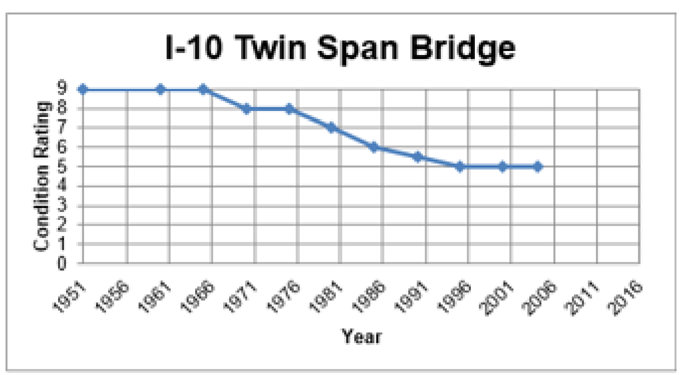
SCORECARD	
State:	Louisiana
Place Number:	New Orleans
Country:	Orleans
Asset Type:	Bridge
Asset Location:	0.1 MI EAST OF LA 11
Latitude:	30 09 11.57 N
Longitude:	89 51 20.28 W
Year Built:	1951
Level of Service:	Mainline Roadway
Owner:	State Highway Agency
Asset Material Design:	Steel Continous
Asset Dimensions:	
Other Asset Information:	L:5.4 mi; W:60 ft; H:9 ft
Asset Structural Condition:	# of Spans : 62; Average Daily Traffic: 38520; Expected Remaining Service Life 30 years without maintenance will result in a Condition Rating of 2
Asset Substructure Conditions:	Deck: Good Condition, Superstructures: Fair Condition
Asset Rating (IRI, SR, etc.):	Condition Rating: 5
Asset Climate Change Risk	Risk (2005) High to Strom Sruge Huricane Category 3
Asset RPN	90 due to Strom Surge Hurricane Category 3
Asset Historical Condition	

Figure 49. I-10 Twin Span Bridge Scorecard, Page 1

Current Condition									Proposed Solutions		
Extreme Climatic Event	Asset Type	Scenarios of Potential Cause(s) of Failure	Detection Action	Severity (1-10)	Frequency (1-10)	Current Controls	Risk Chart Result	RPN	Recommended Action	Responsibility and Target Completion Date	Action Taken
Hurricane/ Storm Surge	I-10 Twin Span Bridge	25 ft Storm Surge	Visual, Height of water	3	10	None	M	30	Rebuild with 30ft Elevation	State DOT	-
Hurricane/ Storm Surge	I-10 Twin Span Bridge	15 ft Storm Surge	Visual, Height of water	8	10	None	H	80	Rebuild with 30ft Elevation	State DOT	-
Hurricane/ Storm Surge	I-10 Twin Span Bridge	5 ft Storm Surge	Visual, Height of water	10	4	None	M	40	Rebuild with 30ft Elevation	State DOT	-
Hurricane/ Storm Surge	I-10 Twin Span Bridge	25 ft Storm Surge	Visual, Height of water	3	10	None	M	30	Repair	State DOT	-
Hurricane/ Storm Surge	I-10 Twin Span Bridge	15 ft Storm Surge	Visual, Height of water	8	10	None	H	80	Repair	State DOT	-
Hurricane/ Storm Surge	I-10 Twin Span Bridge	5 ft Storm Surge	Visual, Height of water	10	4	None	M	40	Repair	State DOT	-

Results/Revisit				Investment
Revisited Severity (1-10)	Revisited Frequency (1-10)	Risk	RPN	Cost
5	6	M	30	$80 Million
10	1	M	10	$80 Million
10	1	M	10	$80 Million
3	10	M	30	$30 Million
8	10	H	80	$30 Million

Occurance										
10	M	M	M	M	H	H	H	H	H	H
9	M	M	M	M	H	H	H	H	H	H
8	L	L	M	M	M	M	H	H	H	H
7	L	L	M	M	M	M	H	H	H	H
6	L	L	L	L	M	M	M	M	H	H
5	L	L	L	L	M	M	M	M	H	H
4	L	L	L	L	L	L	M	M	M	M
3	L	L	L	L	L	L	M	M	M	M
2	L	L	L	L	L	L	L	L	M	M
1	L	L	L	L	L	L	L	L	M	M
Severity	1	2	3	4	5	6	7	8	9	10

Figure 50. I-10 Twin Span Bridge Scorecard, Page 2

In combination with the score cards, GIS tools can be used for analysis and report purposes. The GIS maps facilitates to visualize the location of the assets at risk in a region. For the individual example in the case study, Figure 51, represented by a line with triangles, shows a high-risk level of a Storm Surge condition of the old bridge, while Figure 52, represented by a line with squares, shows the medium level of risk after the new bridge was built for a Category 3 Hurricane. These reports are useful to prioritize budget allocation by identifying the assets at high risk based on the RPN.

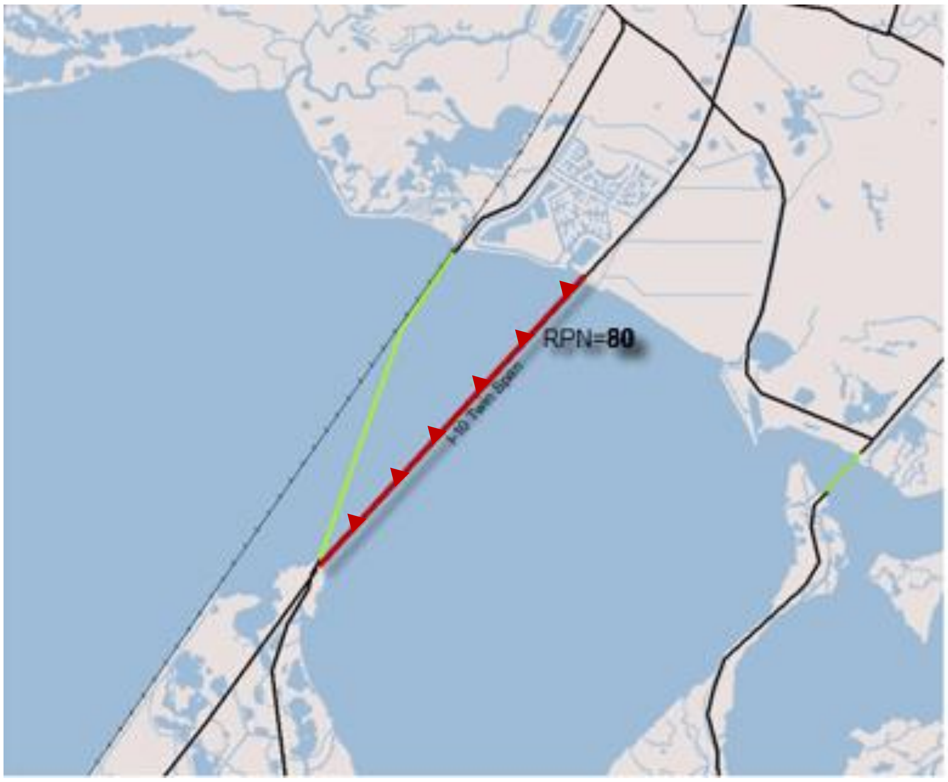


Figure 51. RPN GIS Map, Old I-10 Twin Span Bridge

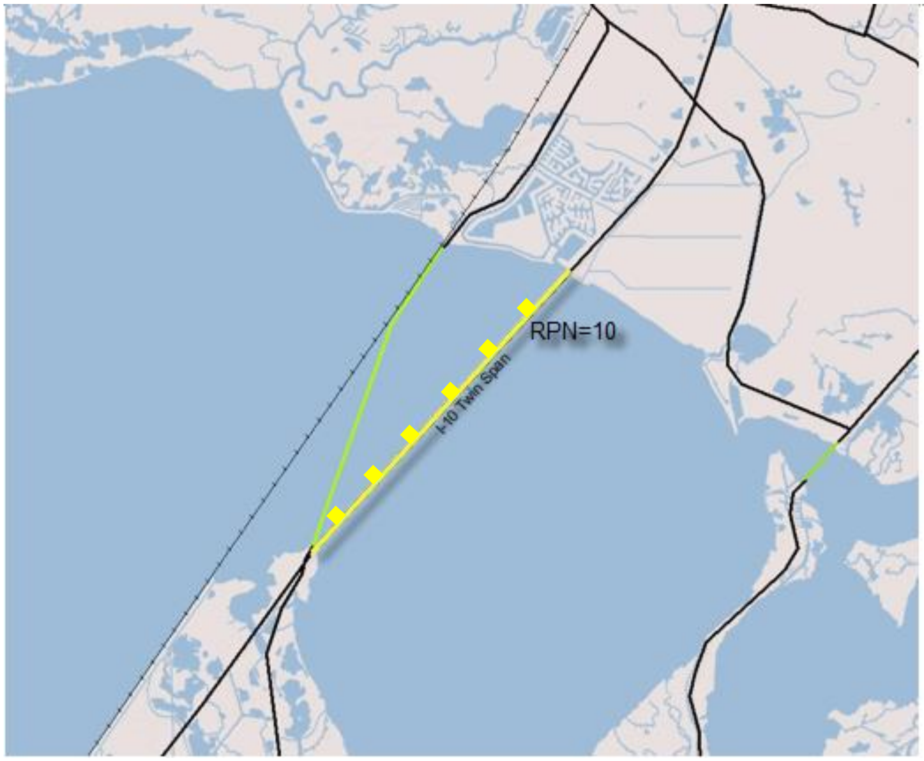


Figure 52. RPN GIS Map, New I-10 Twin Span Bridge

Step 8: Bridge Asset Management Program to Mitigate the Impacts of Climate Change

Figure 53 shows the condition rating over time of the Twin Span Bridge right after construction of the new bridge. The mitigation strategy conducted for this bridge was to raise the elevation of the bridge to reduce the risk of failure. This case study was for an individual project but the agency should apply the risk analysis to all the assets to fully implement the framework in TAM practices. The TAM framework with risk mitigation practices requires to reevaluate future climate change threats. The recommendation is to maintain historical records of the bridge condition and maintenance treatments over time to calibrate the bridge condition deterioration models. Climate change information with performance predictions should also be recorded to periodically review the climate change models.

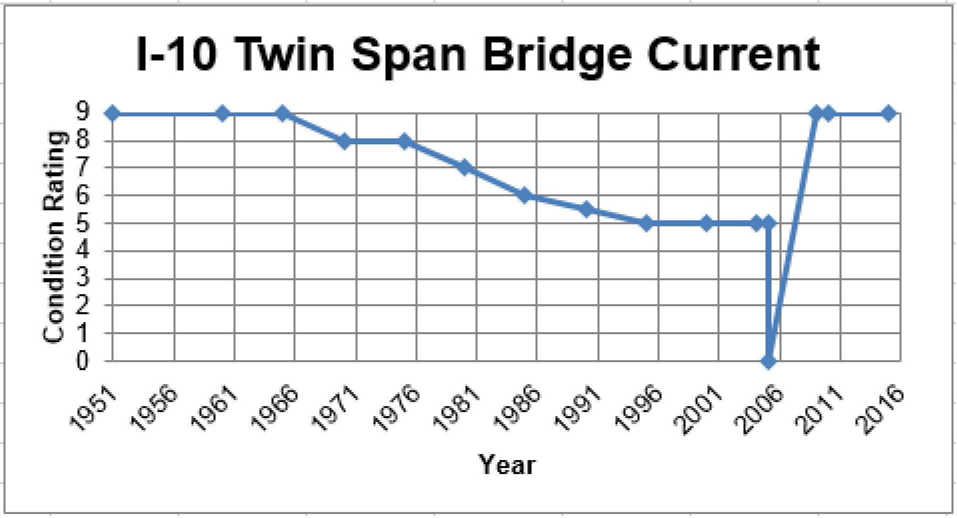


Figure 53. Condition Rating over time for the I-10 Twin Span Bridge

3.2. ROAD IN FRANKLIN AVENUE

In 2005, many roads were heavily damaged in Louisiana during Hurricane Katrina. The road selected for the case study is located on Franklin Avenue between Robert E. Lee Blvd. and Fillmore Av. in New Orleans, Louisiana.

Step 1: Roads Goals and Policies

Since the road is located in New Orleans, Louisiana; the goals, objectives and performance measures of the Regional Planning Commission (RPC) are summarized in Table 22, and serves as a reference for the New Orleans Metropolitan Planning Organization.

Table 24. Summary of Goals and Objectives in New Orleans Metropolitan Planning Organization [72]

Goal Area	Objectives	Performance Measures
Safety	• Reduce the number of serious injuries and fatalities resulting from auto crashes by 50% by 2030. • Reduce the number of pedestrian and bicyclist accidents by 50% by 2030 • Assist transit agencies in reducing transit vehicle accidents per 1,000,000 vehicles.	• Annual number of serious injuries or fatalities • Annual number of serious injuries or fatalities per vehicle mile travelled • Annual number of serious pedestrian injuries or fatalities • Annual number of serious bicycle injuries and fatalities • Transit vehicle accidents per 1,000,000 vehicle revenue miles.
State of Good Repair	• Complete a full conditions inventory of the Congestion Management System every four years • Select and implement roadway overlay and rehabilitation projects • Assist transit agencies in reducing the average number of miles between in-service failures on regional fixed route transit service	• Percentage of Congestion Management System roadway condition data collected annually • Miles of roadway overlays or rehabilitation completed annually • Average miles between in-service failures on regional fixed route service
Economic Competitiveness	• Invest in projects that improve freight movements on the National Highway System • Invest in projects that are in and will benefit economically depressed areas • Invest in projects that are in and will benefit areas that have predominantly minority populations • Invest in projects that are in and will benefit employment centers	• Miles of roadway improvements on National Highway System completed annually • Number of street overlay or transportation enhancement projects within census tracts with an average median household income at or below the poverty level completed annually • Number of street overlay or transportation enhancement projects within census tracts that are predominantly minority completed annually • Number of street overlay or transportation enhancement projects in identified employment centers
Environmental Sustainability	• Encourage the increased use of clean fuels in public and private fleets. • Implement projects that encourage transportation choices beyond single-occupancy vehicle • Consider the potential future impacts of change in the planning and implementation of roadway construction projects.	• Reductions in traditional fuel consumption in gasoline gallons equivalent by participants in the Southeast Louisiana Clean Fuel Partnership • Unlinked passenger trips on all regional transit • Number of projects that increase roadway grade or otherwise improve resiliency against sea level rise or natural disasters

Since these are general goals and objectives, performance measures that directly correlate climate change with asset conditions are recommended at the network level. For example, the number of roads at high, medium, or low risk of damage by an extreme climatic event. Very specific objectives must be, to preserve 90 percent of roads in a state of good repair, or to reduce 20% of roads from high to low risk.

Step 2: Roads Asset Inventory

In this step, inventory records for all the roads are required. An example of the information recommended in an inventory road record is shown in Figure 54.

State:	LA
Place Number:	New Orleans
Country:	Orleans
Road Name:	Franklin Ave
Route Section:	2
Intersection 1:	Robert E Lee Blvd.
Intersection 2:	Filmore Ave.
Year Built:	1940
Level of Service:	Mainline roadway
Owner:	State Highway Agency
Highway Agency District:	2
Maintenance Responsibility:	State Metropolitan Planning Organization
Functional Class:	Principal Arterial - Other, Urban
Type of Road	Asphalt
Subgrade Condition	Poor
Subbase	12"
Base	2.5"
Surface:	1.5"
Latitude:	30 01 14 50 N
Longitude:	90 03 06 10 W
Elevation:	-6ft to sea level
Section Length (miles):	1
Lanes:	4
Median:	Yes
Average Daily Traffic:	6729
Year of Average Daily Traffic:	2008
Rutting:	None
Cracking	Joint Reflection Cracking
Structure Open?:	Open, no restrictions
Structure Evaluation:	Equal to present minimum criteria
IRI:	130
CI	72

Figure 54. Example of a Roadway Inventory Record, Franklin Avenue

The information in the road inventory record requires additional data to quantify the risk of flooding. Figure 55 shows the road section elevation profile obtained from The National Map online tool developed by the U.S. Geological Survey [73].

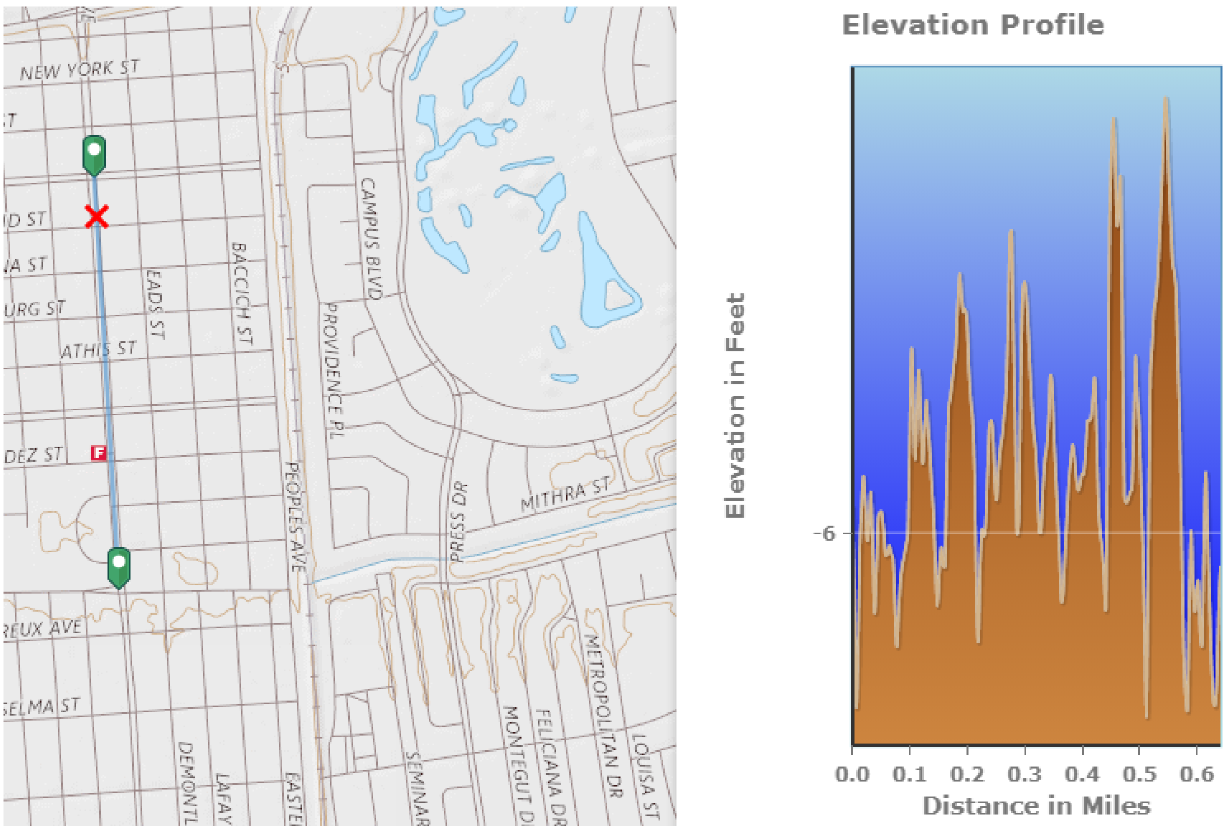


Figure 55. USGS Elevation Profile for Franklin Avenue [73]

Step 3: Road Condition Assessment

The Pavement Condition Index (PCI) is used to assess the road condition. PCI is calculated from individual pavement distresses recorded in the field based on severity and quantity. It ranges from 100 to 0 (very good condition to very poor condition). Pavement condition categories are defined with the PCI as shown in Table 23.

Table 25. Pavement Condition Categories

Category	PCI	Condition Category
I	100- 90	Very Good
II	90 – 70	Good
III	70 – 50	Fair
IV	50 - 25	Poor
V	Under 25	Very Poor

For the case study, it was assumed that the PCI was below a PCI of 50 before Hurricane Katrina as shown in Figure 56.

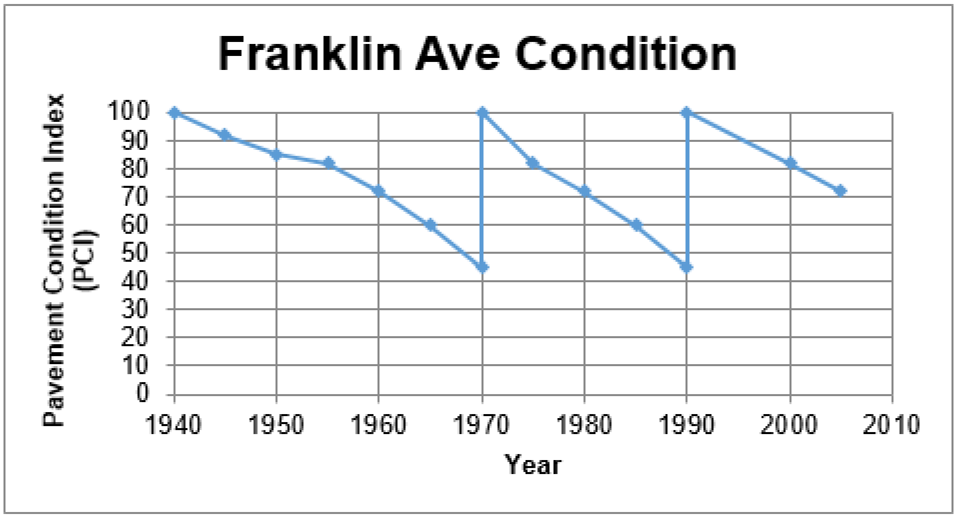


Figure 56. PCI over time for Franklin Ave. Road Section Before Hurricane Katrina

Step 4: Road Risk Assessment

In this step, climate scenarios are formulated to assess the risk of road failure. The climate scenarios for analysis are the same as for the storm surge described in the I-10 twin span bridge case study because "most of the levee failures were caused by overtopping, as the storm surge rose over the top of a levee and scoured out the base of the landward embankment or floodwall" [74]. The following climatic impact scenarios are analyzed:

- Scenario 1: High risk impact scenario that corresponds to a Category 5 Hurricane with a storm surge of 25 ft.
- Scenario 2: Medium risk impact scenario that corresponds to a Category 3 Hurricane with a storm surge of 15 ft.
- Scenario 3: Low risk impact scenario that corresponds to a Category 1 Hurricane with a storm surge of 5 ft.

Before Hurricane Katrina, the levee heights were 15 ft high. Occurrence and severity quantifies the risk of damage. For occurrence, the NOAA Historical Hurricane Tracks toolkit is used to determine the frequency of hurricanes with a levee in a 100-year return period [62]. Appendix B includes the data used for the calculations. For severity, H_R is the current height of the levee and the water level is in feet; H_L is the height of potential storm surge height in feet, and the difference between the storm surge and the height of the levee is C_p. Tables 24 and 25 show the complete analysis for the occurrence and severity respectively.

Table 26. Franklin Avenue Flooding Occurrence, 15ft Levees

Hurricane Category	Number of Events (b)	Return Period (Years)	1/Return Period	Probability P(X≥1)	Occurrence
TD	5	30.0	0.033	0.97	10
TS	40	3.8	0.267	1.00	10
H1	10	15.0	0.067	1.00	10
H2	6	25.0	0.040	0.98	10
H3	5	30.0	0.033	0.98	10
H4	1	150.0	0.007	0.49	5
H5	1	150.0	0.007	0.49	5
Number of Years of Climatic Events (a)	150				
Asset Remaining Life (n) (Years)	50				

Table 27. Franklin Avenue Flooding Severity, 15 ft Levees

Storm Surge	Hr/Hsurge	z=ln(Hr/Hsurge)	Cumulative Normal Standard Probability	Probability of Failure	Clearance (Cp) (ft)	Severity Calculation	Severity
1	15.000	0.997	0.997	0.003	14	0.020	1
2	7.500	0.978	0.978	0.022	13	0.154	1
3	5.000	0.946	0.946	0.054	12	0.430	1
4	3.750	0.907	0.907	0.093	11	0.838	1
5	3.000	0.864	0.864	0.136	10	1.360	1
6	2.500	0.820	0.820	0.180	9	1.977	2
7	2.143	0.777	0.777	0.223	8	2.676	3
8	1.875	0.735	0.735	0.265	7	3.442	3
9	1.667	0.695	0.695	0.305	6	4.266	4
10	1.500	0.657	0.657	0.343	5	5.139	5
11	1.364	0.622	0.622	0.378	4	6.052	6
12	1.250	0.588	0.588	0.412	3	6.999	7
13	1.154	0.557	0.557	0.443	2	7.976	8
14	1.071	0.528	0.528	0.472	1	8.977	9
15	1.000	0.000	0.500	0.500	0	10.000	10
16	0.938	-0.065	0.474	0.526	-1	11.040	10
17	0.882	-0.125	0.450	0.550	-2	12.096	10
18	0.833	-0.182	0.428	0.572	-3	13.164	10
19	0.789	-0.236	0.407	0.593	-4	14.242	10
20	0.750	-0.288	0.387	0.613	-5	15.330	10
21	0.714	-0.336	0.368	0.632	-6	16.425	10
22	0.682	-0.383	0.351	0.649	-7	17.527	10
23	0.652	-0.427	0.335	0.665	-8	18.633	10
24	0.625	-0.470	0.319	0.681	-9	19.744	10
25	0.600	-0.511	0.305	0.695	-10	20.858	10

In both of the previous tables, the scenarios are highlighted in green. The occurrence shows that there is a high probability that the asset will experience a hurricane Category 1 and 3, but a lower of experiencing a hurricane Category 5 in the next 100 years. The severity table shows that the asset will experience damage in a hurricane Category 3 and 5 and little to no damage on a hurricane Category 1.

Using both values from the occurrence and the severity tables, the RPN and risk assessment matrix for each climate scenario and potential causes of failure are tabulated in Table 26.

Table 28. Risk Analysis Matric for Franklin Avenue Current Conditions

Extreme Climatic Event	Asset Type	Climatic Scenarios of Potential Cause(s) of Failure	Detection Action	Occurrence (1-10)	Severity (1-10)	Current Controls	Risk Chart Result	RPN
Hurricane/ Storm Surge	1-10 Twin Span Bridge	1: 25 ft Storm Surge	Visual, Height of Water	5	10	None	H	50
Hurricane/ Storm Surge	1-10 Twin Span Bridge	2: 15 ft Storm Surge	Visual, Height of Water	10	10	None	H	100
Hurricane/ Storm Surge	1-10 Twin Span Bridge	3: 5 ft Storm Surge	Visual, Height of Water	10	1	None	M	10

Step 5: Road Needs (Gap) Analysis

In this step, the agency identifies the actions and budget needed to repair or rebuilt the road. The road flooding is an indirect result of the levees and its repair cost was $14.5 billion [75]. New Orleans also built a 26-foot Storm Surge Barrier that cost $1.1 billion [75].

Table 27 shows the occurrence for 17 ft levees and the storm surge barrier. The NOAA Historical Hurricane Tracks toolkit was used to determine the number of hurricanes [62]. Table 28 and 29 shows the recalculation of severity for the increased levee elevation and storm surge barrier respectively. For the increased levee elevation, H_R is the new clearance of the levee and the water level in feet, H_L remains the height of storm surge in feet, and Cp is recalculated with the new clearance with the storm surge. For the storm surge barrier, H_R is the height of the storm barrier. The RPN values are recalculated for the actions recommended to reduce the level of risk.

Table 29. Franklin Avenue Flooding Occurrence, 17 ft Levees and 26 ft Surge Barrier

Hurricane Category	Number of Events (b)	Return Period (Years)	1/Return Period	Probability P(X≥1)	Occurrence
TD	5	30.0	0.033	0.97	10
TS	40	3.8	0.267	1.00	10
H1	10	15.0	0.067	1.00	10
H2	6	25.0	0.040	0.98	10
H3	5	30.0	0.033	0.98	10
H4	1	150.0	0.007	0.49	5
H5	1	150.0	0.007	0.49	5
Number of Years of Climatic Events (a)	150				
Asset Remaining Life (n) (Years)	50				

Table 30. Franklin Avenue Flooding Severity, 17 ft Levees

Storm Surge	Hr/Hsurge	z=ln(Hr/Hsurge)	Cumulative Normal Standard Probability	Probability of Failure	Clearance (Cp) (ft)	Severity Calculation	Severity
1	17.000	0.997	0.998	0.002	16	0.009	1
2	8.500	0.978	0.984	0.016	15	0.081	1
3	5.667	0.946	0.959	0.041	14	0.248	1
4	4.250	0.907	0.926	0.074	13	0.518	1
5	3.400	0.864	0.889	0.111	12	0.884	1
6	2.833	0.820	0.851	0.149	11	1.339	1
7	2.429	0.777	0.813	0.187	10	1.875	2
8	2.125	0.735	0.775	0.225	9	2.480	2
9	1.889	0.695	0.738	0.262	8	3.149	3
10	1.700	0.657	0.702	0.298	7	3.872	4
11	1.545	0.435	0.668	0.332	6	4.643	5
12	1.417	0.348	0.636	0.364	5	5.457	5
13	1.308	0.268	0.606	0.394	4	6.308	6
14	1.214	0.194	0.577	0.423	3	7.191	7
15	1.133	0.125	0.550	0.450	2	8.104	8
16	1.063	0.061	0.524	0.476	1	9.041	9
17	1.000	0.000	0.500	0.500	0	10.000	10
18	0.944	-0.057	0.477	0.523	-1	10.979	10
19	0.895	-0.111	0.456	0.544	-2	11.974	10
20	0.850	-0.163	0.435	0.565	-3	12.985	10
21	0.810	-0.211	0.416	0.584	-4	14.008	10
22	0.773	-0.258	0.398	0.602	-5	15.043	10
23	0.739	-0.302	0.381	0.619	-6	16.088	10
24	0.708	-0.345	0.365	0.635	-7	17.142	10
25	0.680	-0.386	0.350	0.650	-8	18.204	10

Table 31. Franklin Avenue Flooding Severity, 26 ft Surge Barrier

Storm Surge	Hr/Hsurge	z=ln(Hr/Hsurge)	Cumulative Normal Standard Probability	Probability of Failure	Clearance (Cp) (ft)	Severity Calculation	Severity
1	26.000	3.258	0.999	0.001	25	-0.003	1
2	13.000	2.565	0.995	0.005	24	-0.021	1
3	8.667	2.159	0.985	0.015	23	-0.046	1
4	6.500	1.872	0.969	0.031	22	-0.061	1
5	5.200	1.649	0.950	0.050	21	-0.050	1
6	4.333	1.466	0.929	0.071	20	0.000	1
7	3.714	1.312	0.905	0.095	19	0.095	1
8	3.250	1.179	0.881	0.119	18	0.239	1
9	2.889	1.061	0.856	0.144	17	0.433	1
10	2.600	0.956	0.830	0.170	16	0.679	1
11	2.364	0.860	0.805	0.195	15	0.974	1
12	2.167	0.773	0.780	0.220	14	1.318	1
13	2.000	0.693	0.756	0.244	13	1.709	2
14	1.857	0.619	0.732	0.268	12	2.144	2
15	1.733	0.550	0.709	0.291	11	2.620	3
16	1.625	0.486	0.686	0.314	10	3.137	3
17	1.529	0.425	0.665	0.335	9	3.690	4
18	1.444	0.368	0.643	0.357	8	4.278	4
19	1.368	0.314	0.623	0.377	7	4.900	5
20	1.300	0.262	0.603	0.397	6	5.551	6
21	1.238	0.214	0.585	0.415	5	6.232	6
22	1.182	0.167	0.566	0.434	4	6.939	7
23	1.130	0.123	0.549	0.451	3	7.671	8
24	1.083	0.080	0.532	0.468	2	8.426	8
25	1.040	0.039	0.516	0.480	1	9.203	9

The tables show the scenarios in green. Table 27 shows the same occurrence with the added Hurricane and similar analysis period. Table 28 shows a slight reduction to severity in a hurricane Category 3. Table 29 shows a reduction in severity in both hurricane Category 3 and 5. Using both occurrence and severity tables, Table 30 is tabulated and also shows the cost of each action.

Table 32. Risk Analysis Matrix for Reevaluation of Franklin Avenue Solutions

Current Condition			Propose Solution			Results/ Revisit				Investment Cost
Extreme Climate Event	Asset Type	Climatic Scenarios of Potential Causes(s) of Failure	Recommended Action	Responsibility and Target Completion Date	Action Taken	Revisited Occurrence	Revisited Severity (1-10)	Risk	RPN	Cost
Hurricane/ Storm Surge/ Flooding Due to Levee Overtop	Franklin Avenue	1: 25 ft Storm surge	Rebuild 17ft Elevation	USAGE	-	5	10	M	50	$14.5 Billion
Hurricane/ Storm Surge/ Flooding Due to Levee Overtop	Franklin Avenue	2:15 ft Storm surge	Rebuild 17ft Elevation	USAGE	-	10	8	M	80	
Hurricane/ Storm Surge/ Flooding Due to Levee Overtop	Franklin Avenue	3:5 ft Storm surge	Rebuild 17ft Elevation	USAGE	-	10	1	M	10	
Hurricane/ Storm Surge/ Flooding Due to Levee Overtop	Franklin Avenue	1:25 ft Storm surge	26ft Storm Surge Barrier	USAGE	-	5	9	H	45	$1.1 Billion
Hurricane/ Storm Surge/ Flooding Due to Levee Overtop	Franklin Avenue	2:15 ft Storm surge	26ft Storm Surge Barrier	USAGE	-	10	3	M	30	
Hurricane/ Storm Surge/ Flooding Due to Levee Overtop	Franklin Avenue	3:5 ft Storm surge	26ft Storm Surge Barrier	USAGE	-	10	1	M	10	

Step 6: Road Scenario Analyses

In this step, the three climate risk impact scenarios are evaluated with two budget scenarios. The RPNs before and after are calculated with the occurrence and severity obtained from the analysis in step 5. Since the case study is conducted for an individual bridge, the significance is assumed to be 1 in the RPN calculations.

For the Franklin Avenue, the percent of risk reduction of each scenario is shown in Tables 31 and 32 for $14.5 Billion and $1.1 Billion budgets respectively.

Table 33. Percent Risk Reduction Franklin Avenue, 17 ft Levees and $14.5 Billion Budget

Scenario	Climate Event	RPN Before	RPN After	Risk Percent Reduction
1	H5/ 25ft Storm Surge	50	50	0%
2	H3/ 15ft Storm Surge	100	80	20%
3	H1/ 5ft Storm Surge	10	10	0%

Table 34. Percent Risk Franklin Avenue, Surge Barrier and $1.1 Billion Budget

Scenario	Climate Event	RPN Before	RPN After	Risk Percent Reduction
1	H5/ 25ft Storm Surge	50	45	10%
2	H3/ 15ft Storm Surge	100	30	70%
3	H1/ 5ft Storm Surge	10	10	0%

The percent of risk reduction for rebuilding the levees with a 17 ft height is 20% for a Category 3 Hurricane with a 15 ft storm surge, and there is no risk reduction for a Category 5 and Category 1 Hurricane with a 25 ft storm surge or 5 ft storm surge. The percent of risk reduction for building a surge barrier is 10% for a Category 5 Hurricane with a 25 ft storm surge, and 70% for a Category 3 Hurricane with a 15 ft storm surge. There is no risk reduction for a Category 1 Hurricane with a 5 ft storm surge.

Step 7: Road Asset Management Report

In this step, a report is prepared to communicate decision-makers the level risk for the climate scenarios. By upgrading the levee to 17 ft high and building the storm surge barrier, the level of risk is reduced. Figure 57 and 58 shows the scorecard for the road before the landfall of Hurricane Katrina as an example of how to report an asset at risk.

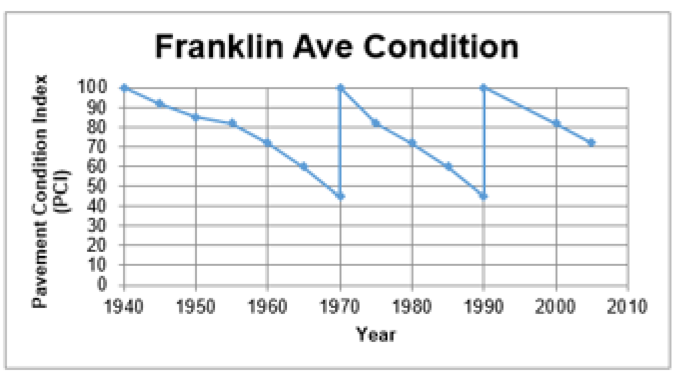
SCORECARD	
State:	Louisiana
Place Number:	New Orleans
Country:	Orleans
Asset Type:	Road (Franklin Avenue Section)
Asset Location:	Intersection 1: Robert E. Lee; Intersection 2; Filmore Ave.
Latitude:	30 01 14 50 N
Longitude:	90 03 06 10 W
Year Built:	1940
Level of Service:	Mainline roadway
Owner:	Regional Planning Commission
Asset Material Design:	Asphalt
Asset Dimensions:	L; 0.7 mi; W; 65. 7 ft.;
Other Asset Information:	# of Lanes: 4; Separated by Median; Expected Remaining Service Life 30 years without maintenance will result in a Condition Rating of 30. Subbase 12', Base: 2.5", Surface: 1.5", Average Daily Traffic 6729
Asset Structural Condition:	Fair
Asset Substructure Conditions:	Good Condition
Asset Rating (IRI, SR, etc.):	Condition Rating: 5: PCI 50
Asset Climate Change Risk	Risk (2005) High to Storm Surge Hurricane Category 3 and 5
Asset RPN	100 due to Storm Surge Hurricane Category 3
Asset Historical Condition	

Figure 57. Franklin Avenue Scorecard, Page 1

Current Condition			Proposed Solutions		
Extreme Weather Event	Asset Type	Potential Cause(s) of Failure	Reccomended Action	Responsibility and Target Completion Date	Action Taken
Hurricane/ Storm Surge/ Flooding Due to Levee Overtop	Franklin Avenue	25 ft Storm Surge	Rebuild with 17ft Elevation	USACE	-
Hurricane/ Storm Surge/ Flooding Due to Levee Overtop	Franklin Avenue	15 ft Storm Surge	Rebuild with 17ft Elevation	USACE	-
Hurricane/ Storm Surge/ Flooding Due to Levee Overtop	Franklin Avenue	5 ft Storm Surge	Rebuild with 17ft Elevation	USACE	-
Hurricane/ Storm Surge/ Flooding Due to Levee Overtop	Franklin Avenue	25 ft Storm Surge	26ft Storm Surge Barrier	USACE	-
Hurricane/ Storm Surge/ Flooding Due to Levee Overtop	Franklin Avenue	15 ft Storm Surge	26ft Storm Surge Barrier	USACE	-
Hurricane/ Storm Surge/ Flooding Due to Levee Overtop	Franklin Avenue	5 ft Storm Surge	26ft Storm Surge Barrier	USACE	-

Results/Revisit				Economic
Revisited Occurrence (1-10)	Revisited Severity (1-10)	Risk	RPN	Cost
5	10	M	50	$14.5 Billion
10	8	M	80	$14.5 Billion
10	1	M	10	$14.5 Billion
5	9	H	45	$1.1 Billion
10	3	M	30	$1.1 Billion
10	1	M	10	$1.1 Billion

Occurance	1	2	3	4	5	6	7	8	9	10
10	M	M	M	M	H	H	H	H	H	H
9	M	M	M	M	H	H	H	H	H	H
8	L	L	M	M	M	M	H	H	H	H
7	L	L	M	M	M	M	H	H	H	H
6	L	L	L	L	M	M	M	M	H	H
5	L	L	L	L	M	M	M	M	H	H
4	L	L	L	L	L	L	M	M	M	M
3	L	L	L	L	L	L	M	M	M	M
2	L	L	L	L	L	L	L	L	M	M
1	L	L	L	L	L	L	L	L	M	M

Severity

Figure 58. Franklin Avenue Scorecard, Page 2

In combination with the score cards, GIS tools can be used for analysis and report purposes. Figure 59 displays the level of risk of a storm surge for the existing conditions before the storm surge, while Figure 60 shows the level of risk with the upgraded levees. These reports are useful to prioritize budget allocation by identifying the assets at high risk based on the RPN.

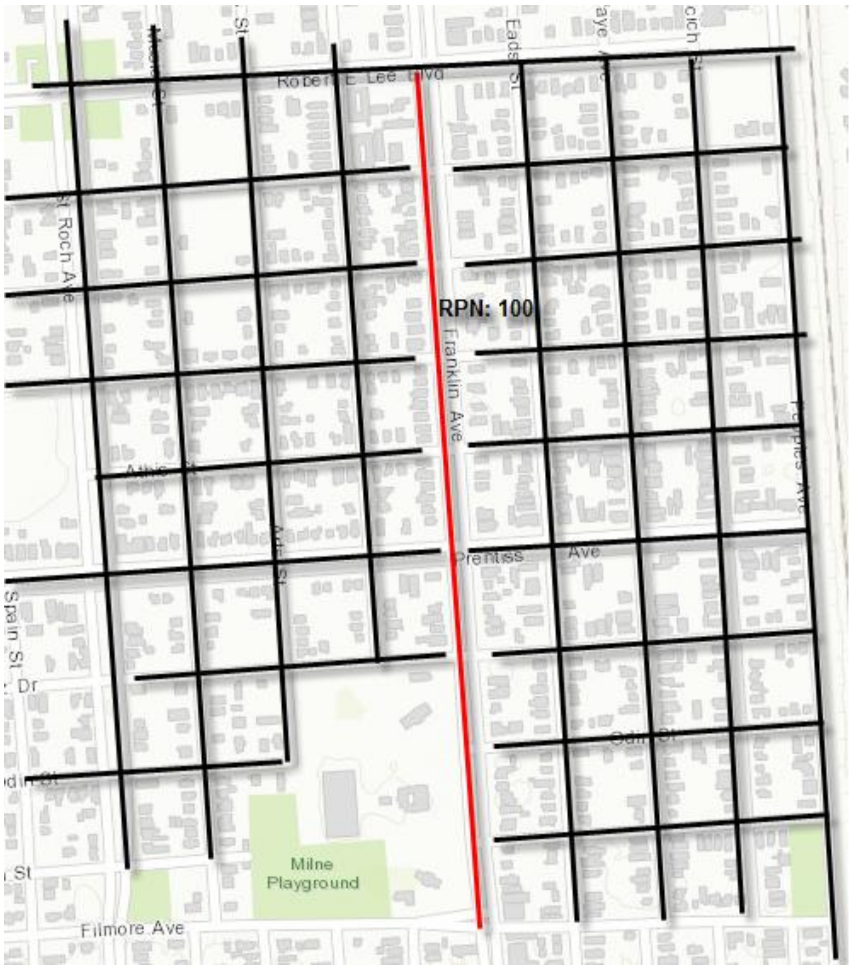


Figure 59. RPN GIS Risk Map, Franklin Avenue before the Hurricane

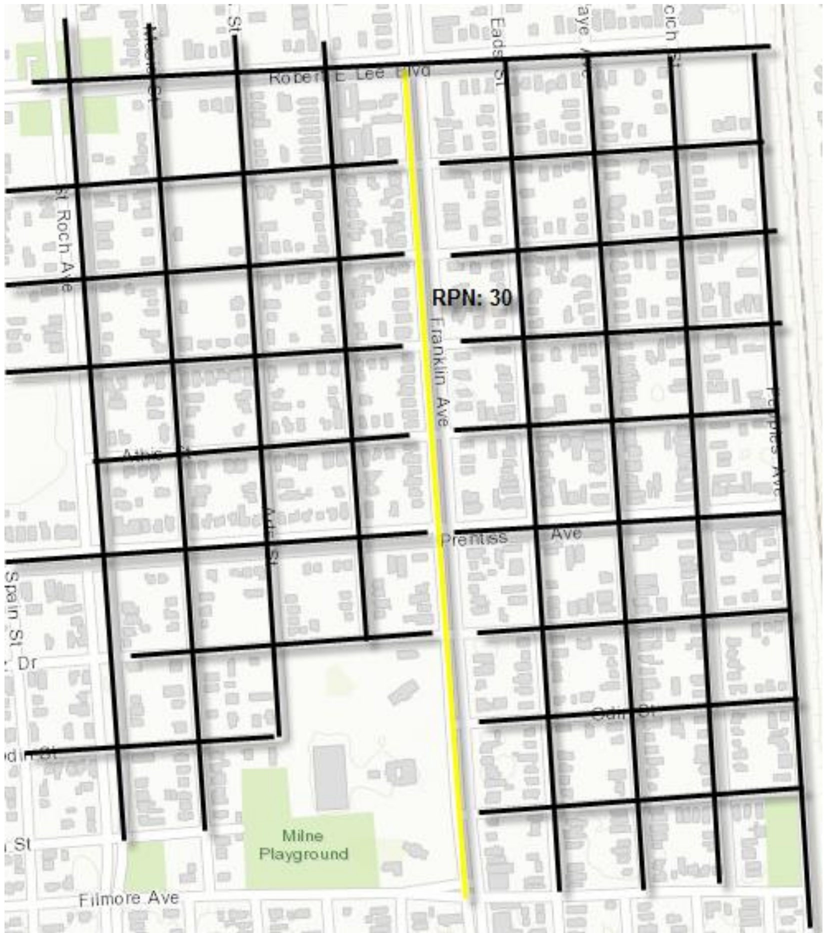


Figure 60. RPN GIS Risk Map, Franklin Avenue after Recommended Actions

Step 8 Road Asset Management Program to Mitigate the Impact of Climate Change

This roadway is 6 ft below sea level and the risk mitigation strategy was to raise the elevation of the levees and build a storm surge barrier. Figure 61 shows the projected PCIs after repairing the road.

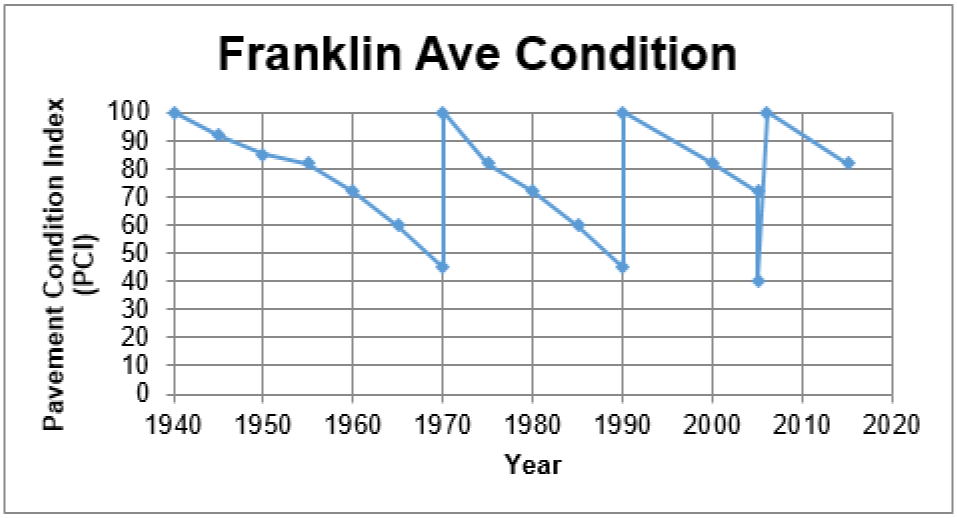


Figure 61. PCI over time for Franklin Avenue Road after Recommended Actions

As in the bridge example, the road case study was for an individual project but the agency should apply the risk analysis to all the roads to fully implement the framework in TAM practices. The same recommendations as for the bridge case study apply to the road network.

CHAPTER 4
DISCUSSION OF THE
CLIMATE RISK ASSESSMENT MODEL

This chapter provides a discussion of the climate risk assessment model through a sensitivity analysis of the parameters used to quantify the risk of damage. Sensitivity analyses are conducted to identify the most relevant parameters for occurrence and severity. TopRank is the software used to perform “what if” analysis to determine the sensitivity of the outcomes. Monte Carlo simulations of severity, occurrence, and RPN are also performed. @Risk is the software used to perform the Monte Carlo simulations in order to analyze the likelihood of alternative scenarios to occur [14].

4.1. OCCURRENCE

The risk assessment model determines the probability of occurrence of a climate event. In this model, there are three inputs for the occurrence to analyze: the Number of Years of Climatic Events (a), the Number of Events (b), and the Remaining Asset Life (n). The number of years of climatic events is the years from the first climatic event recorded to the last year of the analysis, and the asset remaining life is the number of years that the asset is expected to remain in service. Figure 62 shows the Excel formulas used to calculate the occurrence.

	H	I	J	K	L	M
2	**Hurricane Category**	**Number of Events (b)**	**Return Period (Years)**	**1/Return Period**	**Probability P(x≥1)**	**Occurrence**
3	TD	=COUNTIF(C4:C75,”TD”)	=$I$10/I3	=1/J3	=1-(((FACT($I$11))/(FACT(0)*FACT($I$11)))*(K3)^0*(1-(K3))^$I$11)	=L3*10
4	TS	=COUNTIF(C4:C75,”TS”)	=$I$10/I4	=1/J4	=1-(((FACT($I$11))/(FACT(0)*FACT($I$11)))*(K4)^0*(1-(K4))^$I$11)	=L4*10
5	H1	=COUNTIF(C4:C75,”H1”)	=$I$10/I5	=1/J5	=1-(((FACT($I$11))/(FACT(0)*FACT($I$11)))*(K5)^0*(1-(K5))^$I$11)	=L5*10
6	H2	=COUNTIF(C4:C75,”H2”)	=$I$10/I6	=1/J6	=1-(((FACT($I$11))/(FACT(0)*FACT($I$11)))*(K6)^0*(1-(K6))^$I$11)	=L6*10
7	H3	=COUNTIF(C4:C75,”H3”)	=$I$10/I7	=1/J7	=1-(((FACT($I$11))/(FACT(0)*FACT($I$11)))*(K7)^0*(1-(K7))^$I$11)	=L7*10
8	H4	=COUNTIF(C4:C75,”H4”)	=$I$10/I8	=1/J8	=1-(((FACT($I$11))/(FACT(0)*FACT($I$11)))*(K8)^0*(1-(K8))^$I$11)	=L8*10
9	H5	=COUNTIF(C4:C75,”H5”)	=$I$10/I9	=1/J9	=1-(((FACT($I$11))/(FACT(0)*FACT($I$11)))*(K9)^0*(1-(K9))^$I$11)	=L9*10
10	Number of Years of Climate Events (a)	150				
11	Asset Remaining Life (n) (Years)	100				

Figure 62. Excel Formulas for Occurrence

For hurricanes, the first input in the model is the number of events. From historical records, the number of events is extracted using a Countif function, but when modeling for events in the future events, a probability distribution is used. For other types of climate events, such as flooding, this first input could be days with extreme precipitation or temperatures; but in our case, it is the number of hurricanes by category. The occurrence model uses the number of events and number of years of climatic events to estimate the return period. The return period is the recurrence interval for an event and it is calculated by dividing the number of years of climatic events over the number of events or frequency of that event. The next column is the 1/Return Period, or turnover rate that is required to determine the probability of an asset to experience similar events in the future. This probability (P$[X \geq 1]$) is calculated with a Binomial Distribution equation. Occurrence is calculated by multiplying this probability by ten in order to establish a 1 to 10 scale. Occurrence is useful to analyze the dynamics of climate change in a region. It is expected that when the number of years without a climatic event increases then the occurrence decreases, and when the number of events increases the occurrence also increases.

TopRank analyzes the sensitivity of the parameters used to calculate occurrence [14]. Figures 63 and 64 show the Tornado and Spider graphs respectively. Figure 63 shows that the effects of the inputs in the calculation of the occurrence are similar, although the most sensitive parameter is the Number of Years of Climatic Events. Changing the input values by ten percent yields similar results.

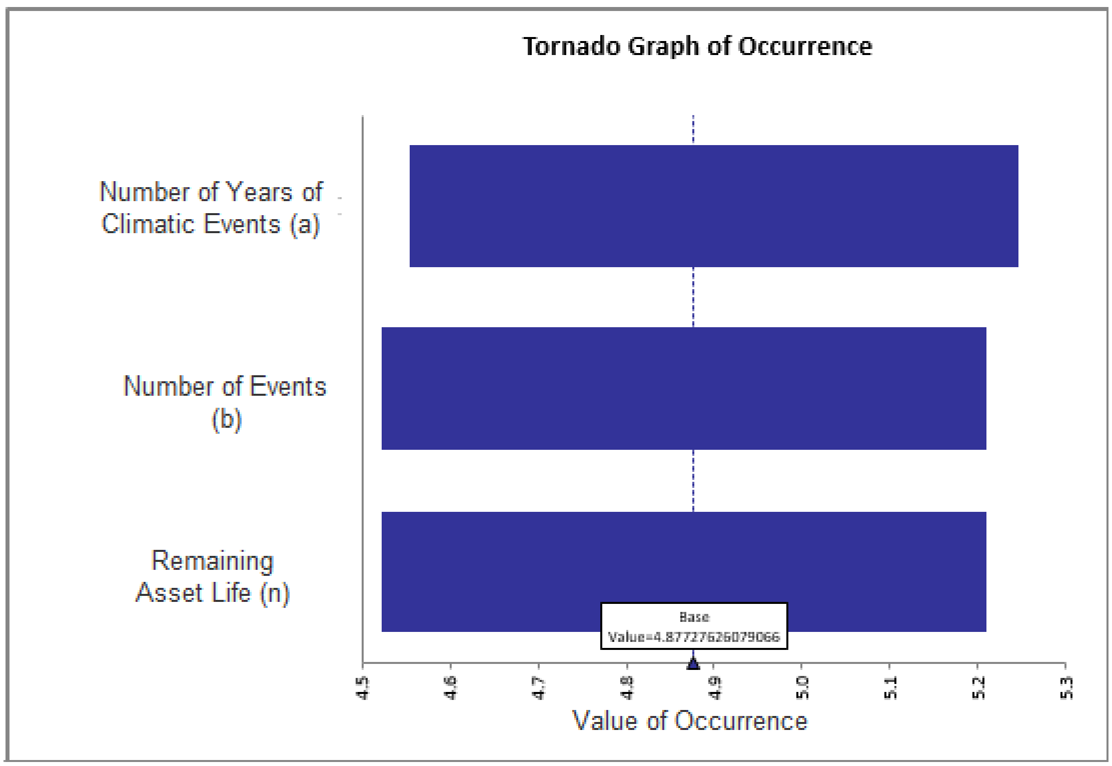


Figure 63. Tornado Graph of Occurrence

The spider graph in Figure 64 shows the correlation between the number of years of climatic events, the number of events, and the asset life. It is observed that as the number of years of climatic data increases the occurrence decreases. If the remaining asset life of climatic event increases or the number of events increases, then the occurrence increases.

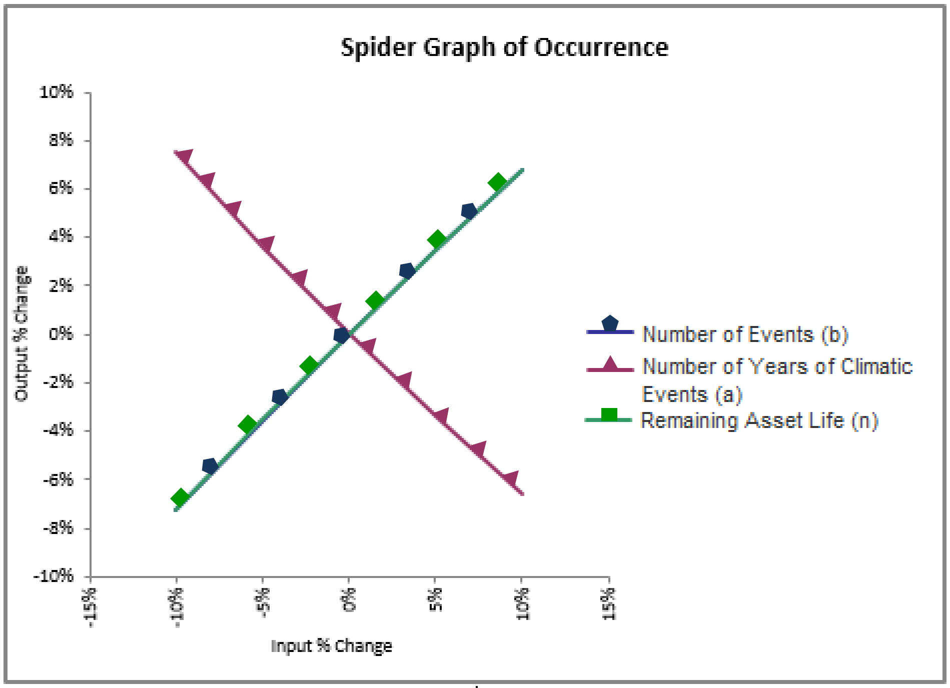


Figure 64. Spider Graph for Occurrence

Using @Risk to conduct MonteCarlo simulations, the Remaining Asset Life is modeled with a Weibull distribution as shown in Figures 65. Weibull distributions are often used to model the length of life and endurance data [76]. The Number of Years of climatic events is modeled with a uniform distribution as shown in Figure 66. The uniform distribution has a minimum at 162 years that refers to the years in the existing records, and a maximum at 262 years. The maximum value of 262 years is obtained by adding the remaining asset life to the number of years of climatic events in order to evaluate the asset performance in the future. For example, if the asset remaining life or evaluation period is 20 years, then the maximum point will be at 182 years.

To model the Number of Events, a triangular distribution from @Risk was used for a Hurricane Category 1, 3, and 5 as shown in Figures 67 to 69. The minimum value is the number of events that already occurred, and the remaining asset life is added to obtain the maximum value. The number of expected events is the remaining asset life or analysis period divided by the return period.

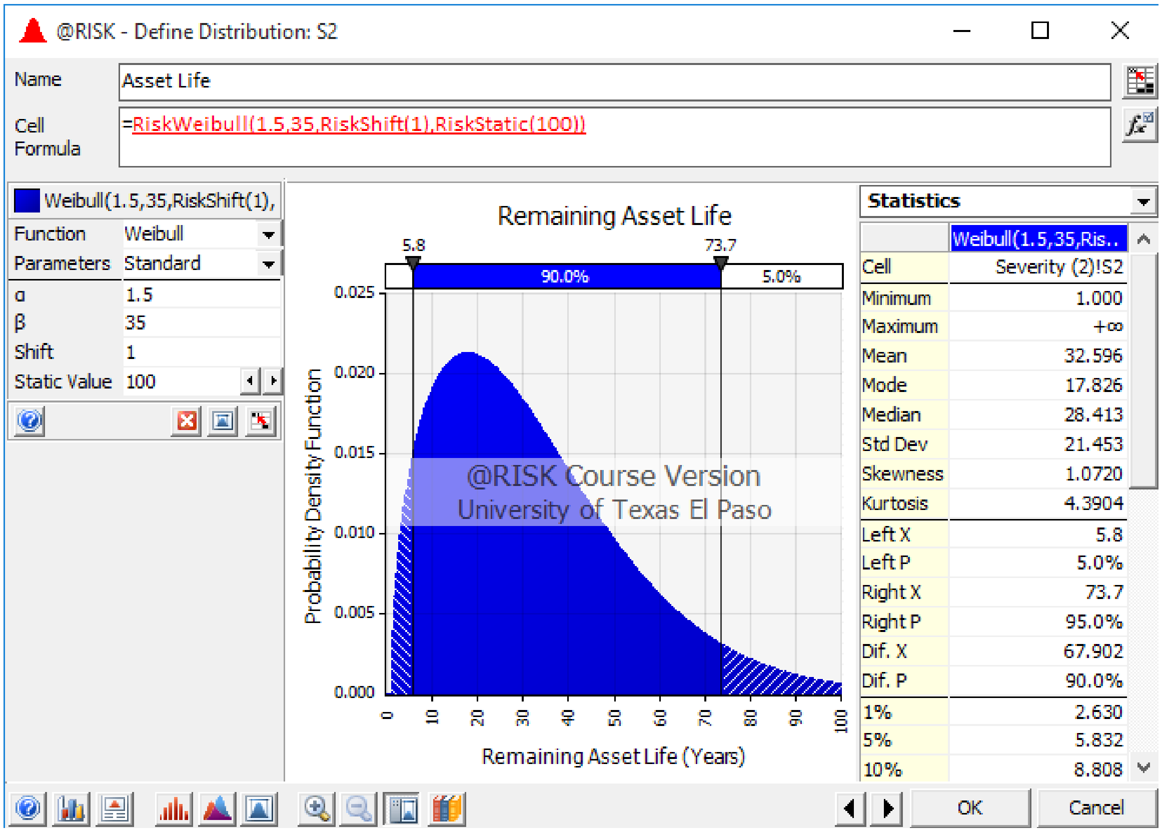


Figure 65. Remaining Asset Life (n) Weibull Distribution

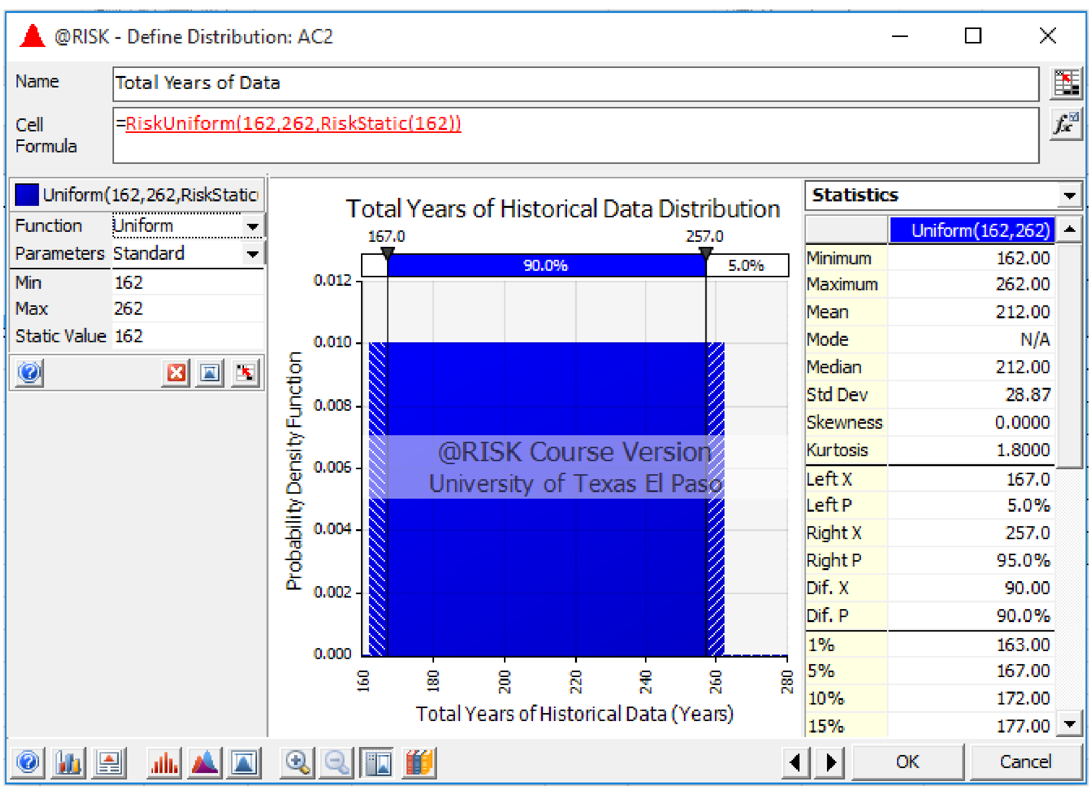


Figure 66. Uniform Distribution to Project the Number of Years (a)

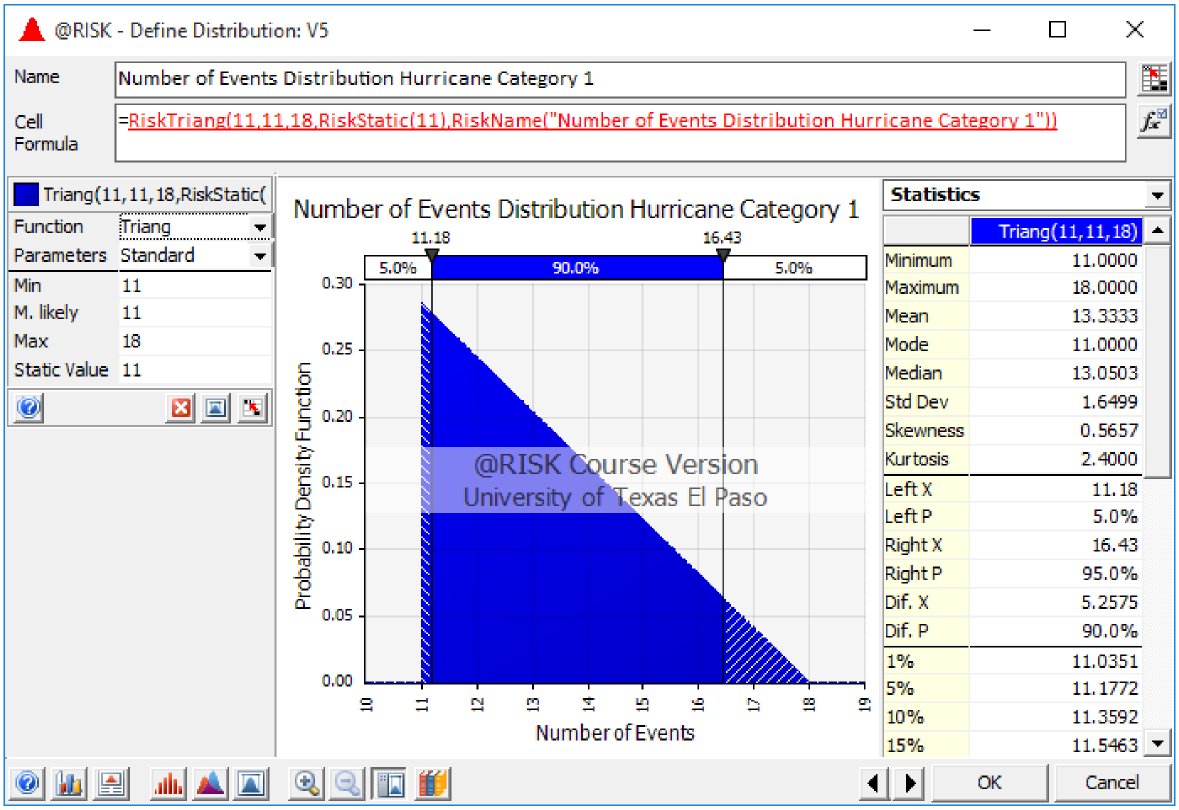


Figure 67. Triangular Distribution for Number of Events, Hurricane Category 1

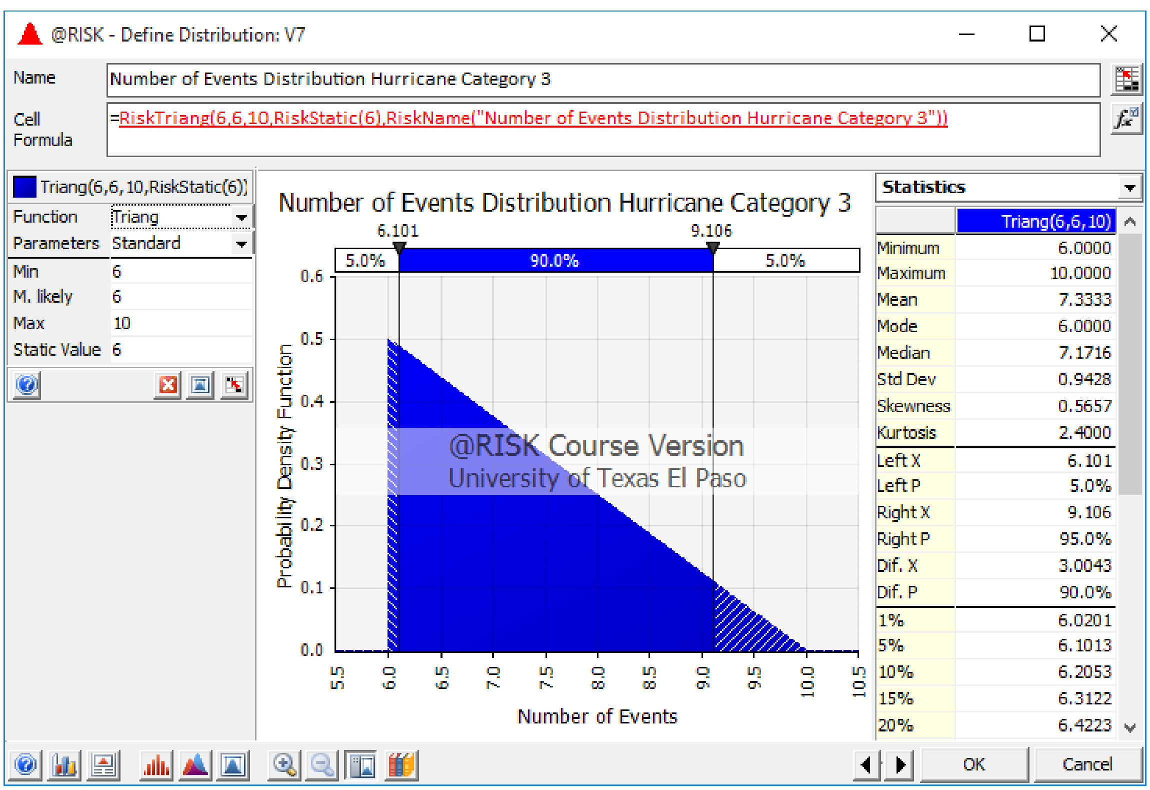


Figure 68. Triangular Distribution for Number of Events, Hurricane Category 3

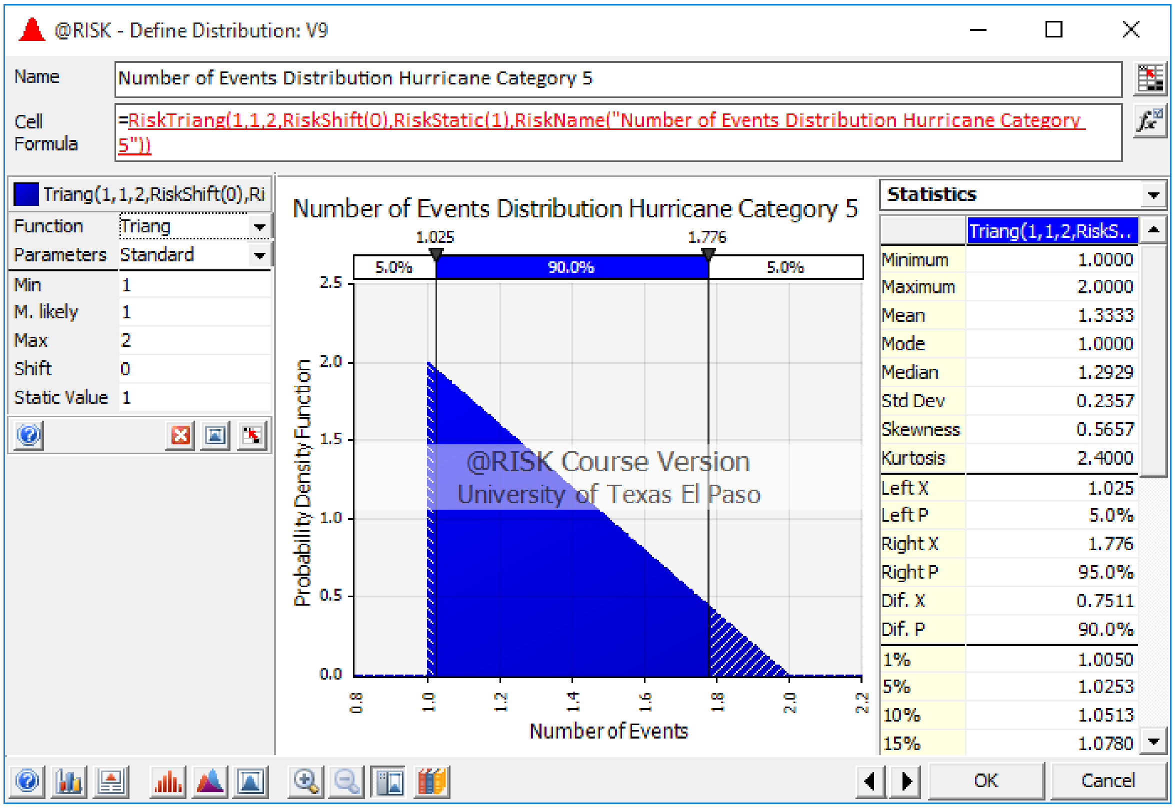


Figure 69. Triangular Distribution for Number of Events, Hurricane Category 5

Figures 70 to 72 show the occurrence outputs of the simulations for a Category 1, Category 3, and Category 5 hurricane. Occurrence is related to the probability of an asset to experience the hurricanes during its service life. The simulations provide the relative frequency or frequency of occurrence divided by the total number of simulations. The confidence level of the output moves from low to high occurrence. Figure 70 shows that the occurrence is between 9.9 and 10 throughout the remaining life of the asset for a Category 1 hurricane. Figure 71 shows that the occurrence is between 9.3 and 9.9 throughout the remaining life of the asset for a Category 3 hurricane. Figure 72 shows that that the occurrence is between 3.6 and 5.9 at a 90% confidence interval for a Category 5 hurricane. From these three figures, it is observed that it is more likely that the asset will experience a Category 1 Hurricane in their remaining service life rather than a Category 5 Hurricane.

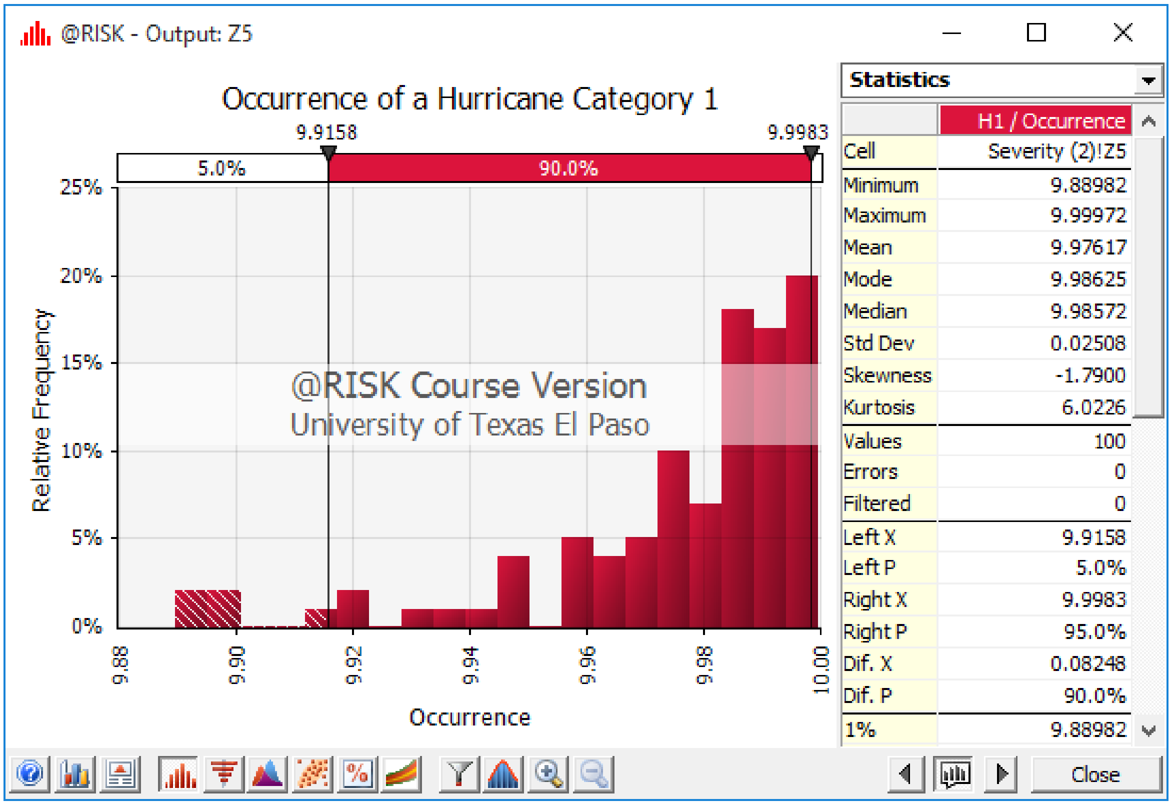


Figure 70. Occurrence Distribution, Category 1 Hurricane

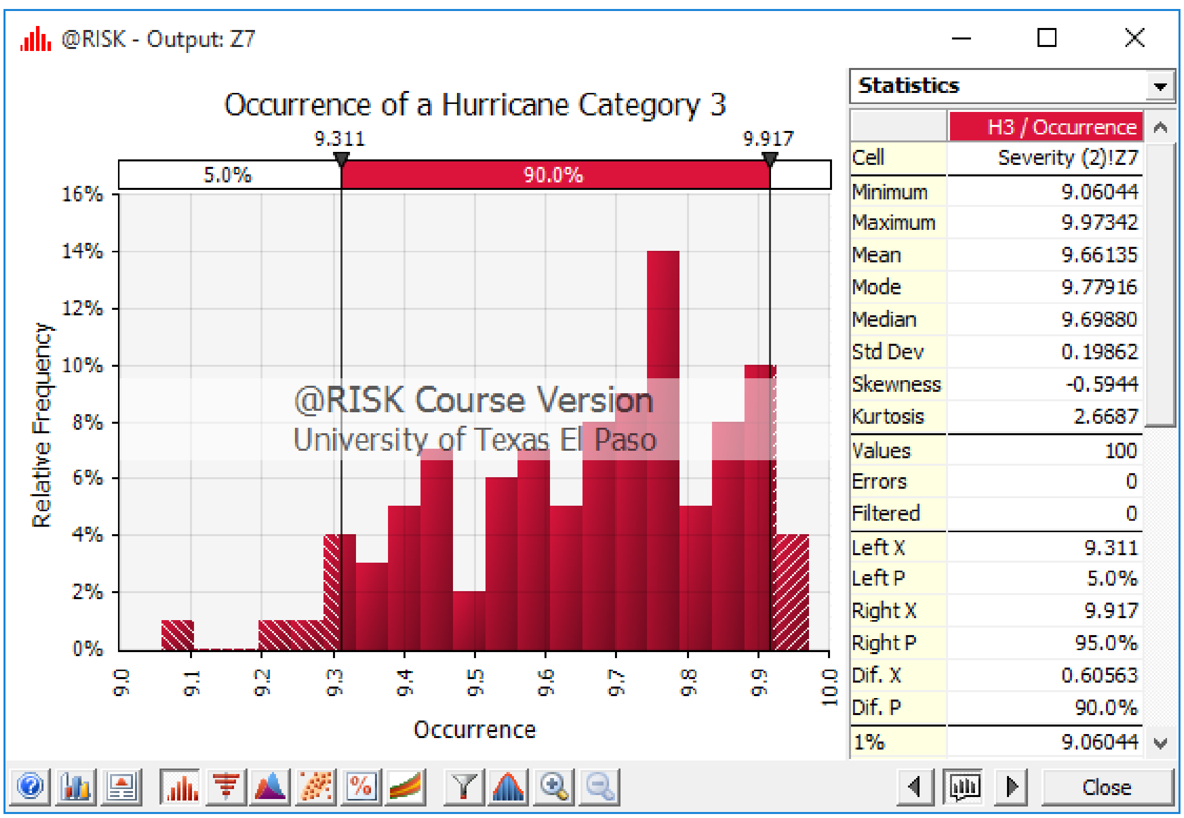


Figure 71. Occurrence Distribution, Category 3 Hurricane

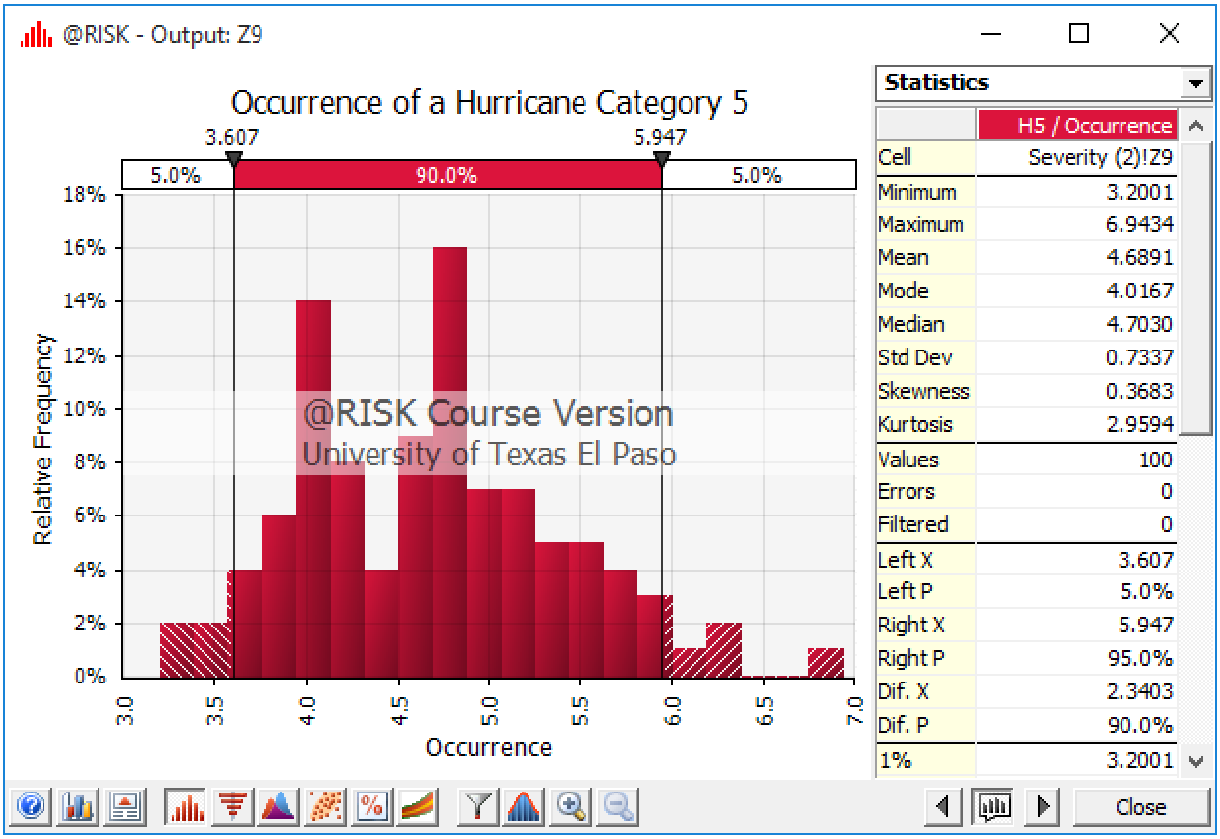


Figure 72. Occurrence Distribution, Category 5 Hurricane

4.2. SEVERITY

Figure 73 shows the Excel formulas used to calculate the severity.

	A	B	C	D	E	F	G	H
1								
2	H(r)bridge	26	ft					
3	Storm Surge (HL)	Hr/HL	x=ln(Hr/HL)	Cumulative Normal Standard Probability	Probability of Failure	Clearance	Severity Value Calculation	Severity
4	1	=$B$2/A4	=LN(B4)	=NORM.S.DIST(C4,TRUE)	=1-D4	=$B$2/A4	=E4*(20-F4)	=IF(G4>10,10,IF(G4<1,1,G4))

Figure 73. Excel Formulas for Severity

For hurricanes, there are two input parameters for severity: resistance and acting. H_R, is the resistance parameter while H_L, is the acting parameter that can damage the asset. The model calculates the severity for a given H_R. These parameters are used for storm surge, but the resistance and acting may be represented by other parameters in other type of climate events. For example, in track buckling the H_R is the spacing in the track and H_L is the track expansion due to high temperatures.

In Figure 74, $H_{R,}$ the resisting parameter, is the height of a bridge and $H_{L,}$ the resisting parameter, is the Storm Surge. In the next step, a Cumulative Normal Standard Probability of the natural log of the resisting parameter over the acting value is calculated, and the probability of failure is calculated by subtracting 1 from this probability. The clearance number is obtained by subtracting H_r from H_L. The severity is obtained by multiplying the risk times 20 minus the clearance. Since the severity calculation may be lower than 1 or higher than 10, an If statement formula is needed to be within the 1 to 10 range.

TopRank sensitivity analysis results are shown with Tornado and Spider graphs in Figures 74 and 75 respectively. The Tornado graph shows that H_R is the most sensitive parameter for severity.

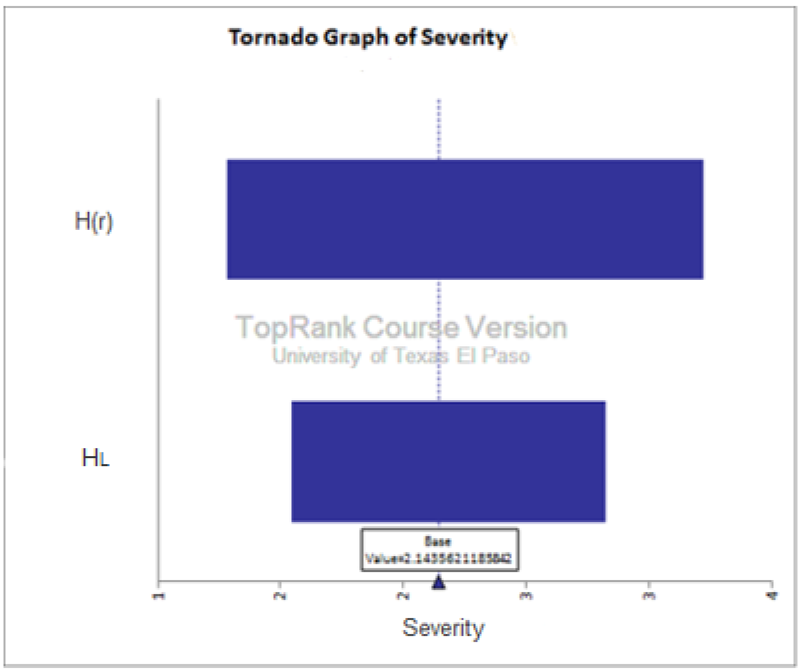


Figure 74. Tornado Graph of Sensitivity

The spider graph in Figure 75 shows the correlation between H_R and H_L. As H_R increases the severity decreases. Also as H_L decreases then the severity decreases.

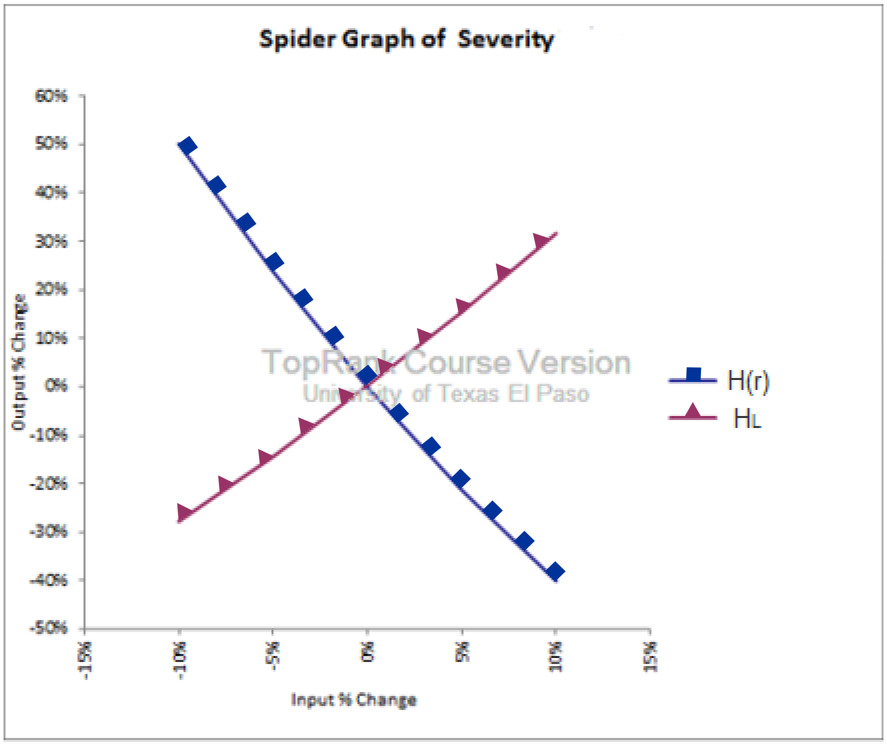


Figure 75. Spider Graph for Severity

In order to identify the confidence interval for the severity, H_L is modeled with a normal distribution as shown in Figure 76. Figures 77 to 79 show the outputs of the simulations for severity using @Risk for the relative frequency. Figure 77 shows a severity of 1 for a bridge with 26ft height and a storm surge of 5 ft at the 100% confidence interval. This means that that probability of this bridge to be damaged by a category 1 hurricane is very low. Figure 78 shows a severity between 1.5 and 4 for a bridge with 26 ft height and a storm surge of 15 ft at the 90% confidence interval. This shows that the probability that the bridge to be damaged by a category 3 hurricane is low. Figure 79 shows a severity between 6 and 10, and most of the outputs for the severity are high for a bridge with 26 ft height and a storm surge of 25 ft at the 90% confidence interval. This means that the probability of the bridge to be damaged by a category 5 hurricane is high.

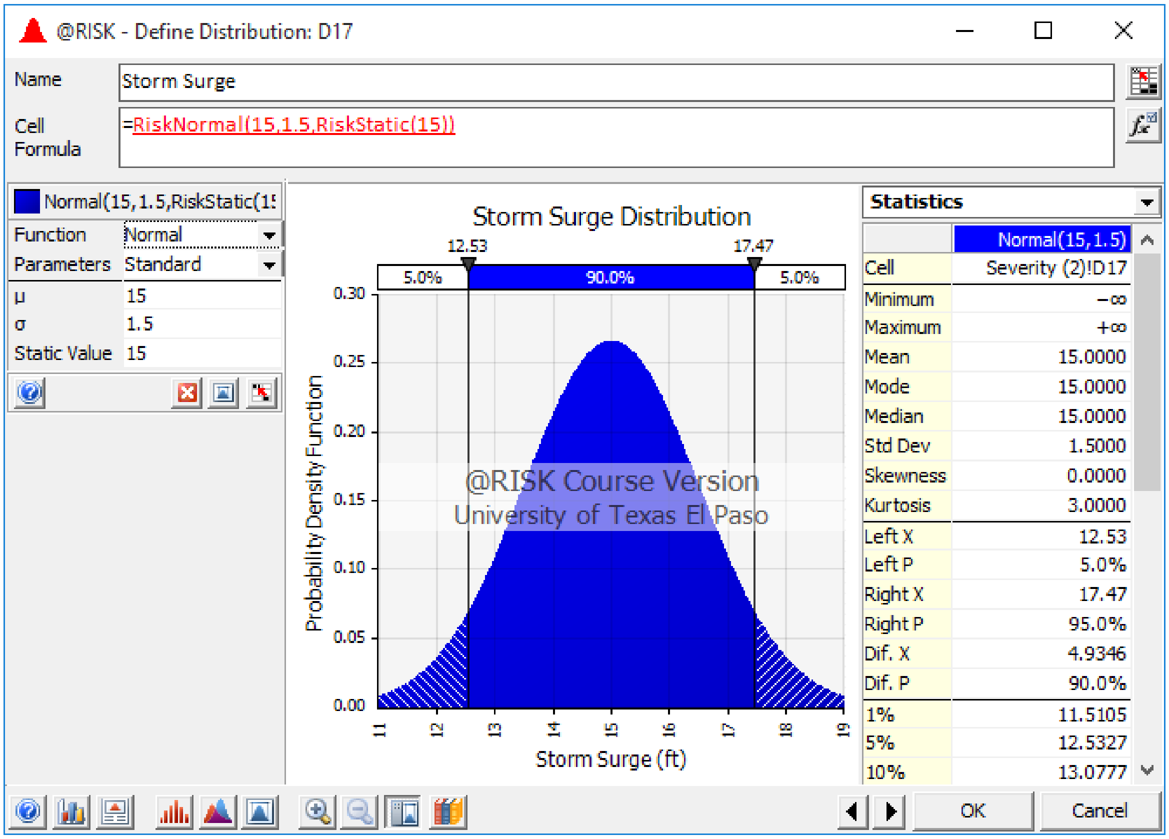


Figure 76. Normal Distribution for H_L

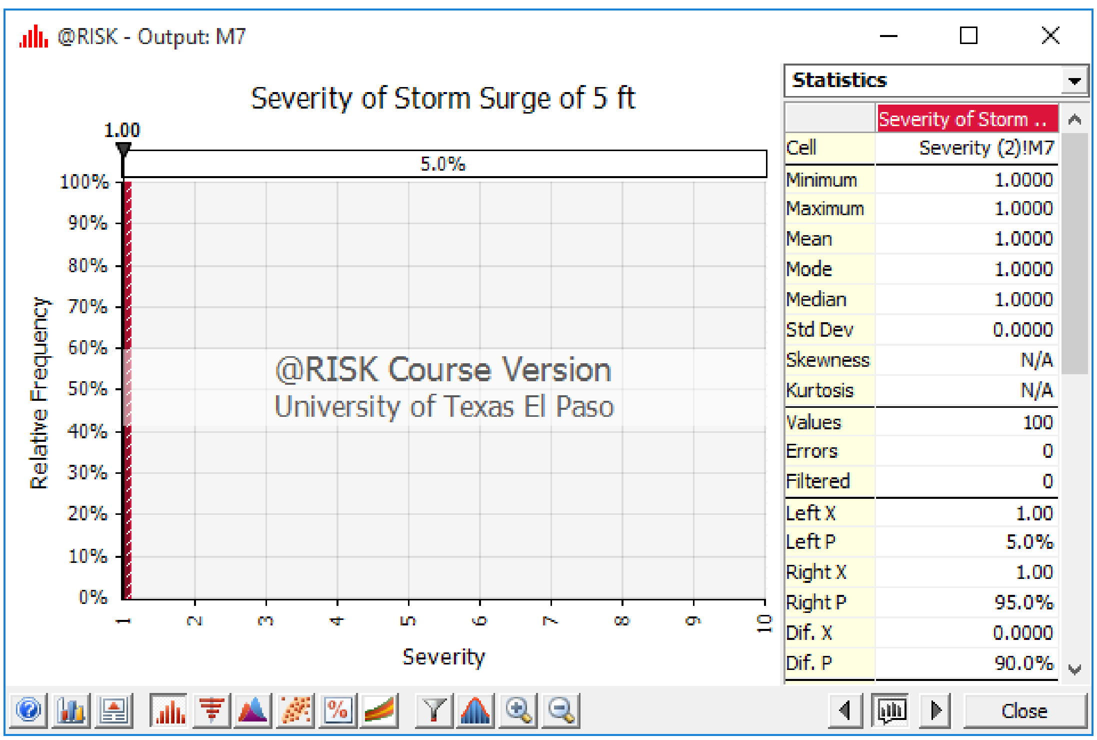


Figure 77. Severity Distribution, Category 1 Hurricane

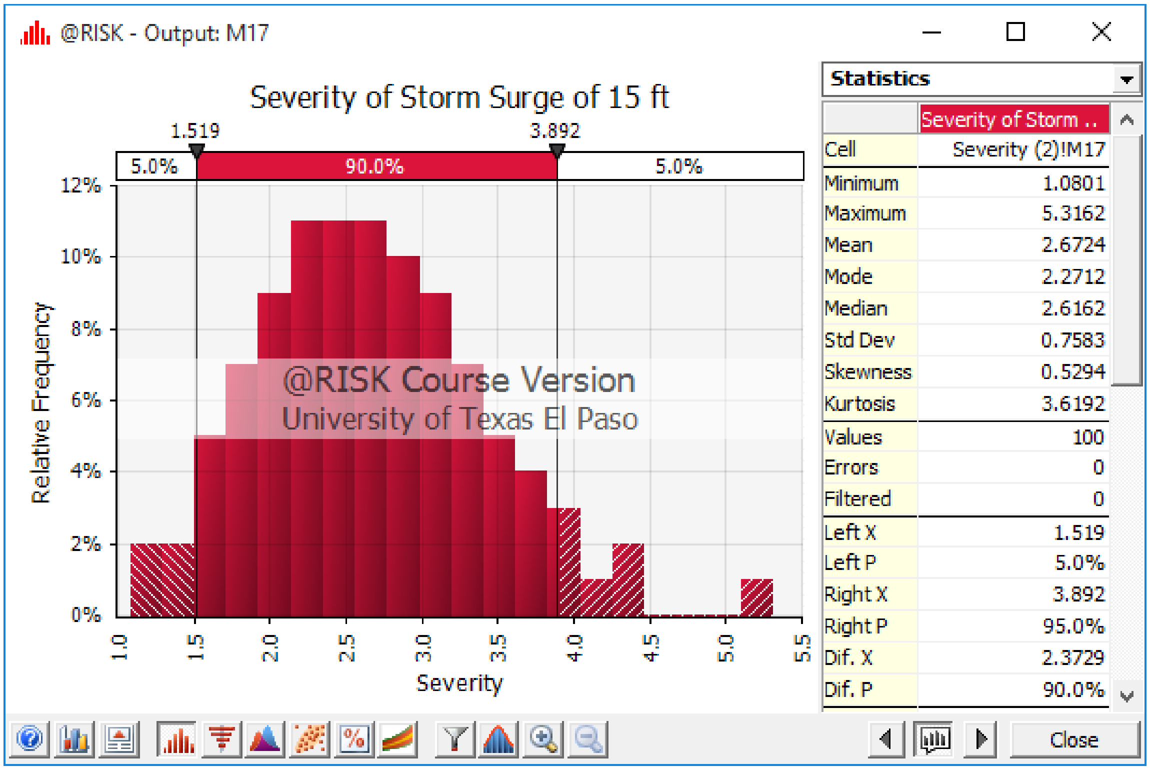


Figure 78. Severity Distribution, Category 3 Hurricane

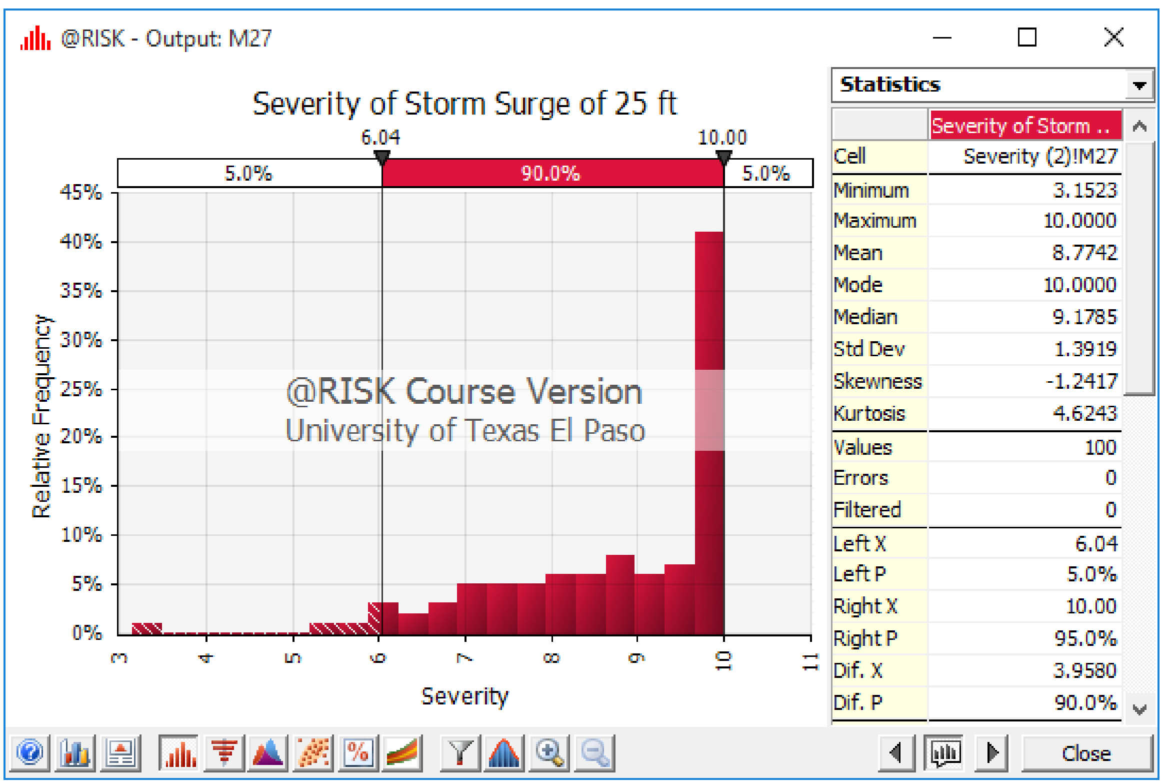


Figure 79. Severity Distribution, Category 5 Hurricane

4.3. RISK PRIORITY NUMBER (RPN)

To analyze the RPN confidence interval, occurrence and severity are combined. RPN expresses the risk of failure due to a climatic event and it is obtained by multiplying occurrence and severity. Figures 80 to 82 show the RPN outputs of the simulations using the relative frequency. Figure 80 shows RPN outputs between 9.9 to 10 for a bridge with 26 ft height and a storm surge of 5 ft at the 90% confidence interval. This means that the bridge is at a low risk of damage by a category 1 hurricane. Figure 81 shows RPN outputs between 12.1 and 40.8 for a bridge with 26 ft height and a storm surge of 15 ft at the 90% confidence interval. This shows that the bridge is at a slightly higher risk of damage by a category 3 hurricane. Figure 82 shows RPN outputs between 24.3 and 55.6 for a bridge with 26 ft height and a storm surge of 25 ft at the 90% confidence interval. This means that there is a higher risk of damage by a category 5 hurricane.

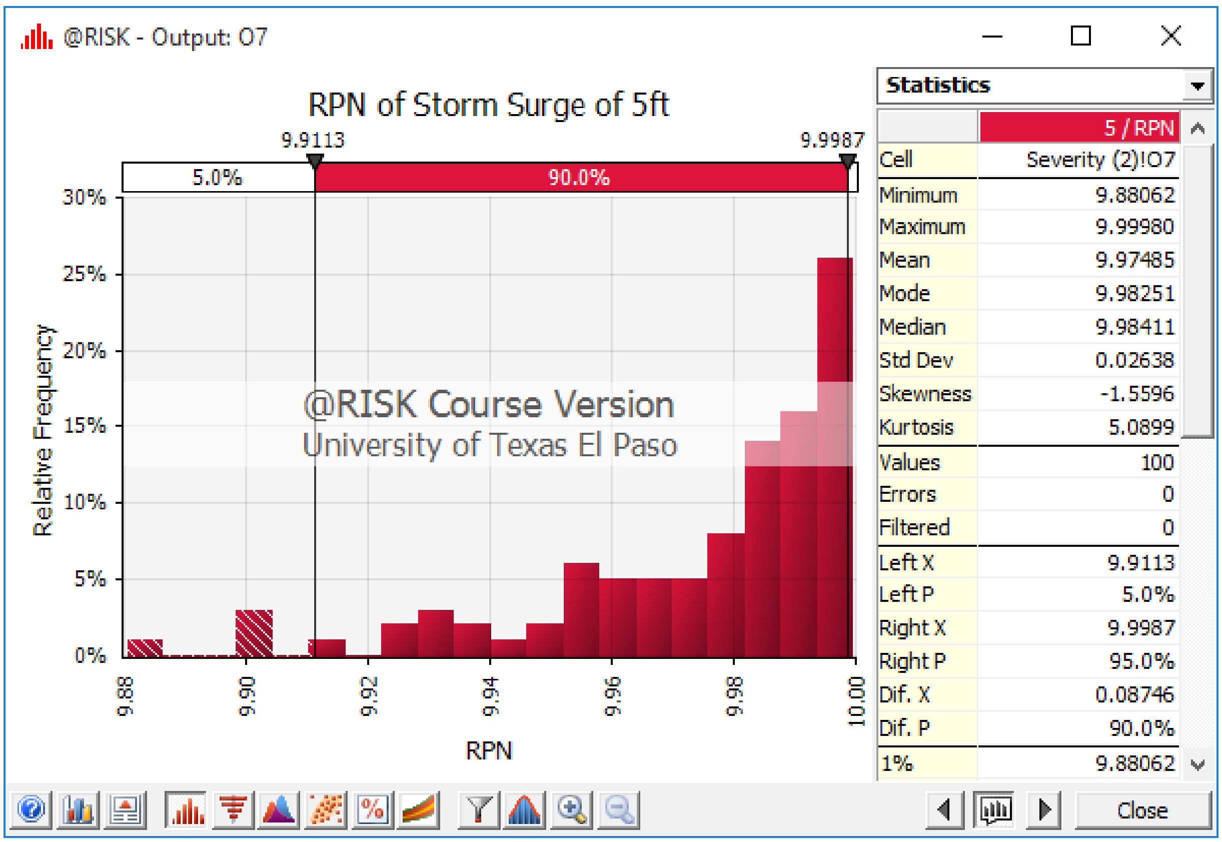


Figure 80. RPN Relative Frequency Distribution, Category 1 Hurricane

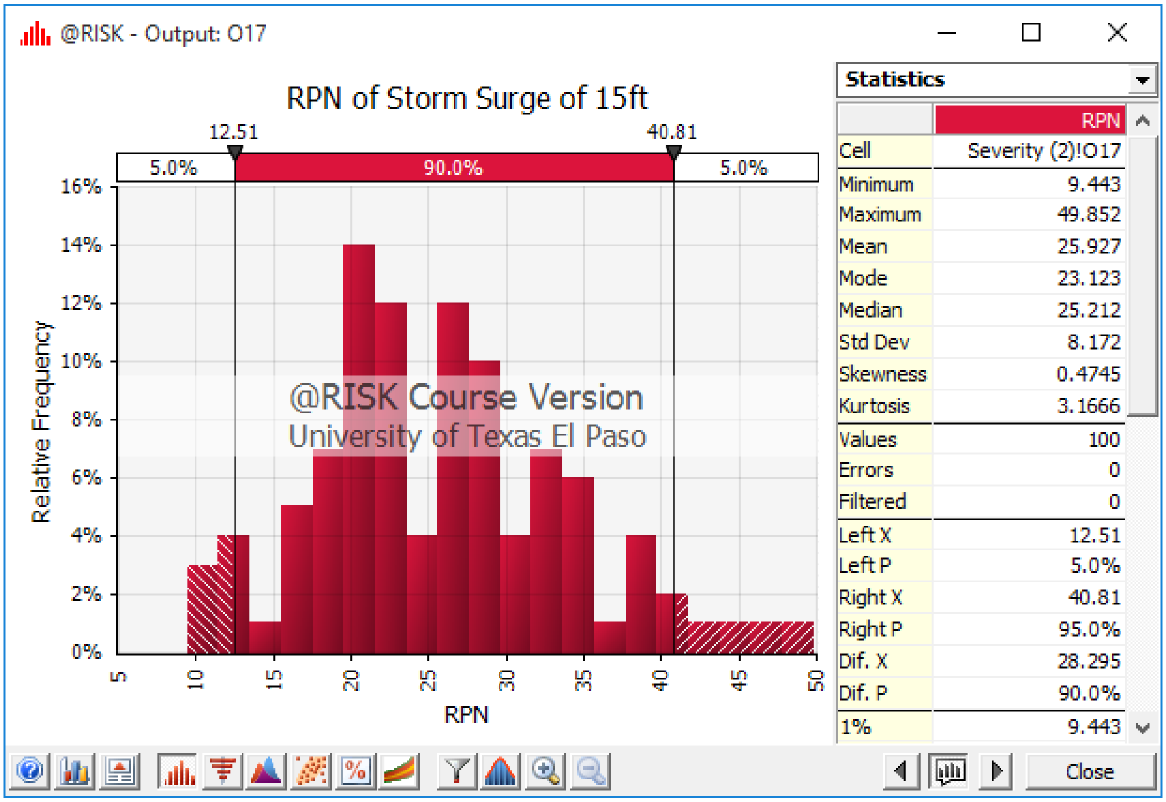


Figure 81. RPN Relative Frequency Distribution, Category 3 Hurricane

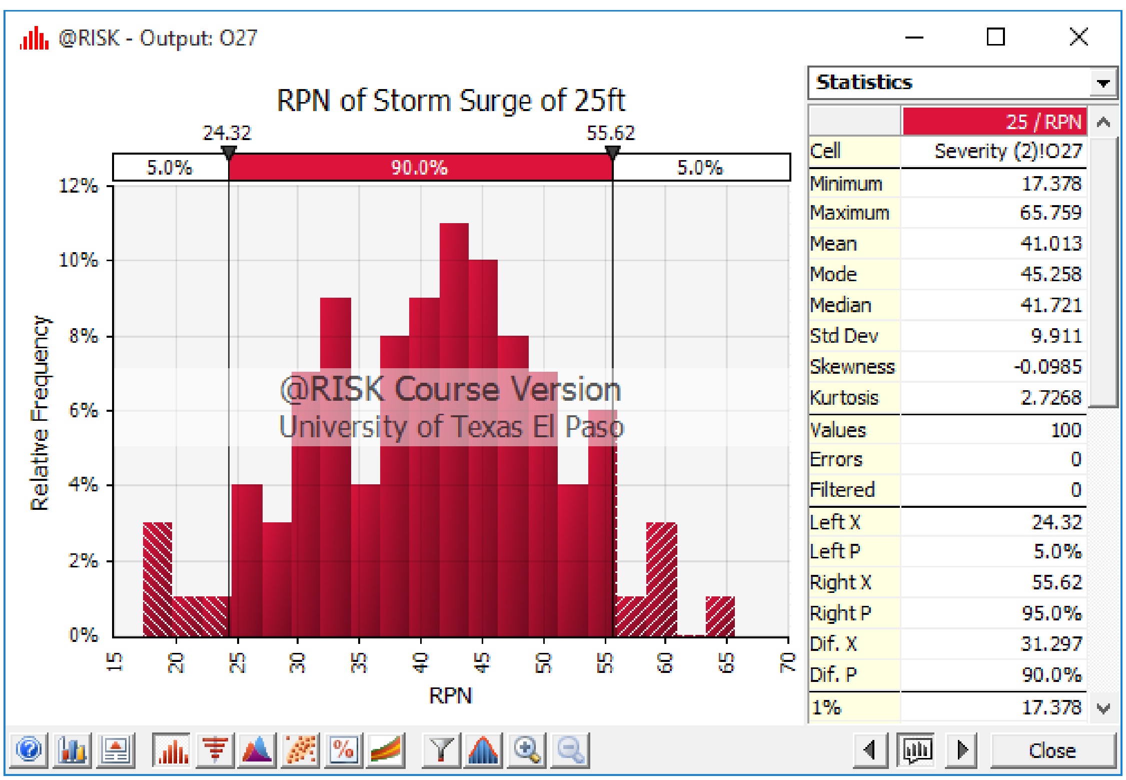


Figure 82. RPN Relative Frequency Distribution, Category 5 Hurricane

Another way to represent the outcomes of the simulation is using the Cumulative Distribution function as seen in Figures 83 to 85. The benefit of using this type of distribution, is that the probability can be read directly. For example, in Figure 83, the probability that the RPN is 9.96 or lower, is 20 percent for a hurricane 1.

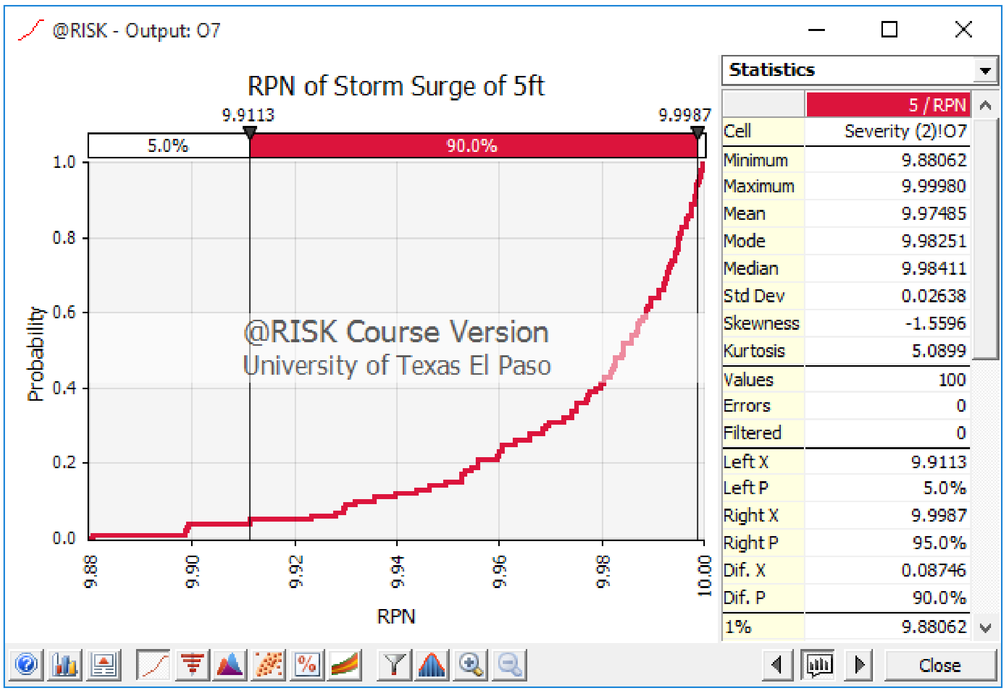


Figure 83. RPN Cumulative Distribution, Category 1 Hurricane

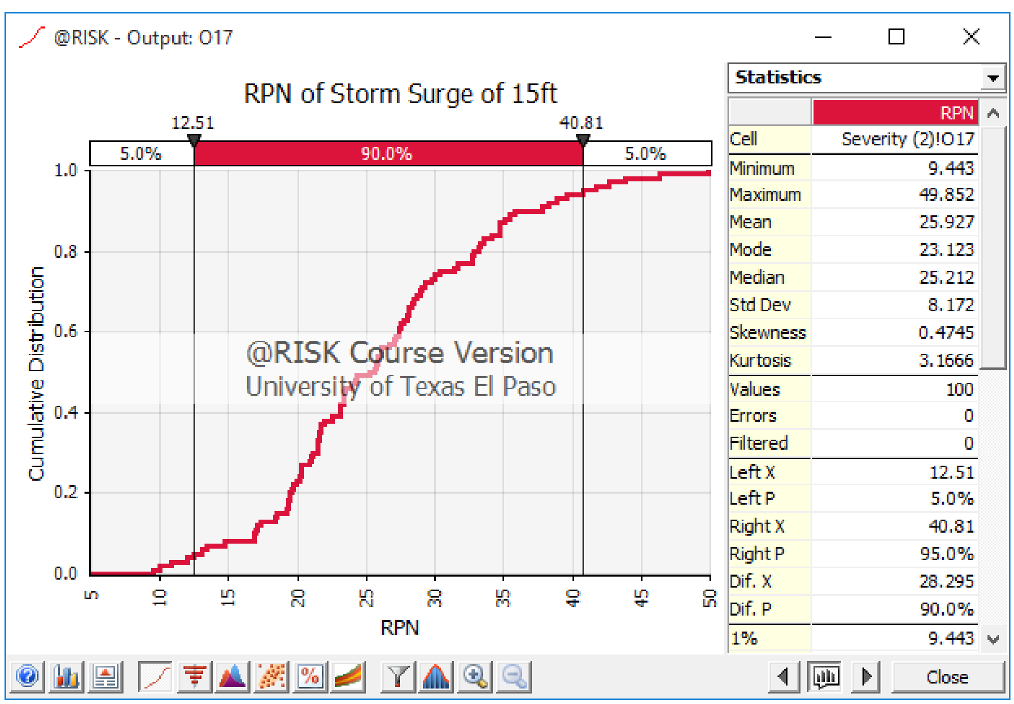


Figure 84. RPN Cumulative Distribution, Category 3 Hurricane

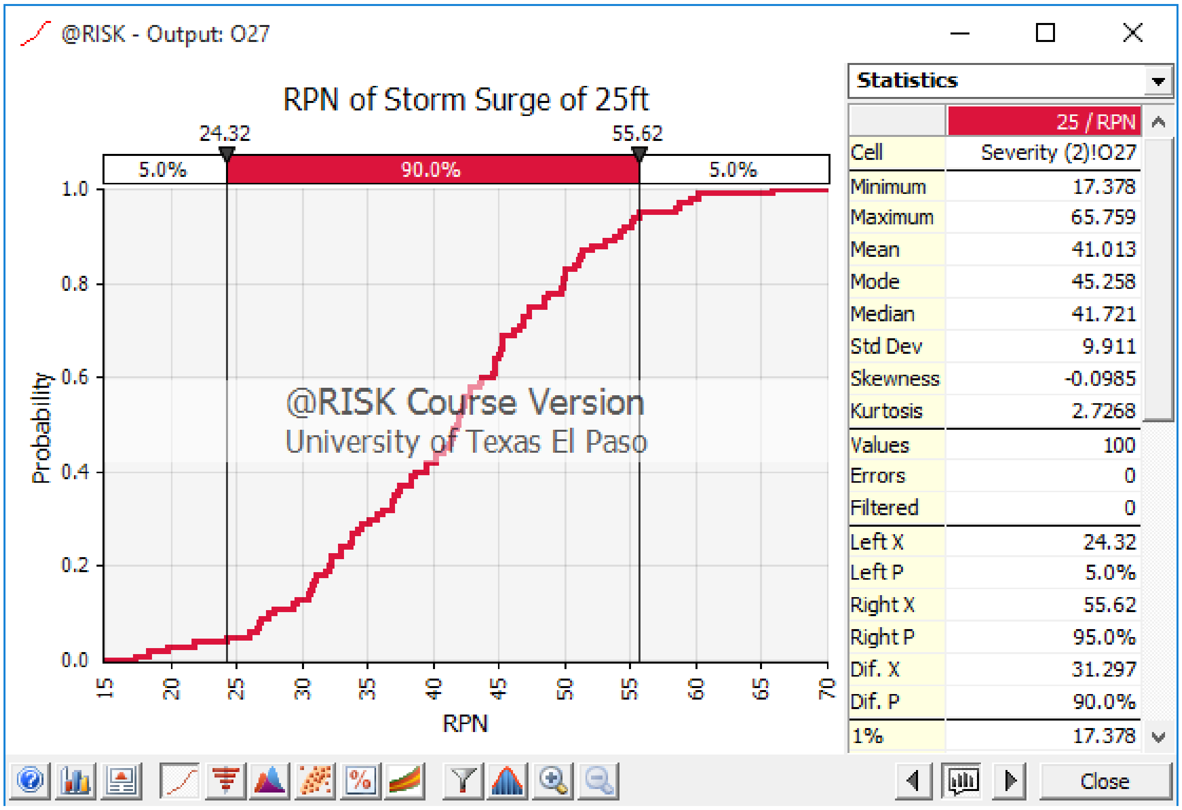


Figure 85. RPN Cumulative Distribution, Category 5 Hurricane

CHAPTER 5
CONCLUSIONS AND RECOMMENDATIONS

This chapter summarizes the research findings and recommendations as a result of the study about the impact of extreme climatic events on the "State of Good Repair" of transportation infrastructure.

5.1. SUMMARY OF RESEARCH FINDINGS

a. The first objective of this research was to identify climate change threats, risks, and performance measures on transportation infrastructure, in particular in the Southern Plains region (NM, TX, OK, AR, and LA). The threats, risks, and performance measures were summarized in Chapter 2. Climate change definition, causes, impact on transportation infrastructure, laws on transportation (MAP-21 and FAST Act), and TAM practices were reviewed. Climate change is the statistical shift of weather patterns and is caused by the Earth in response to human induced changes like CO_2 emissions. The level of service of transportation assets, including roads, bridges, culverts, and rails, is affected by climate stressors that occur more frequently as a result of climate change. Examples of climate stressors are: increased temperature and extreme heat, precipitation-driven inland flooding, sea level rise/extreme high tides, storm surge, winds, droughts, dust storms, wildfires, winter storms, changes in freeze/thaw, and permafrost thaw. As a result of the literature review, it was concluded that traditional TAM practices do not explicitly consider a risk assessment for extreme climatic events, and there is a need to incorporate a methodology to quantify the risk of damage of transportation assets.

b. The second objective of this research was to develop a framework to incorporate risk assessment into TAM practices and criteria to prioritize funding allocation. A general framework with eight main steps is presented:
   - Step 1: Goals and Policies
   - Step 2: Asset Inventory
   - Step 3: Condition Assessment
   - Step 4: Risk Assessment
   - Step 5: Perform Needs (Gap) Analysis
   - Step 6: Conduct Scenarios Analyses
   - Step 7: Asset Management Reports and Risk Assessment
   - Step 8: Asset Management Program to Mitigate the Impact of Climate Change on Transportation Infrastructure.

c. The third objective was to incorporate analytical methods to study the impact of extreme climatic events on transportation assets. A methodology to quantify the risk of damage of an asset under different climate scenarios was developed. Two parameters are defined in this methodology: occurrence that expresses the likelihood of the extreme climatic event to occur, and severity. The equations for occurrence and severity are:

Occurrence= $P[X \geq 1] * 10 = 1 - f_x(k) = (1 - \binom{n}{k} * p^k * (1-p)^{n-k}) * 10$

where:

$P[X \geq 1]$	=	Probability of an asset to experience at least one extreme climate event during its service life.
n	=	Remaining life or number of years for the analysis.
a	=	Number of years of climatic events
b	=	Number of climatic events
Rep	=	Return Period is a/b
p	=	1/Return Period of the extreme climate event (e.g. 1 storm in 50 years = 0.02)
k	=	Number of expected extreme climate events in the analysis period.

Note that 1 – p in the equation, represents the probability of one or more extreme climate events to occur and therefore k=0.

Severity $= P[Z < 0] * (20 - C_p) = (1 - \Phi(Z)) * (20 - C_p)$

$=(1 - \Phi\left(ln\left(\frac{R}{L}\right)\right)) * (20 - C_p)$

where:

$P[Z < 0]$	=	Probability an asset to experience failure or damage at the time of occurrence of the extreme climate event.
$\Phi(Z)$	=	Cumulative standard normal distribution
R	=	Resistance parameter (e.g. height of bridge, volumetric capacity of culvert, etc.)
L	=	Acting parameter or climate stressor that can cause failure (e.g. height of storm surge, flow due to heavy precipitation, etc.)
C_p	=	Clearance Parameter (R - L)

Critical assets are identified by the Risk Priority Number (RPN). The RPN (Risk Priority Number) is obtained by multiplying occurrence, severity, and significance.

Significance is a value from 1 to 10. An asset that is vital to the transportation infrastructure, or places more people's lives at risk if it fails, have a higher significance value. The higher the RPN, the higher the priority for action since the threat to preserve the transportation infrastructure in a "State of Good Repair" is higher.

In Chapter 4, a sensitivity analysis was conducted for occurrence and severity. For occurrence, it was found that as the number of years without an extreme climatic event increases, the occurrence decreases. If the remaining asset life increases, the occurrence also increases. For severity, it was observed that as the resisting parameter increases or, as the acting parameter decreases, then severity decreases.

d. Two case studies, bridge and road, were conducted to demonstrate the applicability of the framework and methodology to quantify the risk. Both case studies relied upon historical data from an extreme climatic event that already occurred. The occurrence and severity were calculated to compare the level of risk before the event and after the solutions (e.g. increasing the bridge height). RPNs before and after the solutions, recommended actions, were calculated to determine if the risk was reduced. Table 33 shows a summary of the risk analysis for both case studies.

Table 35. Summary of the Analysis Results for the Case Studies

Case Study	Budget Scenario	Recommended Action	Scenario	Climatic Event	RPN Before	RPN After	Risk Reduction
Bridge	$800 Million	Rebuild bridge with 30 ft elevation	1	H5/ 25ft Storm Surge	30	30	0%
Bridge	$800 Million	Rebuild bridge with 30 ft elevation	2	H3/ 15ft Storm Surge	80	10	88%
Bridge	$800 Million	Rebuild bridge with 30 ft elevation	3	H1/ 5ft Storm Surge	40	10	75%
Bridge	$30 Million	Rebuild bridge with 9 ft elevation	1	H5/ 25ft Storm Surge	30	30	0%
Bridge	$30 Million	Rebuild bridge with 9 ft elevation	2	H3/ 15ft Storm Surge	80	80	0%
Bridge	$30 Million	Rebuild bridge with 9 ft elevation	3	H1/ 5ft Storm Surge	40	40	0%
Roadway	$14.5 Billion	Rebuild bridge with 17 ft elevation	1	H5/ 25ft Storm Surge	50	50	0%
Roadway	$14.5 Billion	Rebuild bridge with 17 ft elevation	2	H3/ 15ft Storm Surge	100	80	20%
Roadway	$14.5 Billion	Rebuild bridge with 17 ft elevation	3	H1/ 5ft Storm Surge	10	10	0%
Roadway	$1.1 Billion	Build a 26 ft storm surge barrier	1	H5/ 25ft Storm Surge	50	45	10%
Roadway	$1.1 Billion	Build a 26 ft storm surge barrier	2	H3/ 15ft Storm Surge	100	30	70%

Table 36. Summary of the Analysis Results for the Case Studies (Cont'd)

Case Study	Budget Scenario	Recommended Action	Scenario	Climatic Event	RPN Before	RPN After	Risk Reduction
Roadway	$1.1 Billion	Build a 26 ft storm surge barrier	3	H1/ 5ft Storm Surge	10	10	0%

From these case studies, we learned that it is feasible to implement the framework and methodology to quantify the risk of damage of existing assets due to climatic events as well as the effects of mitigation and adaptation strategies.

e. The final objective of the study was to recommend practical adaptation strategies to mitigate the impact of climate change threats. Examples of adaptation strategies include: increasing the elevation of bridges, rail lines, and roadways, restrict development in vulnerable areas, and relocation of roadway sections to less vulnerable areas.

   A list of mitigation and adaptation strategies is presented in Chapter 2. The benefits of adopting the recommended mitigation strategies in an asset management program should be reflected in the performance measures over time. Performance measures that directly correlate climate change with asset conditions should be reported (e.g. number of bridges at high, medium, or low risk).

f. Summary reports with the results of the risk assessment analysis are needed to facilitate the communication at the network and strategic management level. A scorecard with information about the asset location, asset condition, remaining service life, current risk level, and RPN is recommended. Examples of the scorecard were presented in the case studies. GIS is also considered a powerful communication tool to analyze and report risk assessment results. For example, GIS dynamic maps are useful to visualize the location of the assets at different levels of risk in the transportation infrastructure network.

5.2. RESEARCH CONTRIBUTIONS

The major contribution of this research is the development of a framework to consider climate change impact in TAM practices, and a methodology to quantify the risk of damage of an asset due to extreme climatic events. The risk of damage or failure is quantified by the occurrence, severity, and risk priority number (RPN). The RPN can be used to prioritize assets for funding allocation, and to quantify the reduction of risk due to implementation of proactive actions in the asset management program.

5.3. AREAS OF FUTURE RESEARCH AND DEVELOPMENT

a. In the case studies, the methodology to quantify risk was applied to individual assets, and further research is needed to evaluate the risk of damage for the entire transportation infrastructure network. The risk assessment of the entire network should consider all transportation assets as interdepend and functioning together to provide the level of service desired by the agency.

b. The incorporation of sustainability performance measures to evaluate the vulnerability and resilience of the entire network due to extreme climate events deserves further study. Agency goals for safety, mobility, and environment are affected by climate events, and there is a need to investigate their impact in these areas.

c. It is recommended to implement a pilot web-based tool to monitor the level of risk in the transportation infrastructure network. The web-based tool should be linked to a dynamic inventory database with updated information about the asset conditions and treatment history. The web-based tool could generate visual reports with the RPNs for all the asset components that may be useful to prioritize investments.

d. Finally, research is required to determine the economic impacts of climate change in a region. In this sense, it is recommended to study the effect of extreme climate events on economic performance measures including: Current Employment Statistics, Current Population Survey (CPS), Local Area Unemployment Statistics (LAUS), Job Openings and Labor Turnover Survey (JOLTS), Producer Price Indexes (PPI), Consumer Price indexes (CPI), Import and Export Price indexes (MXP), and Employment Cost Index (ECI). A cost-benefit study of the recommended strategies to mitigate the impact of extreme climate is also a topic for future research.

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APPENDIX A

GOALS, OBJECTIVES, AND PERFORMANCE MEASURES USED BY THE SOUTHERN PLAIN STATES

A.1. USDOT Goals and Performance Measures

The USDOT performance measures for safety, infrastructure condition, congestion reduction, system reliability, freight movement and economic vitality, environmental sustainability, and reduced project delivery delays goal areas are listed in Table A-1.

Table A-1. USDOT Main Goals and Performance Measures [53]

Goal Area	Performance Measures
Safety	• Number of fatalities on all public roads • Rate of fatalities on all public roads. • Number of serious injuries on all public roads • Rate of serious injuries on all public roads • Number of non-motorized fatalities and non-motorized serious injuries.
Infrastructure Condition	• Percentage of pavement of the Interstate System in Good condition • Percentage of pavement of the Interstate System in Poor condition • Percentage of pavement of the non-Interstate System in Good condition • Percentage of pavement of the non-Interstate System in Poor condition
Congestion Reduction	• Annual Hours of Peak-Hour Excessive Delay per Capita • Percent of non-Single Occupancy Vehicle (SOV) Travel
System Reliability	• Percent of Person-Miles Traveled on the Interstate That Are Reliable • Percent of Person-Miles Traveled on the Non-Interstate That Are Reliable
Freight Movement and Economic Vitality	• Truck Travel Time Reliability (TTTR) Index
Environmental Sustainability	• Annual Hours of Peak-Hour Excessive Delay per Capita • Percent of non-Single Occupancy Vehicle (SOV) Travel • Total Emission Reductions • Percent Change in Tailpipe CO_2 Emissions on the NHS Compared to the Calendar Year 2017 Level
Reduced Project Delivery Delays	-

A.2. TxDOT Goals, Objectives, and Performance Measures

The Texas Goals came together by combining the State's plan with the national goals summarized in Figure A-1 [54].

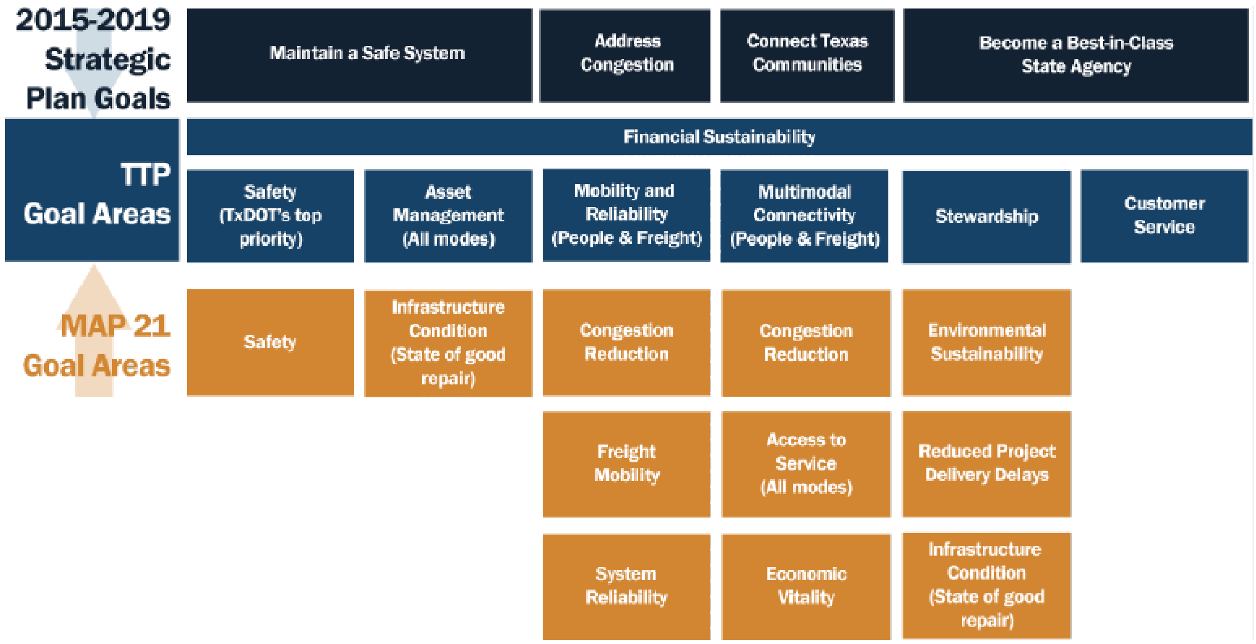

Figure A-1. TxDOT Goals Adaptation from MAP-21 [54]

TxDOT's objectives can be seen in Table A-2 corresponding to the goal areas of safety, asset management, mobility and reliability, multimodal connectivity, stewardship, customer service, and sustainable funding.

Table A-2. TxDOT Goals and Objectives [54]

Goal Area	Objectives
Safety	• Improve multimodal transportation safety • Reduce fatalities and serious injuries • Improve safety of at-grade rail crossings • Eliminate conflicts between modes wherever possible • Increase bicycle and pedestrian safety through education, the design and construction of new facilities, and improvements to existing facilities • Educate the public on the dangers of high-risk driving behaviors • Coordinate with enforcement to improve • Improve incident response times

.

Table A-2. TxDOT Goals and Objectives [54] (Cont'd)

Goal Area	Objectives
Asset Management	• Maintain and preserve multimodal assets using cost-beneficial treatments • Decrease the number of bridges that are structurally deficient, functionally obsolete, or substandard-for-load • Achieve state of good repair for pavement assets, keeping pavements smooth and pothole free • Achieve state of good repair for transit assets such that they are comfortable and reliable • Identify and mitigate risks associated with asset failure • Identify existing and new funding sources and innovative financing techniques for all modes of transportation • Build upon and regularly update the asset inventories for all transportation modes
Mobility and Reliability	• Reduce congestion and improve system efficiency and performance • Plan, design, and construct strategic capacity projects • Implement alternative strategies that reduce peak demand • Improve operations within existing right-of-way • Increase travel options and accessibility for all, especially elderly, disabled, and disadvantaged populations • Increase freight and passenger travel time reliability • Increase the capacity and efficiency of the transportation system across travel modes
Multimodal Connectivity	• Provide transportation choices and improve system connectivity for all passenger and freight modes • Provide and improve access to jobs, transportation choices, and services for all Texans • Provide safe and convenient travel choices for all Texans with a focus on the complete trip • Support the efficient and coordinated movement of goods and services between freight modes to facilitate statewide, national, and global commerce • Support multimodal and intermodal planning, project development, and investments • Improve connectivity between urban, suburban, and rural areas and between travel modes

Table A-2. TxDOT Goals and Objectives [54] (Cont'd)

Goal Area	Objectives
Stewardship	• Manage resources responsibly and be accountable and transparent in decision-making • Identify sustainable funding sources and leverage resources wisely to maximize the value of investments and minimize negative impacts • Develop and implement a project development process that recognizes quality-of-life concerns for all system users and future generations of Texans • Link transportation planning with land use • Reduce project delivery delays • Coordinate project planning and delivery with all planning partners and stakeholders • Minimize impacts to natural, cultural, and historic resources and promote sustainability in project design and delivery
Customer Service	• Understand and incorporate customer desires in decision processes and be open and forthright in all agency communications • Collect and integrate feedback using innovative engagement techniques and technology • Promote and enable public participation in project planning and development • Improve accessibility of information through innovative, understandable, and relatable communication techniques • Educate the public and stakeholders on transportation costs, funding availability, and investment tradeoffs
Sustainable Funding	• Identify and sustain funding sources for all modes • Identify and document costs to meet the state's future transportation needs • Consider all funding sources to fill the needs-to-revenues gap • Educate the public and stakeholders on the costs associated with constructing and preserving the system • Evaluate the feasibility of innovative financing solutions • Improve predictive capabilities for revenue forecasting and long-term needs assessments

TxDOT's performance measures are shown in Table A-3 corresponding to the goal areas of safety, asset management, mobility and reliability, multimodal connectivity, stewardship, customer service, and sustainable funding. Note that this Table has two references because one covers the performance measures of freights.

Table A-3. TxDOT Performance Measures [54, 76]

Goal Area	Performance Measures
Safety	• Total Number of Fatalities and Serious Injuries • Truck Related Crashes and Fatalities • Rail Accidents • At-grade Rail Crossing Safety • Number of fatalities • Number of serious injuries • Number of fatalities/serious injuries per 100 million vehicle miles traveled • Number of fatalities/serious injuries per million population • Number of crashes between train and vehicle • Number of crashes between train and vehicle resulting in fatalities or serious injuries • Number of pedestrian and bicyclist fatalities and serious injuries • Number of pedestrian and bicyclist fatalities per million population • Number of fatal and serious injury crashes involving cell phone use • Number of fatal and serious injury crashes involving speeding • Safety belt usage rate • Number of fatal crashes due to DUI • Average incident response time/incident clearance time
Asset Management	• Percent NHS Pavement Lane-Miles in a State of Good Repair (IRI based) • Percent NHS Pavement Lane-Miles in a State of Good Repair (Condition Score based) • Percent Non-NHS Pavement Lane-Miles in a State of Good Repair (IRI based) • Percent Non-NHS Pavement Lane-Miles in a State of Good Repair (Condition Score based) • Percent Structurally Deficient NHS Bridges Deck Area • Count of Structurally Deficient NHS Bridges • Percent Structurally Deficient Non-NHS Bridges Deck Area • Count of Structurally Deficient Non-NHS Bridges • State of Good Repair on the Strategic Freight Network
Mobility and Reliability	• Rural Level-of-Service • Urban Level-of-Service • Annual Hours of Truck Delay • Truck Reliability Index • Reduction in Freight Bottlenecks • Percent Rail Freight Needs Met • Percent Non-Highway Freight Needs Met • Percent Bicycle and Pedestrian Needs Met

Table A-3. TxDOT Performance Measures [54, 77] (Cont'd)

Goal Area	Performance Measures
Multimodal Connectivity	• Annual Hours of Truck Delay • Truck Reliability Index • Reduction in Freight Bottlenecks • Percent Rail Freight Needs Met • Percent Non-Highway Freight Needs Met • Percent Bicycle and Pedestrian Needs Met
Stewardship	• Daily kilogram of VOC reduced by the latest annual program CMAQ projects in areas with 1 million pop. Or more (5-year average) • Daily kilogram of NOx reduced by the latest annual program CMAQ projects in areas with 1 million pop. Or more (5-year average) • Daily kilogram of CO reduced by the latest annual program CMAQ projects in areas with 1 million pop. Or more (5-year average)
Customer Service	• -
Sustainable Funding	• -

A.3 NMDOT Goals, Objectives, and Performance Measures

The New Mexico objectives are summarized in Table A-4 corresponding to the goal areas of operating with transparency and accountability, improve safety for all system users, preserve our transportation assets for the long term, provide multimodal access and connectivity for community prosperity and respect New Mexico's cultures environment, history and quality of life.

Table A-4. NMDOT Goals and Objectives [55]

Goal Area	Objectives
Operate with Transparency and Accountability	• Cultivate employee excellence and deliver outstanding customer service • Coordinate trusting and working partnerships between federal, state, regional, Tribal, local and other entities to implement projects and programs • Improve financial accountability, minimize financial and other risks, and operate NMDOT in a cost effective and cost efficient manner • Provide access to integrated, high-quality data and information
Improve Safety for All System Users	• Reduce collision- related fatalities and serious injuries for all modes through data-driven, innovative, and proactive processes
Preserve and Maintain Our Transportation Assets for the Long Term	• Develop and implement a "preservation-first" asset management strategy to ensure that NMDOT can maintain all existing and future elements of the state's multimodal transportation system in a state of good repair. • Ensure that NMDOT can affordably meet the minimum condition standards for each roadway tier by right sizing the state-owned network to provide the needed capacity to support statewide connectivity standards.

Table A-4. NMDOT Goals and Objectives [55] (Cont'd)

Goal Area	Objectives
Provide Multimodal Access and Connectivity for Community Prosperity	• Invest efficiently and strategically in state transportation systems to achieve statewide and community economic and quality of life goals. • Make efficient use of both transportation and nontransportation resources to reduce costs and improve mobility of residents and visitors. • Maintain a transportation system that allows mobility and access for all New Mexicans, regardless of age or ability.
Respect New Mexico's Cultures, Environment, History, and Quality of Life	• Transportation projects and programs respect the context within which they are built and implemented. • NMDOT seeks to improve environmental outcomes with both its transportation investments and business operations. • NMDOT celebrates and advances New Mexico economic goals in the areas of recreation and tourism.

Table A-5 shows the performance measures for New Mexico corresponding to the goal areas of operating with transparency and accountability, improve safety for all system users, preserve our transportation assets for the long term, provide multimodal access and connectivity for community prosperity and respect New Mexico's cultures environment, history and quality of life.

Table A-5. NMDOT Performance Measures [55]

Goal Area	Performance Measures
Operate with Transparency and Accountability	• Percent of 2040 Plan actions completed within timeframe identified in this plan • Public ratings of NMDOT in customer satisfaction survey • Percent of positions vacant in all programs • Stakeholder ratings of NMDOT in customer satisfaction survey • Percent of projects obligated versus programmed in the STIP • Percent of cost over bid amount • Number of annual external financial audit findings • Percent of prior year financial audit findings resolved • Percent of essential data sources updated on schedule [measurement approach TBD]
Improve Safety for All System Users	• Total number of fatalities • Total fatalities per 100 million vehicle miles traveled (statewide, rural, and urban) • Total number of serious injuries • Serious injuries per 100 million VMT (statewide, rural, and urban) • Pedestrian fatalities and serious injuries (statewide, rural, and urban)* • Bicyclist fatalities and serious injuries (statewide, rural, and urban)*

Table A-5. NMDOT Performance Measures [55] (Cont'd)

Goal Area	Performance Measures
Preserve and Maintain Our Transportation Assets for the Long Term	• Percent of pavement in good/fair/poor condition by tier • Percent of bridges in good/fair/poor condition by tier • Percent of transit assets in state of good repair by mode (bus, rail) • Number of pavement miles preserved by tier • Percent of airport runways rated "good" • Total maintenance expenditures and maintenance cost per capita
Provide Multimodal Access and Connectivity for Community Prosperity	• Planning time index (reliability) for personal travel (urban areas) • Total person hours of delay per capita (urban areas) • Planning time index (supply chain reliability) for freight • Rail Runner annual ridership • Park-and-Ride annual ridership • Household transportation costs as a percentage of median household income (statewide, rural, and urban) • Percent of adults over age 60 who report that they have transportation options sufficient to maintain an independent lifestyle
Respect New Mexico's Cultures, Environment, History, and Quality of Life	• Stakeholder satisfaction surveys before and after development of major projects • Number of vehicle/wildlife collisions • Effectiveness of mitigation measures as defined through NEPA process

A.4 OkDOT Goals, Objectives, and Performance Measures

Table A-6 shows the objectives for the Oklahoma Department of Transportation corresponding to the goal areas of safe and secure, infrastructure preservation, mobility choice and connectivity and accessibility, economic vitality, environmental responsibility, and efficient intermodal system management and operations.

Table A-6. OkDOT Goals and Objectives [56]

Goal Area	Objectives
Safe and Secure	• Reduce traffic-related fatalities/serious injuries on all public roads. • Increase seat belt usage.
Infrastructure Preservation	• Maintain or improve the highway system in a state of good repair. • Improve state highway system* (SHS) bridge condition. • Improve transit system. • Improve and maintain transit equipment in a state of good repair. • Maintain state-owned freight rail system. • Improve ride quality on NHS roads. • Improve ride quality on entire state road system.
Mobility Choice, Connectivity and Accessibility	• Improve access to transit, passenger rail service. • Improve access to bicycle and pedestrian infrastructure. • Increase transit linkages intra-state and interstate. • Enhance access to jobs for both urban and rural populations.

Table A-6. OkDOT Goals and Objectives [56] (Cont'd)

Goal Area	Objectives
Economic Vitality	• Improve efficiency of freight transportation & freight-related highway infrastructure capacity. • Provide predictable, reliable travel times. • Improve access to intermodal facilities and the efficiency of intermodal transfers.
Environmental Responsibility	• Minimize impacts to cultural and historic resources. • Minimize impacts to wetlands, vulnerable ecosystems, and threatened and endangered species. • Support improved water quality. • Promote use of clean fuels. • Protect existing and design new transportation infrastructure to function under changing weather conditions.
Efficient Intermodal System Management and Operation	• Continue to streamline and improve project delivery. • Continue to improve interagency partnerships. • Continue to improve neighboring state partnerships. • Use technology advances to improve system performance.

Table A-7 shows the performance measures for the Oklahoma department of Transportation corresponding to the goal areas of safe and secure, infrastructure preservation, mobility choice and connectivity and accessibility, economic vitality, environmental responsibility, and efficient intermodal system management and operations.

Table A-7. OkDOT Performance Measures [56]

Goal Area	Performance Measures
Safe and Secure Travel	• Fatalities and Serious Injuries (number & rate)
Infrastructure Preservation	• Number of structurally deficient (SD) bridges on SHS • Basic Option – Avg. Int'l Roughness Index (IRI) • Advanced Option –Good/fair/poor index for IRI + rutting, cracking, faulting
Mobility Choice, Connectivity and Accessibility	• Total annual revenue miles per capita per county for rural transit agencies • Amtrak, Heartland Flyer – Annual ridership and on-time performance
Economic Vitality	• Basic Option – System-wide annual freight tonnage/value for truck, rail, barge modes • Advanced Option – Annual freight tonnage/value for truck, rail, barge + Average truck speed on Interstates • Travel time reliability-based measure
Environmental Responsibility	• Quantity (cubic yards or other measure of weight/volume) of litter and debris cleared from storm drains/culverts/roadsides • Clean fuels as a share of ODOT's total fleet fuel use [in gasoline gallon equivalents (GGE)]
Efficient Intermodal System Management and Operation	•

A.5 ArDOT Goals, Objectives, and Performance Measures

Table A-8 displays the objectives for Arkansas Department of Transportation corresponding to the goal areas of safety and security, infrastructure condition, congestion reduction, economic competitiveness, environmental sustainability, and multimodal transportation systems.

Table A-8. ArDOT Goals and Objectives [57]

Goal Area	Objectives
Safety and Security	• Align safety goals with the goals of the AHTD Strategic Highway Safety Plan (SHSP). • Partner with the Arkansas State Police, local governments, and federal agencies to administer comprehensive traffic safety programs related to driver, roadway, and railroad crossing safety • Partner with counties and local governments to provide training on low-cost safety applications for local roads. • Coordinate with District Engineers to identify roadways and bridges that are vulnerable to extreme weather events and other natural phenomena. Improve the resiliency of the transportation system to meet travel needs in response to extreme weather events. • Coordinate with local governments for disaster preparedness. • Work with emergency management agencies to expand emergency communications infrastructure across the state. • Work with emergency management agencies to ensure efficient and coordinated responses to emergency and disaster events. • Identify non-interstate crash hotspots and develop recommendations that have the potential to reduce crashes.
Infrastructure Condition	• Enforce weight and size restrictions to protect roads and bridges. • Improve ride quality on NHS roads. • Follow asset management principles to optimize preservation strategies on the state highway system. • Identify potential freight corridors within which special attention is given to preempt commercial vehicle bottlenecks.

Table A-8. ArDOT Goals and Objectives [57] (Cont'd)

Goal Area	Objectives
Congestion Reduction	• Provide predictable, reliable travel times. • Complete the Connecting Arkansas Program (CAP) that improves transportation connections throughout the state by increasing roadway capacity. • Implement context sensitive solutions in the transportation system design. • Implement Intelligent Transportation System (ITS) strategies to inform and provide travelers with real-time information regarding weather conditions, travel times, emergencies, and delays. • Use technology advances to improve system performance. • Plan and prepare for autonomous and connected vehicles. • Use output from MPOs' Congestion Management Systems to identify and address congested areas on the NHS. • Work with partners to encourage Travel Demand Management strategies to reduce the traffic demand during peak hours. • Support multimodal transportation alternatives and intermodal mobility.
Economic Competitiveness	• Continue development of the four-lane economic development connectors (Four-Lane Grid System) to improve connectivity to all citizens and promote economic development. • Prioritize and enhance intermodal connections for both passenger and freight movement by establishing an appropriate network of intermodal connectors. • Collaborate with the Arkansas Economic Development Commission to identify projects that will improve the State's economic competitiveness. • Use outputs from State Rail Plan to identify rail improvement needs. • Support the maintenance and operation of state highways, bridges, transit, rail, ports, locks, and dams. • Identify key routes in need of long-term additional capacity to support Arkansas and external trading partners. • Identify projects to address localized congestion /capacity issues that negatively impact freight movement.
Environmental Sustainability	• Identify and reduce barriers to reduce delay and improve the project delivery process. • Minimize impacts to natural, historic, and cultural resources. • Support initiatives to reduce congestion and improve air quality. • Implement context sensitive solutions in the transportation system design.
Multimodal Transportation System	• Develop and sustain efficient intermodal connections to allow for more efficient transfer of goods between modes. • Support multimodal transportation alternatives and intermodal mobility. • Use outputs from State Bicycle and Pedestrian Plan to provide transportation lifestyle options for citizens. • Coordinate with MPOs and local governments' land use planning and regional/local modal plans. • Partner with MPOs and local governments to consider implementing approved and adopted bicycle/pedestrian facilities on the state highway system.

Table A-9 displays the performance measures for the Arkansas Department of Transportation corresponding to the goal areas of safety and security, infrastructure condition, congestion reduction, economic competitiveness, environmental sustainability, and multimodal transportation systems.

Table A-9. ArDOT Performance Measures [78]

Goal Area	Performance Measures
Safety and Security	• Statewide number of fatalities • Statewide number of serious injuries • Fatalities/100 million VMT • Serious Injuries/100 million VMT • Statewide combined number of non-motorized fatalities and serious injuries • Roadway Clearance Time (RCT)
Infrastructure Condition	• Percent of Bridge Deck Area on the NHS in Good Condition • Percent of Bridge Deck Area on the NHS in Poor Condition • Percent of Pavement on the Interstate in Good Condition • Percent of Pavement on the Non-Interstate NHS in Good Condition • Percent of Pavement on the Interstate in Poor Condition • Percent of Pavement on the Non-Interstate NHS in Poor Condition
Congestion Reduction	• Percent of person-miles traveled on the Interstate system that are reliable • Percent of person-miles traveled on the non-Interstate NHS that are reliable • Percent change in tailpipe CO2 emissions on the NHS from calendar year 2017
Economic Competitiveness	• Percentage of the Interstate system mileage providing for reliable truck travel times or Truck Travel Time Reliability (TTTR) Index (referred to as the Freight Reliability Measure) • Year-to-year change in statewide average job accessibility (separate measures for auto and transit modes)
Environmental Sustainability	• Annual hours of peak-hour excessive delay per capita (the PHED measure) • Percent of Non-SOV travel where SOV stands for single-occupancy vehicle • Total emissions reduction
Multimodal Transportation System	• Percent of revenue vehicles with a particular asset class that have either met or exceeded their useful life benchmark (ULB)

A.6 DOTD Goals, Objectives, and Performance Measures

Table A-10 shows the goals and objectives for the Louisiana Department of Transportation corresponding to the goal areas of infrastructure preservation and maintenance, safety, economic competitiveness, community development and enhancement, and environmental stewardship.

Table A-10. DOTD Goals and Objectives [58]

Goal Area	Objectives
Infrastructure Preservation and Maintenance	• Keep Louisiana's state highway pavement, bridges, and highway related assets in good condition. • Assist modal partners in achieving state-of-good-repair for aviation, port, rail, transit, and navigable waterway infrastructure. • Assist local roadway departments in achieving state-of-good-repair for locally owned roads and streets.
Safety	• Reduce the number and rate of highway-related crashes, fatalities, and serious injuries. • Reduce the number of pedestrian and bicycle crashes. • Assist modal partners in achieving safe and secure aviation, port, rail, transit, and waterway performance.
Economic Competitiveness	• Improve the efficiency of freight transportation and the capacity of freight related infrastructure throughout Louisiana. • Improve access to intermodal facilities and the efficiency of intermodal transfers. • Provide predictable, reliable travel times throughout Louisiana. • Ensure small urban areas (5,000+ population) are well connected with one another and with large urban employment centers.
Community Development and Enhancement	• Cooperate with and support MPOs, state planning and development districts, and local governments with the establishment and refinement of land use, transportation, and community development plans. • Increase options available to local governments to seek sustainable revenue for local transportation needs. • Continue the Road Transfer Program as a voluntary program to assist local governments in addressing local transportation needs. • Reduce barriers to state and local collaboration. • Enhance access to jobs for both urban and rural populations. • Improve modal options associated with supporting the economy and quality of life regardless of age, disability, or income. • Identify methods to preserve the integrity and character of "town centers" and preserve open space, or the appearance of open space, between them.
Environmental Stewardship	• Minimize the environmental impacts of building, maintaining, and operating Louisiana's transportation system. • Comply with all federal and state environmental regulations

Table A-11 displays the performance measures for the Louisiana Department of Transportation corresponding to the goal areas of infrastructure preservation and maintenance, safety, economic competitiveness, community development and enhancement, and environmental stewardship.

Table A-11. DOTD Performance Measures [58]

Goal Area	Performance Measures
Infrastructure Preservation and Maintenance	• Percent of State-owned highways meeting pavement condition targets, by system tier – Interstate Highway System (IHS), National Highway System (NHS), Statewide Highway System (SHS), and Regional Highway System (RHS) • Percent of structurally deficient bridges by deck area for each tier • Percent of publicly owned airports meeting the State's standard • Percent of public transit fleets meeting applicable condition standards • Percent of locally owned NHS mileage meeting pavement condition targets • Percent of structurally deficient locally owned bridges by deck area
Safety	• Highway fatalities and serious injuries (number and rate) • Crashes involving trucks (number and rate) • Number of crashes involving pedestrians and bicyclists • Number of crashes involving transit vehicles • Number of crashes at rail crossings • Number of collisions on waterways (12-year rolling average)
Economic Competitiveness	• Percent of principal arterial highways with acceptable volume to capacity ratios • Annual tonnage and value of freight moved at Louisiana marine ports • Annual tonnage and value of freight moved at Louisiana airports • Percent of short line freight rail system capable of supporting 286,000-lb. cars • Place holder for any MAP-21 freight efficiency measurement requirements developed by FHWA • Number of freight bottlenecks addressed • Percent of navigable waterway miles maintained to federally authorized dimensions • Annual hours of delay from incidents on freeways • Percent of highways connecting urban areas that meet minimum state standards
Community Development and Enhancement	• Percent of parishes and municipalities with local comprehensive plans • Number of parishes with general transit service • Number of parishes with elderly and handicapped transit service • Number of parishes with general transit service
Environmental Stewardship	• Percent of DOTD fleet converted to alternative fuels • Percent of state and local public fleets converted to alternative fuels • Acres of wetlands impacted by DOTD or DOTD-funded projects relative to investment • Number of parishes that meet NAAQS mobile source emissions standards • Place holder for any MAP-21 air quality measurement requirements

APPENDIX B

HURRICANE DATA FOR THE SENSITIVITY ANALYSES OF OCCURRENCE

Data used in the analyses conducted for the case studies in Chapter 3 are found in Table B.1. This information includes the name of the hurricane, land fall date, hurricane wind speed, and wind speed.

Table B-1: New Orleans Hurricane Data [62]

Name	Date	Category	Wind Speed (kn)	Wind Speed (mph)
Allison	2001	TS	35	40.3
BABE	1977	TS	30	34.5
Betha	2002	TS	25	28.8
Beryl	1988	TS	45	51.8
Betsy	1965	H2	90	103.6
Bill	2003	TS	45	51.8
Bob	1979	H1	65	74.8
Bonnie	2010	TS	20	23.0
Brenda	1955	TS	55	63.3
Camille	1969	H5	150	172.6
Cindy	2005	TS	50	57.5
Danny	1997	H1	70	80.6
Elena	1985	H3	100	115.1
Esther	1957	TS	50	57.5
Fern	1971	TS	25	28.8
Florence	1988	TS	60	69.0
Gustav	2008	H2	90	103.6
Hermine	1998	TS	35	40.3
Hilda	1964	TS	60	69.0
Isaac	2012	H1	65	74.8
ISIDORE	2002	TS	55	63.3

Table B-1: New Orleans Hurricane Data [62] (Cont'd)

Name	Date	Category	Wind Speed (kn)	Wind Speed (mph)
JUAN	1985	TS	60	69.0
KATRINA	2005	H4	125	143.8
MATTHEW	2004	TS	30	34.5
UNNAMED	1855	H3	110	126.6
UNNAMED	1860	H3	100	115.1
UNNAMED	1860	H2	90	103.6
UNNAMED	1867	H2	90	103.6
UNNAMED	1869	H1	70	80.6
UNNAMED	1872	TS	50	57.5
UNNAMED	1877	H1	70	80.6
UNNAMED	1879	H3	110	126.6
UNNAMED	1879	TS	50	57.5
UNNAMED	1885	TS	60	69.0
UNNAMED	1887	H1	75	86.3
UNNAMED	1888	H2	85	97.8
UNNAMED	1889	H1	70	80.6
UNNAMED	1890	TS	50	57.5
UNNAMED	1892	TS	45	51.8
UNNAMED	1893	H1	70	80.6
UNNAMED	1893	H4	115	132.3
UNNAMED	1895	TS	50	57.5
UNNAMED	1900	TS	40	46.0

Table B-1: New Orleans Hurricane Data [62] (Cont'd)

Name	Date	Category	Wind Speed (kn)	Wind Speed (mph)
UNNAMED	1901	H1	75	86.3
UNNAMED	1905	TS	40	46.0
UNNAMED	1907	TS	40	46.0
UNNAMED	1912	TS	50	57.5
UNNAMED	1914	TS	35	40.3
UNNAMED	1915	H3	110	126.6
UNNAMED	1920	H2	85	97.8
UNNAMED	1923	TS	40	46.0
UNNAMED	1923	H1	70	80.6
UNNAMED	1923	TS	50	57.5
UNNAMED	1926	H3	100	115.1
UNNAMED	1926	TS	40	46.0
UNNAMED	1936	TS	40	46.0
UNNAMED	1936	TS	25	28.8
UNNAMED	1939	TS	45	51.8
UNNAMED	1944	TS	55	63.3
UNNAMED	1945	TS	30	34.5
UNNAMED	1947	TS	35	40.3
UNNAMED	1947	H2	95	109.3
UNNAMED	1948	H1	70	80.6
UNNAMED	1949	TS	50	57.5
UNNAMED	1955	TS	45	51.8

Table B-1: New Orleans Hurricane Data [62] (Cont'd)

Name	Date	Category	Wind Speed (kn)	Wind Speed (mph)
UNNAMED	1956	TS	50	57.5
UNNAMED	1971	TS	25	28.8
UNNAMED	1971	TS	25	28.8
UNNAMED	1975	TS	25	28.8
UNNAMED	1975	TS	25	28.8
UNNAMED	1977	TS	25	28.8
UNNAMED	1980	TS	20	23.0