2018-01-01

A Sustainable Performance-Based Methodology To Address The Impact Of Climate Changes On The

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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

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by

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THESIS

Presented to the Faculty of the Graduate School of

The University of Texas at El Paso

in Partial Fulfillment

of the Requirements

for the Degree of

MASTER OF SCIENCE

Department of Civil Engineering

THE UNIVERSITY OF TEXAS AT EL PASO

May 2018

Acknowledgements

I wish to express my deep sense of gratitude to my beloved mother, father, and wife for their love and support. I would like to thank Dr. Carrasco, Dr. Weidner, Dr. Fullerton and Dr. Chang for their immense help and support all throughout my Master's. I am grateful to all my friends for their care and for always being there to help me whenever needed. This thesis and entire graduate studies could not be completed without them. I am deeply grateful.

Abstract

This research focuses to address the effects of climate change on the transportation asset management. Climate change has resulted in increased storms, droughts, flooding, temperatures, and other climate to become more significantly frequent and powerful. As a result, climate change is now affecting the transportation assets around the world. This thesis is divided into six components: the literature review, development of the framework, development of the methodology, case study, discussion, and conclusions. The literature review will show threats, risks, and performance measures to monitor the climate change impact on transportation infrastructure. The literature review includes transportation asset like bridges, roads, culverts, rails, and the ports and waterways and will be followed by the development of the framework to incorporate risk assessment of infrastructure damage due to extreme climate events into Transportation Asset Management (TAM) practices. Within the framework there is a methodology to quantify the impact, level of risk, and recommendations to mitigate the impact of climate change. A case study follows and shows the applicability of the framework and risk assessment method for a bridge. This research helps identify assets at risk of failure due to extreme climatic events by calculating the occurrence, severity, and the risk priority number (RPN). The RPN is useful for prioritizing funding allocation in the asset management programs.

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Chapter 1: Introduction

OVERVIEW OF TRANSPORTATION ASSET MANAGEMENT (TAM)

Developing strategic plans is a complex process encountered by transportation agencies when addressing short and long-term infrastructure needs. There are new challenges to preserve the transportation infrastructure in a “State of Good Repair”. The needs and threats to infrastructure are increasing due to growing population, aging assets, global climate change, and budget constraints.

In the span of a little over 100 years, between 1901 and 2013, seven of the ten warmest years occurred after 1998. A temperature increase from 1 to 4 °F was reported in the United States in the last 20 years (EPA 2015). Whether the climatic changes are due to the influence of human beings or natural activities, the effects of climate change on the natural system are undeniable. The Intergovernmental Panel on Climate Change (IPCC) indicates that by the end of this century, there could be a rise of up to 7 °F in the average surface temperature (IPCC 2014). This increase in temperature and the increase in extreme rainfall, hurricanes and floods, as well as the gradual changes in the water levels, are likely to affect the transportation infrastructure networks. As the likelihood and intensity of climate change continues to rise, there is a need to develop new strategic plans and asset management practices. These plans and practices will help mitigate the impact on the transportation infrastructure.

In order to address the short and long-term transportation infrastructure needs, strategic plans need to conform to federal and state laws to receive funding. The Moving Ahead for Progress in the 21st Century Act (MAP-21) was signed on July 17, 2012 and extended until 2015. MAP-21 requires State Departments of Transportation (DOTs) to form performance measures in seven national performance goals. They are safety, infrastructure condition, congestion reduction, system reliability, freight movement and economic vitality, environmental sustainability, and reduced project delivery delays. MAP-21 also outlined eight planning factors that emphasized [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. Fixing America's Surface Transportation Act (FAST Act) was enacted in 2015. The FAST Act includes additional performance measures, such as climate-related pollution from transportation from fiscal year 2016 to 2020 to enhance the performance-based program of MAP-21 (Grunwald 2016). Under the FAST Act, DOTs are required to report ozone, carbon monoxide and particulate matter and states that do not comply with the maximum allowed pollution are required to use a portion of federal funding on projects to address the problem (FHWA 2016a).

Asset management is the process of maintaining, upgrading, and operating physical assets by combining engineering principles with sound business practices and economic theory. It also provides tools to facilitate a more organized, logical approach to decision-making (FHWA 1999). The Transportation Asset Management's (TAM) purpose is to provide the most cost-effective level of service of transportation assets. As the occurrence and intensity of extreme climatic events continues to rise, it is vital to consider in the TAM decision-making risk caused by climate change and find pro-active infrastructure strategic solutions. All districts are affected by the climate change and TAM best practices are expected to protect the transportation foundation in a State of Good Repair. The result of the proposed research will give agencies a methodology to evaluate climatic risk to create reasonable TAM decision and mitigate the impact of climatic change on the transportation infrastructure.

BRIEF BACKGROUND

Extreme climatic events can affect transportation infrastructure. Components may deteriorate faster due to the gradual increase in temperatures. Some can even collapse as a result of an extreme climatic event. For example, coastal areas are anticipated to face the risks of sea level rise and flooding. This will result in restricted accessibility to the transportation network. Additionally, the probability and severity of extreme climatic events such as greater snowfall, heat and cold waves, extreme rainfall, and strong winds are likely to increase. This will add more stress to the transportation assets. Therefore, maintenance, repairs, and rehabilitation activities must be performed more frequently (UK Highway Agencies 2011).

Special design requirements and improvements in TAM practices must be established to increase the resilience of transportation assets. The main goal is to maintain safety, mobility, and access to roads

even during the extreme climatic events. The following are relevant studies and efforts conducted to consider climate change effects in the TAM:

(1) Meyer et al. (2009) Transportation Asset Management Systems and Climate Change: An Adaptive Systems Management Approach: This study mentions the need to integrate climate change into TAM. It also proposes climate adaptation strategies. Not mentioned in this study is a methodology to quantify the risk of failure due to the climate events.

(2) FHWA (2010) Regional Climate Change Effects: Useful Information for Transportation Agencies: This study mentions CMIP 3 which is a database developed by a Working Group on Coupled Modelling (WGCM). CMIP 3 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). This study also mentions that the effects of climate change on highway infrastructure, including bridges, roads, and signs, are different region by region.

(3) AASHTO (2012) Integrating Extreme Weather Risk into Transportation Asset Management: This study emphasizes the need for the implementation of TAM practices to tackle extreme weather events. It describes that the major risks that affects transportation systems are due to extreme weather events. Extreme weather event in this study are heavy precipitation, storm surge, flooding, drought, windstorms, extreme heat, and extreme cold. This study also proposes the idea of “risk rating” but it does not quantify the likelihood of occurrence and severity to get the rating.

(4) FHWA (2012) Extreme Weather Vulnerability Assessment: This 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, but concluded that additional efforts are necessary to integrate climate change adaptation strategies into TAM. The FHWA aim was to advance beyond the assessment stage and towards the development and implementation of the framework.

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

(6) NCHRP (2014) Response to Extreme Weather Impacts on Transportation Systems: This study presents eight cases of how extreme weather events affect infrastructure. It includes cases like prolonged heat, wildfires, hurricanes, flooding, tornadoes, intense rains, tropical storms, and severe snowstorms. The main objective was to identify common and recurring themes in state-level responses to extreme weather events. It concluded that in order to identify extreme weather preparedness actions, to build resilience, and to implement adaptation strategies more analytical tools are required.

(7) FHWA (2014) 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. The second phase developed risk management tools to identify what assets to protect. Also proposed in the Gulf Coast study was climate adaptation strategies, and a risk matrix that showed the effects of climate change on transportation assets.

All of the previous research efforts focused on identifying climatic events that may impact the transportation network. None of the studies showed how to quantify the risk of damage. They also did not show how to adopt climate adaptation strategies into TAM practices.

MOTIVATION

With the extreme climatic events (e.g., hurricanes, flooding, storm surge, increased high temperatures) becoming more severe and frequent due to climate change (IPCC 2014), climate change consideration and the risk associated with the climate changing must be considered because they play an important role in affecting the life cycle of transportation assets.

Typically, an asset is designed to a certain life by highway agencies. No considering climate change and the risk that arise from the climate changing can result in asset life reduction, safety issues, and not meeting national infrastructure goals. Many transportation agencies focus on the mitigation, but very little work has been done to quantify the risk of climate change on the transportation assets.

This study has been carried out to determine a framework to incorporate risk assessment of climate change into TAM practices. A methodology has been developed to quantify the risk associated with climate change impacts on the TAM. This study shows, with a case study, how to implement, quantify, and reduce risk using the framework. The traditional method of TAM do not consider climate change risk and with the climate changing this is found to be inadequate in order to keep the infrastructure in a "State of Good Repair."

OBJECTIVES

The major objectives of this thesis are:

1. To develop a framework to incorporate risk assessment of climate change into TAM practices and criteria for prioritization based on infrastructure resilience in order to preserve the "State of Good Repair".
2. To develop a methodology to quantify the risk of climate change impacts on TAM practices.
3. To identify performance measure to monitor climate change impact on transportation infrastructure.
4. To develop mitigation and practical strategies from an implementation perspective to consider climate change performance measures when developing transportation plans.

THESIS ORGANIZATION

This thesis is divided in total seven chapters. Chapter 1 provides a brief introduction to climate change and asset management. Objective and motivations to this project are also discussed. The Literature Review is an important part of this project. It was needed to study the effects of climate change on the transportation infrastructure and study the current transportation asset management. The thorough review of such literature is provided in Chapter 2. Chapter 3 proposes a framework to model

risk assessment of climate change into TAM. The framework is divided into eight steps and is explained in detail in that chapter. A methodology to quantify the risk of damage on transportation infrastructure is shown Chapter 4. Two case studies for bridges and pavements that demonstrates the applicability of the framework and methodology proposed in this report to quantify the risk of failure are shown in Chapter 5. Chapter 6 contains a discussion of the climate risk assessment model. The discussion contains the results of a sensitivity analysis to identify the most relevant parameters in the risk assessment model. TopRank and @Risk, software tools developed by Pallisade, are used for the analyses (Palisade 2017). The conclusions along with the recommendations for the future research are included in Chapter 7.

Chapter 2: Literature Review

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)" (NOAA, 2007). Around the world temperature changes, changes in precipitation patterns, sea level rise, and changes in winter storms patterns can be seen resulting in droughts, flooding, dust storms, possibility of wildfires, and changes in freeze/thaw cycles. A report conducted by the Intergovernmental Panel on Climate Change (IPCC) for the U. S. Department of Transportation displays the changes in climate. Figures 1 and 2 demonstrate the rising temperature trend in the world and an increase in temperature by location respectively.

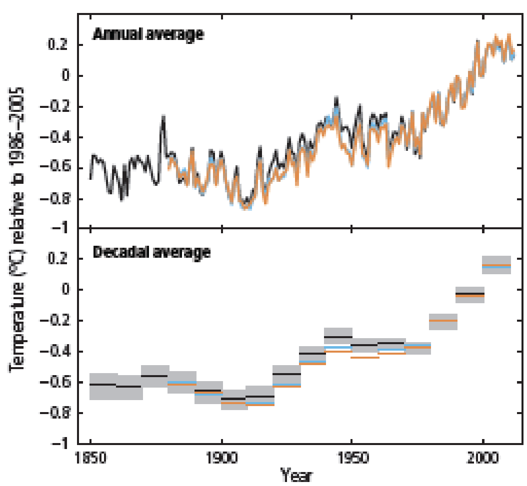


Figure 1.1: Globally Average Combined Land and Ocean Surface Temperature Anomaly 1850-2012 (IPCC 2014)

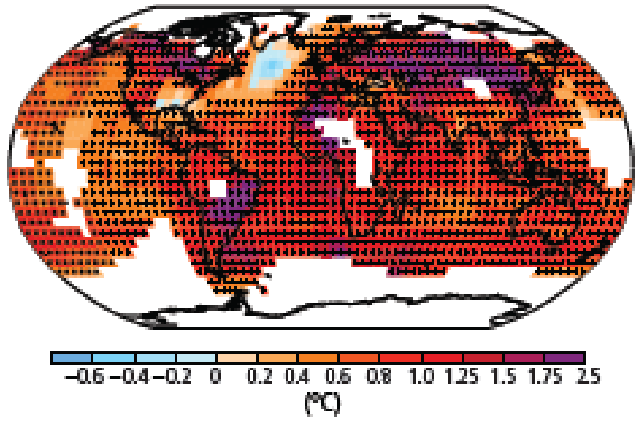


Figure 2: Change in Surface Temperature 1901-2012 (IPCC 2014)

From the figures, a projected increase of the surface temperature of 2° C can be seen. In the annual IPCC report, a rising trend in sea level and change in annual precipitation can be seen. These can be seen in Figures 3 and 4 respectively.

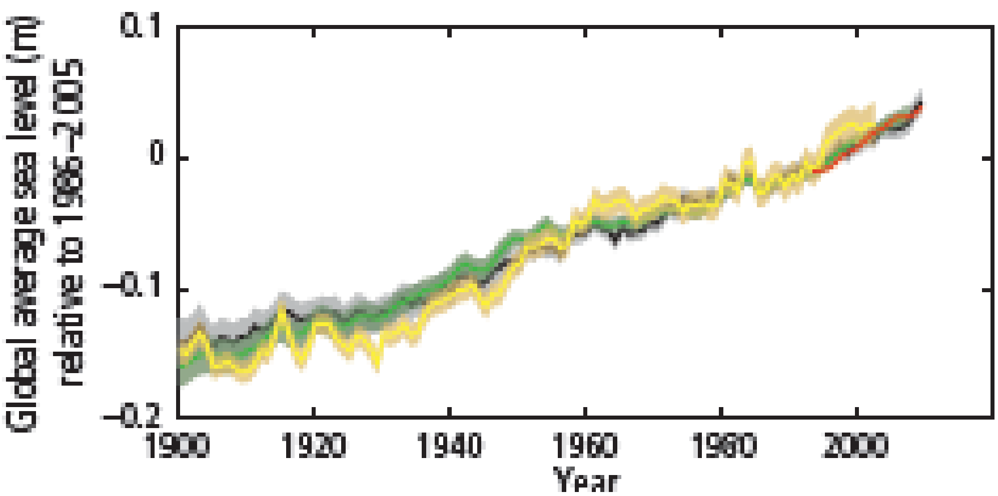


Figure 3: Global Mean Sea Level Change 1900-2010 (IPCC 2014)

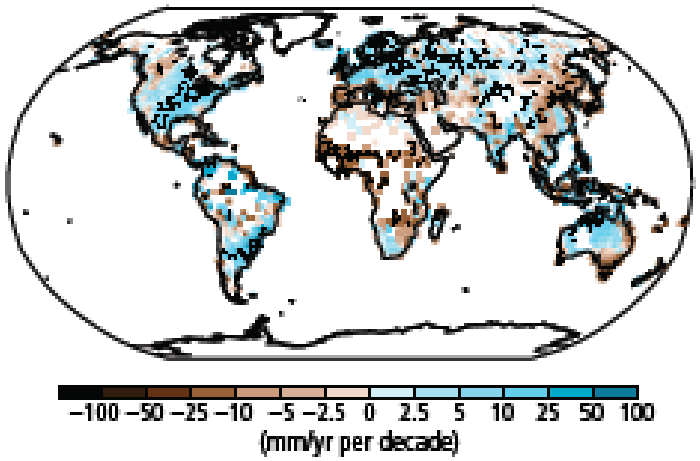


Figure 4: Observed Change in Annual Precipitation 1951-2010 (IPCC 2014)

The IPCC also ran mathematical climate models which to predict the Earth's climate system. The models projected a rise on temperature, average precipitation, and average sea level. Figures 5 to 7 shows IPCC's projections for temperature, precipitation and sea level respectively. The three figures show the observed changes from 1986 to 2005 on the left. On the right, the figures show the projected change from 2081 to 2100. From the figures, an increase of 4-5 °C, 10 percent increase in precipitation, and a 0.5-0.6 m increase in sea level by 2100 can be seen in the United States.

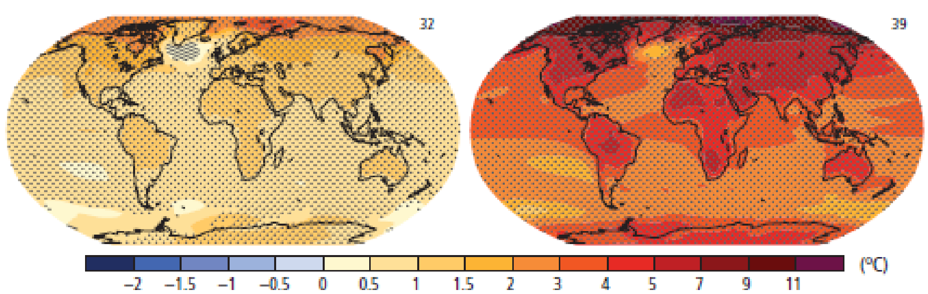


Figure 5. Change in Average Surface Temperature (1986-2005 to 2081-2100) (IPCC 2014)

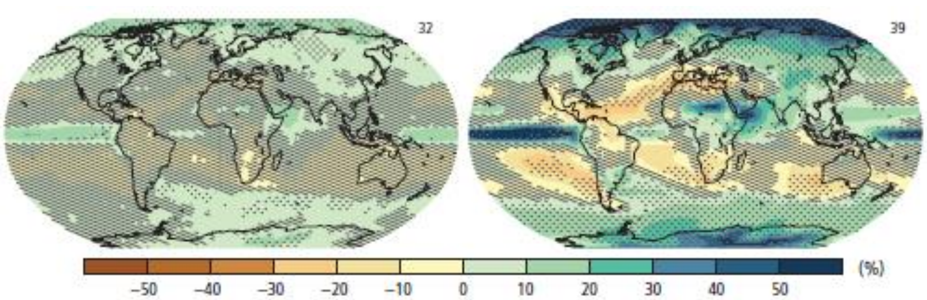


Figure 6. Change in Average Precipitation (1986-2005 to 2081-2100) (IPCC 2014)

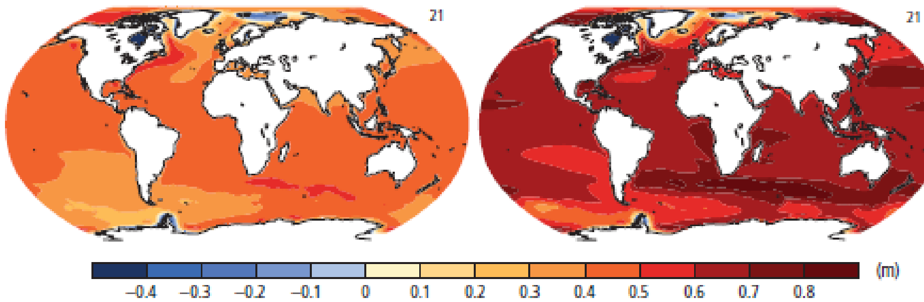


Figure 7. Change in Average Sea Level (1986-2005 to 2081-2100) (IPCC 2014)

Causes of Climate Change

According to NOAA, there are two reasons why the climate is changing. The first is that there is a natural variability in the Earth. 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" (NOAA 2007). The second is that there is a human-induced change. The human induced change is caused by "the increase in anthropogenic greenhouse gas concentrations" (NOAA 2007, IPCC 2014). Figure 8 shows a relationship developed by IPCC for the anthropogenic change. From the figure, the mean temperature increases as a function of cumulative total global carbon dioxide (CO2) emissions (IPCC 2014).

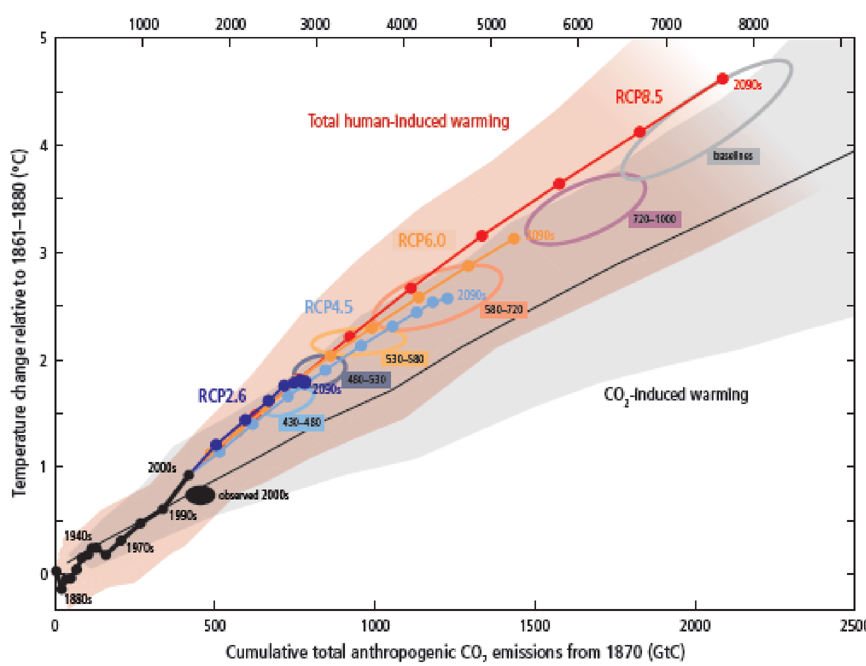


Figure 8: Cumulative Total Anthropogenic CO2emissions from 1870 (GtCO2) (IPCC 2014)

HOW THE CLIMATE CHANGE AFFECTS THE TRANSPORTATION INFRASTRUCTURE

The transportation infrastructure is composed of multiple assets. The assets are bridges, roads, rails, airports, and 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+" (ASCE 2009, ASCE 2013). A "D" rating is defined as "Poor". This 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" (ASCE 2013).

Currently, the "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" (EPA 2016). The combination of poor condition of the infrastructure and climate change could result in a lower infrastructure rating. A sensitivity matrix that was developed for the United States Department of Transportation by ICF International, a global consulting firm with over 5000 specialized experts, evaluated transportation infrastructure and measured the sensitivity that certain infrastructure had to different climate stressors. This matrix was a result of the FHWA Gulf Coast Study (FHWA 2014). "Sensitivity is the degree to which an asset or a system responds to a given change in climate stressor" (ICF International 2014). The different climate stressors covered were:

a. Increased temperature and extreme heat
b. Precipitation-driven inland flooding
c. Sea level rise/extreme high tides
d. Storm surge
e. Wind
f. Drought
g. Dust storms
h. Wildfires
i. Winter storms
j. Changes in freeze/thaw
k. Permafrost thaw

The following subsections describe how climate change affects bridges, roads and culverts, rails, and ports and waterways. Also shown in the subsections are a number of performance measures used for each type of asset.

Bridges

In bridges, increased temperatures and extreme heat results in looking at thermal expansion on the structure and on paved roads. Some bridges with non-movable supports might fail since they are designed to a certain temperature range. In Washington, thermal expansion is considered. The Washington State Department of Transportation (WSDOT) uses Equation 1 below to calculate the total thermal movement range of bridges (WSDOT 2016).

$$\Delta T=\alpha*L_{trib}*\delta T$$

Equation 1: Thermal Expansion on Bridges by WSDOT 2016

Where

ΔT: 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.

Another climatic event that can damage a bridge is floods. Floods can pile debris on bridge decks, impart lateral forces on railings, and in some cases lift the deck from the supports. In the substructure of the bridge, excessive precipitation can increase the flow velocity and depth of a stream or river. This affects the local scour depth or depth of erosion to the bridge supports. When the water from a body of water reaches the low chord bridge elevation, "the scour depth could increase by 200%-300%" (ICF International 2014). Damages can result in the bridges being removed from service. Debris can also result in bridges being unserviceable until the "debris is cleared and/or structures are repaired and evaluated for integrity" (ICF International 2014).

Sea level rise combined with extreme storms can increase water levels near a bridge. Since "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." Clearance under bridges is reduced due to higher baselines (ICF International 2014, Froehlich 2003).

Storms can create waves that stress the superstructure and the substructure of a bridge. ICF International state 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." This shift can damage abutments, bent caps, and girders. During Hurricane Katrina, most bridges damaged were near water (ICF International 2014, Padgett et al. 2009). Figure 9 displays a bridge along the Texas coast thaw was damaged after Hurricane Ike.

Figure 9: State Highway 87 Rollover Pass Bridge Along the Texas Coast (Padgett et al. 2009)

Another climate stressor on bridges is wind. Winds can stress bridges with additional horizontal forces and larger waves created by higher winds speeds. High winds can also lead to dust storms. The dust storms can buildup material on the bridge deck, which will only retain water or moisture. This moisture can be damaging to the bridge deck and structure (ICF International 2014). High winds can also spread wildfires at a faster rate. "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 (ICF International, 2014, Cannon and DeGraff 2009).

Winter precipitation has also started to change. According to the National Research Council, there is a "tendency for increasing winter precipitation and decreasing summer precipitation as global temperatures increase" (NRC 2008). This increase in precipitation can saturate soils and as a result the bridge is exposed to greater movement. Early start of seasonal warming can lead to shorter winters but longer thaw seasons. This change in the freeze-thaw cycle can result in damage to bridge decks and expansion in joints. Water begins seeping into the pavement on the bridge deck and accumulates in the aggregate, resulting in the cement becoming susceptible to cracking. Over time, this cracking expands upward until it reaches the road surface (ICF International 2014, NRC 2008). Figure 10 displays the damage to concrete from freeze-thaw. This happens when an increase in the freeze-thaw cycles cracks concrete and pavement surfaces (ICF International 2014).

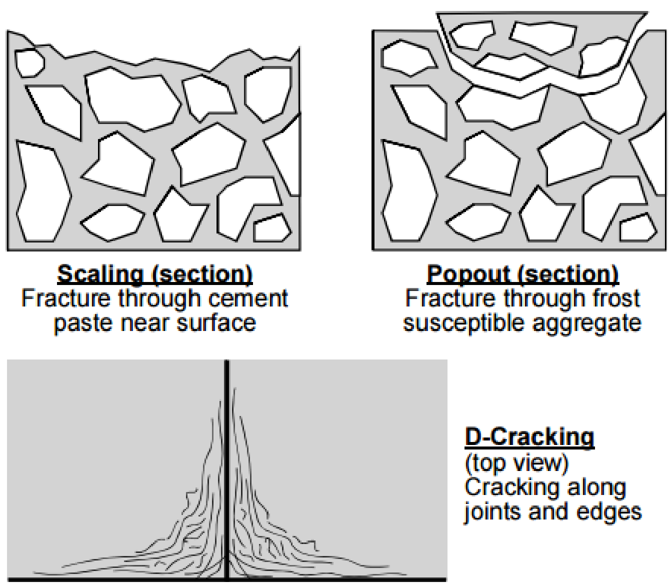


Figure 10: Forms of Freezing and Thawing Damage to Concrete (West et al. 1999)

The impact of these climate change events on bridges can be monitored using performance measures seen in Table 1 implemented by Departments of Transportation.

Table 1: Common Performance Measures for Bridges (Chang et al. 2017)

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.

Roads and Culverts

Constant high temperature can result in asphalt concrete pavement to soften resulting in rutting and shoving. According to a report conducted 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" (Willway et al. 2008). In July 2006, 80km of damage to rural highways of Leicestershire, England occurred due to high temperatures (Willway et al. 2008)

Precipitation falling as rain rather than snow leads to immediate runoff. This increases the risk of floods, landslides, slope failures, and consequent damage to roadways, especially rural roadways in the winter and spring months. In paved roads, flooding can cause pavement and embankment failure and is more prevalent when the water is high enough to flow over the roadway surface. Over time, precipitation can also worsen existing pavement damage like cracking. During heavy precipitation events, rain can leak in under the pavement due to the cracks and damage the subgrade. The subgrade is

very sensitive to moisture levels (NRC 2008, ICF International 2014). Unpaved roads and culverts can also be affected by heavy precipitation. In culverts, heavy precipitation can cause debris accumulation, sedimentation, erosion, scour, piping, and conduit structural damage. All these can result in flooding (ICF International 2014).

Roadways can get damaged by the storm surge from hurricanes like Hurricane Sandy and many other hurricanes. Hurricane Sandy caused massive flooding of roads and tunnels in New York and New Jersey Roadways and tunnels in New York City. The flooding included the Brooklyn-Battery, Holland, and Midtown Tunnels and the Battery Park underpass (Kaufman et al. 2012 and ICF International 2014). Figure 11 displays the flooding resulting from Hurricane Sandy on New York City.

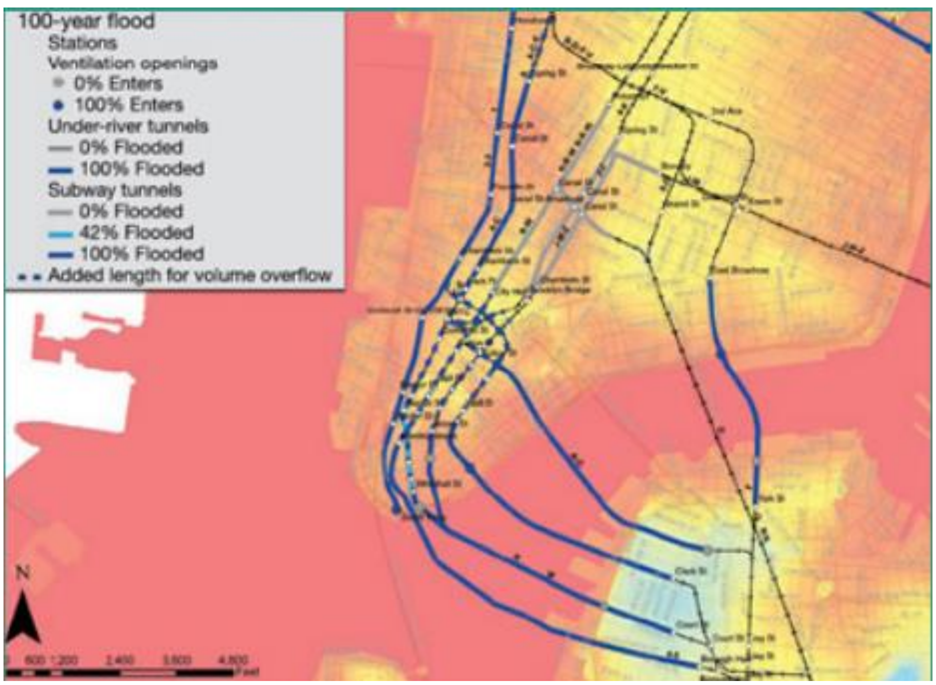


Figure 11: Flooding in New York as a Result of Hurricane Sandy (Kaufman et al. 2012)

High winds usually accompany storms. Although winds do not directly damage the road, they can severely disrupt road traffic and other service activities by damaging trees, buildings, and other structures to disrupt activities (ICF International 2014). In New York, Hurricane Sandy's strong winds knocked down trees resulting in power outages to millions (Kaufman et al. 2012). The debris can also

end up in the storm water drainage. This can result in flooding impacts to the surrounding area (ICF International 2014).

Drought can also damage pavements by creating cracking and splitting. In 2011, droughts in Texas led to asphalt splitting and cracking (ICF International 2014 and Auber 2011). During a drought, the clayey soil will shrink and if the movement is great, the asphalt will crack as a result. This is due to the fact that clayey soils are susceptible to shrinking and swelling. Figure 12 below shows the cracks that formed in Fort Worth as a result of a drought.

Figure 12: Cracks in Pavement Due to Drought in Texas (Auber 2011)

Wildfires are extremely dangerous to human life and roadways. The wildfire's high heat can ignite road surfaces and soften the asphalt, which can result in rutting. After a wildfire, hillslopes of vegetation and soil properties change resulting in the change of watershed hydrology and the sediment-transport processes (ICF International 2014). A rainstorm after a wildfire can increase runoff that can erode soil, rock, ash, and vegetative debris from the hillslopes and damage roads and culverts (Verdin et al. 2012). The debris-flow can result in blocking drainage ways, and damage structures (ICF International 2014). Figure 13 displays a landslide that covered a roadway in Arizona after the South Canyon wildfire.

Figure 13: South Canyon Landslide in Arizona (USGS 2012).

The increase in temperatures is also resulting in more freeze-thaw cycles a roadway experiences. When a roadway experiences a freeze thaw cycle, damage occurs when the melting of ice lenses below the pavement expand. This happens when the water in the soil rises due to capillary action. After rising, the cold freezes the water creating ice lenses. The ice lenses will expand the pavement upward. This can be seen in Figure 14. When the temperature increase, the ice lenses melt. The water is then trapped between the pavement and the frozen soil below which weakens the soil. Traffic loads during the time results in the damage to pavements (Orr et al. 2017).

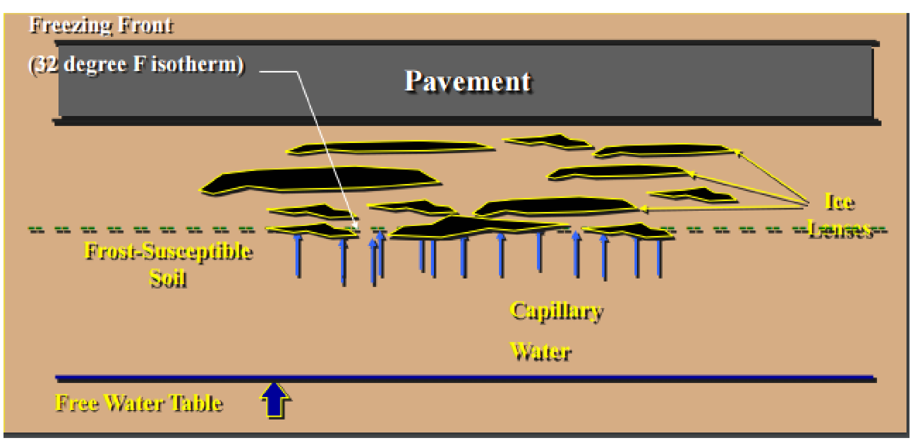


Figure 14: Pavement Heave Due to Creation of Ice Lenses (Orr et al. 2017).

Figure 15 shows variation of the subgrade resilient modulus over a freeze-thaw cycle. This figure shows that, during freeze periods, the soil will gain more strength. During thaw periods, the strength is lower than the normal strength before returning to normal.

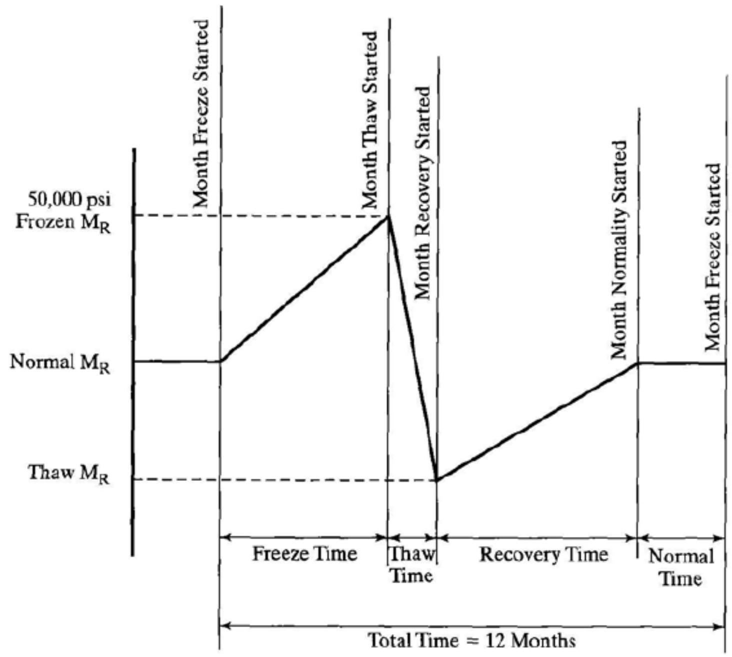


Figure 15: Subgrade Resilient Modulus Seasonal Variation (Huang 1993)

Tables 2 and 3 summarize the performance measures implemented by Departments of Transportation of pavements and culverts respectively that can be used to monitor the impact of these climate change events.

Table 2: Common Performance Measures for Pavements (Chang et al. 2017)

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"

Table 2: Common Performance Measures for Pavements (Chang et al. 2017) (cont'd)

Performance Measure	Description
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"
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.

Table 2: Common Performance Measures for Pavements (Chang et al. 2017) (cont'd)

Performance Measure	Description
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 (Chang et al. 2017)

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)

Rails and Tunnels

High temperatures can also affect railways and can cause buckling. Buckling occurs when the metal in the track expands beyond the capacity of the supporting infrastructure. If the metal cannot expand beyond the limitations, the track can buckle either vertically or horizontally. (ICF International 2014). Figure 16 displays an example of rail buckling due to high temperatures.

Figure 16: Example of Railroad Buckling (U.S. DOT 2015)

Precipitation also affects rail systems. Underground systems are sensitive to heavy rains and storm surge. The situation is worst for systems near bodies of water due to the rise in sea levels. Precipitation events can also flood transit systems and stations. If the water reaches the electrified third rail, the flooding can also cause rail sensor failure and permanent damage to rail (ICF International 2014). Hurricane Sandy flooded many subway tunnels. Figure 17 displays the pumping of a tunnel after the flooding had occurred in New York (ICF International 2014).

High velocity winds can damage rail infrastructure indirectly especially in wooded areas since falling trees and other wind related debris can damage the track. High velocity winds can damage rail infrastructure indirectly similar to roads. Falling trees and other wind related debris can damage and disrupt rail, signals, and crossing gates (ICF International 2014). High winds can also aid the progress of a wildfire that can directly damage wooden bridges and rail ties. A wildfire's high temperatures can cause the rail to buckle. Since wildfire temperatures can reach 2,000℉ and buckling can occur at rail temperatures of just over 100℉, railways can easily buckle (ICF International 2014).

Figure 17: Flooding of a Subway Tunnel after Hurricane Sandy in New York City (Kaufman et al. 2012)

The rail infrastructure is also affected by freeze-thaw cycles. Similar to roads, the water expansion from the freeze-thaw cycles can cause damage to railways due to the changes in strength of the soil foundation. Table 4 summarize the performance measures implemented by Departments of Transportation of rails and tunnels that can be used to monitor the impact of these climate change events.

Table 4: Common Performance Measures for Rails and Tunnels (Chang et al. 2017)

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 (Stenstrom et al. 2012)
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 (Liu et al. 2015).
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 (Liu et al. 2015).

Table 4: Common Performance Measures for Rails and Tunnels (Chang et al. 2017) (cont'd)

Performance Measure	Description
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 (Liu et al. 2015).
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 (Liu et al. 2015).
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 (ICF International 2014).
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 (Allen et al. 2015).
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 (Allen et al. 2015).
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 (Allen et al. 2015).

Ports and Waterways

Ports and waterways are a major part of the transportation network and can also be affected by climate change. They are essential for international and domestic trade. According to ICF International, "Higher sea levels can increase the risk of chronic flooding" (ICF International 2014).As for flooding, the flooding can damage channels, damage 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" (ICF International, 2014).

High winds and changes in the freeze-thaw cycle can also affect ports and waterways. "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" (ICF International 2014). As discussed in previous section, freeze-thaw can undermine the foundations of infrastructure through the weakening of soil.

One performance measure for ports and waterway was found. The Physical Condition Rating of Critical Coastal Navigation Infrastructure rates the ports and waterway's infrastructure on a scale of A to F (significant damage to completely degraded) (CMTS 2015).

ECONOMIC IMPACT

Economic losses for a region can be a result of extreme climatic events. This can result due to the unbudgeted expenses that an agency will have to invest to return the transportation system to a working condition. This can be seen in a study conducted to report the bridge damage and repair costs from Hurricane Katrina. In damages only to bridges, the hurricane cost an estimated $8.15 million to Alabama, $52.23 million to Louisiana, and $569 million to Mississippi (Padgett et al. 2008).

One way to determine the economic impact is described in NCHRP Report 750. It describes a benefit cost methodology to evaluate climate change adaptation strategies. The methodology described in this report consists of eight steps. The steps are 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 (NCHRP 2013).

TRANSPORTATION INFRASTRUCTURE LAWS

Presently, there are two main national laws on transportation infrastructure. They are the Moving Ahead for Progress in the 21st Century (MAP-21) and Fixing America's Surface Transportation (FAST) Act. The first law, MAP-21, was signed on July 17, 2012 and established a performance and outcome based program. MAP-21 was extended until May 2015. "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” (U.S. DOT 2013). The seven national goals are shown in Table 5.

Table 5: MAP-21 National Goals (U.S. DOT 2013)

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 FAST Act 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” (House Transportation and Infrastructure Committee 2015). The bill enacted in December 2015 and extended until fiscal year 2020.

In October 24, 2016, the Federal Highway Administration (FHWA) released a rule for asset management plan. The plan stated 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” (FHWA 2016b). In the next sections, transportation asset management and risk management practices are discussed.

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" (U.S. DOT 2007). TAM is comprised of seven components and is displayed in Figure 18. They are 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 by first identifying goals and policies for maintenance, repair and rehabilitation. Goals and policies need to be clearly defined having clear performance measures to set targets to be able to measure progress for the transportation infrastructure. The next step in the system is asset inventory. An agency, to be successful, must keep updated records of the asset inventory to provide reliable data for all the assets. After the asset inventory, TAM requires performing periodical condition assessments of all the assets in the inventory. It also requires performance models to forecast the future condition. Alternatives for maintenance and rehabilitation programs are analyzed next. The programs are used to determine the best course of action in terms of performance and resource allocation. The next step is the short- and long- range plans, which come as a result of the evaluations. Following the plans, program implementation begins to preserve the assets in the most cost-effective manner. The final step in the TAM is to monitor the asset performance and check if the assets operates as expected. This checks to see if the goals are being accomplished (Meyer et al. 2009).

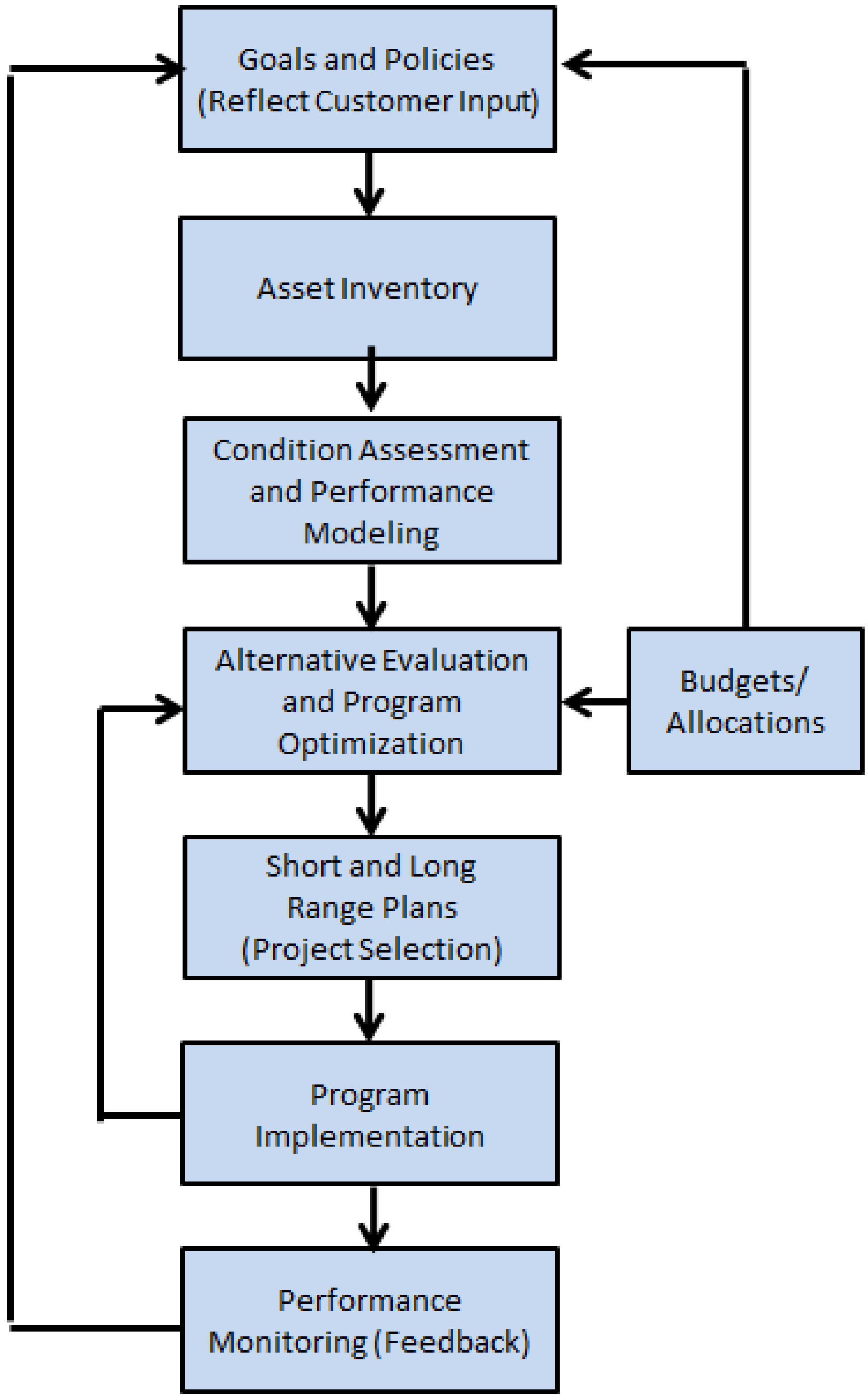


Figure 18: Transportation Asset Management Process (U.S. DOT 2007)

Chapter 3: Development of the Framework for Modeling Climate Change in TAM

Framework for Climate Change Modeling in TAM

As climate change continues to change weather patterns, the resilience of transportation assets must be considered (U.S. DOT n.d. a). Although there are a number of definitions for resiliency, in this thesis resilience in infrastructure is defined as “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” (Minaie 2016). A highly resilient asset continues to function properly under extreme circumstances. As a result, TAM practices should consider the impact of climate change on the resilience of transportation infrastructure.

If an asset is not resilient, an extreme climatic event will have costly impacts to humans and budgets (NCHRP 2014). AASHTO (2012) and FHWA (2012) offered deterministic methods like low, medium, or high levels of risk to integrate climate change into TAM practices. 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” (AASHTO 2012). As for the FHWA, it 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 19 displays the project management process for individual assets. The first step in this process begins with the monitoring of the current performance measures to develop the project plans. After that, the forecast of the asset performance is conducted for the actions considered in the project plans. Next, depending on available funding, the project is then designed and delivered. As a result of this process, an improved performance is expected for this asset while it is being monitored over time. The project management process must be part of the overall TAM and should consider climate mitigation practices for the entire transportation network.

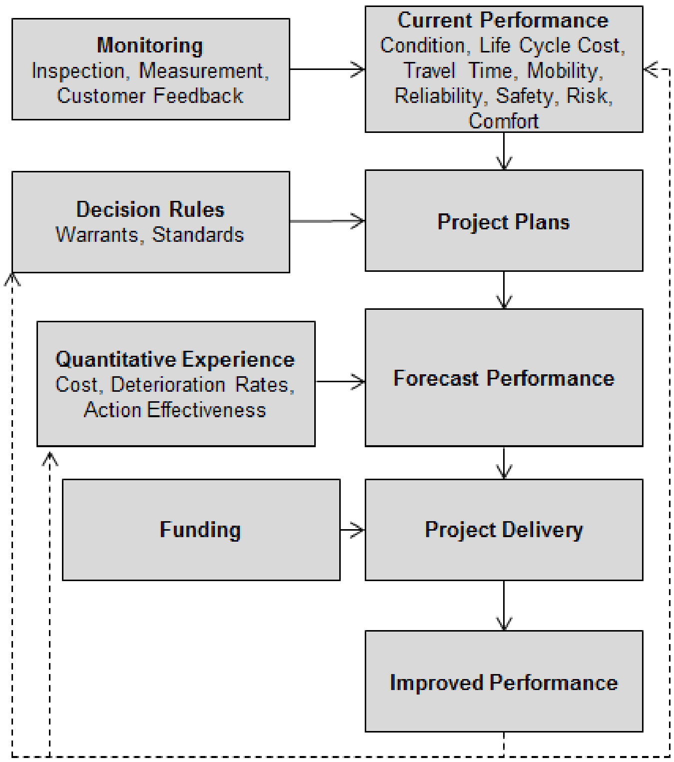


Figure 19: Project Management Process (AASHTO 2011)

The framework for climate change modeling in TAM is presented in Figure 20. This was developed using the Transportation Asset Management Process and the Project Management Process described previously. The framework for climate change modeling in TAM was developed for the entire transportation network and consists of eight main steps.

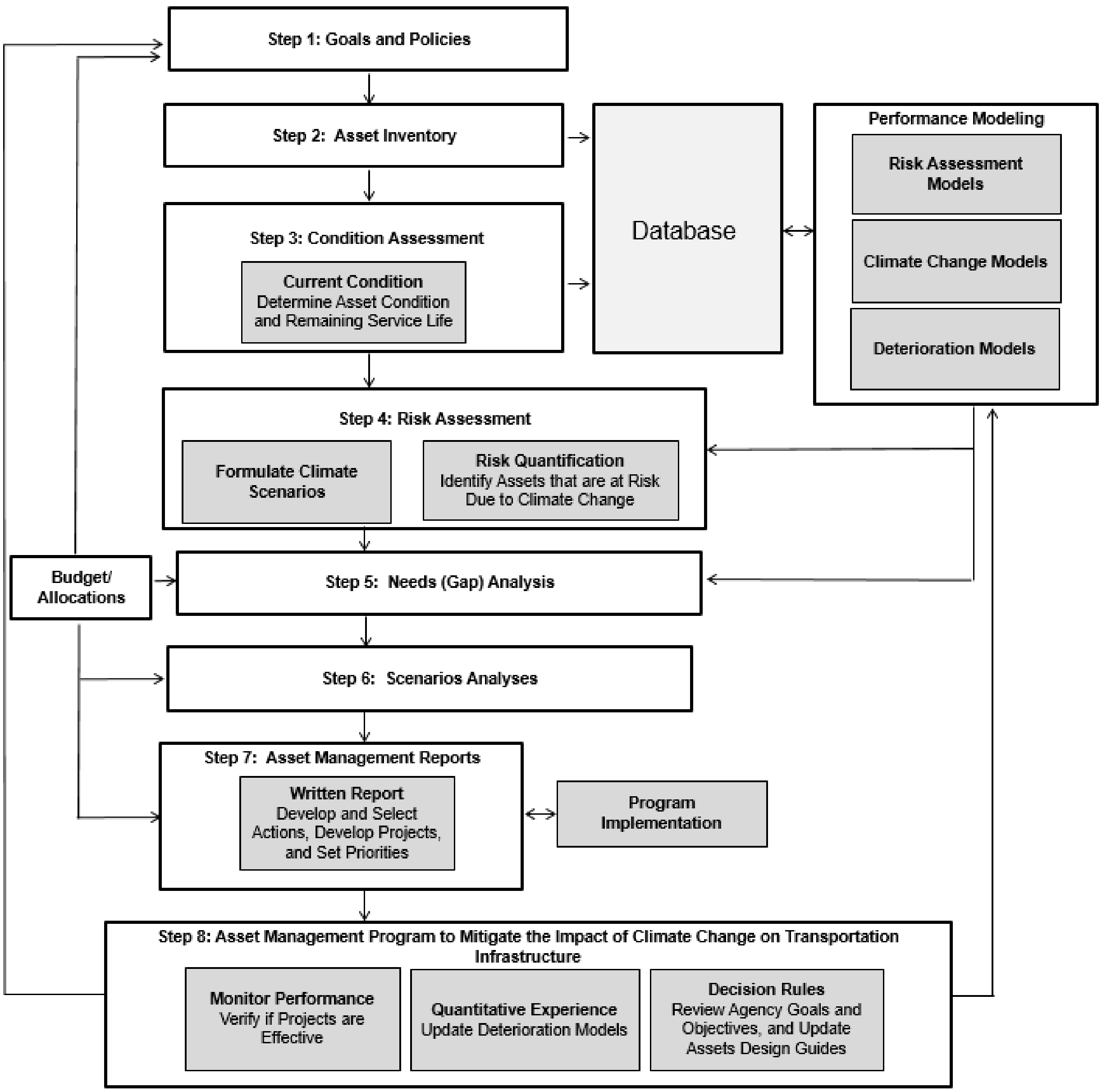


Figure 20: Framework to Integrate Climate Change Impact Analysis into TAM Practices

Step 1: Goals and Policies

The framework begins with an agency defining the goals and policies. Goals are the "results to be achieved" while policies are the "intentions and direction of an organization" (ISO 2014). Without clearly identifiable goals, a lack of guidance and direction will exist. Goals and policies help in the evaluation of assets and facilitate planning. In this step, an agency must also define the desired level of service, life cycle, or performance of an asset. The development of performance measures can useful to gage the asset's conditions and track progress towards achieving the goals. Climate change performance

measures will need to be selected in this step. This will facilitate and track progress of the goals and policies. More specific performance measures are required to properly evaluate the effects of climate change. An example of a performance measure is the number of bridges in high risk of climate change impact.

Step 2: Asset Inventory

According to the FHWA, "a major component of an effective Asset Management program is the existence of an inventory of infrastructure assets by type and their condition" (FHWA 2017). The inventory should include the following:

- Type of asset
- Dimensions
- Location
- Any other pertinent information to identify the asset 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" (FHWA 2017). Apart from collecting asset information, climate data collection is important in the region. The National Oceanic and Atmospheric Administration (NOAA) created an online database with climate change tools, as see in Table 6, that can help to analyze climate change scenarios (NOAA 2017).

Table 6: NOAA Climate Change Tools (NOAA 2017)

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/

Table 6: NOAA Climate Change Tools (NOAA 2017) (cont'd)

Tool Name	Climate Data	Description
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/
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=852 ca645500d419e8c6761b923380663

If the information in the toolkits is not found for a region, then data collection must be conducted. This is done 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 5 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 powerful storms that return at a faster rate.

Step 3: Condition Assessment

In this step, the current condition of an asset is determined. This is important to the framework because periodic evaluations are essential to identify needs and budget. It is also important to do periodic evaluations to determine if an asset component is at risk of failing due to an extreme climatic event. Typical inspections for main transportation assets including pavements, bridges, culverts, and signs are conducted once a year while other assets like pavement markings and guardrails are inspected tice a year or when a crash occurs. It is important to recognize the relationship between asset condition and the remaining service life. Remaining service life is the time that takes an asset to go from serviceable to no longer serviceable and the condition is a measurement of health of an asset.

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)" (Ashely et al. 2006). By combining the likelihood and the impact, one can access the level of risk due to an event using Figure 21.

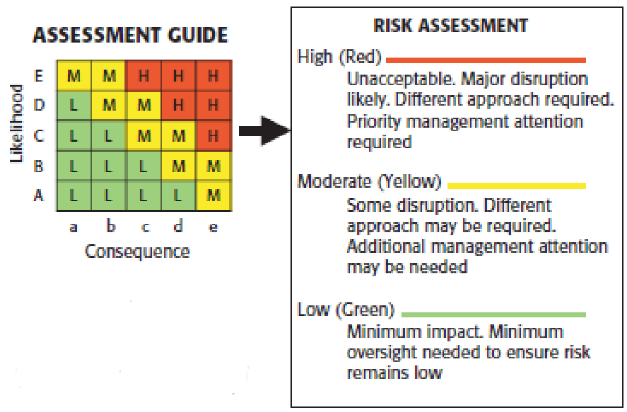


Figure 21: Risk Assessment Matrix (Ashely et al. 2006)

In this step, the likelihood of a climate event to occur and the severity of the damage to the asset's condition is evaluated under different climate scenarios. "What If" analyses need to be used to assess the risk of an asset of being damaged under high, medium and low risk impact scenarios. For example, for temperature change, the 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) Analyses

The Needs Analysis is also referred to as a Gap Analysis. This 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". This is done by reducing the risk of failure due to climate change events. The risk reduction is determined by calculating the RPN discussed later in Chapter 4. For each scenario, the All Needs Scenario must be found. This determines the level of investment required to

reduce the risk to an acceptable level. Figure 22 shows the risk management process. In order to reduce the risk, the whole process must be considered.

Figure 22: Risk Management Process (Ashley et al. 2006)

The FHWA proposed this risk management process for individual projects, and it can also 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. In this step, "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. They are 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" (Ashley 2006)

According to Ashley, there are four alternatives to manage risk. Avoidance is the elimination of risk and 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 while acceptance is the agreeing of risk as they occur. In the fourth step, "Allocate", risk management activities are assigned 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" (Ashley 2006).

Climate mitigation involves actions to reduce the consequences of climate change by focusing on the source (e.g. greenhouse gases). 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 7 summarizes some climate mitigation and adaptation strategies. Some of the climate adaptation strategies were fostered by the United Nations (2013) and (U.S. DOT n.d. b).

Table 7: 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. • Build a sheetpile wall and cap. • Relocated sections of roadways to less vulnerable to flooding. • Create a living shoreline (e.g. mashes) • 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. • Check bridge designs to assure decks are tied to substructure.

Table 7: Climate Mitigation and Adaptation Strategies (cont'd)

Climate Change Stressor	Transportation Asset Affected	Mitigation and Adaptation Strategies
Increase in Frequency of Strong Storms	• Rail lines • Bridges • Roads	• Increase levee height and strength. • Increase drainage capacity. • Return some coastal areas to nature. • Protect critical evacuation routes. • Decentralize systems.

These mitigation and adaptation strategies can be implemented in any 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. An example of an expensive strategy is increasing the elevation of a bridge or relocating sections of roadways. Other strategies, such as painting white tracks, are not as expensive.

Step 6: Conduct Scenarios Analyses

In this step, scenario analyses can be formulated for different budget levels, climatic events, and risk tolerance. An example for budget scenario 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 favor 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 these 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 Report and Risk Assessment

Here, a risk assessment section is included in the asset management reports. This section describes the threats and actions to improve the resilience of the asset by reducing the risk of damage where the actions are grouped into project categories and prioritized by asset groups. The driving factors of these projects are the 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 improve the action or manage the risk. 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 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. It should include the actions needed to mitigate the impact of climate change in the short and long-term planning period. Performance monitoring must be conducted in order to check if the program implemented is working as expected. The asset condition is also monitored to determine if the deterioration models used are reliable or need calibration. Climate change information is 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 due to extreme climatic events.

Chapter 4: Methodology to Quantify and Report the Risk of Asset Failure Due to Climatic Events

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

RISK ANALYSIS MATRIX AND RISK QUANTIFICATION

A risk analysis matrix, shown in Figure 23, is used to determine the assets at risk of failure due to a climatic event. Based on this information, assets in the transportation network are prioritized.

Identify				Assess/Analyze					Mitigate & Plan	Allocate		Monitor & Control			
Current Condition									Proposed Solutions				Results/Revisit		
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
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	6	L	24
		2: 15 ft Storm Surge	Visual, Height of water	10	9	None	H	90	Rebuild with 30ft Elevation	State DOT	-	10	1	M	10
		3: 5 ft Storm Surge	Visual, Height of water	4	10	None	M	40	Rebuild with 30ft Elevation	State DOT	-	10	1	M	10

Figure 23: Example of a Risk Analysis Matrix

The risk analysis matrix has the five sections of the risk management process: identify, assess/analyze, mitigate and plan, allocate, monitor and control.

Identify

In this section, information about the extreme climatic events, asset under evaluation, climatic scenarios of potential causes of failure, and recommended detection actions are entered in the matrix. Some examples for potential cause of failure are wildfire closure, and flooding. The detection actions are recommended on how to inspect and check if the asset has failed. This could be either visual or with a monitoring device. Performance measures described in the previous chapter are recommended to evaluate the magnitude of damage.

Assess/Analyze

In this section, probabilistic equations quantify the risk. The risk is in terms of the likelihood of occurrence and severity of damage during the climatic event. The occurrence is the probability of the asset to experience an extreme climate event during its lifetime. This is modeled using 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.

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

Equation 2: Likelihood of Occurrence Equation

Where

P[X≥1]: Probability of an asset to experience at least one extreme climatic 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 climatic events to occur and therefore k=0.

For the severity, this is the probability of an asset to experience damage or failure during the extreme climatic event. Severity is modeled using 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 to express the severity in a 1 to 10 number scale. The number of 20 is used since the standard normal distribution under the constraints given only ranges from 0 to 0.5. Equation 3 shows the equation to calculate the severity.

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

Equation 3: Severity Equation

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.)

Cp: Clearance Parameter (R - L)

The risk of failure is expressed in terms of the occurrence and severity. The level of risk is then assigned using the risk quantification chart shown in Figure 24.

Occurance \ Severity	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

Figure 24: Level of Risk Quantification Chart

To identify assets at high risk, the Failure Modes and Effects Analysis (FMEA) proposes a Risk Priority Number (RPN). The RPN was proposed by the University of Colorado Denver (UC Denver). It calculated the RPN by multiplying the likelihood of occurrence, severity, and detection based on surveys and expert opinion to determine the occurrence, severity, and detection. The detection factor is scaled

from 1 to 10 (detectable to undetectable) and aims to measure if the risk could be detected (UC Denver 2004).

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

$$RPN = Occurrence * Severity * Significance$$

Equation 4: Risk Priority Number Equation

Assets that are vital to an agency or places more people's lives at risk if it fails will have a higher significance value than non-vital assets. An example of this can be seen in assets in an evacuation route would have a higher significance than those that are not.

Mitigate and Plan

In this section of the risk analysis matrix, recommended actions are described. Actions can vary from inspecting the asset more frequently to repair or reconstruction. Other mitigation and adaptation strategies were previously discussed in Chapter 3.

Allocate

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

Monitor and Control

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

HOW TO REPORT THE IMPACT OF CLIMATE CHANGE ON TRANSPORTATION ASSETS

Reports in TAM practices are important. They can communicate the impact of climate change at different management levels: strategic, network, and project. At the strategic level, decisions on policies and funding allocation are made. At the network level, decisions are made on how to allocate available funds among different asset groups like roads and bridges (Chang et. al 2017). At the project level, the most cost-effective risk reduction actions are identified. For each individual asset components in the transportation network, the asset condition, remaining service life, current risk level (risk quantification chart), RPN, Cost to preserve or repair the asset, and recommended risk reduction action and cost should be added in the report. Figure 25 and 26 show an example of a two-page Score Card with this information.

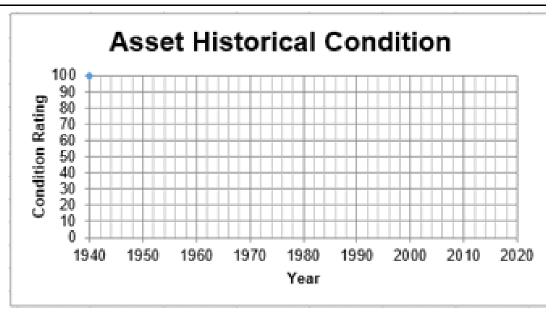
SCORECARD	
State:	
Place Name:	
County:	
Asset Type:	
Asset Location:	
Latitude:	
Longitude:	
Year Built:	
Level of Service:	
Owner:	
Asset Material Design:	
Asset Dimensions:	
Other Asset Information:	
Asset Structural Condition:	
Asset Substructure Conditions:	
Asset Rating (IRI, SR, etc.):	
Asset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

Figure 25: 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 26: Example of a Scorecard, Page 2

Performance measures to show the impact of climate change at the network and strategic levels are necessary to assist agencies and help with the awareness of the assets at risk. Specific performance measures specific to climate change are recommended. Some examples of the performance measures are as follows:

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

It is important to present these performance measures in a concise and easy to understand form. Figure 27 and Figure 28 show an example of how to represent this information graphically. Figure 27 shows the percent of asset components in each asset group at different levels at risk and Figure 28 displays an example of the population at risk due to a climatic event. It is important to note that the data in these figures are not representative of any specific agency and is only provided as an example. For both figures, the left would show the current condition and the right would show the projected results.

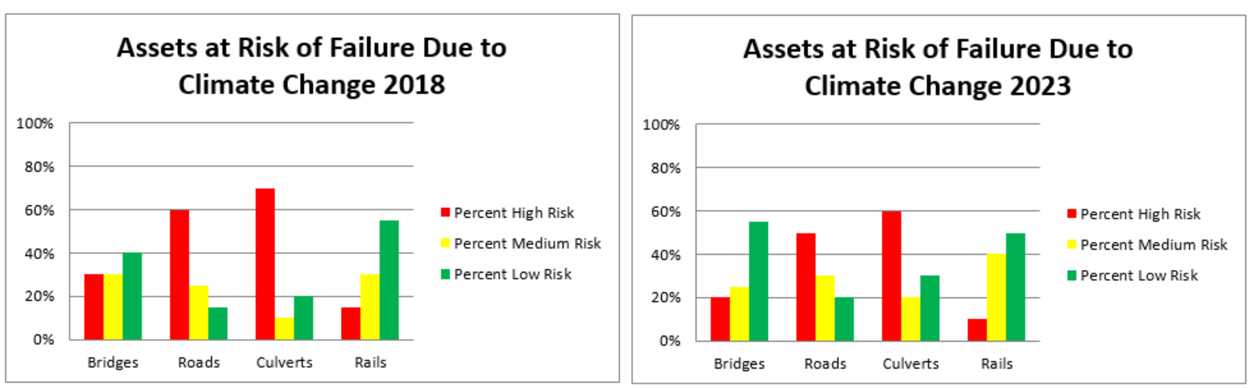


Figure 27: Assets at Risk of Failure Due to Climate Events

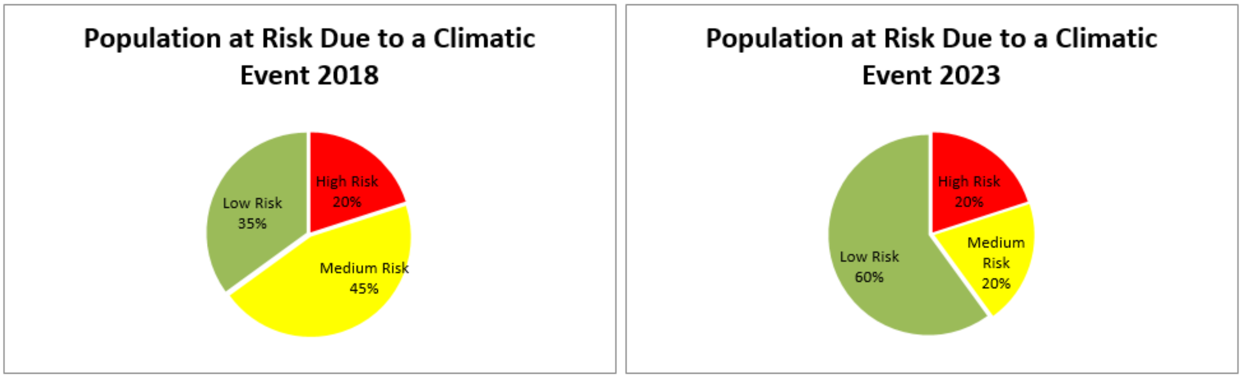


Figure 28: Population at Risk of Failure Due to Climate Events

Graphs like these can be used in the reports to easily show the number of assess at each risk level. They can also show the 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 be included in the reports. The maps can help visually identify the location of the assets at risk due to climate change.

As climate change continues to affect weather patterns, resilience must be included into TAM practices. To measure resilience, a Life Cycle Analysis (LCA) must be conducted as seen in Figure 29. The figure also shows how an extreme climatic event will appears as a vertical line in the life cycle indicating a loss of service life.

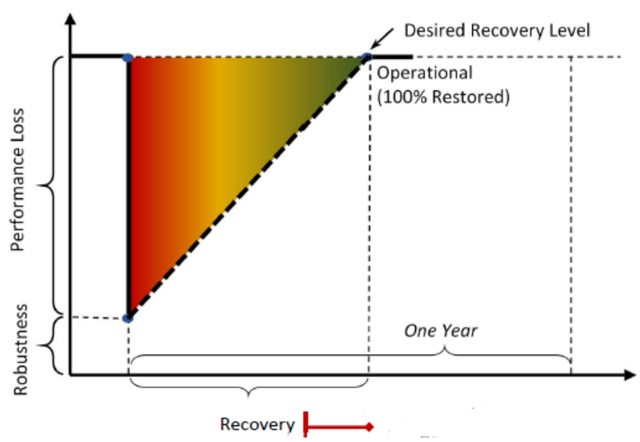


Figure 29: Asset Resilience in LCA (Minaie 2016)

The next sections illustrate the impact on the asset condition due to an extreme climatic event. The events result in the loss of service life. Condition is a measurement of asset health. 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.

Pavements

Figure 30 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 and over time, if no maintenance is conducted, the pavement condition crosses the maintenance and rehabilitation treatment zones where it is in need of reconstruction to reestablish its functionality. Once the pavement reaches the reconstruction stage, its remaining life is over.

On the other hand, the service life of the pavement can be extended if timely maintenance is scheduled. However, when an extreme climate event hits a region, a pavement can suffer a sharp decline in condition. Here the pavement becomes in need of rehabilitation or reconstruction no matter its previous condition. Figure 31 illustrates that if no action is taken to repair the damage, then the pavement becomes unserviceable.

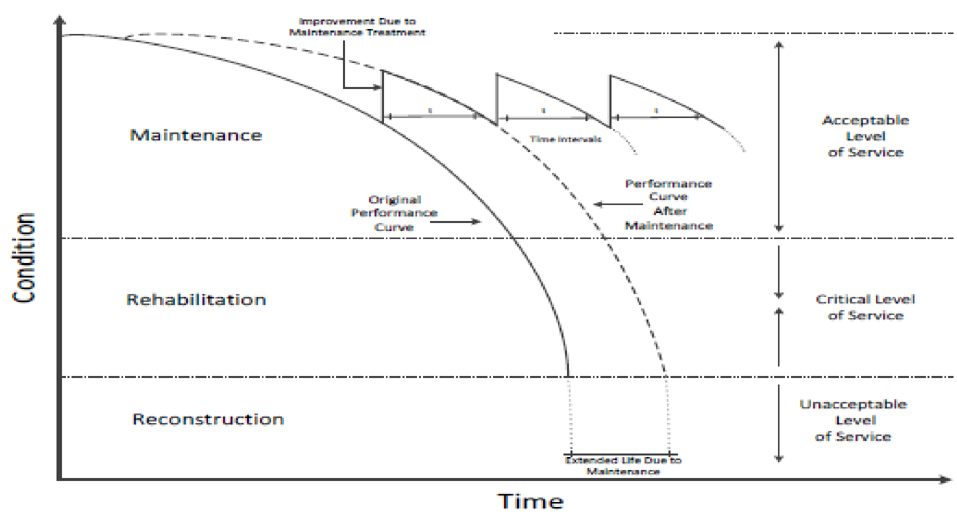


Figure 30: Pavement Condition Deterioration Curve (Chang et al. 2017)

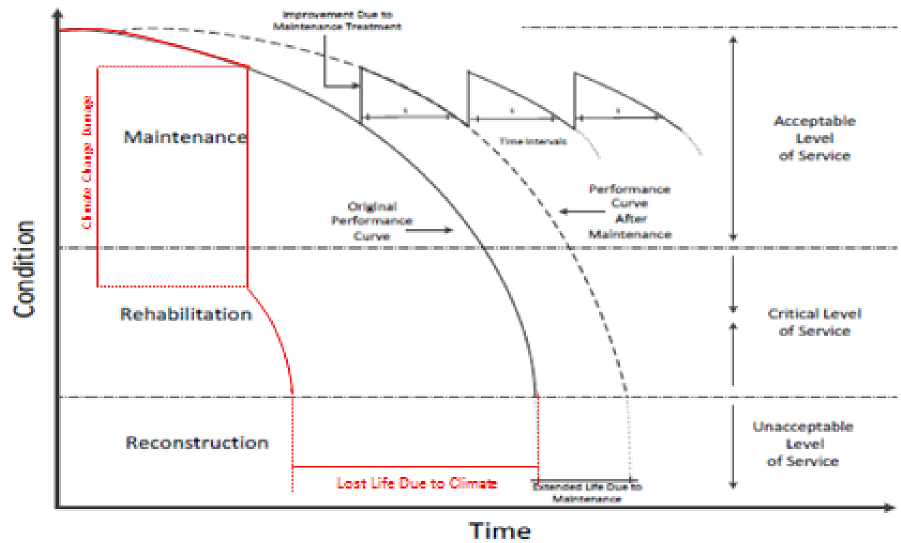


Figure 31: Pavement Condition and the Effect of Sever Climatic Events

An extreme climate event affects the entire pavement network. Figure 32 shows the percentage of pavements in very good/good, and poor/very poor conditions over time in normal working conditions, where the percentage of pavements in state of good repair decreases, the number of pavements in poor condition starts to increase. Figure 33 illustrates that a situation where if an extreme climate event occurred in 2016, then there will be a spike on the graph.

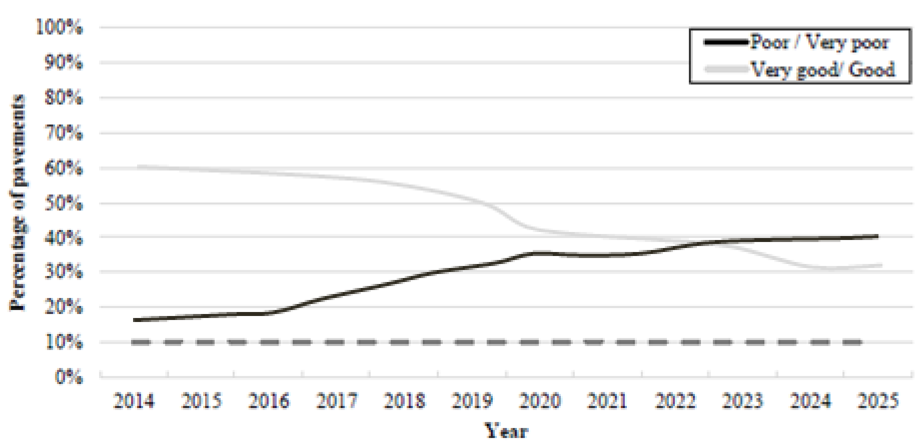


Figure 32: Projection of Pavement Condition Categories over Time in Normal Working Conditions (Chang et al. 2017)

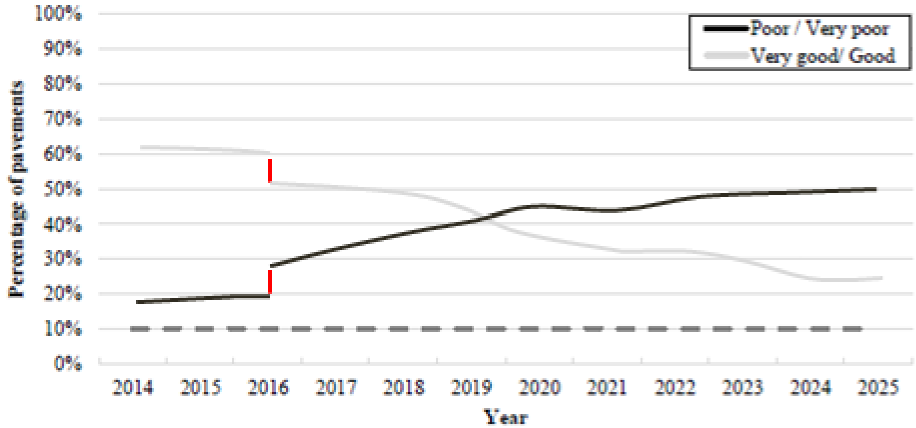


Figure 33: Projection of Pavement Condition Categories over Time Affected by an Extreme Climate Event

To quantify the level of risk of pavements 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. For the severity, the R parameter can be the pavement profile elevation, and the L parameter the height of the water in the flood.

Bridges and Culverts

Figure 34 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 seen in Table 8.

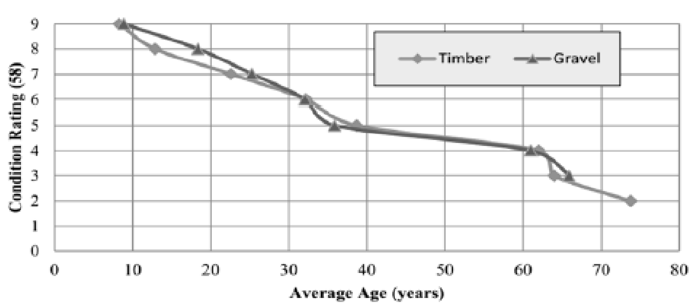


Figure 34: Bridge Deterioration Curve for Timber and Gravel Bridges in Normal Working Conditions (Chang et al. 2017)

Table 8: National Bridge Inventory General Condition Rating (FHWA 2011)

NBI Rating	Description	Commonly Employed Feasible Actions
9	Excellent condition.	Preventive maintenance
8	Very good condition, no problems noted.	
7	Good condition, some minor problems.	
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.	
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.	
2	Critical condition, advanced deterioration of primary structural elements. Unless closely monitored the bridge may have to be closed until corrective action is taken.	
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.	
0	Failed condition, out of service – beyond corrective action	Replacement

The bridge condition deterioration curve shown in Figure 35 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" (Chang et al. 2017). Figure 35 shows the service life of the bridge could be interrupted by an extreme climatic event, suddenly decreasing the NBI condition rating.

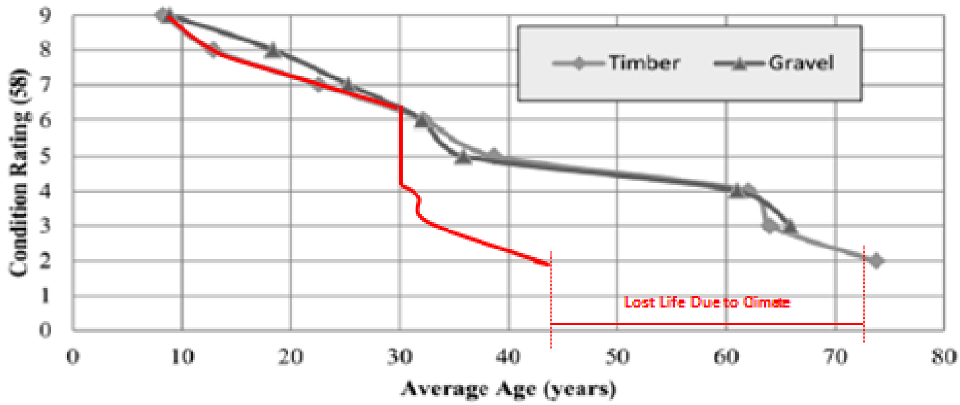


Figure 35: Bridge Deterioration Curve Affected by an Extreme Climate Event

To quantify the level of risk of bridges in terms of occurrence and severity, data should be collected for the specific climatic event that threatens the bridge network. 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 are similar to bridges as shown in Figure 36. The only change is the culvert condition index. In culverts, an extreme climatic event will deteriorate the culvert condition drastically as shown in Figure 37.

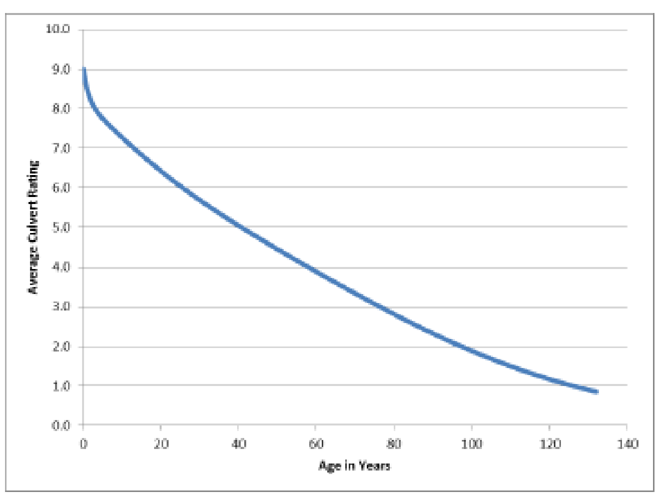


Figure 36: Culvert Condition Deterioration Curve (Chang et al. 2017)

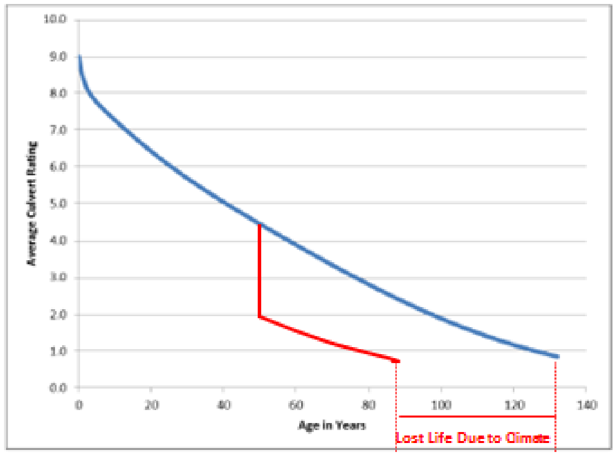


Figure 37: Culvert Deterioration Curve Affected by an Extreme Climatic Event

To quantify the level of risk of culverts in terms of occurrence and severity, data should be collected for the specific climatic event that threatens them like floods. 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. The L parameter can be 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.

Economic Impact

Another type of reports to show the 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 9 provides a brief description of these performance measures.

Table 9: Economic Performance Measure Affected by Climatic Events (BLS 2017)

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.
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 and it was noted that the collection process was affected by the extreme climatic events (BLS 2017). 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 thesis.

Chapter 5: Analysis of a Case Study for Bridges and Pavements

CASE STUDY INTRODUCTION

This chapter introduces a case study for a bridge and a roadway section to demonstrate the applicability of the framework and methodology proposed to quantify the risk of asset damage due to extreme climatic events.

In August 29, 2005, Hurricane Katrina made landfall and caused over "1800 lives lost and caused major flooding and damage that spanned more than 2000 miles along the Gulf Coast of the United States" (O'Connor and McAnany 2008). This hurricane was selected since it significantly affected the New Orleans, Louisiana region. Levees, commercial and public buildings, roads and bridges, utility distribution systems for electric power and water, wastewater collection facilities, and vital communication networks suffered significant damaged due to the hurricane. Winds from the hurricane were estimated at "125 mph and storm surges as high as 25 feet" (O'Connor and McAnany 2008). Prior to landfall, Hurricane Katrina gained strength to a "Category 5 while in the Gulf of Mexico, but quickly dissipated to a Category 3 before landfall" (O'Connor and McAnany 2008). When Hurricane Katrina made landfall, "the wind speeds were substantially reduced before striking land, but the storm surge apparently maintained the heights associated with a Category 5" (O'Connor and McAnany 2008).

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

I-10 TWIN SPAN BRIDGE CASE STUDY

The bridge selected for this case study was the old I-10 Twin Span Bridge located over Lake Pontchartrain. In 2005, this bridge was heavily damaged during Hurricane Katrina. 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.

Step 1: Bridge Goals and Policies

Following the framework proposed, the first step is to identify the goals and policies to maintain the bridge. Since the proposed bridge is in Louisiana, the goals and policies of the Louisiana Department of Transportation are reviewed in this step and summarized in Table 10. The complete list of goals, objectives and performance measures are in Appendix A.

Table 10: Goals and Objectives Relating to I-10 Twin Span Bridge

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 the goals and objectives presented are general, performance measures that directly correlate climate change with asset conditions at the network level should be added. An example of this can be the number of bridges at high, medium, or low risk of damage by an extreme climatic event. Objective must also be specific and quantifiable to monitor the progress. For example, to preserve 90 percent of the bridges in the state of good repair or at low risk is a great objective that is specific and quantifiable.

Step 2: Bridge Asset Inventory

The inventories of all bridges are required in this step. This information can be found for United States bridges in a database developed by the FHWA National Bridge Inventory (Svirsky 2017). If the information is not available, the inventory record of the bridge should be prepared as seen in Figure 38. Another tool that can be used is the Asset Wise Asset Reliability tool developed by Bentley which help inspectors quickly report inspection data from the field (Bentley 2017).

State:	LA
Place Name:	New Orleans
County:	Orleans
NBI Structure Number:	023600000020467
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
RecordType:	Roadway is carried ON the structure
Level of Service:	Mainline roadway
Owner:	State Highway Agency
Highway Agency District:	02
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 condition.
Bridge Railings:	Meet currently acceptable standards.
Historical Significance:	Historical significance is not determinable at this time.
# of Spans in Main Structure:	62
# of Spans in Approach Structures:	182
StructureFlared:	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 waterawy (bridge permit required).
Navigation Horizontal Clearance (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 38: Example of an Inventory Record for the I-10 Twin Span Bridge (Svirsky 2017)

Step 3: Bridge Condition Assessment

In this step, the current condition of the bridge is determined and stored in the database from step 2. For our case study, Figure 38 also 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" (Chang et al. 2017).

To show the effects of Hurricane Katrina on the old Twin Span Bridge, assumptions on the prior condition of the bridge were made. The bridge was originally built in 1965 and when Hurricane Katrina made landfall, the Twin Span Bridge was almost 50 years old. Using the deterioration model for bridges described in Chapter 4, and assuming that only routine maintenance was conducted, the bridge would have been in fair condition (NBI condition rating = 5). Figure 39 displays the bridge condition before Hurricane Katrina.

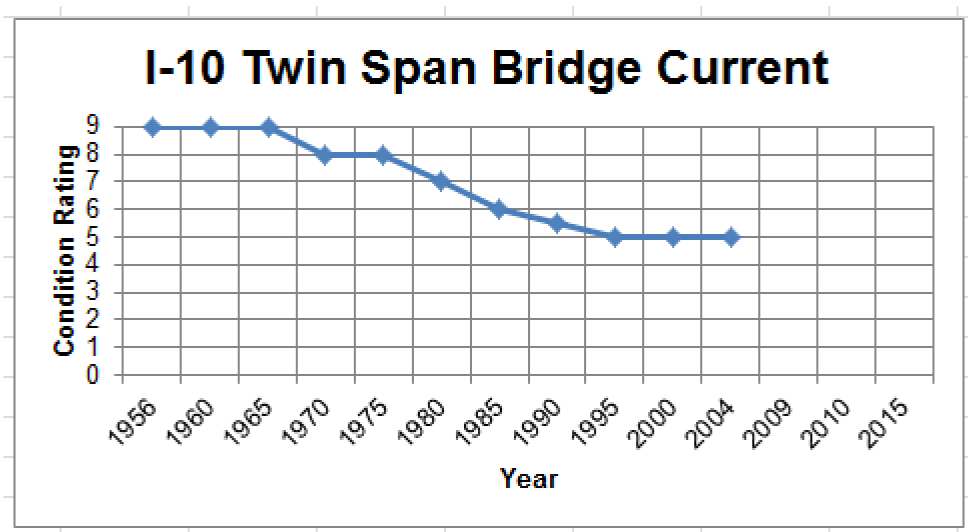


Figure 39: Condition Assessment for I-10 Twin Span Bridge before Hurricane Katrina

Step 4: Bridge Risk Assessment

In this step, climate scenarios are formulated to assess the risk of bridge failure. In our case study, the climate scenario for analysis is the storm surge, which is the most critical parameter that affected the bridges of New Orleans. The following climatic impact scenarios are analyzed:

a. Scenario 1: High risk impact scenario that corresponds to a Category 5 Hurricane with a storm surge of 25 ft.
b. Scenario 2: Medium risk impact scenario that corresponds to a Category 3 Hurricane with a storm surge of 15 ft.
c. Scenario 3: Low risk impact scenario that corresponds to a Category 1Hurricane 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 (Abu-Farsakh et al. 2014). To quantify the risk of damage, the occurrence and severity need to be calculated using the equations from Chapter 4. For occurrence, the NOAA Historical Hurricane Tracks toolkit is used to determine the frequency of the hurricanes (NOAA 2017). Appendix B contains the data 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. Cp is the clearance of the bridge and storm surge height. The RPN is then calculated by multiplying the occurrence, severity, and significance. Note that since the case study is conducted for an individual bridge, the significance is assumed to be 1 in the RPN calculations. Tables 14 and 15 show the complete analysis for occurrence and severity respectively.

Table 11: I-10 Twin Span Bridge Occurrence, 9ft 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				

Table 12: I-10 Twin Span Bridge Severity, 9ft Clearance

Storm Surge	Hr/Hsurge	z=ln(Hr/Hsurge)	Cumulative Normal Standard Porbability	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
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

The acronyms Table 11 for the Hurricane category 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. 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 12 also shows the three risk impact climate scenarios that were analyzed highlighted. As expected, a higher storm surge would result in a higher Severity. The C_p values can show that when the water has reached the height of the bridge and when the bridge has overtopped. When the C_p is zero, the water level has reached the height of the bridge. When the C_p becomes negative, that shows how many feet the bridge has been overtopped by.

Using both values from 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 13.

Table 13: Risk Assessment Matrix for the I-10 Twin Span Bridge

Current Condition								
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	I-10 Twin Span Bridge	1: 25 ft Storm Surge	Visual, Height of water	3	10	None	M	30
		2: 15 ft Storm Surge	Visual, Height of water	8	10	None	H	80
		3: 5 ft Storm Surge	Visual, Height of water	10	4	None	M	40

Step 5: Bridge Needs (Gap) Analyses

In this step, the agency looks at the different actions and economic costs needed to action to maintain, rebuild, or replace the bridge. In this case, the I-10 Twin Span Bridge repair cost was an estimated $30 million, but just repairing the bridge would result in the same risk as before (Padgett et al. 2009). The cost to build the new twin span bridge was estimated at $800 million (LTRC n.d., Abu-Farsakh 2014).

For the analysis, the Occurrence of new I-10 Twin Span Bridge was recalculated using a design life of 100-years. For the severity the changes made were increasing the H_R to the new clearance of the bridge and water level in feet. H_L remained the height of potential storm surge in feet and the C_p is the

new clearance for the storm surge. Tables 14 and 15 show the analysis for the occurrence and severity respectively in the new risk assessment. The RPN values are also recalculated for the recommended actions to deduce the level of risk.

Table 14: I-10 Twin Span Bridge Occurrence, 30ft 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	6	25.0	0.040	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)	100				

Table 15: I-10 Twin Span Bridge Severity, 30ft Clearance

Storm Surge	Hr/Hsurge	z=ln(Hr/Hsurge)	Cumulative Normal Standard Porbability	Probability of Failure	Clearance (Cp) (ft)	Severity Calculation	Severity
1	30.000	3.401	1.000	0.000	29	-0.003	1
2	15.000	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	0.244	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 14, an increase of the occurrence due to the longer analysis period and Hurricane Katrina can be seen and in Table 15 a reduction in severity due to the height of the bridge is seen. With both values the revisited risk and RPN can be tabulated as shown in Table 16. This table also shows that each scenario could need different levels of investment.

Table 16: Risk Analysis Matrix for Reevaluation of the I-10 Twin Span Bridge

Current Condition			Proposed Solutions			Results/Revisit				Investment
Extreme Climatic Event	Asset Type	Climatic Scenarios of Potential Cause(s) of Failure	Reccomended Action	Responsibility and Target Completion Date	Action Taken	Revisited Occurrence (1-10)	Revisited Severity (1-10)	Risk	RPN	Cost
Hurricane/ Storm Surge	I-10 Twin Span Bridge	1: 25 ft Storm Surge	Rebuild with 30ft Elevation	State DOT	-	5	6	M	30	$800 Million
		2: 15 ft Storm Surge	Rebuild with 30ft Elevation	State DOT	-	10	1	M	10	
		3: 5 ft Storm Surge	Rebuild with 30ft Elevation	State DOT	-	10	1	M	10	
		1: 25 ft Storm Surge	Repair	State DOT	-	3	10	M	30	$30 Million
		2: 15 ft Storm Surge	Repair	State DOT	-	8	10	H	80	
		3: 5 ft Storm Surge	Repair	State DOT	-	10	4	M	40	

Step 6: Bridge Scenario Analyses

In this step, the three climate risk impact scenarios are evaluated with two budget scenarios. The RPNs calculated previously in step 4 and step 5 are compared. As stated previously, 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 17 and 18 for $800 million and $30 million budgets respectively.

Table 17: Percent of Risk Reduction for the I-10 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 18: 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 of 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 18 shows that there is no risk reduction if the bridge is just repaired.

Step 7: Bridge Asset Management Report

In this step, a report is prepared to communicate decision-makers with the levels of risk for climate scenarios. The risk reduction calculated in step 6 is expressed through the difference between the RPNs. Figures 40 and 41 show the scorecard for the I-10 Twin Span Bridge before the landfall of Hurricane Katrina as an example of how to report an asset at risk.

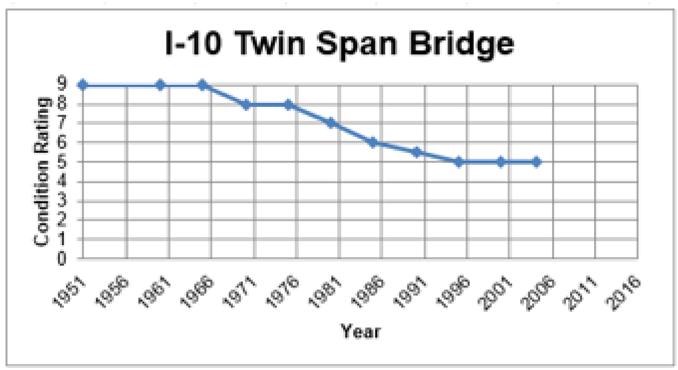
SCORECARD	
State:	Louisiana
Place Name:	New Orleans
County:	Orleans
Asset Type:	Bridge
Asset Location:	0.1 MI EAST OF LA 11
Latitude:	30 09 11.57N
Longitude:	89 51 20.28 W
Year Built:	1951
Level of Service:	Mainline roadway
Owner:	State Highway Agency
Asset Material Design:	Steel Continous
Asset Dimensions:	L:5.4 mi; W:60ft; H:9ft
Other Asset Information:	# of Spans: 62; Average Daily Traffic: 38520; Expected Remaining Service Life 30 years without maintenance will result in a Condition Rating of 2.
Asset Structural Condition:	Deck: Good Condition, Superstructures: Fair Condition
Asset Substructure Conditions:	Good 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 Storm Surge Huricane Category 3
Asset Historical Condition	

Figure 40: I-10 Twin Span Bridge 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
Hurricane/ Storm Surge	I-10 Twin Span Bridge	1: 25 ft Storm Surge	Visual, Height of water	3	10	None	M	30	Rebuild with 30ft Elevation	State DOT	-	5	6	M	30	$80 Million
		2: 15 ft Storm Surge	Visual, Height of water	8	10	None	H	80	Rebuild with 30ft Elevation	State DOT	-	10	1	M	10	
		3: 5 ft Storm Surge	Visual, Height of water	10	4	None	M	40	Rebuild with 30ft Elevation	State DOT	-	10	1	M	10	
Hurricane/ Storm Surge	I-10 Twin Span Bridge	1: 25 ft Storm Surge	Visual, Height of water	3	10	None	M	30	Repair	State DOT	-	3	10	M	30	$30 Million
		2: 15 ft Storm Surge	Visual, Height of water	8	10	None	H	80	Repair	State DOT	-	8	10	H	80	
		3: 5 ft Storm Surge	Visual, Height of water	10	4	None	M	40	Repair	State DOT	-	10	4	M	40	

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 41: I-10 Twin Span Bridge Scorecard, Page 2

In combination with the scorecards, GIS tools can be used for analysis and reporting purposes. GIS maps can facilitate in the location of the assets at risk in a region. For the example in the case study, Figure 42 shows the level of risk of a storm surge condition of the old bridge. Figure 43 shows the level of risk after the new bridge was built for a Category 3 Hurricane. These reports can be useful when prioritizing budget allocations and identifying assets at high risk based on the RPN.

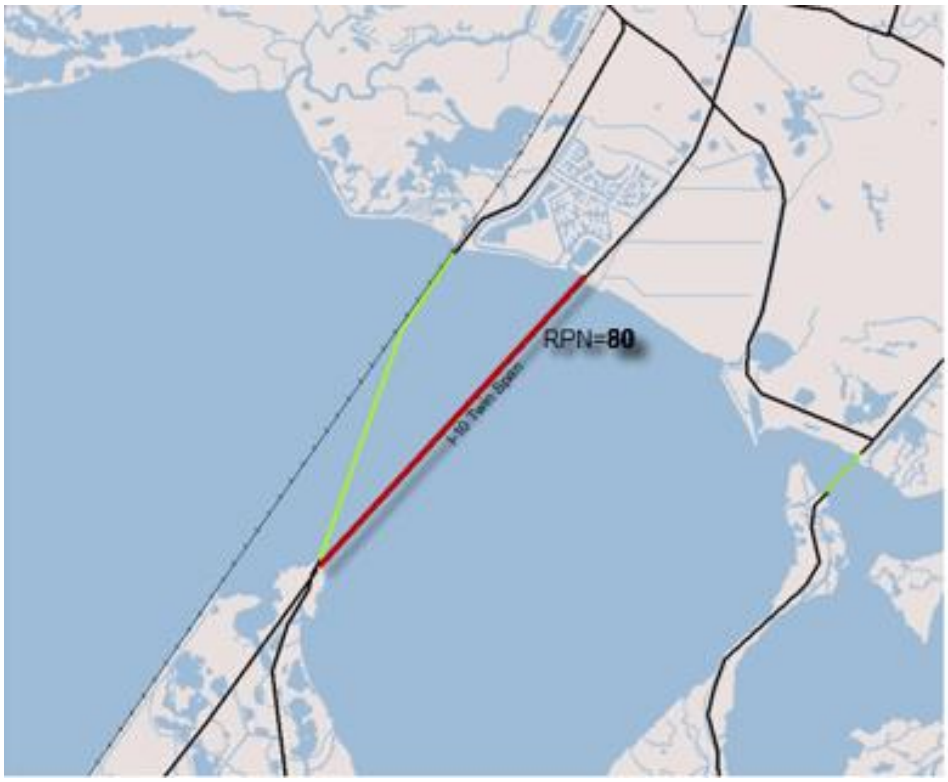


Figure 42: RPN GIS Map, Old I-10 Twin Span Bridge

Figure 43: RPN GIS Map, New I-10 Twin Span Bridge

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

Figure 44 shows the condition rating over time of the Twin Span Bridge. This includes construction of the new bridge (Abu-Farsakh 2014). The mitigation strategy conducted for this bridge was to raise the elevation of the bridge to reduce the risk of failure. It is important to note that this case study was conducted for an individual project but the agency should apply the risk analysis to all the assets to fully implement the framework in TAM practices. Also, 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.

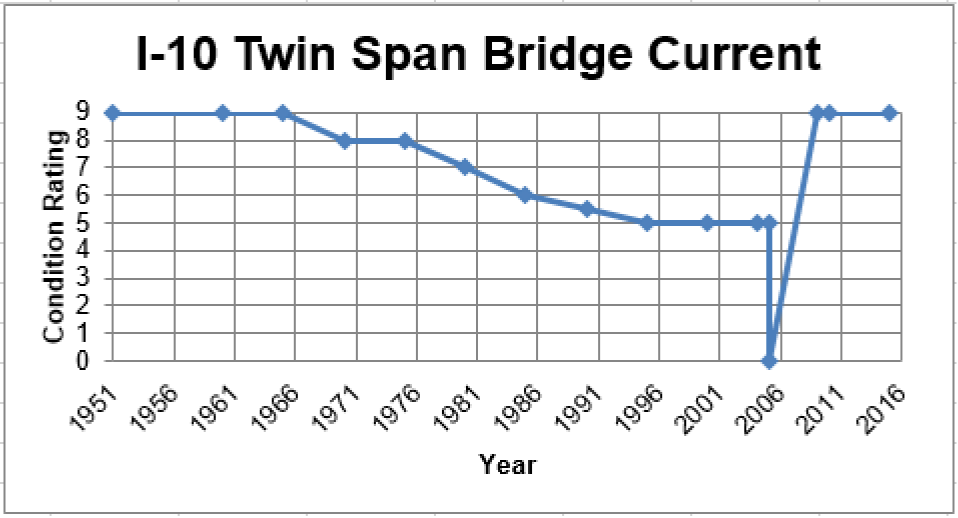


Figure 44: Condition Rating Over Time for the I-10 Twin Span Bridge

ROAD IN FRANKLIN AVENUE

In 2005, Hurricane Katrina heavily damaged many roads in Louisiana. 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

This step is similar to in the bridge section and begins by identifying the goals and policies to maintain the roads. Since the proposed roads are in Louisiana, a check must be conducted on the goals and policies of the governing agency who controls the asset. In this case, the goals, objectives, and performance measures of the Regional Planning Commission (RCP) are summarized in Table 19. The RCP serves as a reference for the New Orleans Metropolitan Planning Organization.

Table 19: Summary of Goals and Objectives in New Orleans Metropolitan Planning Organization (RPC 2015)

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

Table 19: Summary of Goals and Objectives in New Orleans Metropolitan Planning Organization (RPC 2015) (cont'd)

Goal Area	Objectives	Performance Measures
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

Similar to bridges, these are general goals and objectives. Therefore, performance measures that directly correlate with climate change with asset conditions are recommended at the network level. An example of this can be, the number of roads at high, medium, or low risk of damage by an extreme climatic event. Very specific objectives are also recommended. This can be to preserve 90 percent of roads in a state of good repair, or reduce 30% of roads from high to low risk.

Step 2: Roads Asset Inventory

Similar to the bridge inventory, the inventories of all the roads are required. Figure 45 shows an example of the information recommended in an inventory road record. Additional information in the road inventory record is required to quantify the risk of flooding. Figure 46 displays an elevation profile for the section of road below from an online tool developed by the U.S. Geological Survey called The National Map online tool (USGS 2017).

State:	LA
Place Name:	New Orleans
County:	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
Structural Evaluation:	Equal to present minimum criteria
IRI:	130
CI	72

Figure 45: Example of a Roadway Inventory Record, Franklin Avenue

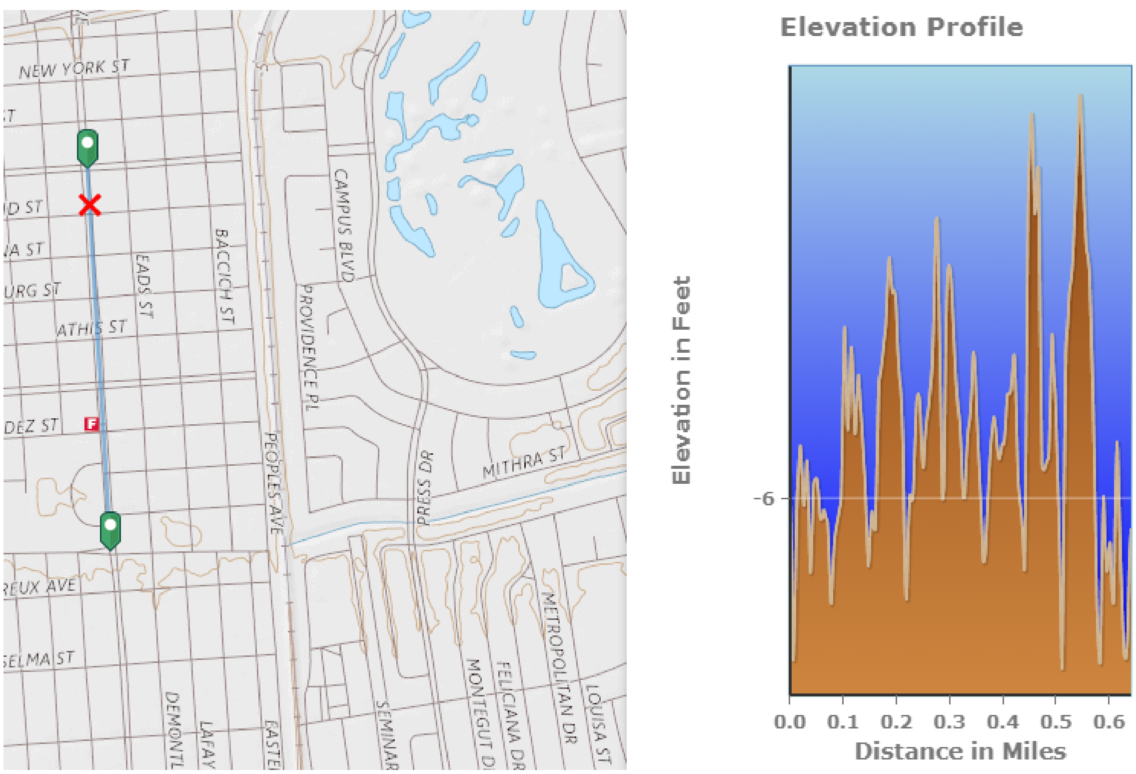


Figure 46: USGS Elevation Profile Tool for Franklin Avenue (USGS 2017)

Step 3: Road Condition Assessment

The Pavement Condition Index (PCI) is used to assess the road condition and is calculated from individual pavement distresses recorded in the field based on severity and quantity. It ranges from 0 to 100 (very poor condition to very good condition). Table 20 shows the pavement condition categories are defined with the PCI.

Table 20: CI and Pavement Condition

Category	CI	Condition
I	91-100	Very Good
II	71-90	Good
III	51 – 70	Fair
IV	25-50	Poor
V	Under 25	Very Poor

Due to the lack of data on the roadway, assumptions were made and it was assumed that the PCI was below a PCI of 50 before Hurricane Katrina as shown in Figure 47.

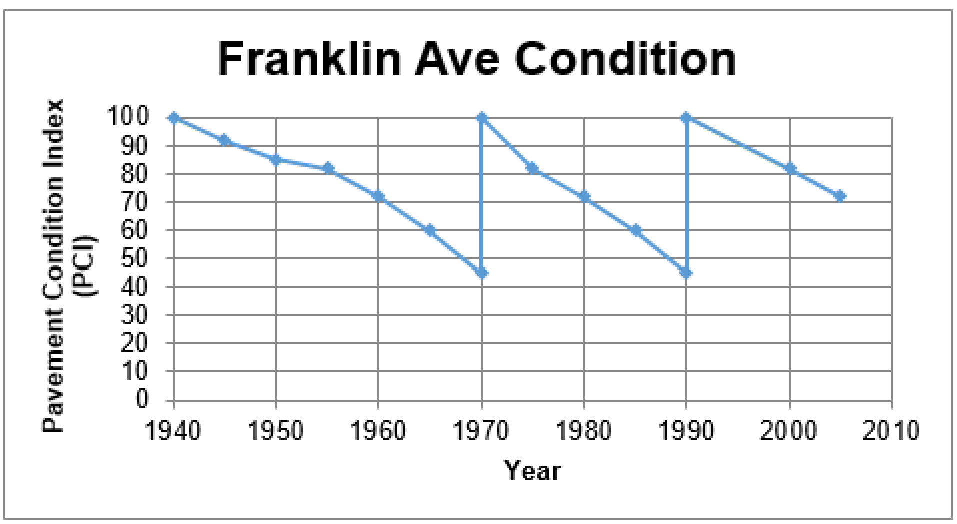


Figure 47: Condition Assessment for Franklin Ave. Road Section

Step 4: Road Risk Assessment

In this step, climate scenarios are formulated to assess the risk of road failure. Since "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", the climate scenarios for analysis are the same as for the storm surge described in the I-10 Twin Span Bridge case study (Kayen et al. 2006). The following climatic impact scenarios are analyzed:

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

Prior to Hurricane Katrina, the levees were 15 ft high. To quantify the risk of damage, the occurrence and severity again need to be calculated using the equations from Chapter 4. For occurrence, the NOAA Historical Hurricane Tracks toolkit is used to determine the frequency of the hurricanes with a levee in a 100-year return period (NOAA 2017). Appendix B contains the data for the calculations. For severity, H_R is the current height of the levee and the water level in feet. H_L is the height of potential storm surge height in feet. The Cp is the clearance of the levee and the storm surge height in feet. The RPN is then calculated by multiplying the occurrence, severity, and significance. Note that since the case study is conducted for an individual case, the significance is assumed to be 1 in the RPN calculations. Tables 21 and 22 show the complete analysis for occurrence and severity respectively.

Table 21: 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	0.97	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)	100				

Table 22: Franklin Avenue Flooding Severity, 15ft Levees

Storm Surge	Hr/Hsurge	z=ln(Hr/Hsurge)	Cumulative Normal Standard Porbability	Probability of Failure	Clearance (Cp) (ft)	Severity Calculation	Severity
1	15.000	2.708	0.997	0.003	14	0.020	1
2	7.500	2.015	0.978	0.022	13	0.154	1
3	5.000	1.609	0.946	0.054	12	0.430	1
4	3.750	1.322	0.907	0.093	11	0.838	1
5	3.000	1.099	0.864	0.136	10	1.360	1
6	2.500	0.916	0.820	0.180	9	1.977	2
7	2.143	0.762	0.777	0.223	8	2.676	3
8	1.875	0.629	0.735	0.265	7	3.442	3
9	1.667	0.511	0.695	0.305	6	4.266	4
10	1.500	0.405	0.657	0.343	5	5.139	5
11	1.364	0.310	0.622	0.378	4	6.052	6
12	1.250	0.223	0.588	0.412	3	6.999	7
13	1.154	0.143	0.557	0.443	2	7.976	8
14	1.071	0.069	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 tables, the scenarios are highlighted. The occurrence shows that there is a high probability that an asset will experience a hurricane Category 1 and 3 in the next 100 years. The occurrence table also shows that the asset has a lower probability 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 while little to no damage on a hurricane Category 1.

Using both values from the occurrence and severity tables, the risk assessment matrix for each climatic scenario and potential causes of failure are seen in Table 23.

Table 23: Risk Assessment Matrix for Franklin Avenue

Current Condition								
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/ Flooding Due to Levee Overtop	Franklin Avenue	1: 25 ft Storm Surge	Visual, Height of water	5	10	None	H	50
		2: 15 ft Storm Surge	Visual, Height of water	10	10	None	H	100
		3: 5 ft Storm Surge	Visual, Height of water	10	1	None	M	10

Step 5: Road Needs (Gap) Analyses

In this step, an agency again identifies different actions and budget needs to repair or rebuild the road. In this case, the road flooding being analyzed is an indirect result of the levees and the repair cost of the levees was estimated at $14.5 billion (Llanos 2015). New Orleans also build a 26-feet Storm Surge Barrier that cost of $1.1 billion (Llanos 2015).

Using the NOAA Historical Hurricane Tracks toolkit to determine the number of hurricanes, Table 24 shows the occurrence for the 17 ft levees and the storm surge barrier (NOAA 2017). Table 25 shows the recalculation of severity for the increased levee elevation. Table 26 shows recalculation of severity for the storm surge barrier. 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 24: Franklin Avenue Flooding Occurrence, 17ft Levees and 26ft 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	0.97	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)	100				

Table 25: Franklin Avenue Flooding Severity, 17ft Levees

Storm Surge	Hr/Hsurge	z=ln(Hr/Hsurge)	Cumulative Normal Standard Porbability	Probability of Failure	Clearance (Cp) (ft)	Severity Calculation	Severity
1	17.000	2.833	0.998	0.002	16	0.009	1
2	8.500	2.140	0.984	0.016	15	0.081	1
3	5.667	1.735	0.959	0.041	14	0.248	1
4	4.250	1.447	0.926	0.074	13	0.518	1
5	3.400	1.224	0.889	0.111	12	0.884	1
6	2.833	1.041	0.851	0.149	11	1.339	1
7	2.429	0.887	0.813	0.187	10	1.875	2
8	2.125	0.754	0.775	0.225	9	2.480	2
9	1.889	0.636	0.738	0.262	8	3.149	3
10	1.700	0.531	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 26: Franklin Avenue Flooding Severity, 26ft Surge Barrier

Storm Surge	Hr/Hsurge	z=ln(Hr/Hsurge)	Cumulative Normal Standard Porbability	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	0.484	1	9.203	9

In the tables, the scenarios are highlighted. Table 24 shows the same occurrence with the added Hurricane and similar analysis period and Table 25 shows a slight reduction to severity in a hurricane Category 3. Table 26 shows a reduction in severity in both hurricane Category 3 and 5. Using both the occurrence and the two severity tables, Table 27 shows the tabulated risk and cost of each action.

Table 27: Risk Analysis Matrix for Reevaluation of Franklin Avenue

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

Step 6: Roads Risk Assessment Report

In this step, the three climate risk impact scenarios are evaluated with two budget scenarios and the RPNs calculated previously in step 4 and step 5 are compared. As stated previously, since the case study is conducted for an individual bridge, the significance is assumed to be 1 in the RPN calculations. Tables 28 and 29 show the percent risk reduction for the $14.5 Billion and $1.1 Billion budget respectively.

Table 28: Percent Risk Reduction Franklin Avenue, 17 ft Levees and $14.5 Billion Budget

Scenario	Climatic 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 29: Percent Risk Reduction Franklin Avenue, Surge Barrier and $1.1 Billion Budget

Scenario	Climatic 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 clearance is 20% for a Category 3 Hurricane with a 15 ft storm surge and no risk reduction for a Category 5 and Category 1 Hurricane with a 25 ft storm surge or 5 ft storm surge respectively. For the storm surge barrier, the percent risk reduction is 10% for a Category 5 Hurricane with a 25 ft storm surge, 70% for a Category 3

Hurricane with a 15 ft storm surge, and 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 with the levels of risk for climate scenarios. The risk reduction calculated in step 6 is expressed through the difference between the RPNs. By upgrading the levee to 17 ft high and building the storm surge barrier, the level of risk is reduced. Figures 48 and 49 show the scorecard for road before the landfall of Hurricane Katrina as an example of how to report an asset at risk.

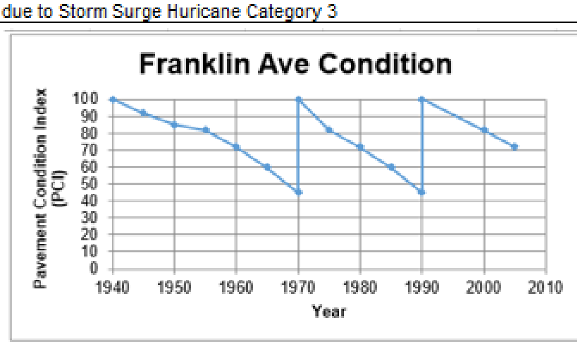
SCORECARD	
State:	Louisiana
Place Name:	New Orleans
County:	Orleans
Asset Type:	Road (Franklin Avenue Section)
Asset Location:	Intersection 1: Robert E. Lee; Intersection 2: Filmore Ave.
Latitude:	30 01 14.50 N
Longitude:	90 03 06.10W
Year Built:	1940
Level of Service:	Mainline roadway
Owner:	Regional Planning Commision
Asset Material Design:	Asphalt
Asset Dimensions:	L:0.7 mi; W:65.7ft;
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 Strom Sruge Huricane Category 3 and 5
Asset RPN	100 due to Storm Surge Huricane Category 3
Asset Historical Condition	

Figure 48: I-10 Twin Span Bridge 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
Hurricane/ Storm Surge/ Flooding Due to Levee Overtop	Frankklin Avenue	1: 25 ft Storm Surge	Visual, Height of water	5	10	None	H	50	Rebuild with 17ft Elevation	USACE	-	5	10	M	50	$14.5 Billion
		2: 15 ft Storm Surge	Visual, Height of water	10	10	None	H	100	Rebuild with 17ft Elevation	USACE	-	10	8	M	80	
		3: 5 ft Storm Surge	Visual, Height of water	10	1	None	M	10	Rebuild with 17ft Elevation	USACE	-	10	1	M	10	
Hurricane/ Storm Surge/ Flooding Due to Levee Overtop	Frankklin Avenue	1: 25 ft Storm Surge	Visual, Height of water	5	10	None	H	50	26ft Storm Surge Barrier	USACE	-	5	9	H	45	$1.1 Billion
		2: 15 ft Storm Surge	Visual, Height of water	10	10	None	H	100	26ft Storm Surge Barrier	USACE	-	10	3	M	30	
		3: 5 ft Storm Surge	Visual, Height of water	10	1	None	M	10	26ft Storm Surge Barrier	USACE	-	10	1	M	10	

Occurance		Severity 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

Figure 49: I-10 Twin Span Bridge Scorecard, Page 2

In combination with the scorecards, GIS tools can be used for analysis and reporting purposes. GIS maps can facilitate in the location of the assets at risk in a region. For the example in the case study, Figure 50 shows the level of risk of a storm surge condition for the existing conditions prior to the storm surge. Figure 51 shows the level of risk with the upgraded levees. These reports can be useful when prioritizing budget allocations and identifying assets at high risk based on the RPN.

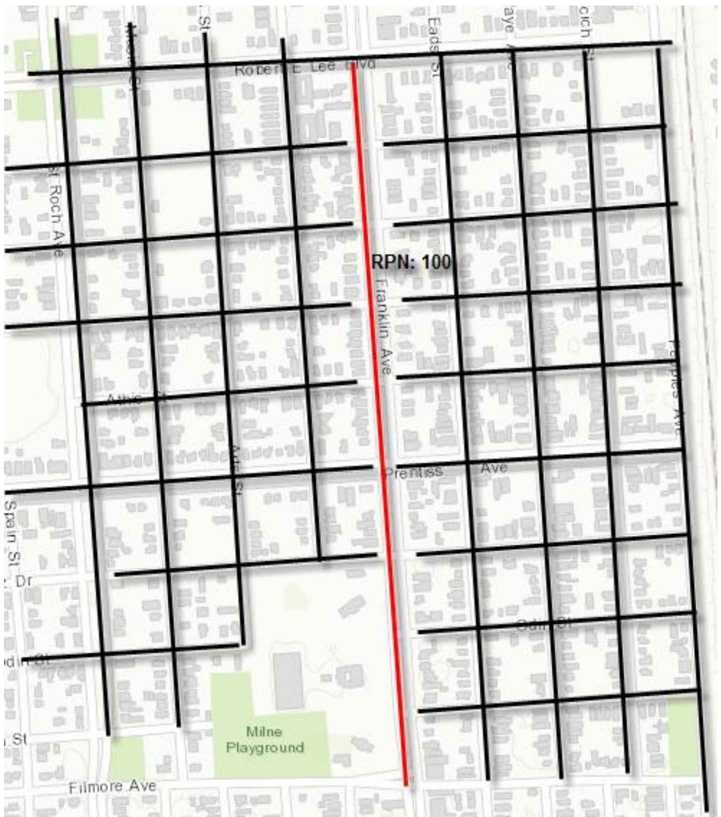


Figure 50: RPN GIS Risk Map, Franklin Avenue before the Hurricane

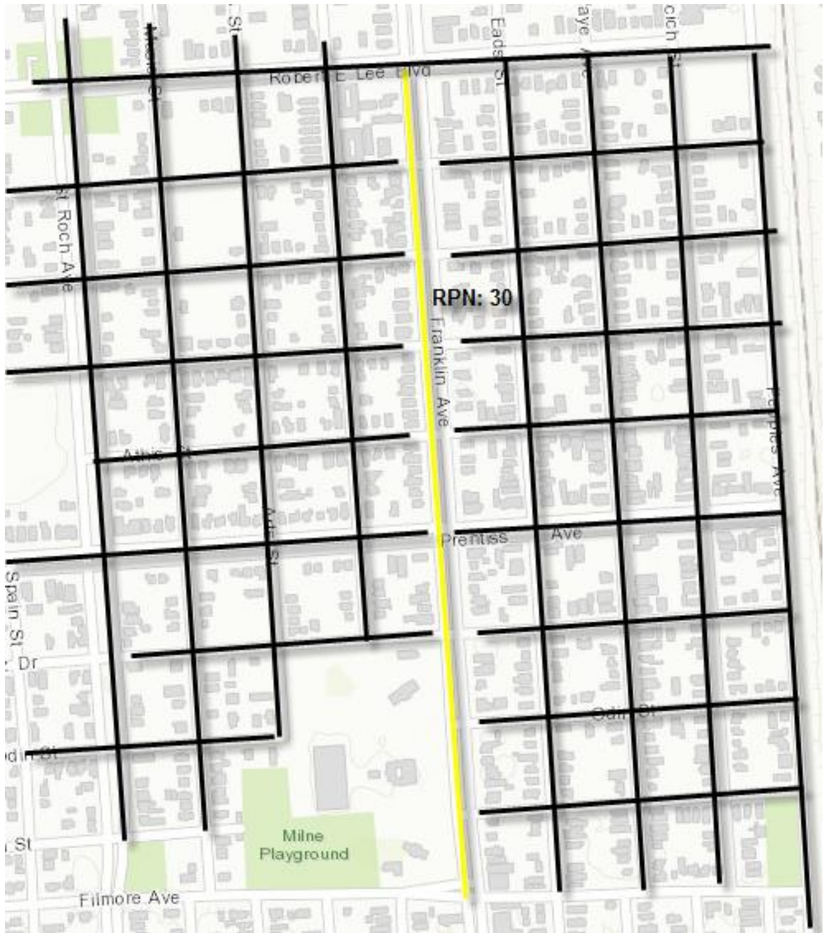


Figure 51: RPN GIS Risk Map, Franklin Avenue after Recommended Actions

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

The roadway presented in this case study is 6 ft below sea level. The risk mitigation strategy was to raise the elevation of the levees and build a storm surge barrier. Figure 52 shows the projected PCIs after repairing the road. Similar to the bridge example, the road case study was for an individual project. It is important to note that 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.

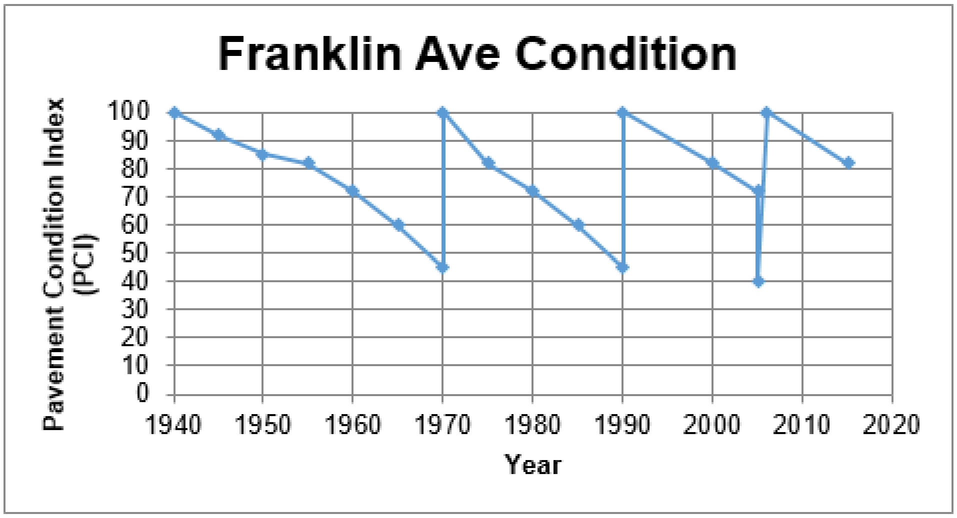


Figure 52: PCI over time for the Franklin Avenue Road after Recommended Actions

Chapter 6: Results and 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. The 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. @Risk is the software used to perform the Monte Carlo simulations in order to analyze the likelihood of alternative scenarios to occur (Palisade 2017). Monte Carlo simulations of severity, occurrence, and RPN are performed in this chapter.

OCCURRENCE

The risk assessment model determines the probability of occurrence of a climate event which has three inputs for the occurrence to analyze. The inputs are 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. The asset remaining life is the number of years that the asset is expected to remain in service. Figure 53 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$11)	=L3*10
4	TS	=COUNTIF(C4:C76,"TS")	=$I$10/I4	=1/J4	=1-(((FACT($I$11))/(FACT(0)*FACT($I$11)))*(K4)^0*(1-(K4))^$I$11)	=L4*10
5	H1	=COUNTIF(C4:C76,"H1")	=$I$10/I5	=1/J5	=1-(((FACT($I$11))/(FACT(0)*FACT($I$11)))*(K5)^0*(1-(K5))^$I$11)	=L5*10
6	H2	=COUNTIF(C4:C76,"H2")	=$I$10/I6	=1/J6	=1-(((FACT($I$11))/(FACT(0)*FACT($I$11)))*(K6)^0*(1-(K6))^$I$11)	=L6*10
7	H3	=COUNTIF(C4:C76,"H3")	=$I$10/I7	=1/J7	=1-(((FACT($I$11))/(FACT(0)*FACT($I$11)))*(K7)^0*(1-(K7))^$I$11)	=L7*10
8	H4	=COUNTIF(C4:C76,"H4")	=$I$10/I8	=1/J8	=1-(((FACT($I$11))/(FACT(0)*FACT($I$11)))*(K8)^0*(1-(K8))^$I$11)	=L8*10
9	H5	=COUNTIF(C4:C76,"H5")	=$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 Climatic Events (a)	150				
11	Asset Remaining Life (n) (Years)	100				

Figure 53: 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. When modeling for events in the future events, a

probability distribution is needed. For other types of climate events, such as flooding, this first input could be days with extreme precipitation or temperatures. 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 which is the recurrence interval for an event. The return period 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 (Palisade 2017). Figures 54 show the Tornado graph which 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.

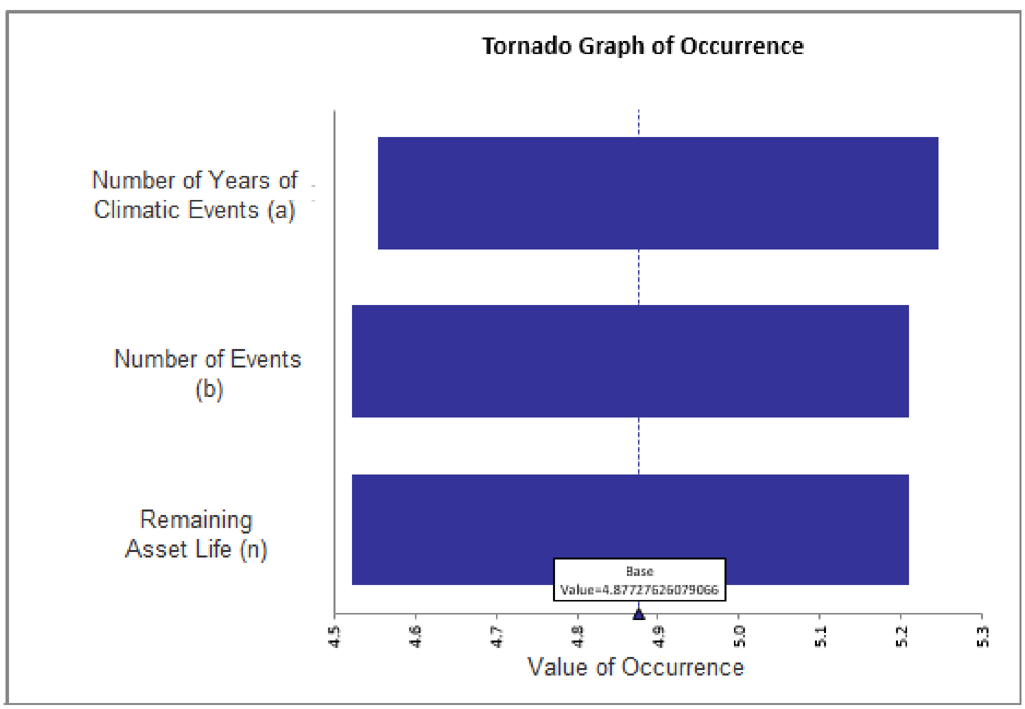


Figure 54: Tornado Graph of Occurrence

Figure 55 shows the spider graph for occurrence, which 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 and if the remaining asset life of climatic event increases or the number of events increases, then the occurrence increases.

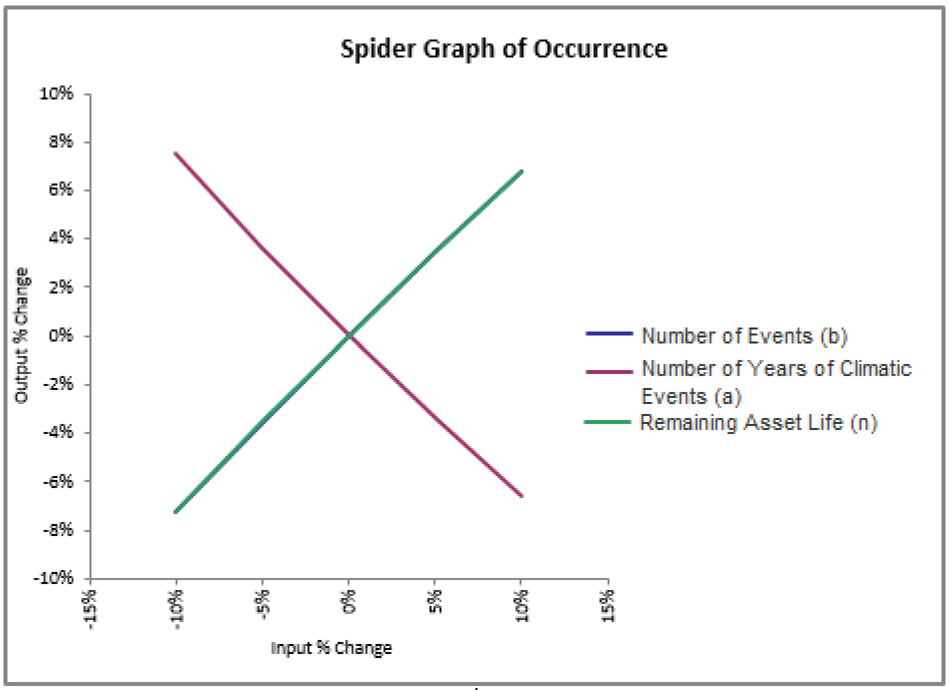


Figure 55: Spider Graph of Occurrence

With @Risk to conduct Monte Carlo simulations, the Remaining Asset Life is modeled with a Weibull distribution as shown in Figures 56. Weibull distributions are often used to model the length of life and endurance data (Yoe 2012). The Number of Years of climatic events is modeled with a uniform distribution as shown in Figure 57, which 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 was used for a Hurricane Category 1, 3, and 5 as shown in Figures 58 to 60. 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.

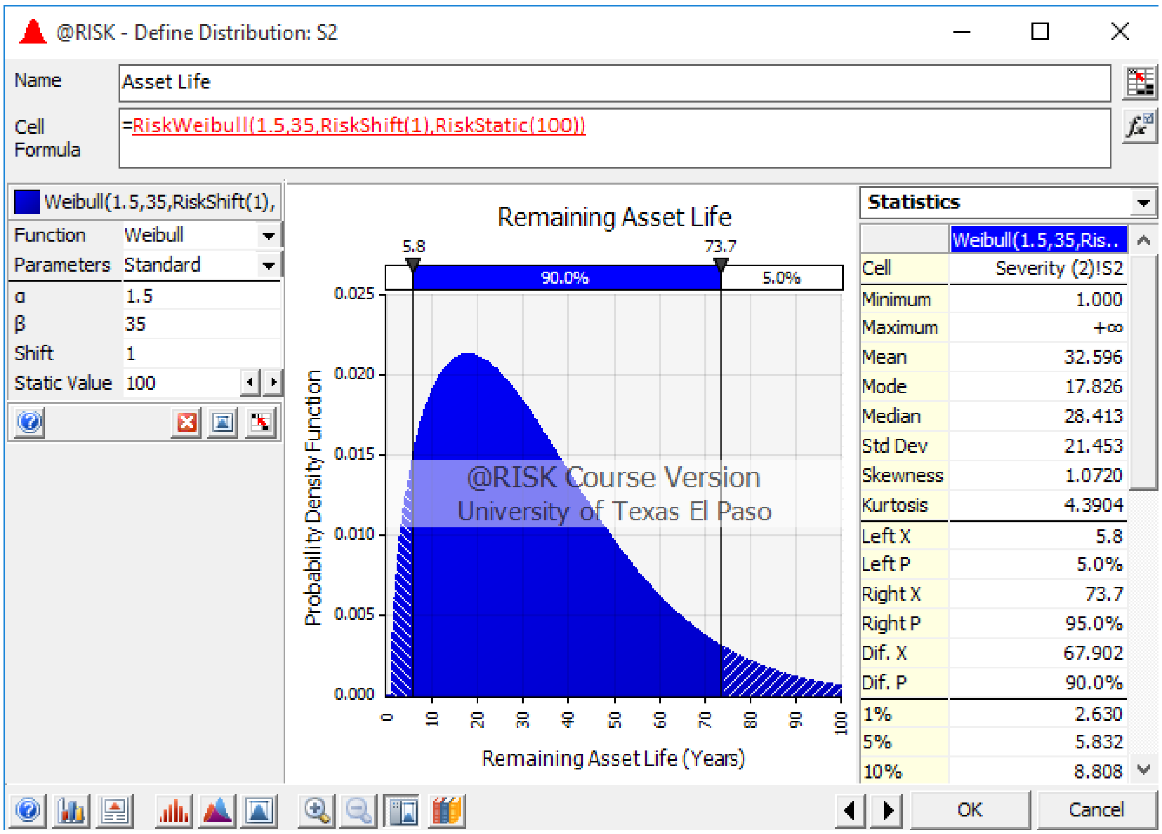


Figure 56: Remaining Asset Life (n) Weibull Distribution

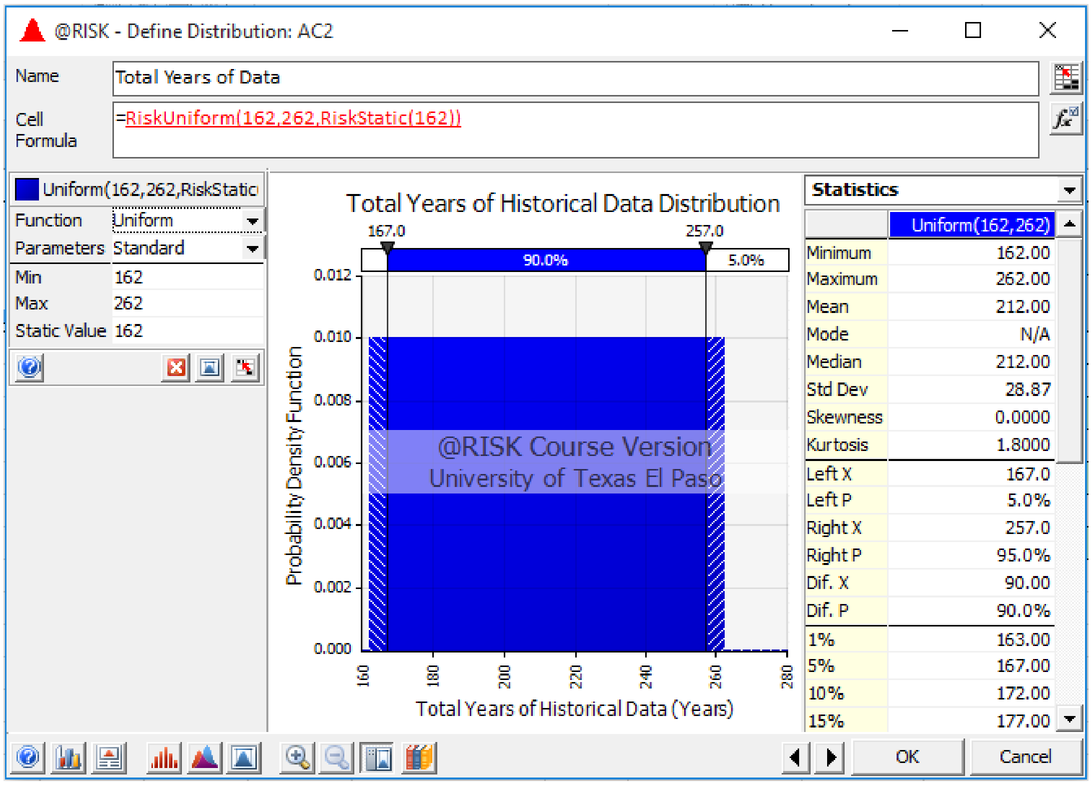


Figure 57: Uniform Distribution to Project the Number of Years (a)

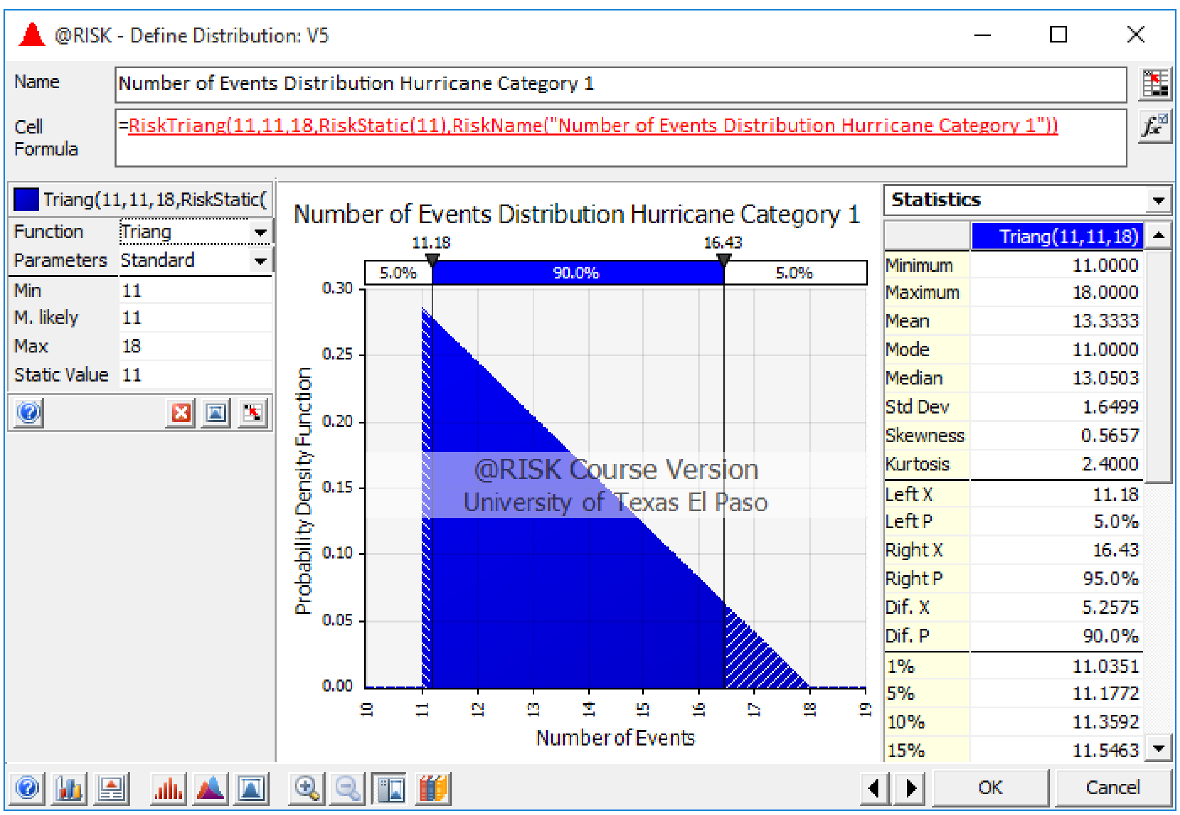


Figure 58: Triangular Distribution for Number of Events, Hurricane Category 1

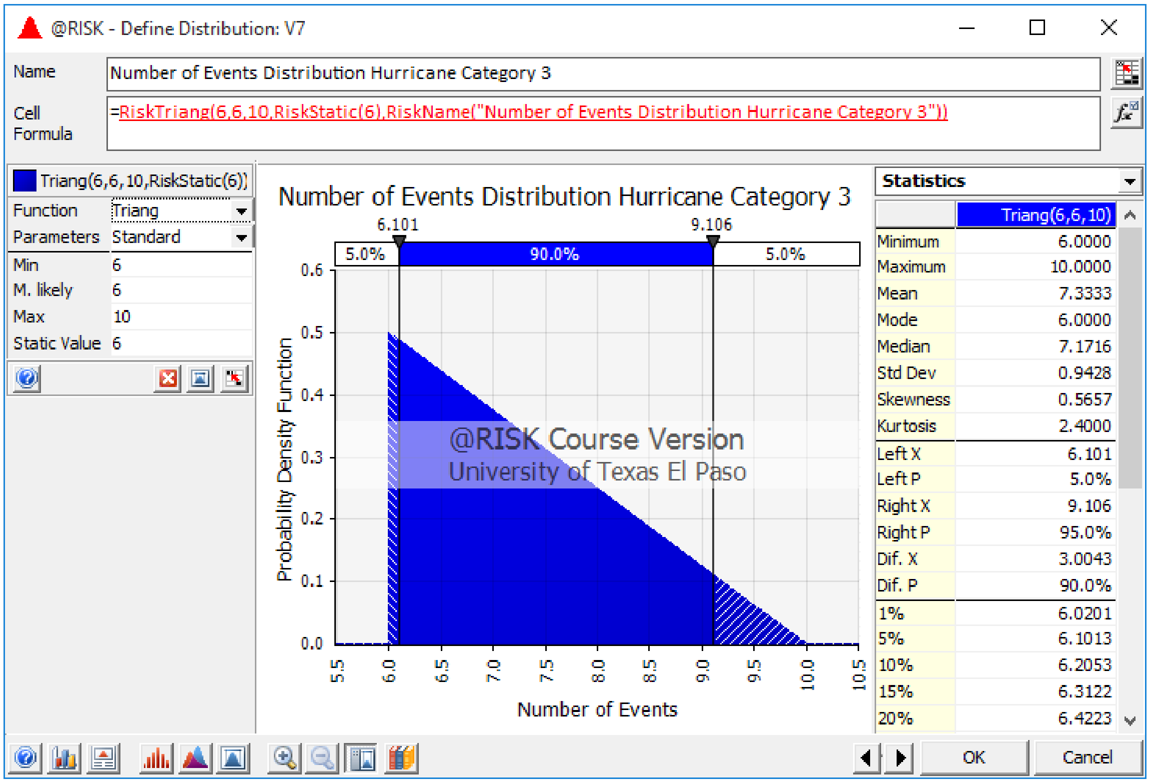


Figure 59: Triangular Distribution for Number of Events, Hurricane Category 3

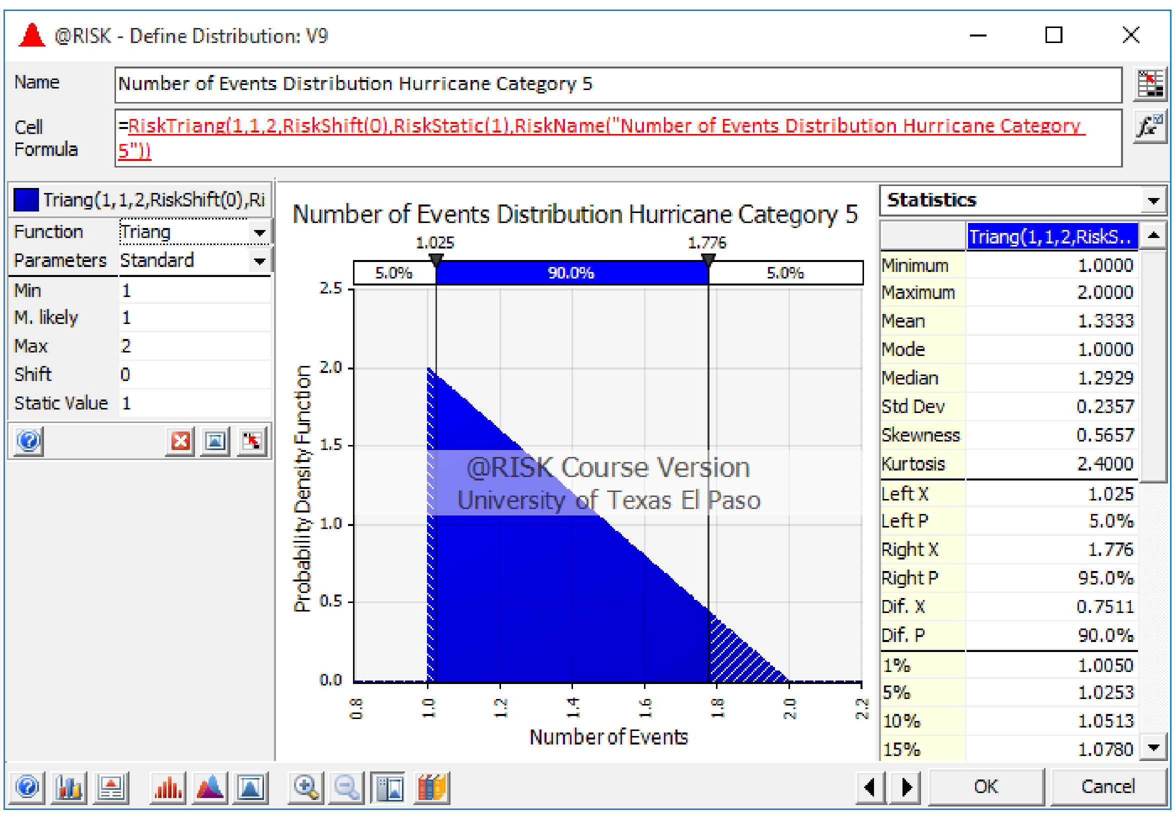


Figure 60: Triangular Distribution for Number of Events, Hurricane Category 5

Figures 61 to 63 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. Relative frequency is the frequency of occurrence divided by the total number of simulations. The confidence level of the output moves from low to high occurrence. Figure 61 shows that the occurrence is between 9.9 and 10 throughout the remaining life of the asset for a Category 1 hurricane. Figure 62 shows that the occurrence is between 9.3 and 9.9 throughout the remaining life of the asset for a Category 3 hurricane. Figure 63 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.

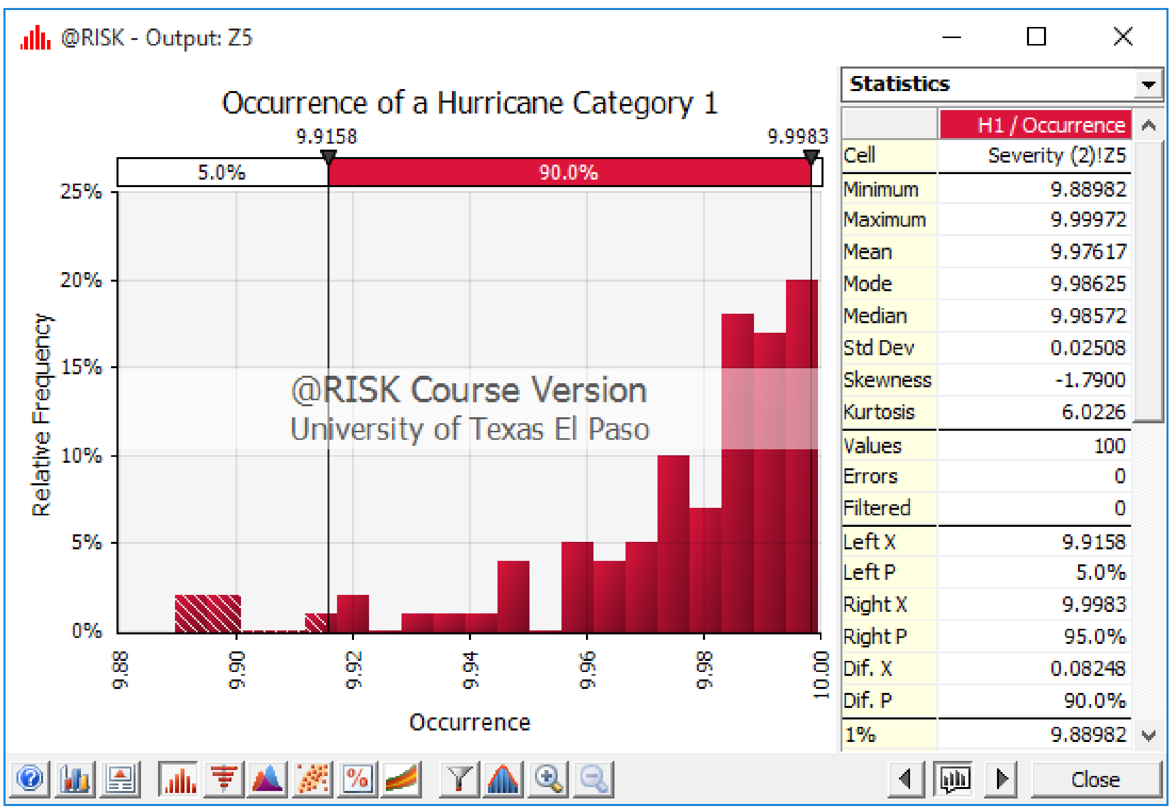


Figure 61: Occurrence Distribution, Category 1 Hurricane

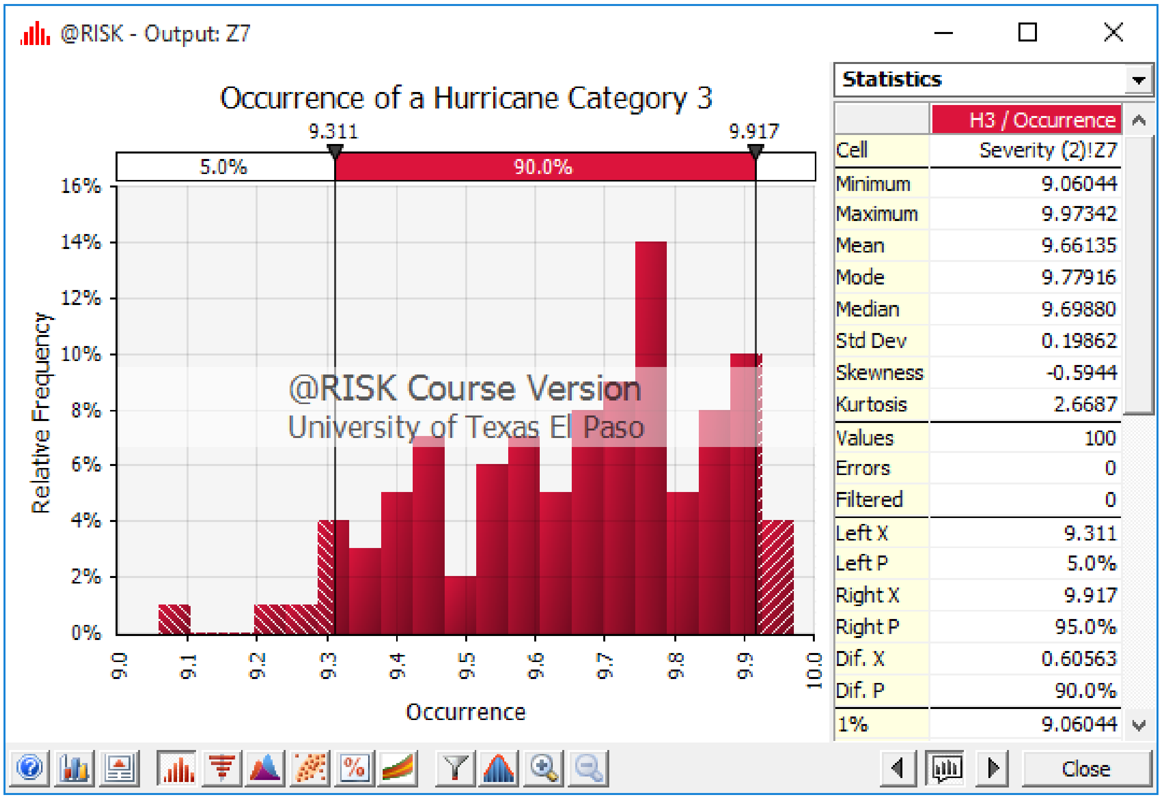


Figure 62: Occurrence Distribution, Category 3 Hurricane

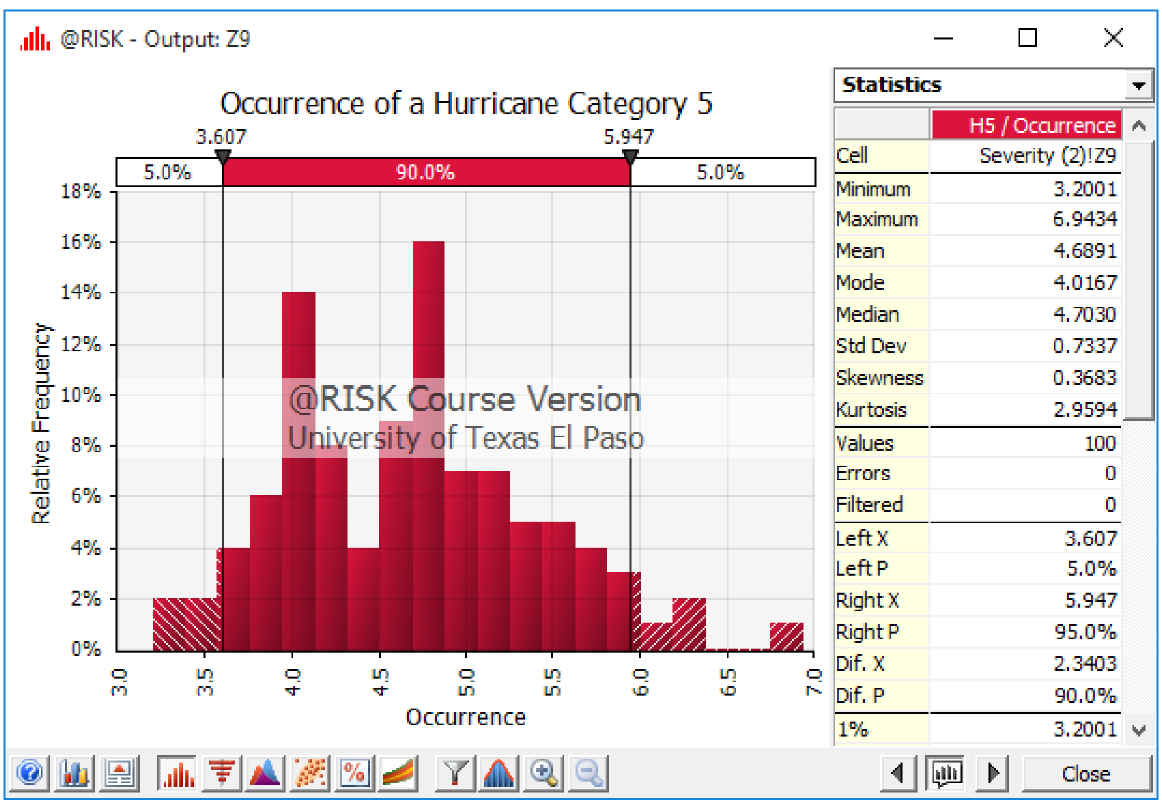


Figure 63: Occurrence Distribution, Category 5 Hurricane

SEVERITY

The following figure, Figure 64, 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 (H_L)**	**Hr/H_L**	**z=ln(Hr/H_L)**	**Cumulative Normal Standard Porbability**	**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 64: Excel Formulas for Severity

For hurricanes, there are two input parameters for severity. The parameters are the resistance and the acting. H_R, is the resistance parameter. H_L is the acting parameter that can damage the asset. The model calculates the severity for a given H_R. The parameters are used for storm surge in this example, 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 64, H_R, the resisting parameter, is the height of a bridge. 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 graph, Figure 65 and Spider graph Figure 65. The Tornado graph shows that H_R is the most sensitive parameter for severity.

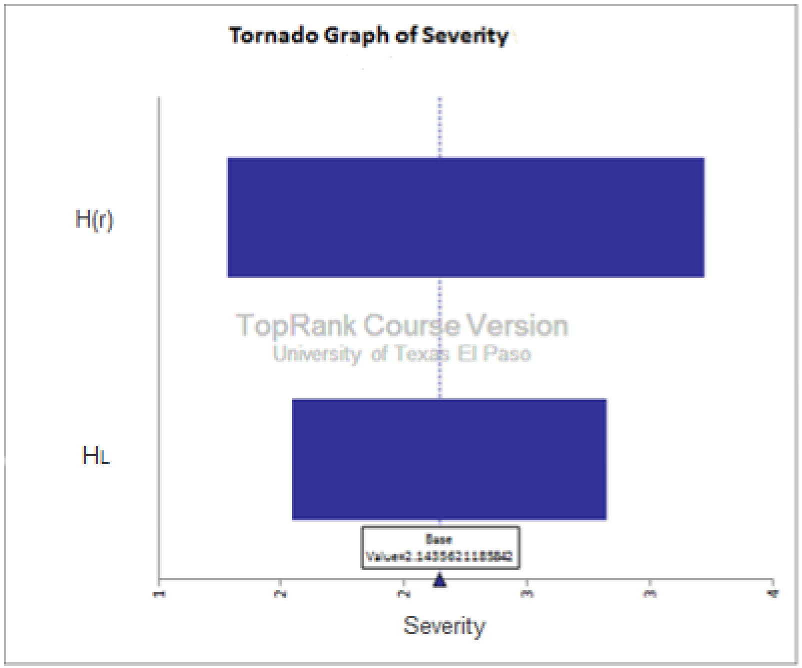


Figure 65: Tornado Graph of Severity

The spider graph in Figure 66 shows the correlation between H_R and H_L whereas the HR increases the severity decreases. Also as HL decreases then the severity decreases.

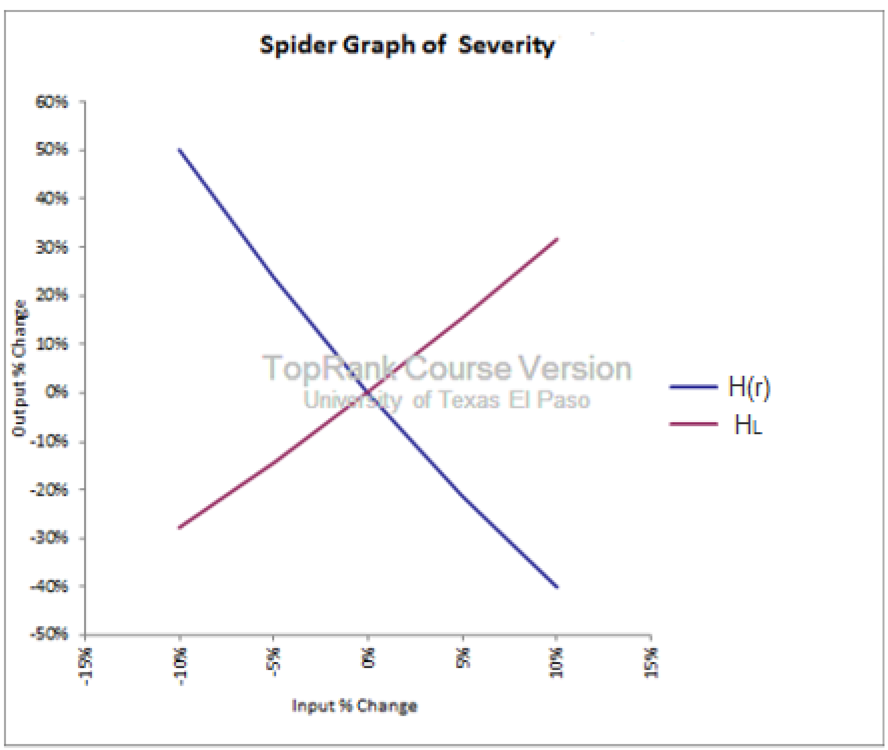


Figure 66: Spider Graph of Severity

In order to identify the confidence interval for the severity, H_L is modeled with a normal distribution seen in Figure 67. Figures 68 to 70 show the outputs of the simulations for severity using @Risk. Figure 68 shows a severity of 1 for a bridge with 26ft height and a storm surge of 5 ft at the 100% confidence interval which means that that probability of this bridge to be damaged by a category 1 hurricane is very low. Figure 69 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 also low. Figure 70 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.

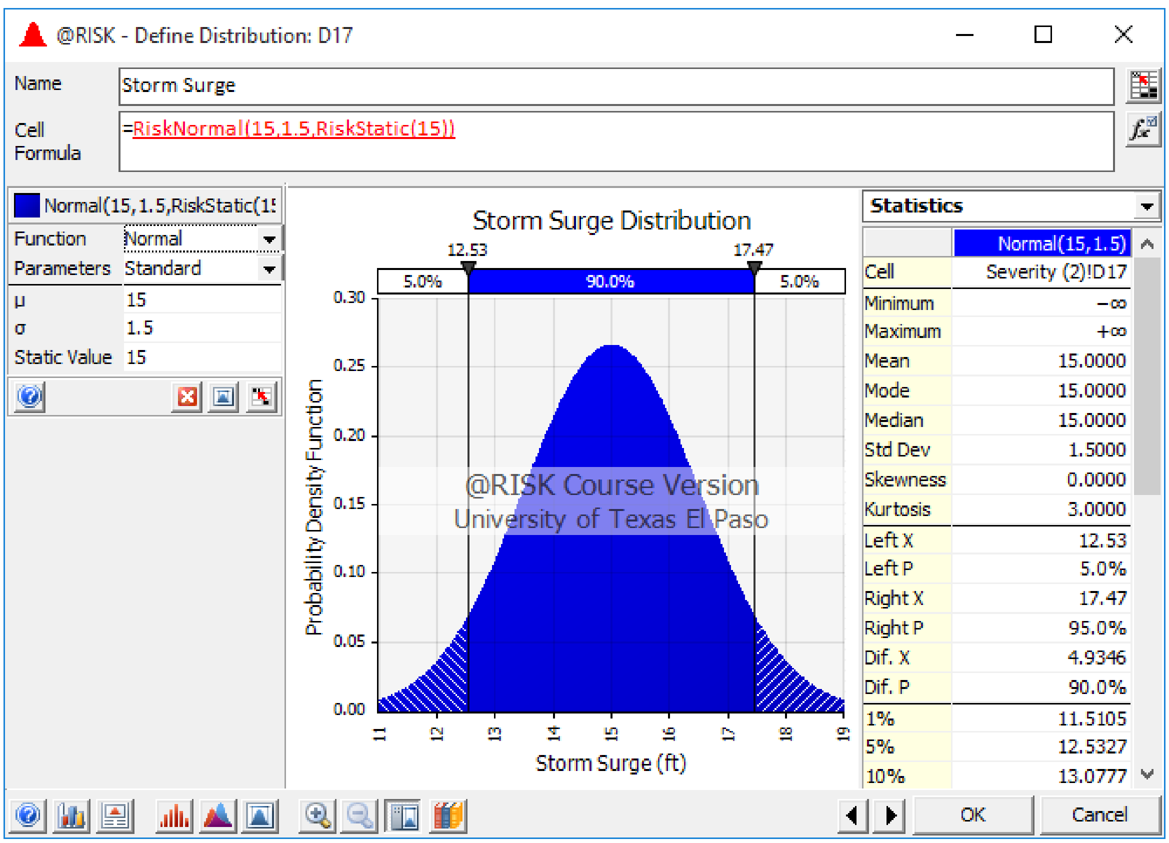


Figure 67: Normal Distribution for H_L

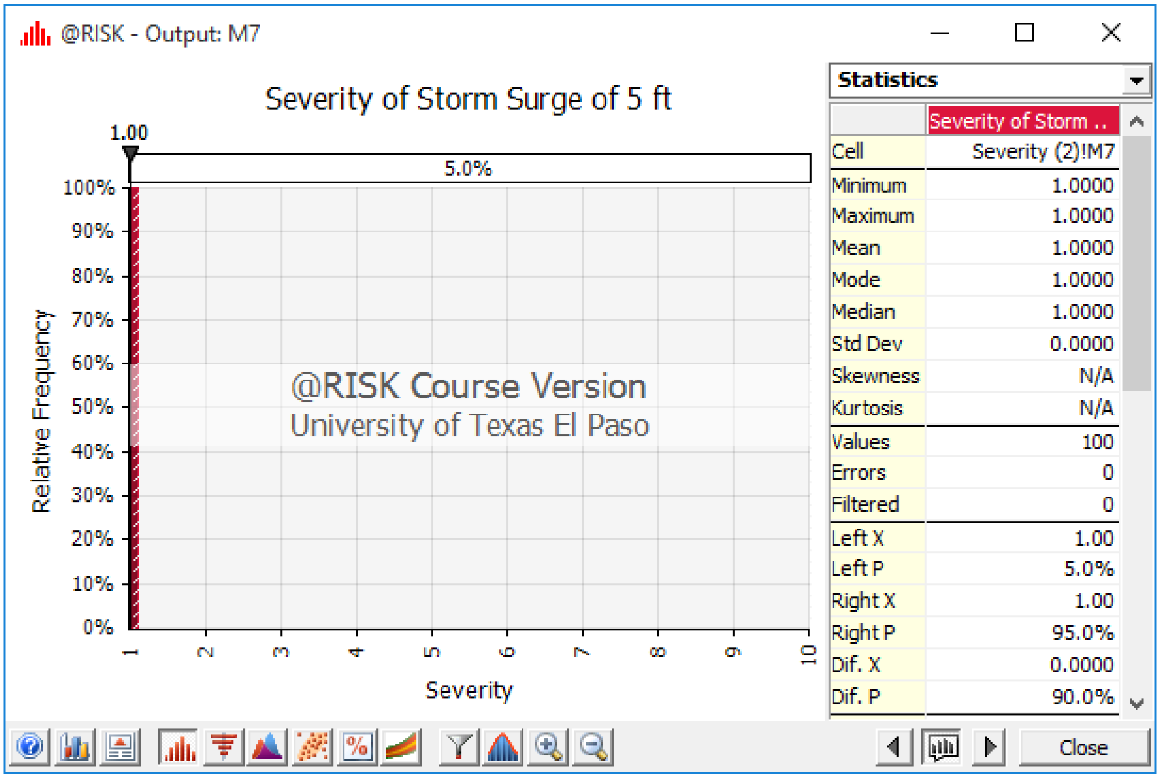


Figure 68: Severity Distribution, Category 1 Hurricane

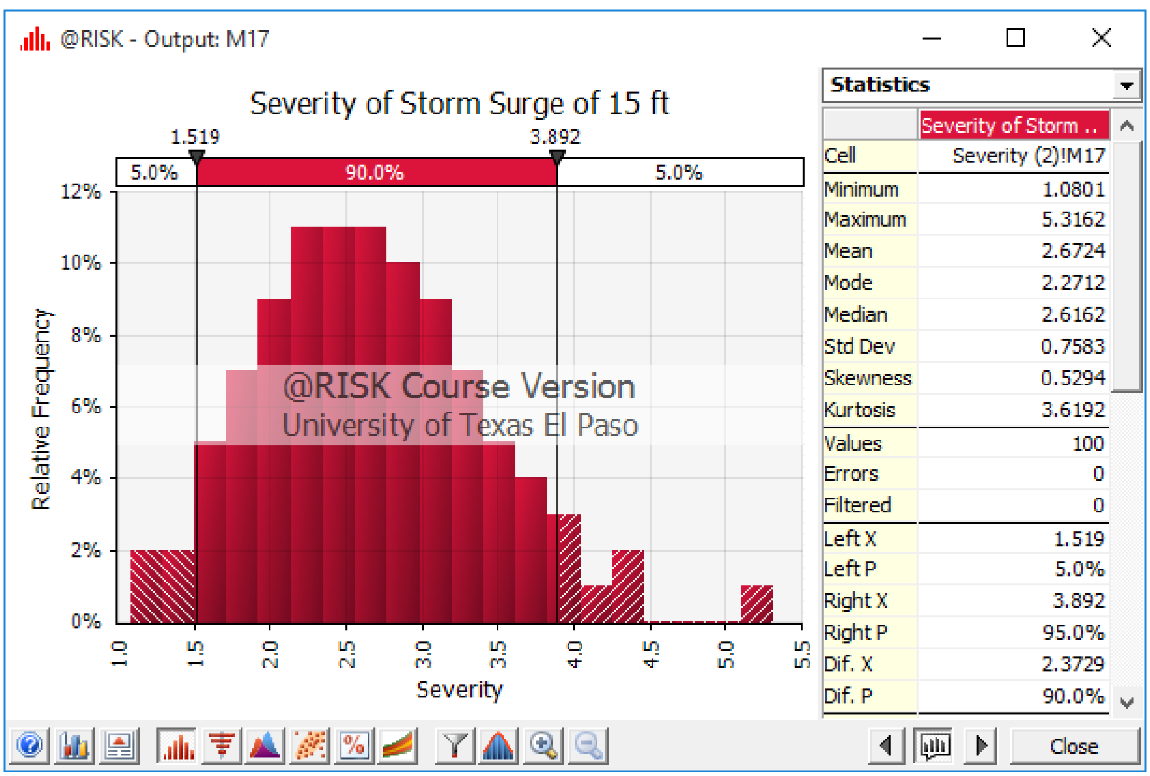


Figure 69: Severity Distribution, Category 3 Hurricane

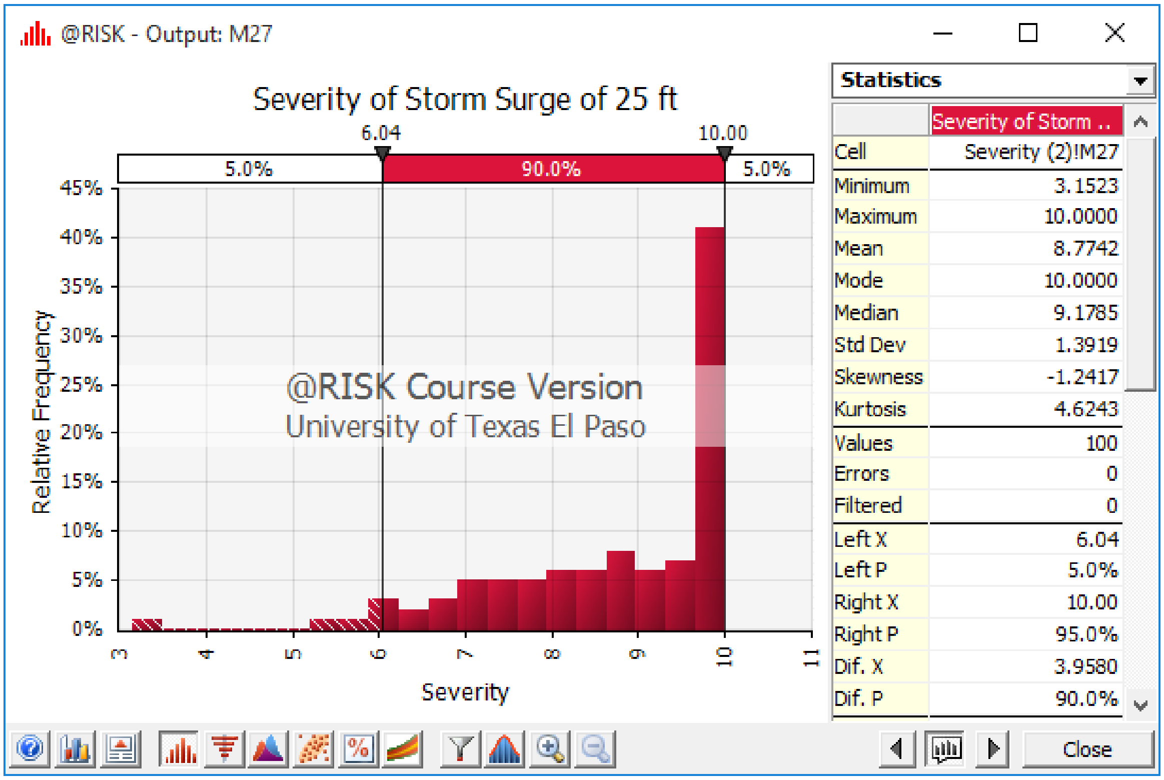


Figure 70: Severity Distribution, Category 5 Hurricane

Risk Priority Number (RPN)

To analyze the RPN confidence interval, occurrence and severity are combined using @Risk. The RPN expresses the risk of failure due to a climatic event, and it is obtained by multiplying occurrence and severity. Figures 71 to 73 show the RPN outputs of the simulations using the relative frequency. Figure 71 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, which means that the bridge is at a low risk of damage by a category 1 hurricane. Figure 72 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, which shows that the bridge is at a slightly higher risk of damage by a category 3 hurricane. Figure 73 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, which means that there is a higher risk of damage by a category 5 hurricane.

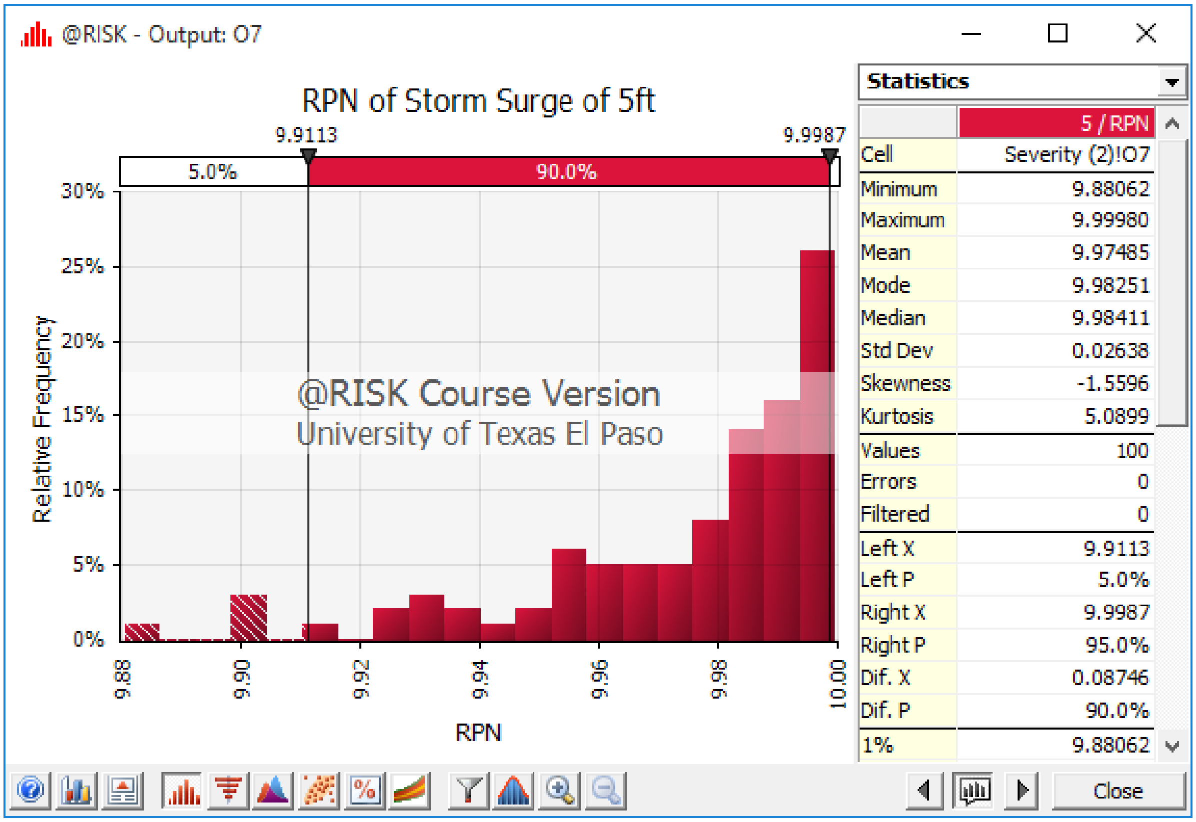


Figure 71: RPN Relative Frequency Distribution, Category 1 Hurricane

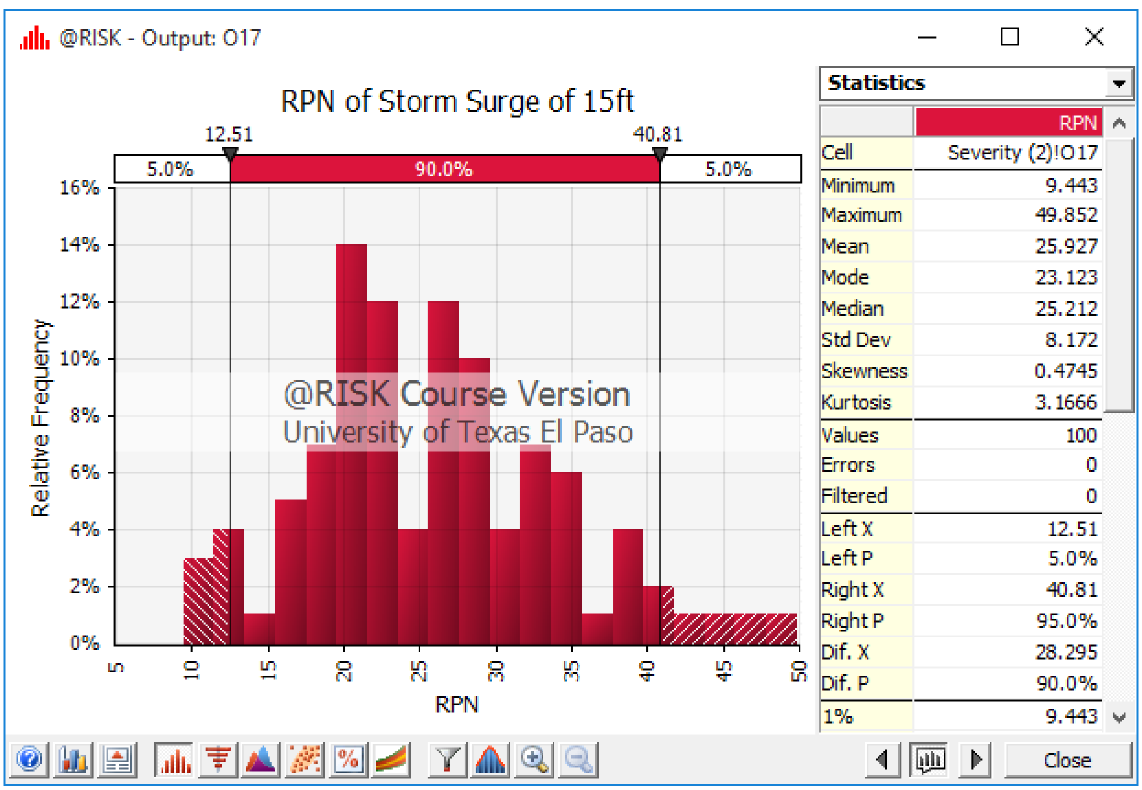


Figure 72: RPN Relative Frequency Distribution, Category 3 Hurricane

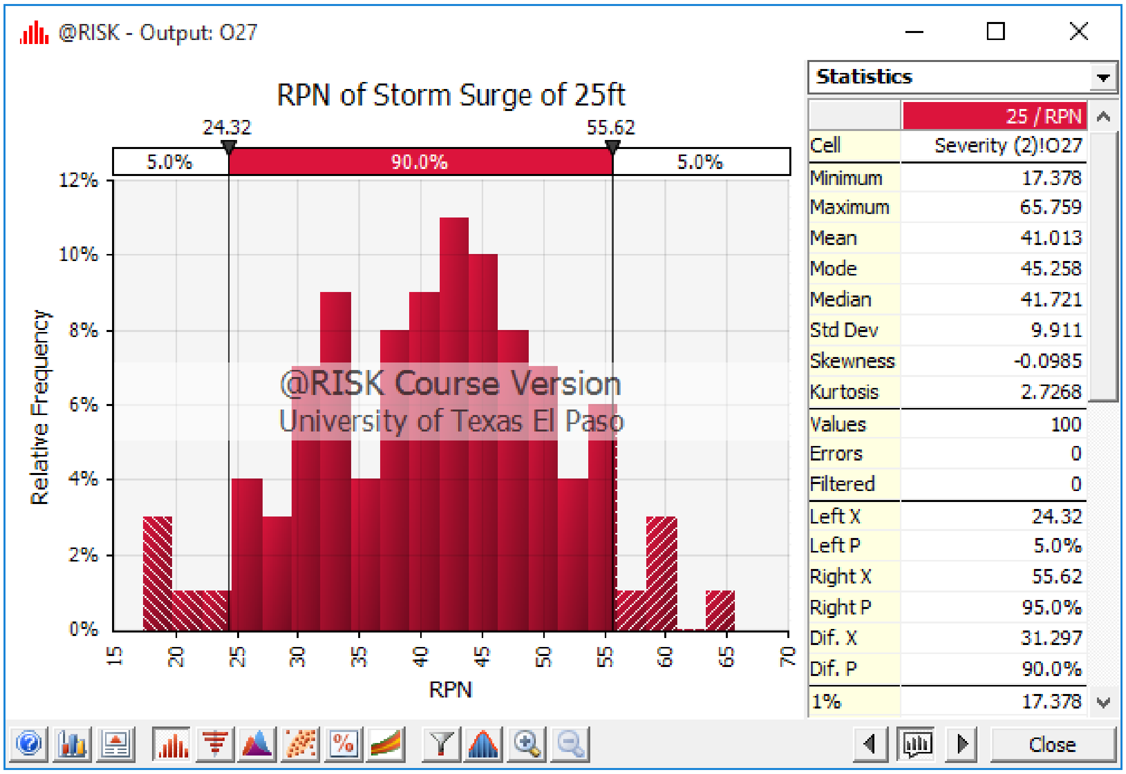


Figure 73: RPN Relative Frequency Distribution, Category 5 Hurricane

Another way to represent the outcomes of the simulation is using the Cumulative Distribution function. These are seen in Figures 74 to 76. The benefit of using this type of distribution, is that the probability can be read directly. For example, in Figure 74, the probability that the RPN is 9.96 or lower, is 20 percent for a hurricane 1.

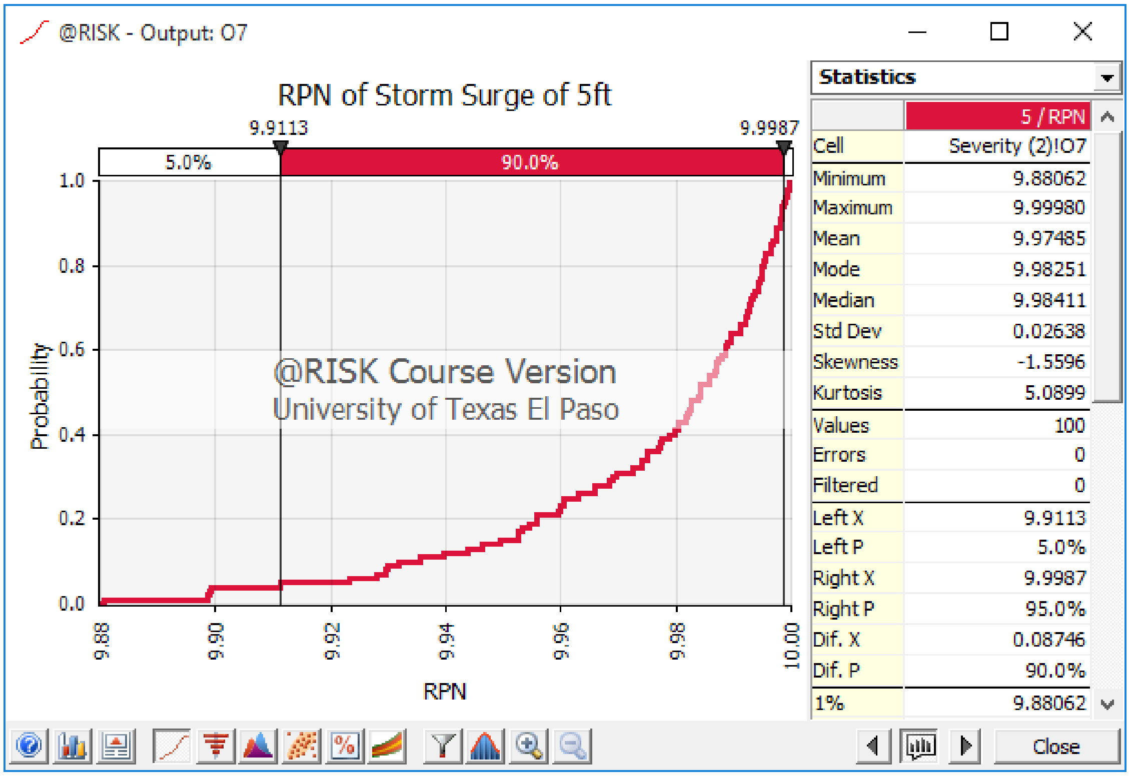


Figure 74: RPN Cumulative Distribution, Category 1 Hurricane

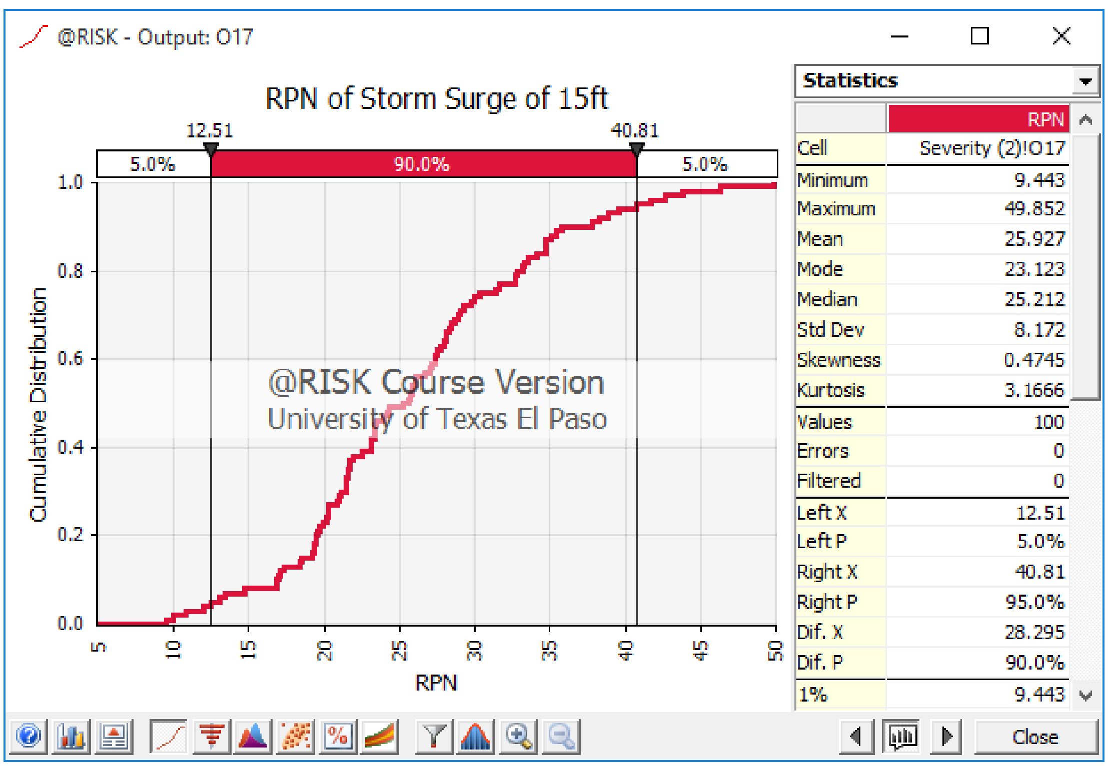


Figure 75: RPN Cumulative Distribution, Category 3 Hurricane

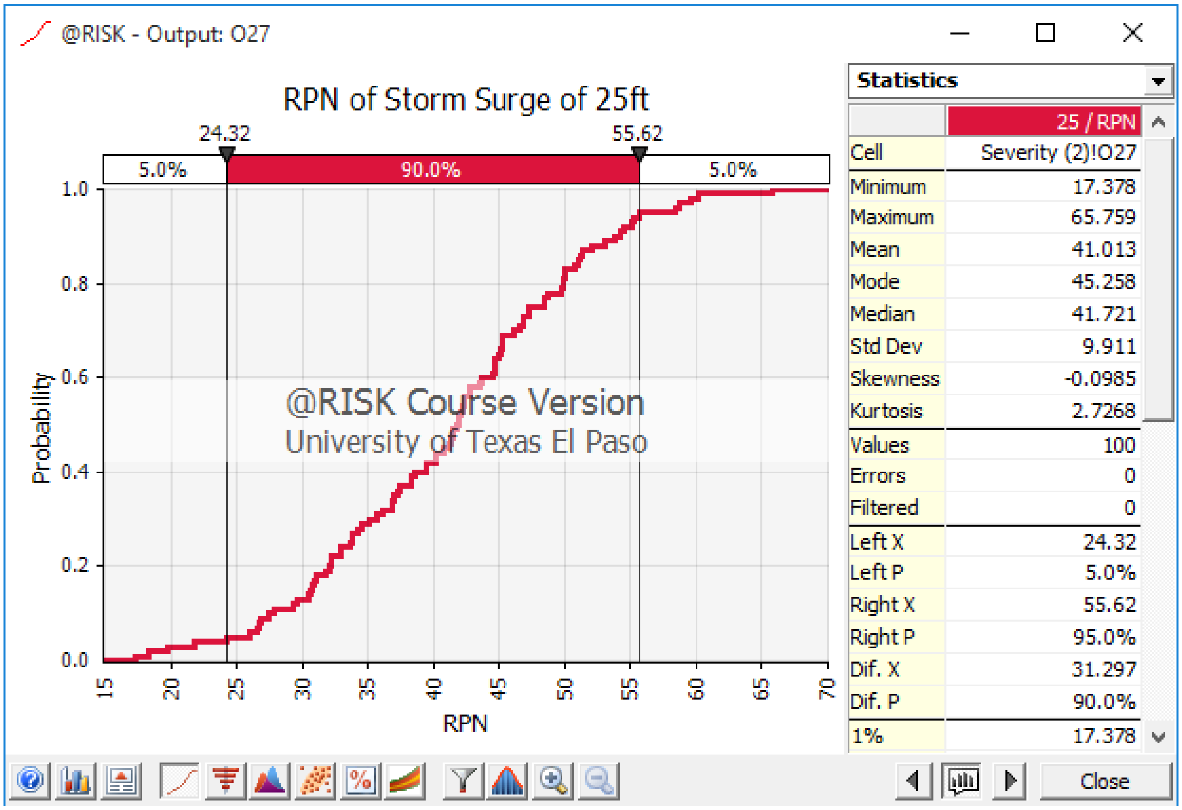


Figure 76: RPN Cumulative Distribution, Category 5 Hurricane

Chapter 7: 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 the transportation infrastructure.

SUMMARY OF RESEARCH FINDINGS

a. The first objective of this research was to identify climate change threats, risks, and performance measures on transportation infrastructure. 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. It is caused by the Earth in response to human induced changes like CO2 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. There is also 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. The steps are:
    - 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 where as a result 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:

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

where:

$\text{P}[X \geq 1]$	=	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 $= P[Z < 0] * (20 - C_p) = (1 - \Phi(Z)) * (20 - C_p)$
$= (1 - \Phi(\ln(\frac{R}{L}))) * (20 - C_p)$

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) which is obtained by multiplying occurrence, severity, and significance. Significance is a value from 1 to 10 and an asset that is vital to the transportation infrastructure, or places more people's lives at risk if it fails will have a higher significance value. The higher the RPN of an asset, the higher the priority for action. This is because the higher the RPN the higher the threat to preserve the transportation infrastructure in a "State of Good Repair".

In Chapter 6, 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 and if the remaining asset life increases, the occurrence 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 were conducted to demonstrate the applicability of the framework and methodology to quantify the risk of a bridge and a road. 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). The RPNs before and after the solutions, recommended actions, were calculated to determine if the risk was reduced. Table 30 shows a summary of the risk analysis for both case studies.

Table 30. 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%
			2	H3/ 15ft Storm Surge	80	10	88%
			3	H1/ 5ft Storm Surge	40	10	75%
	$30 Million	Repair bridge with 9 ft elevation.	1	H5/ 25ft Storm Surge	30	30	0%
			2	H3/ 15ft Storm Surge	80	80	0%
			3	H1/ 5ft Storm Surge	40	40	0%
Roadway	$14.5 Billion	Rebuild levees with 17 ft elevation	1	H5/ 25ft Storm Surge	50	50	0%
			2	H3/ 15ft Storm Surge	100	80	20%
			3	H1/ 5ft Storm Surge	10	10	0%
	$1.1 Billion	Build a 26 ft storm surge barrier	1	H5/ 25ft Storm Surge	50	45	10%
			2	H3/ 15ft Storm Surge	100	30	70%
			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. Some examples of adaptation strategies included 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 4 where 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 also 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 in Chapter 5. 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.

RESEARCH CONTRIBUTIONS

The major contribution of this research is the development of a framework to consider climate change impact in TAM practices. Another major contribution is the 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. The RPN can also be used to quantify the reduction of risk due to implementation of proactive actions in the asset management program.

AREAS OF FUTURE RESEARCH AND DEVELOPMENT

a. In this case studies, the methodology to quantify risk was applied to individual assets. 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 needs 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. Further research is needed to analyze the percent risk reduction to the cost. Currently, it is not clear how much percent risk reduction is attributed to each dollar spent. The future research should consider percent risk reduction per asset and try and correlate it to the amount of dollars spent. A risk reduction network index may be also incorporated and related to the investments made to improve the asset's resiliency.

e. 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

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 (USGPO 2017)

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	-

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 (TxDOT 2015).

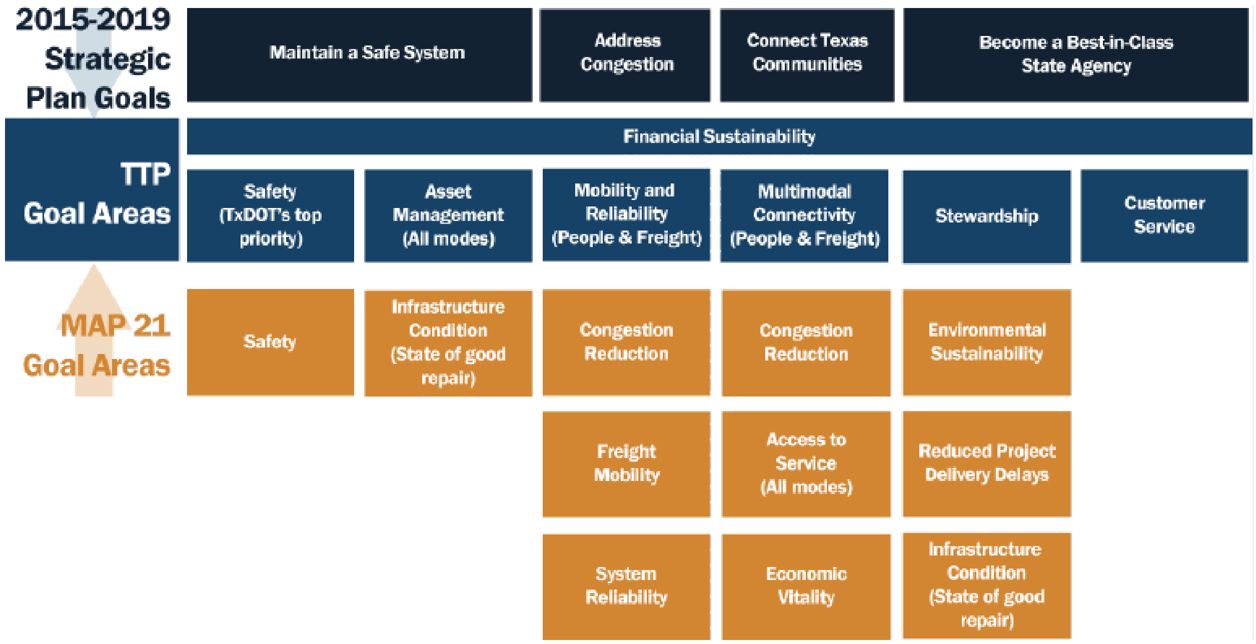

Figure A-1: TxDOT Goals Adaptation from MAP-21 (TxDOT 2015)

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 (TxDOT 2015)

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 (TxDOT 2015) (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 (TxDOT 2015) (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 (TxDOT 2014, TxDOT 2015)

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 (TxDOT 2014, TxDOT 2015) (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	• -

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 (NMDOT 2015)

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

Table A-4: NMDOT Goals and Objectives (NMDOT 2015) (cont'd)

Goal Area	Objectives
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.
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 (NMDOT 2015)

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)*
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

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 (OkDOT 2014)

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.
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 (OkDOT 2014)

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	-

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 (ArDOT 2014)

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.
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.

Table A-8: ArDOT Goals and Objectives (ArDOT 2014) (cont'd)

Goal Area	Objectives
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 (ArDOT 2017)

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)

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 (DOTD 2015)

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 (DOTD 2015)

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

Table A-11: DOTD Performance Measures (DOTD 2015) (cont'd)

Goal Area	Performance Measures
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 5 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 (NOAA 2017)

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
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

Table B-1: New Orleans Hurricane Data (NOAA 2017) (cont'd)

Name	Date	Category	Wind Speed (kn)	Wind Speed (mph)
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
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
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

Appendix C

Sample Calculations for the Risk of Failure of an Asset

This appendix contains sample calculations of a risk scenario from Chapter 5. This sample calculations show how to apply the occurrence, severity, and risk priority calculation (RPN) equations for a single scenario.

SCENARIO INTRODUCTION

These sample calculations will reflect the Scenario 2 of the I-10 Twin Span Bridge discussed in Chapter 5. The current elevation of the bridge is 9 ft from the surface of the water. The bridge has experienced five Category 3 hurricanes in the last 150 years. The bridge has an expected 50 years of life remaining. A) What is the risk priority number of the bridge for a Category 3 Hurricane with a storm surge of 15ft? B) If the bridge is reconstructed after Hurricane Katrina with an elevation of 30 ft and has a new asset life of 100 years what is the percent risk reduction. Note that the significance for the asset is 1 since we are only analyzing one asset.

A) What is the risk priority number of the bridge for a Category 3 Hurricane with a storm surge of 15ft?

- Occurrence= $P[X \geq 1] * 10 = [1 - f_x(k)] * 10 = (1 - \binom{n}{k} * p^k * (1-p)^{n-k}) * 10$
  - n: 50 Years Remaining life
  - a: 150 years of data
  - b: 5 hurricanes
  - Rep: a ÷b = 150 ÷ 5= 30
  - p: 1/Rep = 1/ 30 = .0333
  - k: = 0 because the equation1-p in the equation represents the probability of one or more extreme climatic events to occur.
- Occurrence= $P[X \geq 1] * 10 = [1 - f_x(k)] * 10 = (1 - \binom{n}{k} * p^k * (1-p)^{n-k}) * 10$

$$= (1 - \binom{50}{0} *.333^0 * (1 - .0333)^{50-0}) * 10$$

$$= (1 - \left(\frac{50!}{0!*50!}\right) * 1 * (.9667)^{50}) * 10$$

$$= (1 - (1) * 1 * (.1836)) * 10$$

$$= (1 - (.1836)) * 10$$

$$= (.8164) * 10$$

<u>Occurrence $= 8$</u>

- Severity= $P[Z < 0] * \left(20 - C_p\right) = (1 - \Phi(Z)) * (20 - C_p)$=$(1 - \Phi\left(\ln\left(\frac{R}{L}\right)\right)) * (20 - C_p)$
    - R: 9 ft
    - L: 15 ft
    - Cp: R – L = 9-15= -6ft
- Severity= $P[Z < 0] * \left(20 - C_p\right) = (1 - \Phi(Z)) * (20 - C_p)$=$(1 - \Phi\left(\ln\left(\frac{R}{L}\right)\right)) * (20 - C_p)$

    =$(1 - \Phi\left(\ln\left(\frac{9}{15}\right)\right)) * (20 - (-6))$

    =$(1 - \Phi(-.511)) * (26)$

    =$(1 - .305) * (26)$

    =$(.695) * (26)$

    =18.077

<u>Severity =10</u> Since higher than 10, Severity is maxed at 10.

- RPN = Occurrence * Severity * Significance
    - Occurrence: 8
    - Severity: 10
    - Significance: 1
- RPN = Occurrence * Severity * Significance
- RPN = 8 * 10 * 1
- <u>RPN = 80</u>

B) If the bridge is reconstructed with an elevation of 30 ft and has a new asset life of 100 years what is the percent risk reduction.

- Occurrence= $P[X \geq 1] * 10 = [1 - f_x(k)] * 10 = (1 - \binom{n}{k} * p^k * (1-p)^{n-k}) * 10$
  - n: 100 Years Remaining life since new bridge
  - a: 150 years of data
  - b: 5+1= 6
  - Rep: a ÷b = 150 ÷ 6 = 25
  - p: 1/Rep = 1/ 25 = .04
  - k: = 0 because the equation1-p in the equation represents the probability of one or more extreme climatic events to occur.
- Occurrence= $P[X \geq 1] * 10 = [1 - f_x(k)] * 10 = (1 - \binom{n}{k} * p^k * (1-p)^{n-k}) * 10$

$$= (1 - \binom{100}{0} * .04^0 * (1 - .04)^{100-0}) * 10$$

$$= (1 - \left(\frac{100!}{0! * 100!}\right) * 1 * (.96)^{100}) * 10$$

$$= (1 - (1) * 1 * (.01687)) * 10$$

$$= (1 - (.01687)) * 10$$

$$= (.9831) * 10$$

<u>Occurrence = 10</u>

- Severity= $P[Z < 0] * (20 - C_p) = (1 - \Phi(Z)) * (20 - C_p) = (1 - \Phi\left(\ln\left(\frac{R}{L}\right)\right)) * (20 - C_p)$
  - R: 30 ft
  - L: 15 ft
  - Cp: R – L = 30-15= 15ft
- Severity= $P[Z < 0] * (20 - C_p) = (1 - \Phi(Z)) * (20 - C_p) = (1 - \Phi\left(\ln\left(\frac{R}{L}\right)\right)) * (20 - C_p)$

$$=(1 - \Phi\left(\ln\left(\frac{30}{15}\right)\right)) * (20 - (15))$$

$$=(1 - \Phi(.6931)) * (5)$$

$$=(1 - .756) * (5)$$

$$=(.244) * (5)$$

$=1.22$

<u>Severity =1</u>

- RPN = Occurrence * Severity * Significance
    - Occurrence: 8
    - Severity: 1
    - Significance: 1
- RPN = Occurrence * Severity * Significance
- RPN = 10 * 1 * 1
- <u>RPN = 10</u>

- % Risk Reduction = $\frac{RPN\ Before - RPN\ After}{RPN\ Before}$
- RPN Before = 80
- RPN = 10
- % Risk Reduction = $\frac{RPN\ Before - RPN\ After}{RPN\ Before}$
- % Risk Reduction = $\frac{80-10}{80}$
- % Risk Reduction = $\frac{70}{80}$
- % Risk Reduction = .875
- <u>% Risk Reduction = 88%</u>

Vita

Oscar Ortega was born in Fort Worth, Texas, on March 31, 1988. After finishing high school in 2006, he began his studies in Civil Engineering at the University of Texas at El Paso. After completing his degree in 2010, he began his military service in the United States Army. In 2015, he finished his service in the United States Army achieving the rank of Captain and began his graduate studies at the University of Texas at El Paso. While conducting his graduate studies, he assisted in the editing of final reports for granting agencies like TxDOT, NCHRP, and the El Paso Metropolitan Planning Organization. The reports include "Quantification of the Impact of Roadway Conditions on Emissions", "Consequences of Delayed Maintenance of Highway Assets", and "Development of a Sustainable Based Methodology for Strategic Metropolitan Planning Based on MAP-21" respectively.

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This thesis/dissertation was typed by Oscar Ortega.