# A RESILIENCY FRAMEWORK FOR PLANNING IN STATE TRANSPORTATION AGENCIES

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# A FRAMEWORK FOR RESILIENCY PLANNING IN STATE TRANSPORTATION AGENCIES

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# SUMMARY

This thesis presents a framework for resiliency planning in state departments of transportation and other transportation agencies. The development of this framework is motivated by the need for more resilient transportation systems, due of the increasing frequency and the effect both natural and manmade catastrophic disasters have on transportation systems.

The resiliency framework is based on the urban transportation planning framework and is thus applied in the broader context of general transportation planning. The resiliency framework is then applied in a preliminary review to three statewide transportation plans to show the resiliency deficiencies of those plans and how the framework may be applied to increase resiliency. These plans are selected from three different states with diversity of locations and without any preconceived notions about their incorporation of resiliency in their planning process.

This preliminary review reveals a reactive nature towards investments that increase an agency's resilience. This may be attributed to the problem of limited funding for transportation investments, as well as, limited knowledge by the transportation agencies about the return on such resiliency investments, mostly due to the uncertainty associated with the occurrence of catastrophic disasters, especially the predictability of weather-related events. However, post-disaster transportation system overhauls provide enough evidence for the need for more systemic ways of addressing resiliency in planning processes.

# CHAPTER 1

# INTRODUCTION

The world as we know it still exists because nature has proven over millennia to be resilient. In the study of behavior patterns of ecosystems, it is seen that ecosystems are constantly failing or collapsing, leading to a phase of reorganization ensuring survival (Fisher, 2013). In the same way, humans are not immune to ecosystem collapse; on the contrary, if recent events are any indications, “we are in the midst of an ecosystem collapse” (Fisher, 2013). Natural disaster statistics worldwide indicate an upwards trend in the number of disasters reported as well as, incurred economic losses (EM-DAT, 2009). In the year 2000 alone, there were over 500 reported natural disasters which affected ten or more people; caused at least one hundred fatalities; required international assistance or called for a state of emergency (EM-DAT, 2009). According to the International Federation of Red Cross and Red Crescent Societies (IFRC), between 1991 and 2000, an average of 211 million people were either affected or died from a natural disaster (CRS, 2002). During that same decade an average of 1,300 people were killed across the world every week (CRS, 2002). Figure 1.1 shows total number of natural disasters reported across the world from 1900 to 2010 which clearly shows an exponential rise.

Natural disasters have a significant impact on the U.S. economy, with their costs rising progressively as they increase in frequency and intensity. This is proven by the fact that six of the 10 costliest disasters in U.S. history took place after the year 2000. In 2011 alone, economic damages from natural disasters in the U.S. were well over $55 billion, the highest since the first of such reported data in 1980. The cost of these disasters to transportation infrastructure and community quality of life cannot be over emphasized.

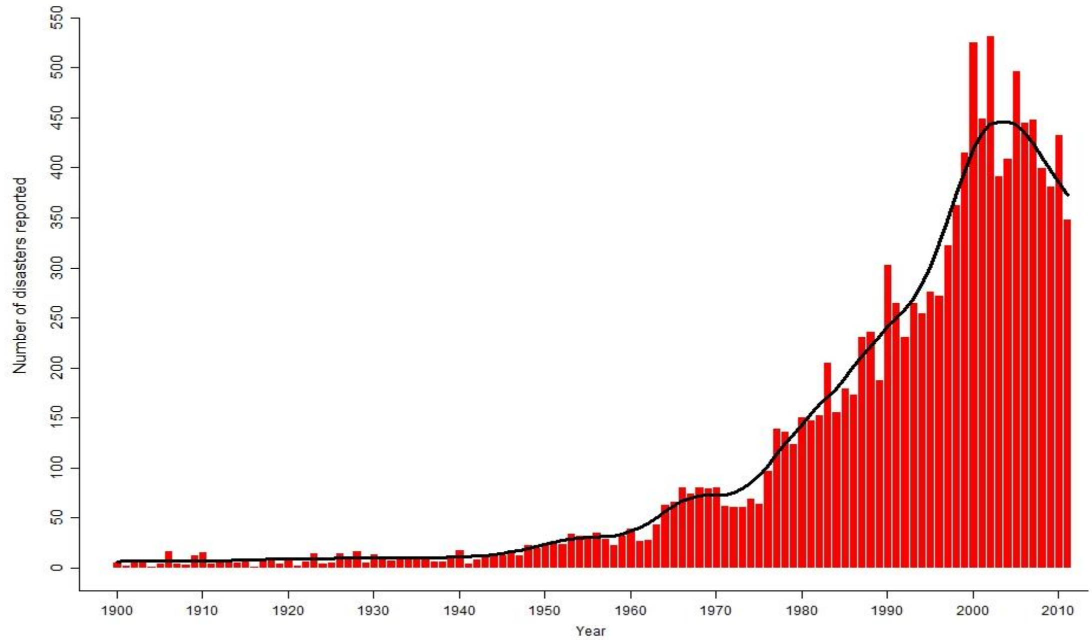


**Figure 1.1: Number of natural disasters reported worldwide from 1900-2010**
*Source: EM-DAT: the International Disaster Database-www.emdat.be-Universite Catholique de Louvain, Brussels-Belgium*

The Federal Highway Administration (FHWA), as of January 2012, received Emergency Relief (ER) funding requests of about $2.967 billion for the repair and reconstruction of roads classified as federal highways which were damaged in 2005 during hurricanes Katrina, Rita, and Wilma (Kirk, 2012). Similarly, the Disaster Relief Appropriations Act of 2013 made available $2.02 billion for the FHWA’s emergency relief program. Consequently, the FHWA on February 15, 2013 allocated $287million to the state of New York, of which $250 million was meant solely for Hurricane Sandy repair and reconstruction (FHWA, 2013).

In addition, of the 38,345 terrorist incidents around the world between 1969 and 2009, 7.8% (2,981) of these were directed against the U.S., causing nearly 5,600 fatalities and 16,300 injuries (Muhlhausen and McNeil, 2011). According to the Heritage Foundation's Center for Data Analysis, calculations based on data from the RAND Database of Worldwide Terrorism show that exactly 20 of these terrorist attacks have directly targeted transportation.

Even without the looming threats of natural disasters and terrorist activity, resilience must still be advocated in light of the country's aging critical infrastructure, which the 2011 National Risk Profile lists alongside extreme weather and pandemics as creating vulnerabilities which increase risk (DHS, 2011). According to the American Society of Engineers (ASCE), one in four (26%) bridges in the United States (U.S.) is either structurally deficient or functionally obsolete and a third of all major roads are also either in poor or mediocre condition (ASCE, 2009). To substantially improve the condition of our bridges and highways, an annual investment of about $17 billion and $186 billion respectively is required (ASCE, 2009).

Finally, the increasing interdependency of critical infrastructure in the U.S. has led to an increased vulnerability to cascading failures. The transportation system is one of 16 defined critical infrastructure systems which the Patriot Act defines as "…systems and assets, whether physical or virtual, so vital to the United States that the incapacity or destruction of such systems would have a debilitating impact on security, national economic security, national public health or safety, or any combination of those matters" (D.H.S, n.d.). The failure of transportation infrastructure during natural disasters exacerbates the consequences of these disasters by breaking the connectivity between other critical infrastructure such as hospitals and emergency shelters.

The increasing frequency of catastrophic events due to extreme weather, aging infrastructure and terrorist attacks are substantiation for the need for a reorganization of long standing planning approaches and operational methods into more resilient approaches. Traditional approaches to strengthening transportation infrastructure have focused on resistance, which primarily focuses on pre-disaster mitigation measures to enhance the performance of infrastructure elements. Resilience, on the other hand is concerned with improving the capacity of systems, not only through pre-disaster mitigation measures, but also in their ability to respond to and recover quickly from disasters or disruptions.

## 1.1 Problem Statement

Although resiliency in transportation has been studied in limited detail, there is still lack of a well-structured and accepted application of this concept to transportation systems. There is a need to apply resiliency concepts to the transportation planning process, thereby addressing issues related to disruptions caused by natural disasters early in the decision making process.

## 1.2 Objective

The objective of this work is to:

I. Provide an overview on the impacts of some natural disasters to linear transportation infrastructure systems such as roads, rail, and bridges.

II. Offer a resiliency planning framework which incorporates resiliency concepts into the transportation planning process.

## 1.3 Scope

The disasters discussed are limited to their effects on the United States, that is, this thesis focuses on hurricane landfalls, damages and fatalities.

## 1.4 Order of Thesis

Chapter one gives the background and motivation for the research. Chapter two provides summaries of the impacts of disasters to some transportation infrastructure, as well as a review of resiliency concepts and its application in transportation engineering. In chapter three, the resiliency planning framework is presented. The framework is then used to evaluate elements of resiliency in three long-range transportation plans from three state departments of transportation in chapter four. Finally, this thesis ends with a conclusion and some recommendations in chapter five.

# CHAPTER 2

# LITERATURE REVIEW

This section of the thesis will first provide an overview of the impacts of some natural disasters on transportation infrastructure in the U.S. It will then introduce the concept of resiliency, its applications and metrics for measurements.

## 2.1 Impacts of Disasters on Transportation Infrastructure

### 2.1.1 Hurricane Katrina

Hurricane Katrina was a category three hurricane that first made landfall on the 29$^{th}$ of August, 2005 as a category one near Miami, Florida, then later as a category three with sustained wind strengths of about 125 mph and minimum pressure of 920 mbar, causing severe damage along the Louisiana-Mississippi-Alabama coasts. There were approximately 1,800 fatalities, with about a million more people displaced making it the deadliest hurricane since the Okeechobee hurricane in 1928 which claimed more than 4,000 lives. It is perhaps worthy to note that the majority of the damage caused by hurricane Katrina was not because of the wind strength or the rain from the storm itself, but rather from the storm surge and levee breaches which caused the subsequent flooding. Much of the destruction occurred in the City of New Orleans which had about 80% of the city submerged, leaving about 100,000 people trapped with no power, food or drinking water. The dire circumstances after the hurricane left residents in a state of fear compounded by fifteen percent of the police force walking off. The destruction and loss from the hurricane affected not only the local economies but the national economy too. The national oil industry was probably the hardest hit with the daily Gulf of Mexico oil production reduced by 95% due to 30 damaged oil platforms, nine closed refineries and oil spills from 44 facilities, resulting in more than 26 million liters of oil being leaked. In total, hurricane Katrina is estimated to have caused $125 billion (2007 dollars) in damages.

#### 2.1.1.1 The Hurricane Protection System

Although the hurricane protection system is not transportation infrastructure, it is important to take note that deficiencies in this system were the main cause of most of the destruction in New Orleans. The main components that were damaged were the levees, the canals and interior drainage and pumping stations. The characteristics of these systems made their failure inevitable in the face of a hurricane such as Katrina. The inadequacies of the design of the hurricane protection system were not exposed mostly because the design was not subject to rigorous review by experts. The piecemeal construction of levees, along with inaccuracies in the construction process, was also brought up in hindsight reviews (ASCE, 2007). In retrospect, failure of the hurricane protection system has been attributed to two facts: that there was no single agency in charge of hurricane protection in New Orleans and that there was a lack of inter-agency coordination among the agencies in charge. Activities such as maintenance of levees and pumps were spread over many agencies with federal, state, parish and local jurisdictions (ASCE, 2007).

#### 2.1.1.2 Bridges

Over 45 bridges sustained damage in Alabama, Mississippi and Louisiana. These were mostly bridges located near water. Damages were mostly to the superstructure with little or no damage to the substructure and were generally caused by four main problems (Kazez, and Vipulanandan, 2010): (1) storm surge - mostly induced loading which caused damages such as breakages in the connections between pilings and piers, as well as unseated decks and further damage to guardrails in both fixed type and movable bridges, (2) bridge scour- caused by the moving water which gradually removed sediment from the bridge piers and thereby weakened the structure (Warren, 2011); (3) inundation – caused damage to mostly electrical and mechanical components which mostly affected movable bridges and (4) High winds – this contributed to other modes of failure by raising the probability of occurrence, such as damage from debris, including loose barges and boats. Some vital bridges that were damaged were I-10 Twin Span Bridge, the Pontchartrain Causeway, St. Louis Bay Bridge and the Biloxi Bridge. During repairs carried out, most bridges were elevated about six meters higher than their original levels. Recommendations for improved bridge design included vertical constraint devices, air vents in bridge diaphragms and transverse shear keys to prevent lateral shifting (DesRoches, and Rix, 2006). These were anticipated to be effective in reducing damage. Sophisticated equipment such as monitoring systems, sensors and a weight motion scale were also installed on some bridges. The overall cost of repair and replacement, including emergency repairs and rebuilding, was estimated to be more than $1 billion (TCLEE, 2006).

#### 2.1.1.3 Roads and Rail

Roads were mostly either submerged or rendered inaccessible due to significant debris deposits by the hurricane. Some sections of roads such as the Louisiana Highway 23 (LA 23) in south Louisiana were also torn apart. There was also significant damage to utilities, traffic signals and signs, driveway aprons, curbs, ramps and road paving. Rail roads suffered from broken anchor bolts and damaged angle clips, with a substantial amount of debris and barges causing major disruption to rail traffic. Among the major railroads and highways damaged were Norfolk Southern's five-mile-long Lake Pontchartrain Bridge, CSX's railroad tracks east of the Saint Louis Bay, and the U.S. 90 Biloxi-Ocean Springs. Railroad reconstruction saw a shift from the use of anchor bolts to through rods on connections to precast I-girders. Also, corrosion protection was ensured by coating the reinforcement bars and using high performance concrete. In total, there was an estimated $200 million for debris removal (TCLEE, 2006).

#### 2.1.1.4 Ports

The river and coastal ports facilities affected by Hurricane Katrina sustained a wide variety of damage, ranging from minor wind damage to complete inundation. High winds, storm surge and failure of the levees were among the main causes of damage (Curtis, 2007) which included flooding, damage to container cranes and a reported fire at Mandeville Wharf in New Orleans. The Port of Gulfport in Mississippi was the hardest hit in terms of structural damage as it suffered a direct hit from the hurricane (Frittelli, 2005). Other hindrances to port operations were the lack of power and the displacement of workers due to the storm damage (Curtis, 2007). According to the National Oceanic and Atmospheric Administration (NOAA), the Port of New Orleans alone was estimated to have accrued a $250 billion loss, in both to port facility damage and disrupted commerce, with the latter making up $20 million of the total sum (NOAA, n.d.).

On the whole, there was a high level of government criticism in the aftermath of Hurricane Katrina, partly due to the fact that knowledge of New Orleans' vulnerability was not hidden from national agencies, on the contrary, the Federal Emergency Management Agency (FEMA) had previously rated New Orleans and San Francisco as the top two cities most vulnerable to catastrophic natural disasters.

### 2.1.2 Hurricane Ike

Hurricane Ike at peak intensity was a category four hurricane but made final landfall near Galveston in Texas on September 13th, 2008 as a category two hurricane. This was the costliest hurricane in Texas history and the third costliest in U.S. history. The hurricane was the fifth hurricane of the 2008 Atlantic hurricane season with sustained winds of 145 mph and a minimum pressure of 935 mbar. Hurricane Ike also recorded the second highest integrated kinetic energy (IKE) for an Atlantic storm in the past forty years. The hurricane caused damages from the Louisiana coastline to Kennedy County in Texas, with flooding damage along the Mississippi coast and the northwestern part of Florida (Florida Panhandle) resulting in $30 billion in damages in the U.S. alone (Blake et al., 2011). In subsequent weeks, the State of Texas estimated $131.8 million for transportation system damage repair costs, with $53.7 million allocated to road and bridge repairs and $78.1 million to debris removal from public rights-of-way and recovery efforts by city and county governments (FEMA, 2008). The Texas Department of Transportation (TxDOT) also required an estimated $36.5 million for debris removal not carried out by the U.S. Army Corps of Engineers (FEMA. 2008). The hurricane caused 103 direct deaths which were attributed to severe flooding, wind, electrocution and car crashes during the storm (Berg, 2009).

#### 2.1.2.1 Bridges

Approximately 53 bridges in the Houston/Galveston area sustained damage primary due to a combination of storm surge and wave forces. This caused impact damage from large debris carried by floodwaters to bridges such as the Union Springs Bridge and the Rice Belt Road Bridges (State of Texas, 2009). Scour was also common in local bridges such as the single-span 3400 Rocky Shore Bridge and the two-span CR-3625 Ebenezer Church Road Bridge (State of Texas, 2009). Most the bridges damaged were timber structures in rural areas but some major bridges with more than five spans, made of steel and concrete were also damaged (Stearns and Padgett, 2011). The Humble Camp Bridge at Hildebrandt Bayou, the Rollover Pass Bridge and the Pelican Island Bridge (AADT of 6,520) were among some of the major bridges damaged from storm surge and wave loading (Bridgehunter.com, 2013; Stearns and Padgett, 2011).

#### 2.1.2.2 Roads and Rail

Roadbeds and shoulders along several miles of roads were washed out from the flooding, for example the five-mile section along the State Highway 87 in Texas. Ninety percent of traffic signals in Houston were either damaged or not functioning due to loss of power. State Highway 87 and portions of County Road 257 in Brazoria County are among some roads that were severely damaged. In the aftermath however, emergency contracts were issued to repair signals and traffic detection systems. State highways and roads that served as barriers to protecting wetlands were also prioritized during repairs (FEMA, 2008). Railroad tracks were littered with debris deposits of blown-down trees and power lines even up to locations 180 miles from the coast. There were also embankment washouts and removal of decks and caps off trestles. On the Galveston Causeway, about 1.5 miles of concrete curb was broken, crushed stone ballast washed out and tracks washed out of line. Union Pacific also had about a mile of their tracks shifted off the road bed. In New Orleans, repairs conducted on 21 miles of railroad tracks that were damaged by Hurricane Gustav were washed away. There was also significant wind damage to railroad buildings. According to the American Association of Railroads, there was a steep decline of 7.8% in freight transported by the major U.S railroads. Emergency repairs and cleaning out carried on railroads restored service on high priority lines within an average of two days, and in about a week on less important lines. The Galveston Railway, connected to the Port of Galveston was reported to have sustained $628,000 in damages to offices, trains and railroad tracks (FEMA, 2008).

#### 2.1.2.3 Ports/Canals

There was erosion damage to the Galveston seawall and the Galveston/Bolivar Ferry operations were disrupted due to extensive damage to hydraulic systems caused by salt water intrusion. The Port of Galveston also sustained extensive damage (FEMA, 2008). The U.S. Army allocated $25 million for rehabilitation of the seawall. There was also an estimated $2.4 billion invested by the State of Texas to carry out repairs for damages caused by erosion, as well as to waterways, ports and coastlines (FEMA, 2008).

### 2.1.3 Hurricane Ivan

Hurricane Ivan was at peak strength a category 5 hurricane which reduced to category 3 at landfall near the Gulf Shores in Alabama east of Mobile on September 16$^{th}$, 2004 (USGS, 2013). At final landfall in southwest Louisiana, it was further reduced to a tropical depression on the 24$^{th}$ of September, 2004. Hurricane Ivan was one of only 12 recorded depressions to become storms given its early location south of 10EN (NOAA, 2012). At peak intensity, hurricane Ivan sustained winds of up to 165 mph and pressures as low as 910 mbar. There were also storm surge heights of 10- 15 feet along the Gulf Coast during its first U.S. landfall (NOAA, 2012). The hurricane caused beach and dune erosion (State of Florida EPA, 2004), severe flooding damage and landslides, and initiated 117 tornadoes across the eastern part of the U.S. Different areas across Alabama, Florida, Louisiana, North Carolina, Georgia and Mississippi were affected by the hurricane. Consequently, Hurricane Ivan caused 25 direct and 32 indirect deaths in the U.S. which were as a result of tornados (7), storm surge (5), fresh water floods (4), mud slides (4), wind (3) and surf (2) (Stewart, 2004). The distributions of deaths across the U.S. are as follows: 14 in Florida, 8 in North Carolina, 2 in Georgia, and 1 in Mississippi (Stewart, 2004). There were 67 other deaths reported deaths in Grenada, Jamaica, Dominican Republic, Venezuela, Cayman Islands, Tobago and Barbados (Stewart, 2004). The coastal areas sustained the most severe damages in terms of structural damage and beach erosion (State of Florida EPA, 2004). Some inland areas were also damaged, as well as offshore drilling operations. According to the State of Louisiana Department of Natural Resources, Hurricane Ivan destroyed seven oil platforms, combined with causing 2.7% and 4.9% of the Gulf of Mexico's annual gas and oil production respectively to shut-in (State of Louisiana, 2004). There was also extensive damage to pipelines with some pipelines at the mouth of the Mississippi River moved as far as 3,000 feet and others also buried under 30 feet of mud (State of Louisiana, 2004).

Damages from the hurricane are totaled at $18 billion with about $800 - $900 million sustained by the U.S. Naval Air Station in Pensacola Florida (EM-DAT, 2009; Stewart, 2004).

#### 2.1.3.1 Bridges

The Escambia Bay Bridges on the Interstate 10 were among the most severely damaged during the hurricane with parts of the bridge either toppled or shifted out of alignment. Parts of the Bob Sikes Bridge in Santa Rosa County in Florida sustained heavy damage but reopened after about a week to Santa Rosa residents only (AARoads, 2011). The Navarre Beach Causeway, also in Santa Rosa County sustained heavy structural damage and was closed until November 3, 2004 (AARoads, 2011). Portions of the I-10 Bridge across Pensacola Bay, Florida, sustained severe damages at various locations along its length caused by storm surge and wave action resulting in parts of the bridge collapsing into the bay (State of Florida EPA, 2004). The U.S 98 Lillian Highway Bridge was also closed due to flooding and structural damage (AARoads, 2011).

#### 2.1.3.2 Roads

Storm surge and water flow across roads caused severe damage, from overtopping to scour, washouts, undercutting, subsidence and burying of roads by sand. There was also wave attack on revetment slopes, which affected roads nearby. In Alabama, State Road 182 sustained damage from a breach by flood waters and the Florida 399 between Pensacola Beach and Navarre Beach was also damaged. Other roads damaged were the Perdido Key county Road 292, Florida 292 and the U.S 98 approach to Pensacola (Douglass et al., 2004). Damaged roads in Alabama alone cost an estimated $28 million according to state transportation officials (McGrew, 2004). The North Carolina Department of Transportation received a total of $27.1 million from the North Carolina Division of Emergency Management (NCDEM) to pay for projects related to debris removal, road repairs and bridge replacements (DHS, 2011).

### 2.1.4 Hurricane Wilma

Hurricane Wilma is the fourth costliest storm in U.S history. It made landfall in southwest Florida as a Category 3 hurricane on October 24, 2005. It had wind speeds of up to 185 mph and a minimum pressure of 882 mbar, making it the lowest central pressure recorded for an Atlantic hurricane since Hurricane Gilbert of September, 1988 (NOAA, 2012). The hurricane affected parts of Mexico, Cuba and Florida which resulted in ten tornadoes between 23-24 October in Florida alone (NOAA, 2012). One in each of the following counties: Collier, Hardee, Highlands, Indian River, Okeechobee, and Polk, and four in Brevard County (Pasch et al., 2006). Hurricane Wilma caused a total of 23 fatalities, five of which were in Florida with the other 18 divided between Haiti (12), Jamaica (1), Mexico (4) and Bahamas (1) (Pasch et al., 2006). The hurricane caused water shortages and loss of power after the storm. According to Florida Power and Light, approximately 6 million people were without power including the entire Florida Keys area, with some for as long as 2-3 weeks (NCDC, 2005). The lack of electrical power led to gasoline shortages and inoperative sewage systems. This was the largest power disruption to be experienced by Florida with up to 98% of South Florida without power (Pasch et al., 2006).  Total damage estimates for hurricane Wilma were estimated to be $14.3 billion (EM-DAT, 2009).

#### 2.1.4.1 Bridges

In South Florida, there was some structural damage to bridges such as the Marco Island Bridge which sustained some scour (Steimle, 2009). The Max Brewer Crossway Bridge between Titusville and Playlinda Beach was also closed due to impact damage sustained from a loose boat (SERT, 2005). Other damages were as a result of flooding and wave action around piers (Dillon, 2006). Estimates for eight Marco bridges damaged during the hurricane sum up to about $1 million, excluding the east Winterberry Drive Bridge whose estimate is $4.4 million (Kaiser, 2005).

#### 2.1.4.2 Roads and Rail

Substantial signal and sign damage on state roads and I-95 (SERT, 2005). Only 18 out of Miami’s 2600 traffic signals were left working. An estimated $40 million spent on traffic signal repairs (Turnbell, 2006). Florida received $480 million towards costs for replacing signals, clearing highway debris, and repairing roads across 21 counties for damages caused by Hurricanes Rita and Wilma (Roads & Bridges, 2006).

Hurricane Wilma also caused some rail damage, although not as widespread, Tri-Rail services in Miami was shut down for 17 days (SFRTA, 2011). The Railway also suspended service for 14 days until the tracks were all cleared. The hurricane was estimated to reduce Florida East Coast Railway's (FECR) fourth quarter revenues by about $1.5 to $2.5 million (FECI, 2005). Estimated cost incurred by FECR for clean-up, property damage and grade crossing operations was between $2.5 and $3 million (FECI, 2005).

### 2.1.5 Hurricane Irene

Hurricane Irene made its first landfall in North Carolina on August 27, 2011 as a category 1 hurricane and its final landfall as a tropical storm in New York City on August 28, 2011 (Avila and Cangialosi, 2011). The hurricane's highest sustained wind speed was 120mph in the Bahamas as a category 3 hurricane, however, highest gust in the U.S was 83 mph. Flooding records were broken in 26 rivers: in New Jersey, 14 in New York and 4 in Vermont (NOAA, 2011). Forty-nine direct deaths were attributed to Hurricane Irene: 41 in the U.S, 5 in the Dominican Republic and 3 in Haiti (Avila and Cangialosi, 2011). The causes of deaths in the U.S. were storm surge (6), wind (15) and floods (21) (Avila and Cangialosi, 2011). Hurricane Irene caused severe wind damage causing downed trees and power lines; however, its most devastating impacts were major floods caused by torrential rainfall (Lubchenco and Furgione, 2012). Severe flooding and storm surge affected Vermont, New York, New Jersey, northern New Hampshire, North Carolina and

Connecticut (Lubchenco and Furgione, 2012). In New York, a storm surge of between 3-6 feet was experienced (Lubchenco and Furgione, 2012). Flood levels in southern Vermont caused damage to 2400 roads, 300 businesses, 800 homes and businesses, and 6 railroads either destroyed or damaged (Avila and Cangialosi, 2011). Impact to agriculture in New York, according to the governor, was estimated at $45 million (Avila and Cangialosi, 2011). According to the New Jersey Department of Environmental Protection Bureau of Dam Safety, six dams failed as a result of the storm on August 14, caused by the hurricane (New Jersey Water Science Center, 2013). In New York, high flood levels left five towns in the Catskill Mountains completely dilapidated; Prattsville, Windham, Tannersville, Phoenicia and Margaretville (McKnight, 2012). In Connecticut and Long Island, heavy rains and wind caused power outages to more than 3 million residents for about a week (Avila and Cangialosi, 2011). In total, 8 million people were without power after Hurricane Irene hit (Lubchenco and Furgione, 2012).

The hurricane also caused several flight cancellations, airport closures and suspended rail service. Several airports were affected, including John F. Kennedy Airport, Newark Liberty International, LaGuardia Airport, Stewart International and Philadelphia International Airport, causing approximately 11,800 cancelled flights affecting 650,000 travelers (Avila and Cangialosi, 2011). In total, damages caused in the U.S were estimated at $15.8 billion (Avila and Cangialosi, 2011).

#### 2.1.5.1 Roads and Bridges

In Vermont, a total of 263 roads and bridges were washed out with damages exceeding $700 million (Mackin, 2012). Thirty state bridges and 260 roads were also closed down in Vermont which cut off access to 10 towns (Associated Press, 2011). Damage to roads consisted of sediment deposit within roadside drainage, loss of embankments and other damages to culverts and headwalls. In North Carolina, over 270 roads and 21 bridges suffered damaged from flooding and debris deposits, and were subsequently closed down (Lubchenco and Furgione, 2012). The Allen Road in Tannersville-New York had 100 feet of its pavement washed out with resulting erosion damage that exposed sewers and water mains (NYC-EP, 2013). Repairs in the area included debris removal, replacement of utilities and guardrails, as well as rebuilding washed out parts of the road, and slope stabilization. Reports from the City of New York Department of Environmental Protection (NYCEP) also stated that there were substantial damages to the Schoharie Bridge on New York State Route 990V in Gilboa, the Bushkill Bridge on Route 28A in West Shokan, and the Lowes Corner Bridge on Route 55A in Grahamsville. The Schoharie Bridge lost 245 feet and 189 feet of bank protection on the eastern and western abutments respectively. Repairs carried out on the bridge include providing temporary access from Route 990V, provision of cofferdams and fortifying the retaining walls. According to NYC Environmental Protection, repairs to the Allen Road, the Schoharie Bridge, the Bushkill Bridge, and the Lowes Corner Bridge, summed up to a total of $2.1 million (NYC-EP, 2013). Total aid awarded in New York State for transportation costs incurred during Hurricane Irene and Tropical Storm Lee was estimated at $297 million (NYC Governor's Press Office, 2012). In addition, the U.S. Department of Transportation's Federal highway Administration provided approximately $45 million towards the repair and replacement federal highways damaged in Massachusetts by Hurricane Irene and previous tornadoes (House Leadership, 2012).

2.1.5.2 Rail

Apart from the halt on transit rail service operations preceding the hurricane; there was also heavy damage to railroads. In Vermont, the FEMA Public Assistance program approved 80 rail related repair and replacement projects. These comprise 16 bridge projects at $18.3 million and 64 railroad track projects at $3.7 million, totaling $22 million, of which FEMA's Public Assistance program pays 90 percent (FEMA, 2013). In Philadelphia, 16 regional railroad cars were partially flooded with 12 reported to have been left with long term damage (Campisi, 2011). New York City's Metro Transit Authority (MTA) also submitted claims of $65 million, of which FEMA has approved $27.7 million for 59 projects (Yang, 2012).

### 2.1.6 Hurricane Sandy

Hurricane Sandy was a category 1 hurricane which weakened to a post-tropical cyclone at landfall on October 29, 2012, south of Atlantic City- New Jersey with maximum winds of up to 155mph and minimum pressure of 940 mbar (Sharp, 2012). It was an extremely large hurricane, at 900 miles in diameter; its area was about 150 percent the size of Texas (Burnson, 2012). It initially made landfall in Caribbean on October 25, causing extensive damage in Haiti, Jamaica, and Cuba (Center for Disaster Philanthropy, 2013). In New York, the hurricane had storm surge levels of up to 12.65 feet and storm tides (the combination of surge and tide) of up 14.06 feet (Blake et al., 2013). Hurricane Sandy affected states across the southeast, mid-Atlantic, Appalachia and mid-west of the U.S. These were New York, Maryland, Virginia, West Virginia, Connecticut, Massachusetts, New Hampshire, Ohio, Florida and New Jersey. In southeast

Florida, though the hurricane did not make landfall, it caused some coastal flooding and substantial beach erosion (National Weather Service, 2012). In Miami-Dade County, resulting wave heights were reported to have been between 10 -20 feet high (National Weather Service, 2012). In Palm Beach County alone, damages from Hurricane Sandy were totaled at $14 million (National Weather Service, 2012).

Hurricane Sandy caused at least 72 direct and 87 indirect deaths in the U.S., the highest number of deaths caused by a tropical cyclone in the northeast since Hurricane Agnes of 1972 (Blake et al., 2013). Overall death estimates remain at 147 direct and 138 indirect deaths, with storm surge accounting for 57% of U.S. deaths (Blake et al., 2013). Other causes of deaths were flooding, hypothermia, car crashes, falling trees, fires, and carbon monoxide poisoning (Serna, 2012). In all, Hurricane Sandy caused over $75 billion in damages, making it the second costliest hurricane to hit the U.S. after Hurricane Katrina in 2005 (Nevitt, 2013).

#### 2.1.6.1 Roads and Rail

The New York and New Jersey Transit systems suffered dramatic losses as a result of the storm. Roads suffered embankment washouts, shoulder drop-offs, tilted street light poles, excessive debris, damaged traffic signals and signs. There was also flooding damage as a result of weak dune structures and storm surge. All seven tunnels the East River flooded, as well as one subway bridge, three subway yards and six bus facilities. According to MTA NYC Transit, the Rockaway Flats line which runs between Howard Beach and the Barrier Island, sustained severe damage leaving 35,000 customers stranded. There were track washouts and destroyed fences, as well as loose boats, oil tanks, logs and significant debris deposited on the tracks. All seven East River tunnels were flooded (New York Times, 2012). Electrical components at rail stations such as plus signals and mechanical rooms suffered severe damage from the flooding. MTA sustained an estimated cost of about $5 billion in damage and lost revenue (Blake et al., 2013). According to New Jersey Transit, the transit system sustained damages to 62 of their 203 locomotives and 261 of their 1,162 rail cars. In total, New Jersey Transit sustained an estimated $400 million in damages (Levin, 2012). Amtrak has asked Congress for a total of $336 million as a result of damages caused by Hurricane Sandy; $276 million of the amount is to be used for improvements at the Penn Station in New York (Levin, 2012). Total funding from the Emergency Relief Fund of the Federal Highway Administration (FHWA) for New Jersey is estimated at $ 224 million (U.S.DOT, 2013). These funds will be used to reimburse the state for repairs to damaged highways and bridges caused by the storm. An estimated $800 million in needed for improvements to protect the system against future storms (Levin, 2012).

In summary, whether we are facing sudden external threats such as natural disasters and terrorist attacks, or internal threats such as design flaws and construction errors, the overall hazard (a function of threat likelihood, threat consequence and system resilience) may be reduced to the barest minimum by increasing system resilience (Labi, 2013). Table 2.1 is a summary of the nine most expensive natural disasters to hit the U.S. showing hurricanes Katrina, Sandy, Ike, Wilma, and Ivan with their relative positions.

**Table 2.1: Top nine natural disasters in the United States sorted by economic damage costs (1984-2013)**

| Date | Disaster | Damage (billion US$) |
|---|---|---|
| 08/29/2005 | Hurricane Katrina | 125 |
| 10/28/2012 | Hurricane Sandy | 75 |
| 01/17/1994 | Northridge Earthquake | 30 |
| 09/12/2008 | Hurricane Ike | 30 |
| 08/24/1992 | Hurricane Andrew | 26.5 |
| 09/15/2004 | Hurricane Ivan | 18 |
| 09/23/2005 | Hurricane Rita | 16 |
| 08/13/2004 | Hurricane Charley | 16 |
| 10/24/2005 | Hurricane Wilma | 14.3 |

## 2.2 Defining Resilience

The word resilience is obtained from the Latin verb “resilio”, which means to rebound (Rose, 2009). The Merriam-Webster online dictionary defines resilience as “an ability to recover from or adjust easily to misfortune or change”. Resilience as a concept has been defined differently by several authors in different domains. In systems, it has been defined by Tamvakis and Xenidis (2012), as “the ability of a system to react from stresses that challenge its performance” and also by Croope et al. (2010) as “the ability of a system to withstand or respond to changes”. Ta et al. (2009) on the other hand, defines resilience for a freight transportation system as “the ability of a system to absorb the consequences of disruptions, to reduce the impacts of disruptions and maintain freight mobility’. In disaster research, resilience is defined as “…the ability of social units (e.g., organizations, communities) to mitigate hazards, contain the effects of disasters when they occur, and carry out recovery activities in ways that minimize social disruption and mitigate the effects of future disasters" (Tierney and Bruneau, 2007). The more popular and perhaps, most widespread definition of resilience is "the ability to accommodate change gracefully without any catastrophic failure" (Foster, 1997). According to Reggiani (2012), resilience may have two definitions, i) engineering resilience, based on the measuring the speed a system takes to return to equilibrium (Pimm, 1984) and ii) ecological resilience, the agitation, perturbation or disturbance that can be absorbed by a system before it is displaced from one state to another (Holling, 1973, 1986, 1992).

Resilience is commonly described as having dimensions, properties or characteristics. Though defined differently in the literature, these terms inherently stand for characteristics that describe the nature of a resilient system. The most common of these is the R4 Framework developed by the by the Multidisciplinary Center for Earthquake Engineering Research (MCEER). According to Tierney and Bruneau (2007), this consists of:

i. Robustness: This describes the inherent strength or ability to withstand disasters without significant degradation.
ii. Redundancy: The extent to which other system units can be substituted to perform other functions to maintain system performance
iii. Resourcefulness: The system's ability to "diagnose, prioritize and initiate solutions" (Tierney and Bruneau, 2007).
iv. Rapidity: The time it takes to restore the system's functionality

Other characteristics of resiliency that have been identified in the literature

Resiliency is also said to have three aspects (Reggiani, 2012). That is, a resilient system should show a reduced probability of failure, reduced consequences of failure, and reduced time to recovery. These should be targeted by specific strategies which form a system's mitigation, preparedness, response and recovery strategies (Ta et al., 2009). Systems may also show inherent or adaptive resilience (Cox et al., 2010; Tierney and Bruneau, 2007). Inherent resilience is shown by systems with resources that provide the ability to deal with crises. For example, the aftermath of the London 2005 bombing which saw a general mode shift from heavy rail to other modes such as bus, was only possible due to the availability of bus services. Such resources already in place may be "…enhanced prior to a disaster and so that capabilities that are not damaged or eroded can be implemented in the disaster aftermath" (Cox et al., 2010). Adaptive resilience on the other hand, is an ability to maintain functionality during a disruption or to speed up the recovery process by some special measures such as working overtime.

### 2.2.1 Applications of Resilience

The concept of resiliency has arisen in the study of disruptions in various disciplines; supply chains, enterprises, infrastructure and disaster research. In Sheffi and Rice's (2005) study of disruptions of enterprise supply chains, they state that the nature of a company's reaction to disruptions generally follows eight stages as shown in Figure 2.1.

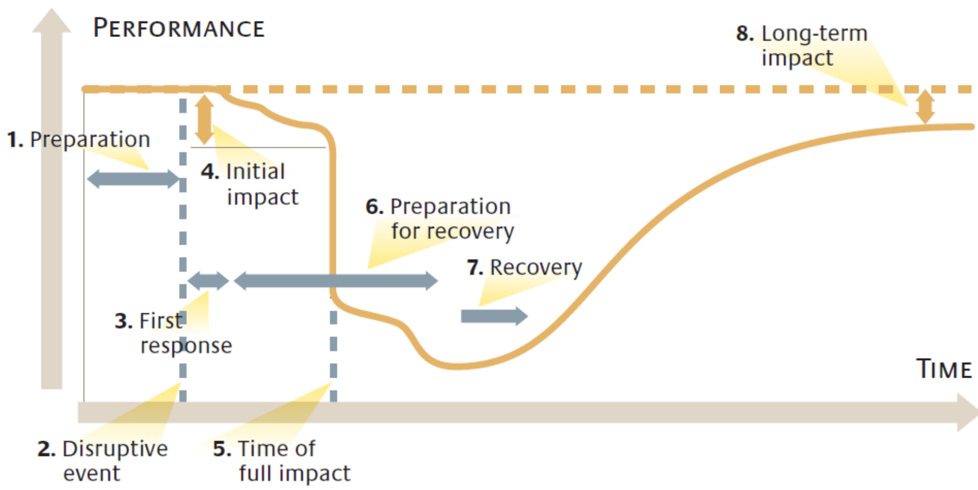


**Figure 2.1: The eight stages of a company's disruption profile**
*(Source: Sheffi and Rice, 2005)*

The initial stage is the preparation stage. This is a common characteristic of cases in which early warnings are issued, for example tornado and hurricane alerts, or in other cases where prior events suggest imminent disruptions, for example, a strike action by company employees. The second stage is the disruptive event itself; the occurrence of an explosion or a supplier cut off for example. Third is the organization's first response. This is usually targeted at containing the immediate situation to reduce the effects of the disruption and reduce losses. The initial impact is then experienced. Here, Sheffi and Rice suggest that the full impact of certain disruptions are not felt immediately, rather there's an initial impact stage at which the company's performance begins to decline at a rate which is a function of the "magnitude of the disruption, the available redundancy, and the inherent resilience of the organization and its supply chain" (Sheffi and Rice, 2005). The fifth stage is the full impact stage. As mentioned earlier, the onset of a full impact may be either immediate or delayed, however, once it sets in, there's a drastic drop in performance. Following this is the recovery preparation stage which either starts with the first response or before that, depending on whether or not the disruption is anticipated. These preparations may involve stocking up on inventories, finding alternate suppliers or finding alternate transportation routes or modes. The recovery stage involves the establishment and sanctioning of strategies to restore performance to pre-disruption levels. Last is the potential long-term impact disruptions may have on companies. For example, a supplier's inability to meet a customer's demand as a result of a disruption may cause a strained or damaged supplier-customer relationship.

In assessing the vulnerability of companies to these disruptions, Sheffi and Rice (2005) promote the use of "enterprise vulnerability maps" to characterize potential disruptions as functions of their probability and consequences. These maps designate threats as either i) low probability-low impact, ii) low probability-high impact, iii) high probability-low impact or iv) high probability-high impact. To address these vulnerabilities, they encourage building the resilience of companies, which he describes as being created by either redundancy or flexibility. However, flexibility is advocated in this work over redundancy because of the more common place results in daily operations produced by strategies to that build flexibility such as the use of informal networks which increase rapidity and good communication within and between organizations. Redundancy on the other hand, is described as less desirable due to its sometimes high cost of implementation and benefits which may not be realized until the occurrence of a major disruption (which have high impact but low probability of occurring).

In disaster research, the concept of the resilience triangle has also been developed to show the effect of a disruption and the time it takes to recover. Figure 2.2 shows the resilience triangle of a system with a 50% loss of functionality. The depth of the triangle shows the severity of the damage, and the length shows the time until full recovery, that is, time $t_0$ which is the onset of the disruption, to time $t_1$, the pre-disaster conditions. The aim of building resiliency into a system is to reduce the size of this triangle, primarily through the adoption of various resilience strategies that target disruption mitigation, preparedness, response and recovery (Ta et al., 2009).

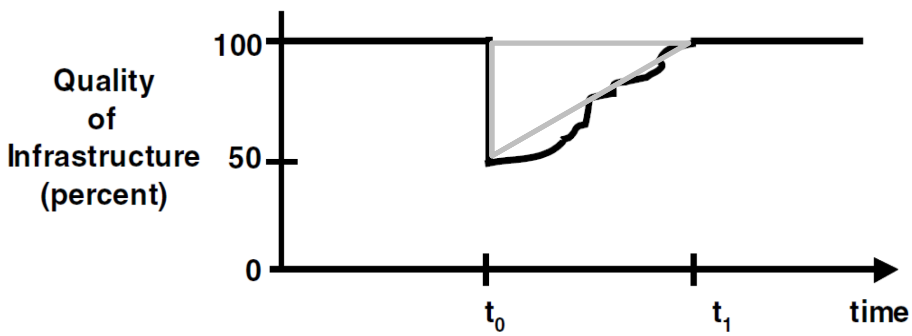


**Figure 2.2: Resilience triangle showing 50% loss in functionality**
*(Source: Ta et al., 2009)*

Also in disaster research, systems are thought of as having four resilience domains (TOSE), these are the technical, organizational, social and economic domains (Tierney and Bruneau, 2007). The technical domain comprises all physical components of the system-- for example highways, bridges and ITS equipment. The organizational domain comprises the governing bodies or institutions in charge of the system; for example state DOTs and similar agencies. The social domain represents social groups and communities in contact and hence affected by the system. Last, the economic domain represents both local and foreign economies such as businesses which are linked to the system. According to Tierney and Bruneau (2007), useful resilience metrics may be developed for a system by combining the R4 framework with the TOSE domains, and consequently resilience strategies developed.

Work on freight system resiliency by Ta et al., (2009) introduces three dimensions which should be targeted by resilience strategies; the infrastructure, the user and the managing organization dimensions. Similar to the TOSE domains of disaster research, the infrastructure dimension represents the physical components of the freight system, that is the nodes (warehouses, ports) and links (railroads, bridges, roadways), as well as the information infrastructure built into them. The user dimension is made up of the individuals and organizations that use the system to transport people and goods. Last, the managing organization, as the name suggests, is the body in charge of construction, maintenance and daily functionality of the infrastructure (Ta et al., 2009). Table 2.2 provides the definitions for the three resiliency dimensions as described by Ta et al., (2009). Leu et al. (2010) also describes the transportation system as being made up of three distinct but interweaving layers: the physical layer consisting of roads, bridges, ports, equipment, machines, etc.; the service layer representing the actual flows in a system such as commute trips; and last, the cognitive layer which represents the human contributions to the transportation system.

**Table 2.2: Dimensions of Resilience according to Ta et al., (2009)**

| Dimension | Definition |
|---|---|
| Infrastructure Resilience | Ability of a network, given its capacity to supply lane miles, facilitate movement of good under capacity constrained conditions that are due to a disruption such as the inaccessibility of a road or bridge |
| Managing Organization Resilience | Ability to prepare for and respond to disruptions in a timely manner by effectively managing, allocating and deploying resources |

Table 2.2 (continued)

| | |
|---|---|
| User Resilience | Ability to behave in a way that supports the system's function. For example, preparedness of users |

Transportation system resiliency has also been linked with its critical components having characteristics such as redundancy, diversity, interdependence, efficiency, autonomy of components, strength, adaptability, collaboration, mobility, safety, and recovery (Leu et al., 2010; Ta et al., 2009; VTPI, 2010; Tamvakis and Xendis, 2012). Table 2.3 provides a summary of some of the characteristics of resiliency based on Ta's (2009) work on freight resiliency.

**Table 2.3: Characteristics of Resilience**

| Characteristics | Physical Infrastructure Dimension | Managing Organization Dimension | User Dimension |
|---|---|---|---|
| Redundancy | Availability of multiple and alternate routing options | Multiple information sources and points of delivery | Multiple parts and materials suppliers; information backed up on distributed servers |
| Autonomy of Components | The ability of a highway system to function independently; independent signal controls for each intersection | Independence of functional units in an organization, e.g. approvals and decision making can be independent of established hierarchies | Independence of functional units in an enterprise, e.g. procurement, billing, manufacturing, and distribution |
| Collaboration | Working partnership between federal, state, regional and local public agencies to plan, construct | Good internal communication across divisions and external communication with system users; | Public-private partnerships between organizations |

Table 2.3 (continued)

| | | | |
|---|---|---|---|
| | and operate the full transportation network to optimize system use | leadership across all levels of the organization | |
| Efficiency | Network designs that reduce travel time between origin and destination | Use of effective mechanisms to prioritize spending within the organization and on infrastructure | Coordination across the supply chain with relationships built across the different parties |
| Adaptability | Designed with intent for regular replacement or with the capability to expand capacity without affecting entire facility | Familiarity of roles and responsibilities across levels of the organization; cross trained employees; ability to engage leadership at all levels | Ability to reschedule decision making and movement of goods and services |
| Interdependence | Seamless mode transfers; intermodal facilities | Relationships are established across separate, but related agencies and within agencies; mutual understanding of the value and benefit from interaction | Standardization of parts and interchangeability |

*Source*: modified from Toledo-Duran, (2010)

### 2.2.2 Measuring Resilience

In the literature, one may come across several proposed methodologies for measuring a system's resilience to disruptions. Table 2.4 summarizes some of those methodologies by different authors in the transportation engineering field.

**Table 2.4: Proposed Methodologies and Metrics for Measuring Resilience**

<table>
<tr><th>Author</th><th colspan="2">Proposed Methodology</th></tr>
<tr><td rowspan="3">Serulle (2010)</td><td colspan="2">Fuzzy systems approach to quantify resiliency at pre-event conditions using measurable inputs that represent redundancy, cost, available capacity and accessible capacity.</td></tr>
<tr><td>Variables</td><td>Metrics</td></tr>
<tr><td>Prevailing LOS<br>Road density<br>Average delay<br>Average speed reduction<br>Personal transportation cost<br>Commercial/industrial cost<br>Alternate infrastructure<br>proximity<br>Level of intermodality<br>Network management</td><td>Highway Capacity Manual (HCM)<br>Lane-miles/square-miles<br>Hours or minutes<br>%below speed limit<br>Dollars/mile<br>Dollars/mile<br>Distance b/n key infrastructures/links<br>Linguistic variable (low to high)<br>Linguistic Variable (level 1 to level 5)</td></tr>
<tr><td rowspan="5">Croope et al. (2010)</td><td colspan="2">Improving resiliency by using conceptual framework for a decision support system for critical infrastructure(CIR-DSS) repair, replacement and serviceability in a post-disaster environment by using 3 components:</td></tr>
<tr><td>Component</td><td>Description</td></tr>
<tr><td>Spatial Decision Support System</td><td>GIS/HAZUS-MH</td></tr>
<tr><td>Infrastructure Management System</td><td>FEMA benefit/cost analysis principles: net present value, avoided damages, etc for highway asset management</td></tr>
<tr><td>Management Information System</td><td>Based on resiliency concepts and principles</td></tr>
</table>

Table 2.4 (continued)

<table>
<tr><td></td><td>The CIR-DSS is applied considering :<br>— Physical infrastructure conditions (deterioration and maintenance dynamics)<br>— Functional assessments (practices of estimating life-cycle cost)<br>— Vulnerability and damage assessment within specified location<br>Measures of resilience and system performance used were measured before, during, immediately following event, during recovery and after restoration.<br>— Capacity in veh/hr/ln<br>— Number of available lanes<br>— Pavement condition index<br>Measures may differ depending on available information</td></tr>
<tr><th>Author</th><th>Proposed Methodology</th></tr>
<tr><td>Tamvakis and Xenidis (2012)</td><td>Utilizes notion of entropy to develop a framework to assess a systems resilience, i.e, the transportation system’s resilience is assessed on the basis of the resilience of its components.<br>Analysis process:<br>— Describe system<br>— Evaluate system’s service level<br>— Identify weaknesses<br>Evaluation process:<br>— Collection of data:<br>○ Properties of variables<br>○ Interdependencies between variables<br>○ probabilities and impacts of adverse events on system<br>— Application of notion of entropy: definition of system at both:</td></tr>
</table>

Table 2.4 (continued)

<table>
<tr><td></td><td colspan="3">
<ul>
<li>Micro level: physical system, service provision and information system</li>
<li>Macro level: some data to collect at this level include:
<ul>
<li>Nodes and links in the system</li>
<li>System capacity</li>
<li>Structural strength</li>
<li>Stability and robustness</li>
<li>Nature of system stresses</li>
</ul></li>
</ul>
Resources to respond to stresses</td></tr>
<tr><td>Ash and Newth (2007)</td><td colspan="3">Uses “evolutionary algorithm” as a transport network approach and “load capacity” as a network resilience measure to evaluate resilience in traffic flow networks</td></tr>
<tr><td rowspan="4">Leu et al. (2010)</td><td colspan="3">Paper f uses a GPS based network approach to assess network resiliency.<br>Measures of resilience</td></tr>
<tr><td>Component</td><td>Variable</td><td>Metric</td></tr>
<tr><td>The structure</td><td>Degree<br>Betweeness<br>Clustering Coefficient</td><td>Average number of connections a node has<br>The fraction of shortest paths between other nodes that pass through node i<br>Amount of alternative routes available over the network</td></tr>
<tr><td>Node removal concept</td><td>Topological integrity<br>Distance gap</td><td>Probability that removal of node k breaks the network in n pieces<br>Distance created by removal of a node is used as a proxy to estimate the cost of re-establishing the</td></tr>
</table>

Table 2.4 (continued)

| | | | |
|---|---|---|---|
| | | | network |
| | Spatial distribution of risk | Zones | 5km contours represent zones. Groups of nodes with similar topological integrity and distance gaps in zones and population size of that zones is used as a proxy to determine possible impact of an event on the local population |

| **Author** | **Proposed Methodology** |
|---|---|
| Cox et al.(2010) | Uses economic resilience approach to examine the contribution of trips to the value of goods and services they produce.<br>Measures transportation system resiliency using 2 components:<br>— Static resiliency: ability of an entity to maintain function, measured in % of maximum disruption avoided by resilience behaviors.<br>Where<br>○ Max. Disruption = reduction in pax journeys for the attacked mode<br>○ Resilience behaviors = increase in pax journeys for alternate modes<br>— Dynamic resilience: capability to recover rapidly to achieve a desired state, i.e. Speed of recovery beyond a normal speed measured in pax/km |
| Ip and Wang (2009) | Resilience of networks flow by use of optimization model with computational algorithm using weighted average number of passageways between nodes |
| Matisziw and Murray (2009) | Uses network's "vital paths" as resilience measure in an optimization model to evaluate network resiliency |

Table 2.4 (continued)

| | |
|---|---|
| Rosenkrantz et al.(2005) | Maximum number of failures to a node that a network can tolerate- algorithms in context of service oriented networks |
| Taylor and Susilawati (2012) | Measures changes to accessibility levels at different network states to assess traffic flow resilience |

These methodologies for measuring a system's resilience, although somewhat varied, are quite narrow, concentrating on only certain elements of the system. A combination of some of these methods with other resilience strategies that target other components of the transportation system will form the basis for a more holistic framework for resiliency in transportation.

# CHAPTER 3

# A FRAMEWORK FOR RESILIENCY PLANNING

This chapter presents a conceptual framework for resiliency planning in transportation systems to be used in state departments of transportation and similar agencies. The framework presented in this chapter is guided first by Meyer and Miller's (2001) book on urban transportation planning and second, by work done by the Victoria Transportation Policy Institute on evaluating transportation resilience. This framework is a simplification of a very complex and multifaceted process given the diverse nature of resilience. Consequently, a case-by-case analysis approach is recommended in order to find suitable solutions along each dimension (Ta et al., 2009). The framework shown in Figure 3.1 shows how to incorporate resiliency planning into the broader approach to transportation planning, with the steps in red highlighting the areas where resiliency is considered.

## 3.1 The Framework

### 3.1.1 The Vision

The framework begins with the visioning stage. Every planning process begins with visioning; similarly, the state DOT or MPO using this framework has to clearly define its vision, whether it is for a new system or adapting an old one to increase resilience. This may be done through the integrated effort of the agency and the community, or by aligning with the national vision for critical infrastructure resilience. In Figure 3.1, the vision displayed reflects the interaction between a safe, secure and resilient transportation system.

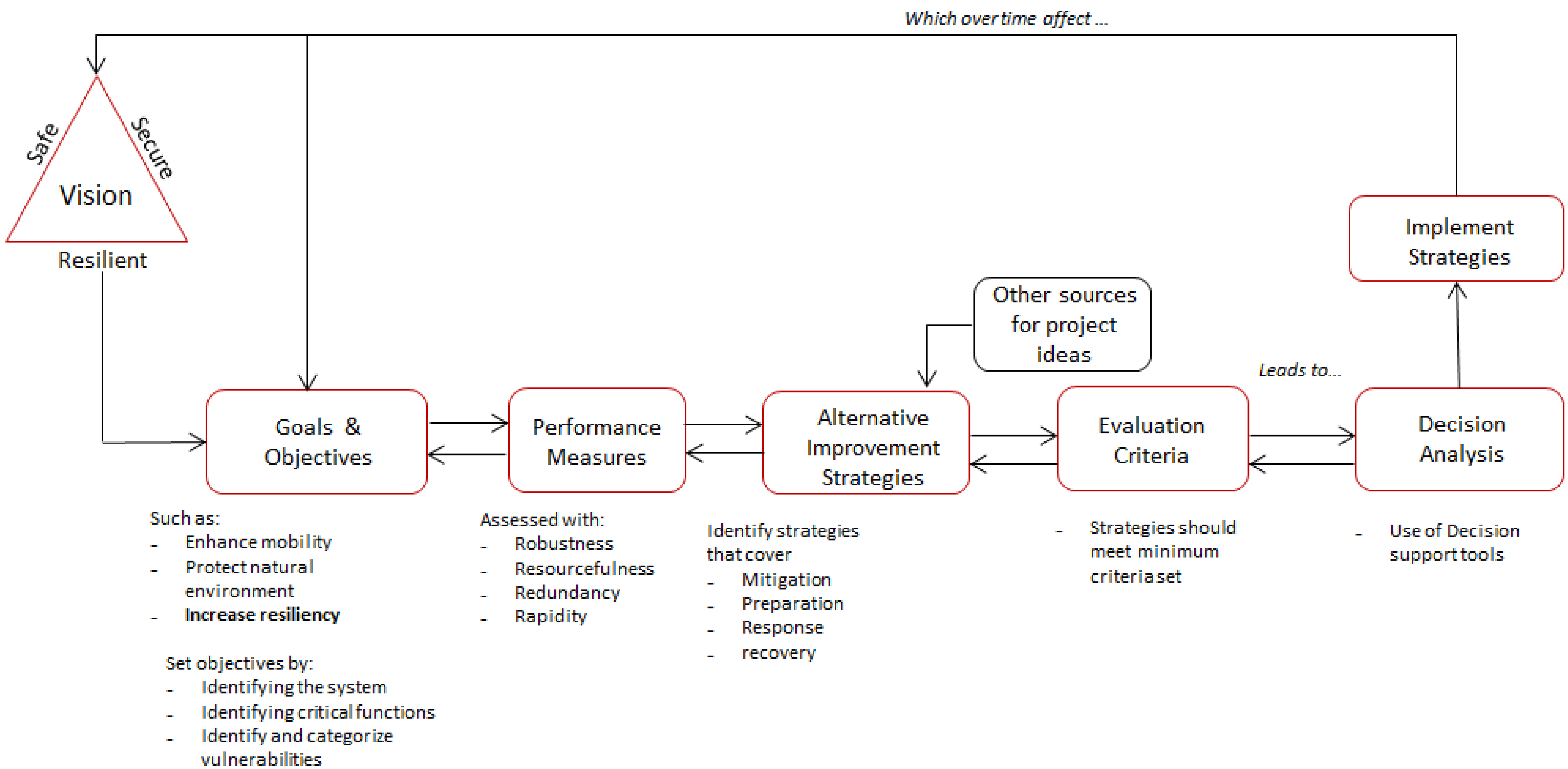


**Figure 3.1: Framework for Resiliency Planning – modified from Meyer and Miller (2001), and influenced by VTI (2010), Bruneau et al., (2003)**

These three desired states in the vision are based on the Department of Homeland Security's National Protection and Programs Directorate's (NPPD) vision of "a safe, secure, and resilient infrastructure so that the American way of life can thrive" (NPPD, 2012). A similar vision plan shown in Table 3.1 is offered by the Public Transportation System Security and Emergency Preparedness Planning Guide, developed by the Federal Transit Administration of the U.S. DOT. This visioning process is to enhance the security and emergency preparedness planning for public transportation systems.

**Table 3.1: Security and Emergency Management Planning Vision for Public Transportation Systems**

| |
|---|
| **COMMIT** to a program that enables the public transportation system to: |
| ➢ **RESPOND** decisively to events that cannot be prevented, mitigate loss, and protect employees, passengers, and emergency responders; |
| ➢ **SUPPORT** response to events that impact local communities, integrating equipment and capabilities seamlessly into the total effort; and |
| ➢ **RECOVER** from major events, taking full advantage of available resources and programs |

*Source: FTA, 2003*

As mentioned earlier, the agency may adopt any of the two sample visions presented or design their own, keeping in mind that the elements of resiliency should be present.

### 3.1.2 Goals

After the vision is defined, the agency moves a step further by getting more specific and defining a set of goals to meet the vision of a safe, secure and resilient transportation system. In this framework, the goals are based on the aspects of resiliency (Bruneau et al., 2003; Reggiani, 2012). That is, the goals of the agency should be related to:

i. Reduced probability of failure
ii. Reduced consequences of failure
iii. Reduced time to recovery

These goals make a system resilient and may be achieved through defining a set of agency objectives and the subsequent implementation of target specific strategies that touch on the different stages of the disaster life cycle: preparedness, mitigation, response and recovery (*Beenhouwer et al., 2003*).

### 3.1.3 Objectives

#### 3.1.3.1 <u>Define the System</u>

Once the goals are clearly defined and understood, the objectives set may differ for each branch of the agency. That is, to set the objectives, the agency first needs to define the boundaries being dealt with (VTI, 2010). Similar to the TOSE dimensions of resilience in disaster research, the transportation system may also be said to have three dimensions i) the infrastructure dimension (technical), ii) the managing organization dimension (organizational) and iii) the user dimension (social and economic) (Tierney and Bruneau, 2007; Ta et al., 2009). Here, the infrastructure dimension comprises all physical components of the system such as highways, bridges, and railroads, as well as the technology associated with them. A good asset management program is required to inventory assets. The managing organization dimension is made up of the governing bodies, institutions or agencies in charge of construction, maintenance and performance of the infrastructure (Ta et al., 2009). The user dimension refers to the communities that use the infrastructure and are affected by it either directly or indirectly.

#### 3.1.3.2 Identify Critical Functions

Following a clear definition of the dimension under consideration, the agency should then go ahead to identify its critical functions and assets, especially those that have a cascading effect when damaged. Ham and Lockwood (2002) define critical assets as "those major facilities, the loss of which would significantly reduce inter-regional mobility over an extended period and thereby damage the national economy and defense mobility." For example, in the infrastructure dimension there are over 4 million miles of public roads; 46,000 interstate highways; 160,000 miles of rail; 600,000 bridges; 2 million miles of pipeline; 500,000 train stations; and 300 tunnels; however, not all 600,000 bridges or 47,000 miles of interstate highways are critical to the nation or even to a state (Bureau of Transportation Statistics, 2011; Pommerening, 2013; FHWA, 2011). Similarly in the managing organization dimension, where several divisions may exist, the critical functions of each of these divisions need to be defined. The agency may be comprised of divisions such as administrative, construction, engineering, finance, operations, planning, field services, maintenance, emergency and projects delivery divisions. An example of how criticality may be screened is by using the analytical tool shown in Table 3.2 which is a modified version of the tool developed by the U.S. General Accounting Office (GAO) in their efforts to identify critical assets for their work on mass transit antiterrorism practices. Expert opinion is required to determine the impact the loss of a particular transportation system asset has on 1) the users and operators of the system (people) and 2) the ability to provide service (U.S. DOT, 2001). The losses may be graded in terms of monetary value, historical significance, operational significance or even public opinion (GAO, 1988). Functions ranked as high in both categories may then be included in the vulnerability analysis.

**Table 3.2: Function/Asset Criticality matrix**

| Transportation System Unit Function/Asset | Asset Loss Impact on | |
|---|---|---|
| | People | System |
| (Function/Asset) | High<br>Medium<br>Low | High<br>Medium<br>Low |

*Source:* modified from U.S. DOT, 2001

For transportation infrastructure, Ukkusuri and Yushimito (2009), define the set of criteria to assess the criticality of a highway network as follows:

i. Casualty Risk
ii. Emergency Relief Function
iii. National Recognition
iv. Economic Disruption
v. Collateral Damage Exposure
vi. Military Support Function

Another example of a criticality rating scale is that of Washington State DOT (WSDOT) shown in Figure 3.2. This scale is used to categorize their infrastructure assets and uses a qualitative assessment varying from very low in blue to very critical in red.

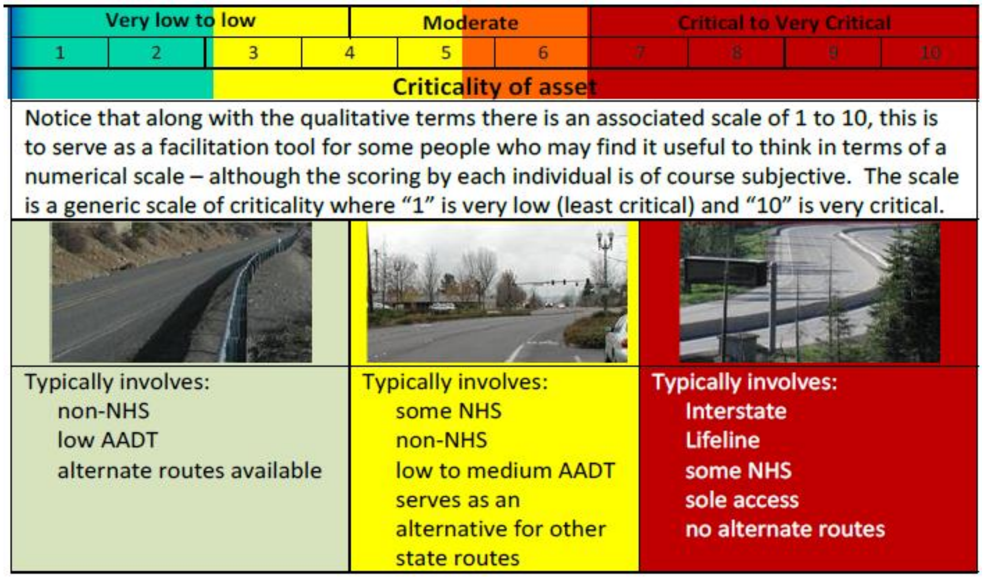


**Figure 3.2: WSDOT Rating Scale for Asset Criticality**
*Source*: WSDOT, 2011

3.1.3.3 Identify and Categorize Vulnerabilities

"Mutual dependence and the interconnectedness made possible by the information and communications infrastructure lead to the possibility that our infrastructure may be vulnerable in ways that they never have been before."
– *Critical Foundation: Protecting America's Infrastructures, October 1997*

Next, the agency should proceed to identify possible threats and categorize its vulnerabilities. This is a very important step because it is necessary to evaluate the vulnerabilities of critical sections of the system against specific threats. According to Labi (2013) as illustrated in Figure 3.3, threats to civil engineering systems may be external or internal, sudden or gradual, natural or man-made. Generally, threats may be identified from either historical data or based on expert opinion and the existence of evidence (GAO, 1988).

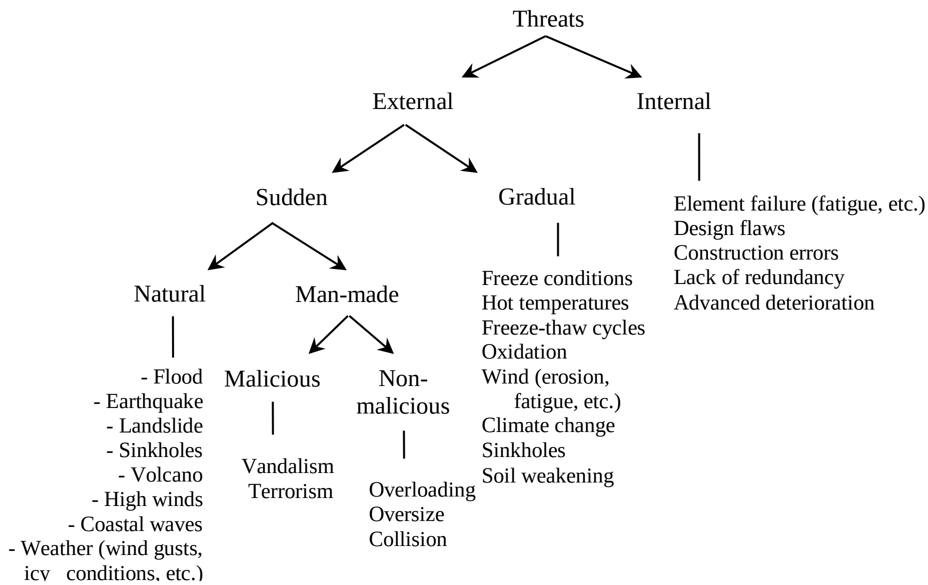


**Figure 3.3: Categories of Threats to Civil Engineering Systems**
*Source:* Labi, 2013.

Vulnerability is any weakness that makes the system susceptible to a disruption, and in this case cause catastrophic failure. A successful vulnerability assessment includes an in depth evaluation at the dimension level (infrastructure, user and managing organization). These threats and vulnerabilities must be updated periodically in an iterative manner in order to the account for the changing nature of threats, assess the effectiveness of implemented strategies and lessen the system's vulnerability to uncertainty (Cox et al., 2010). For larger agencies with more resources, moving a step further to perform a complete risk assessment (including the probabilities of the various threats occurring) is preferred. With regards to the threat of extreme weather events, FHWA's climate change risk assessment model for state DOTs and MPOs shown in Figure 3.4 may prove to be a useful tool which may be modified slightly to suit the agency's desired outcome. For instance, the Washington State DOT, in implementing the

FHWA model during one of the pilot programs made modifications (shown in Figure 3.5) resulting in a model that was more for vulnerability assessment than risk assessment (WSDOT, 2011). FHWA currently has seven agencies in their 2013-2014 pilot vulnerability assessment programs.

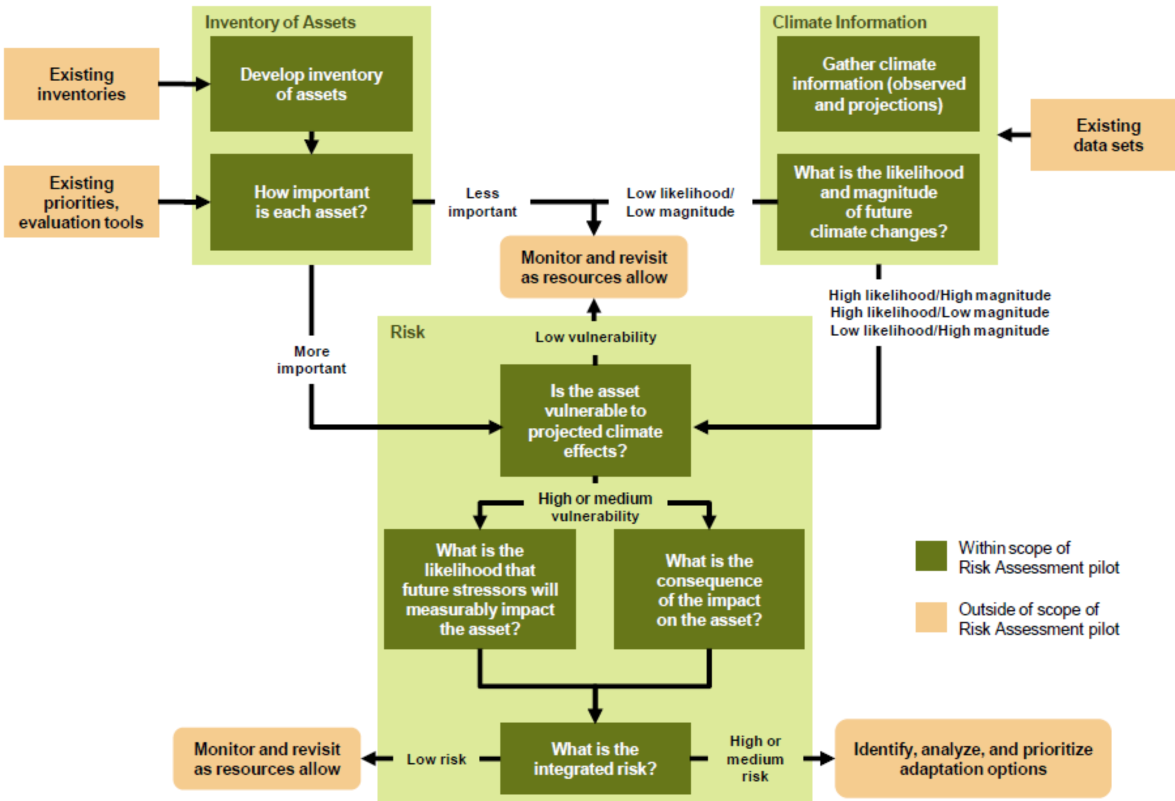


**Figure 3.4: The FHWA Climate Change Risk Assessment Methodology**
*Source*: WSDOT, 2011.

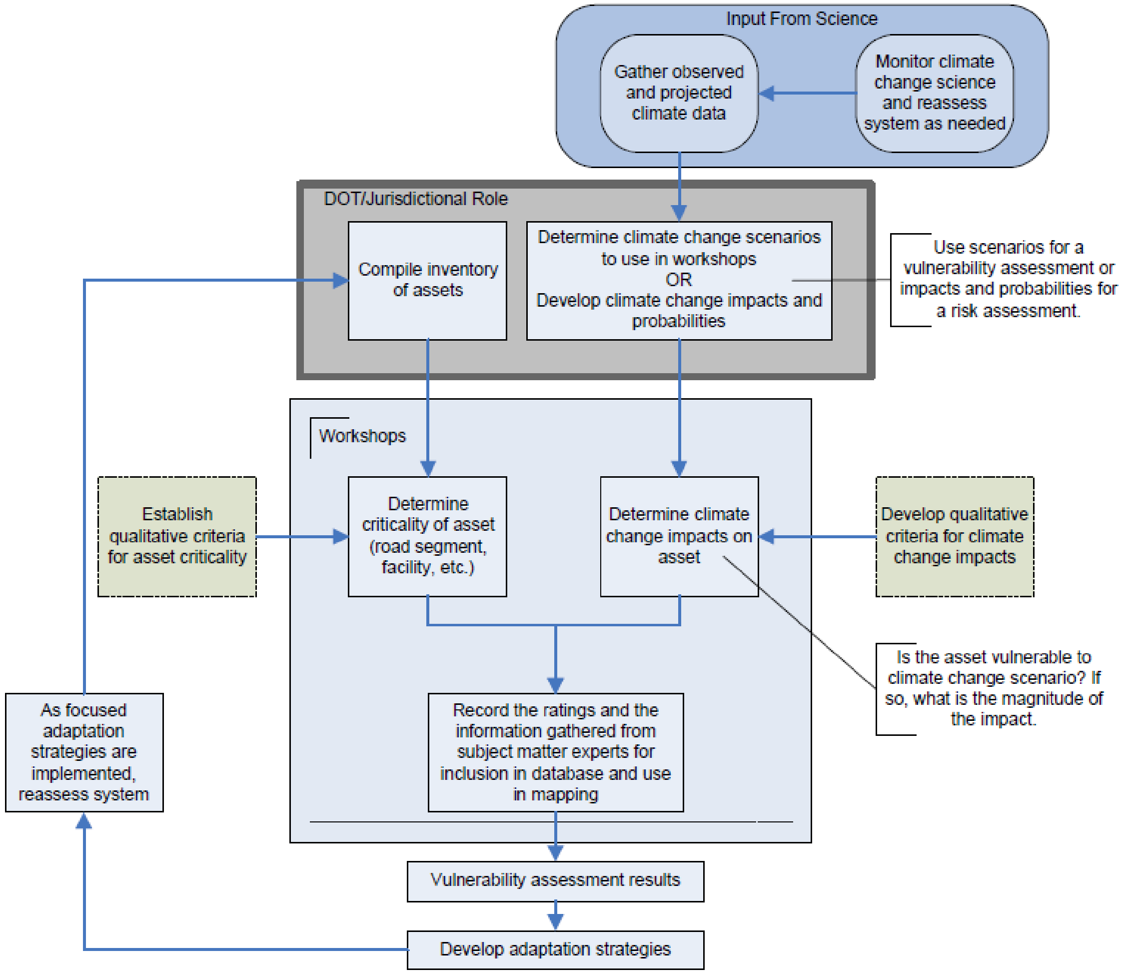


**Figure 3.5: WSDOT Recommended Vulnerability Assessment Methodology**
*Source*: WSDOT, 2011

On completion of these steps, the agency will now have a holistic understanding of the system and can now set specific objectives targeted at the most critical components of the system.

### 3.1.4 Performance Measures

Once the objectives are set, performance measures are required for each of the identified objectives. The FHWA reports the specific definition of performance measurement from the National Performance Review as "a process of assessing progress toward achieving predetermined goals, including information on the efficiency with which resources are transformed into goods and services (outputs), the quality of those outputs (how well they are delivered to clients and the extent to which clients are satisfied) and outcomes (the results of a program activity compared to its intended purpose), and the effectiveness of government operations in terms of their specific contributions to program objectives." In a broader sense, the NCHRP Project 8-32(02), Multimodal Transportation: Performance-Based Planning Process (1998) defines performance measurement as “The use of statistical evidence to determine progress toward specific defined organizational objectives. This includes both evidence of actual fact, such as measurement of pavement surface smoothness, and measurement of customer perception such as would be accomplished through a customer satisfaction survey. Performance measures provide information to managers about how well that bundle of services is being provided. Performance measures should reflect the satisfaction of the transportation service user in addition to those concerns of the system owner or operator.”

Currently, some state agencies already use performance measures especially for their infrastructure, mostly larger agencies in large population areas; however, several more have not yet adopted any measures and still rely on experience and intuition when evaluating strategies for improving conditions (NCHRP-311, 2003). According to Pickrell and Neuman (2000), adoption of performance measures in the planning process provides accountability, efficiency, effectiveness, improvement, clarity and better communication to customers and stakeholders. Performance measures adopted by some agencies may be categorized under mobility, accessibility, reliability and safety of the system and should be specified for both pre- and post-disruption conditions. Table 3.3 provides a summary of some performance measures currently in use by 35 U.S state DOTS and MPOS (NCHRP-311, 2003).

**Table 3.3: Performance Measures as Reported in a Survey of State DOTS and MPOS**

| Performance Measure | Typical Definition |
|---|---|
| Level of service (LOS) | Qualitative assessment of highway point, segment, or system using A (best) to F (worst) based on measures of effectiveness |
| Traffic volume | Annual average daily traffic, peak-hour traffic, or peak-period traffic |
| Vehicle-miles traveled | Volume times length |
| Travel time | Distance divided by speed |
| Speed | Distance divided by travel time |
| Incidents | Traffic interruption caused by a crash or other unscheduled event |
| Duration of congestion | Period of congestion |
| Percent of system congested | Percent of miles congested (usually defined based on LOS E or F) |
| Vehicle occupancy | Persons per vehicle |
| Percent of travel congested | Percent of vehicle-miles or person-miles traveled |
| Delay caused by incidents | Increase in travel time caused by an incident |
| Density | Vehicles per lane per period |
| Rail crossing incidents | Traffic crashes that occur at highway–rail grade crossings |
| Recurring delay | Travel time increases from congestion; this measure does not consider incidents |
| Travel costs | Value of driver's time during a trip and any expenses incurred during the trip (vehicle ownership and operating expenses or tolls or tariffs) |
| Weather-related traffic incidents | Traffic interruption caused by inclement weather |
| Response times to incidents | Period required for an incident to be identified, verified, and for an appropriate action to alleviate the interruption to traffic to arrive at the scene |
| Commercial vehicle safety violations | Number of violations issued by law enforcement based on vehicle weight, size, or safety |
| Evacuation clearance time | Reaction and travel time for evacuees to leave an area at risk |
| Response time to weather-related incidents | Period required for an incident to be identified, verified, and for an appropriate action to alleviate the interruption to traffic to arrive at the scene |
| Security for highway and transit | Number of violations issued by law enforcement for acts of violence against travelers |
| Toll revenue | Dollars generated from tolls |
| Travel time reliability | Several definitions are used that include (1) variability of travel times, (2) percent of travelers who arrive at their destination within an acceptable time, and (3) range of travel times |

*Source*: NCHRP Synthesis 311, 2003

It is important that the performance measures adopted by an agency address the identified vulnerabilities of the system. To create or increase resiliency of the system, the performance measures should be categorized under robustness, redundancy, resourcefulness and rapidity as shown in Figure 3.1. These criteria are not mutually exclusive, that is, strategies adopted to meet certain performance objectives under one category may also work to meet objectives set in another category. Bruneau et al., (2003) describe redundancy and resourcefulness as a “means” to the “ends” of robustness and rapidity.

#### 3.1.4.1 Robustness

Robustness refers to the inherent strength or ability to withstand disruptions or shocks without significant degradation (Tierney and Bruneau, 2007). For infrastructure, performance measures under this criterion may include measures that check capacity, structural strength, stability, pavement condition and the amount of damage in dollars avoided in the event of a disruption. Use of a Network Robustness Index (NRI), as described by Scott et al., (2006) to assess network flows, link capacity and network topology would also be a useful measure for an agency. For the managing organization, performance measures that check its continued ability to carry out functions are also needed; for example, the percentage of employees still in service or the amount in dollars of direct and indirect economic losses avoided after a disruption (Bruneau et al., 2003).

#### 3.1.4.2 Redundancy

Redundancy refers to the extent to which other system elements can be substituted to perform particular functions. This may be in terms of actual excess capacity, diversity or adaptability in which a different means may provide for the same end results. For example, performance measures under this criterion for an agency’s critical infrastructure could be the number of alternative routes within a given radius, number of backups or duplicate systems or equipment. In addition, the ability of the system to support different mode choices, such as transit (rail and bus), auto, biking and walking, to certain extents for users is a potential resilience objective. For the managing organization, increasing redundancy requires some amount of flexibility and adaptability. There should be cross training where possible, to increase the familiarity of roles and responsibilities among employees. Allowing for a certain amount of flexibility gives employees the ability to make decisions without adhering to regular chains of command during disruption can increase rapidity.

#### 3.1.4.3 Resourcefulness

Resourcefulness refers to "the capacity to identify problems, establish priorities, and mobilize resources when conditions exist that threaten to disrupt some element, system, or a unit of analysis" (Bruneau et al., 2003). It may also refer to the agency's capacity in terms of financial, technological, physical and informational resources (Bruneau et al., 2003). Thus, resourcefulness may be in human capacity terms or in terms of the wealth of an agency. In the managing organization dimension resourcefulness may be shown by an agency having various plans, models, policies and procedures to cope with emergencies or disruptions. For example, an agency may have a transportation security plan, a recovery plan, a risk management and vulnerability assessment plan, an emergency response plan, or even an economic recovery plan. It is important that agencies have all the necessary resources in order to be resilient. A study on freight resiliency in state DOTs conducted by the MIT Center for Transportation and Logistics included a review of various state DOT transportation plans. The survey revealed that across the 50 state DOTs, 6 of them do not mention security at all in their transportation plans, 18 mention security briefly but not as a separate section, 12 mention security with safety as a separate section, 9 mention security as a separate section by itself, and only two state DOTs had a separate document such as a security technical report (MIT-CTL, 2006).

In the infrastructure dimension, agencies can adopt technologies that diagnose and detect infrastructure damage to reduce response time. For example, Bridge Hunter and Bridge Doctor are two near real-time highway bridge damage assessment tools developed by the University of New Mexico and ImageCat Inc., under a U.S.DOT and NASA joint program. Bridge Hunter uses remote sensing methods to register key features of bridges with airborne and satellite sensor images and Bridge Doctor then assesses the damage level based on pre and post event images captured. Also, some bridges rebuilt after Hurricane Katrina were equipped with monitoring systems which included motion scales and other sensors to measure the weights of trucks, as well as to detect any impact on the infrastructure.

#### 3.1.4.4 Rapidity

Performance measures that are set under the rapidity criterion should be those that optimize the time to return to pre-event functional levels or better (Bruneau et al., 2003). This includes setting specified time frames for completion of activities, from restoration of road access to the time it takes to initiate response tasks. The use of decision support tools to prioritize access to scarce resources, as well as make investment decisions optimizes time spent in decision making. Also, improved technologies which aid in asset location, as well as damage extent and severity detection are all tools that increase rapidity. Table 3.4 illustrates the different performance measure which may be set under the four criteria and across the three dimensions.

**Table 3.4: Performance Measures for Resiliency**

| Performance Measures | Performance Criteria | | | |
|---|---|---|---|---|
| | Robustness | Redundancy | Resourcefulness | Rapidity |
| Infrastructure | Damage avoided in dollars<br>Percentage of service in continued provision | Number of backup or duplicate systems, equipment and supplies<br><br>Number of alternative routes to major centers | Diagnostic and damage detection technologies and methodologies (e.g., bridge monitoring systems, remote sensing technologies) | Optimizing time to return to pre-event functional levels or better |
| Managing Organization | Continued ability to carry out designated functions | Percentage of resources backed up to sustain operations | Information sharing capabilities<br>Plans and resources to cope with damage and disruption (e.g., emergency plans, decision support systems) | Minimize time needed to restore services and perform key response tasks |
| User | Avoidance of casualties and disruption in the community<br><br>Avoidance of direct and indirect economic | Number of alternatives for providing for user, i.e. diversity in mode choice | Number of available stabilizing measures (e.g., capacity enhancement and demand modification, external | Optimizing time to return to pre-event functional levels or better |

Table 3.4 (continued)

| | | | | |
|---|---|---|---|---|
| | losses | | assistance, optimizing recovery strategies) | |

*Source:* modified from Bruneau et al., (2003)

### 3.1.5 Develop Resilience Strategies

The next stage involves the development of strategies to meet the previously set objectives, which also satisfy the performance measures set. These are actions or behaviors by the managing organization or its users that increase resilience (Cox et al., 2010). As mentioned earlier, the properties of resilience are in not mutually exclusive, as such, any of the strategies developed and adopted may contribute to the increase of one or more resilience properties. Strategies that increase the autonomy, robustness, diversity and resourcefulness in a system's critical components, ultimately create redundancy, efficiency, adaptability and rapidity of the system. They are those that usually target the infrastructure, the organization itself, its policies, resources and analysis procedures. These strategies should ultimately lead to a reduced probability to failure, reduced consequence of failure and a reduced time to recovery; consequently, they would cover mitigation, preparedness, response and recovery.

The approach this framework takes in developing strategies is by dividing resilience strategies into two broad groups. First are the strategies that serve as a blockade to prevent any disruptions and also increase the inherent strength of the agency and its infrastructure; these are the resiliency barriers (Mansouri et al., 2009). They are mainly to prevent failure when possible or to mitigate any effects of a disruption that could have dire consequences. Such strategies must include those that make critical components of the system self-correcting, repairable and autonomous, to ensure that failure of one component does not hinder or automatically lead to failure of other system components (VPI, 2010). They also include strategies that increase robustness such as enforcing strict design and building codes, as well as rigorous and regular inspections of infrastructure. A clear example of the omission of such as strategy is shown in the aftermath of Hurricane Katrina which revealed the inadequacies and inaccuracies in the design and construction of the hurricane protection system. Also, according to Kunreuther (1997), about a third of the total damage sustained in Florida during Hurricane Andrew in 1992 could have been avoided if Florida's state building codes were properly enforced. An agency may also ensure the use of only disaster-resistant designs for new constructions and retrofitting existing ones to increase strength. The use of sensors and other advanced technologies provide early detection of damaged infrastructure and hence, reduce the time to recovery. Strategies directed towards the agency as an organization with employees should be those that encourage effective communication and increase flexibility to enable rapid decision making during crises by cutting out regular bureaucracies (Petrenj et al., 2011). Redundancies created in the system also facilitate required role substitutions during emergencies. Strategies that increase diversity such as providing a wide array of mode choices (e.g. bus, heavy rail, light rail, bicycling, etc.) for travelers must be included. For example, after the 2005 London train bombings, the availability of other mode choices provided a substitute for commuters during and immediately after the incidents. There was an observed increase in the use of other modes of travel (Cox et al., 2010). Other strategies include maintaining emergency stockpiles, creating excess capacity, and continually finding new ways of increasing efficiency.

The second set of strategies consists of those that take effect just before, during and after a disruption. They comprise response and recovery strategies that are mainly contingency plans, policies and procedures, instituted by the agency that increase resiliency. It must be emphasized here that response is not equal to recovery. Although the two may overlap, they are distinct in nature. Response can be defined as “all actions taken prior to, during, and just after an incident with the onus on saving lives, minimizing damage, and recuperation over the long term” whereas recovery involves “post-event actions taken to return vital economic systems to minimum standards of health in the short term and to full health over a longer period” (MIT-CTL, 2006). Bus drivers’ working overtime in the event of a disaster, for example, is a response strategy which was unavailable to New Orleans’ transit dependent population during Hurricane Katrina, worsening the overall effects of the disaster (Litman, 2006).

Other examples of resilience strategies can be seen in in Hurricane Sandy’s recent impact on New York’s transportation system. Published reports in the aftermath of the disaster identified some of the New York MTA’s infrastructure vulnerabilities as (i) the disruption of service from power outages as a result of extreme precipitation events, and (ii) their low-lying transportation systems such as the subways and passenger car tunnels which put them at risk of storm surge, flooding from rising sea levels and extreme precipitation events (Rosenzweig, 2013). In response, certain strategies to be implemented in their operations and management departments include improving drain maintenance, adjusting travel routes, reducing travel frequency, changing repair cycles to anticipate ongoing repairs to damaged infrastructure and the movement of rolling stock to high ground in advance of storms (Rosenzweig, 2013). Other strategies that require capital investment in infrastructure include retrofitting existing vulnerable infrastructure, installation of pumps to reduce flooding of vulnerable facilities and hardening to prevent exposure of certain infrastructure from the elements (Rosenzweig, 2013). The agency also acknowledged the importance of strategies that target their current policies such as integrating climate risks into the locations of their transportation projects, avoiding the implementation of projects such as the construction roads and rail in vulnerable areas (Rosenzweig, 2013).

### 3.1.6 Evaluation and Decision Analysis

The implementation of resilience strategies, whether to improve inherent resilience at design level, or to increase the overall resilience of a system at a later time may be a costly investment. However, when compared with possible future benefits, implementation of these strategies will more often than not prove to be wise investments. As part of the development of strategies, a set of alternatives also need to be developed. The process of defining alternatives may include the “no action” alternative where all the tradeoffs, benefits or costs of not implementing certain strategies are outlined. There are various methods suggested by federal and state agencies for defining alternatives such as those of the FTA or FHWA (FTA, 2005; FHWA, 2010).

After a set of strategies and alternatives are developed, it is important to evaluate them under certain criteria to enable decision makers select among alternatives. Evaluation is “the process of determining the desirability of different courses of action and of presenting this information to decision makers in a comprehensive and useful form" (Meyer and Miller, 2001, pg. 484). During this stage, questions about appropriateness, efficiency, equity, effectiveness, adequacy, feasibility and sensitivity must be addressed (Meyer and Miller, 2001). According to Meyer and Miller (2001), evaluation should have the following characteristics:

- Focus on the decisions being faced by decision makers.
- Relate the consequences of alternatives to goals and objectives.
- Determine the effects of the proposal on different groups.
- Be sensitive to the time frame in which project impacts are likely to occur.
- In the case of regional transportation planning, produce information on the likely impacts of alternatives at a level of aggregation that permits varying levels of assessment.
- Analyze the implementation requirements of each alternative.
- Assess the financial feasibility of the actions recommended in the plan.
- Provide information to decision makers on the value of alternatives in a readily understandable form and in a timely manner.

These characteristics, however, may be modified to suit an agency's needs. In effect, the agency needs to specify the evaluation criteria and the subsequent method (e.g. cost-effectiveness, benefit-cost, lifecycle cost analysis, etc.) to be used to arrive at the final decision (Litman, 2001). This framework proposes the use of decision analysis tools which assess the costs and benefits of the proposed strategies, mainly because the implementation of most transportation investments relies heavily on the availability of funds. Such decision analysis tools include net present value (NPV), return on investment

(ROI), real option valuation, internal rate of return (IRR), sensitivity analysis, payback time, decision tree analysis or multi criteria decision analysis (www.innovation management.org, 2007). The use of these tools helps in prioritizing strategies to implement and the eventual selection process.

### 3.1.7 Implement Resilience Strategies

The final step of the framework is to finally implement the vetted strategies. Whether the strategies to increase resilience are to retrofit existing infrastructure, change design standards, implement policies, or to cross-train employees, all the implemented strategies need to be monitored to determine their performance. Over time, some of these strategies may change due to the changing nature of threats or to accommodate changes in an agency’s goals and objectives.

# CHAPTER 4

# PRELIMINARY REVIEW OF RESILIENCY IN THE TRANSPORTATION PLANNING PROCESS

This chapter is a preliminary review of the long-range transportation plans of three state DOTs, chosen for their diversity of locations and without any preconceived notions about their incorporation of resiliency. State 1 is located in the Pacific Northwest and serves a population of about 4 million people. State 2 is located in the South Atlantic sub region of the U.S. and serves a population of approximately 10 million. Last, State 3 is a Midwest state with a population of about 10 million. Currently among the three state agencies, there are no formal resiliency planning processes; however, some of their current plans and policies on emergency operations, safety and security contribute to some extent to the agency's level of resilience. This resiliency planning deficiency may be due in part to the fact that there are currently no federal policies that require state transportation agencies to adopt such planning methods.

In this preliminary review, statewide long-range transportation plans (STP) from the three agencies are assessed with the main elements of the resiliency framework provided in the previous chapter.

## 4.1 The Preliminary Review

Table 4.1 below is a matrix which identifies elements of resiliency across the three state plans. It is noteworthy that across all three state transportation plans, there is no mention of transportation system resilience. All three plans, however, include sections on safety and security. Safety within the context of these plans refers to reducing the risk of transportation-related crashes and security involves reducing the exposure to criminal and terrorist activity, as well as natural disasters.

**Table 4.1: Elements of STP that contribute to resiliency**

| State | Vision & Goals | Critical Asset/ Function Identification | Threat/ Vulnerability Assessment | Security Section | Emergency Operations/ Response Section | Recovery Section |
|---|---|---|---|---|---|---|
| State 1 | ✓ Highlights safety, security, accessibility, mobility, technology, multimodality, communication, cooperation, communication, efficiency, TDM, resource management | × Does not mention identification of critical assets and functions | × Acknowledges presence of certain threats but does not mention a comprehensive vulnerability assessment for critical assets or functions | ✓ TSP contains separate security section and security technical report | ✓ Mentioned under security section, Emergency operations plan | × Recovery or recovery plans not mentioned in TSP but adopts state's recovery framework in emergency operations plan |
| State 2 | ✓ TSP has no stated long-term vision for transportation. Goals highlight safety, security, mobility, accessibility, | × Does not mention identification of critical assets and functions | × Acknowledges the presence of certain threats but does not mention a comprehensive vulnerability assessment | ✓ Contains security section but only mentions designs for | × Emergency operations not mentioned in TSP but department has a hurricane | × Does not include recovery section or refer to recovery plan |

Table 4.1 (continued)

| | | | | | | |
|---|---|---|---|---|---|---|
| State 2 | efficient management and operation, multimodality | | for critical assets or functions | hurricane evacuations and security cameras | preparedness and response plan | |
| State 3 | ✓ Vision and goals prioritize improvements that enhance efficiency, mobility, access, communication, cooperation, safety, security, and technological advancement Vision also highlights flexibility, adaptability and multimodality | ✓ Security strategies include identifying potential targets for threats | ✓ Transportation Risk Assessment and Protection Team; “all hazards approach” in conducting vulnerability and risk assessments on certain facilities at international border crossings | ✓ Security technical report addresses all modes of transportation, as well as technology, with regards to natural and man-made threats | ✓ Emergency response contained in security section and security technical report | ✓ Does not include recovery section but mentions interagency collaboration to develop recovery plans |

## 4.2 Discussion

The visions for two of the agencies, State 1 and State 3, contain elements of resiliency as they promote the safety and security of people, goods, services and information. All three plans support diversity by means of encouraging multimodality, diverse transportation energy sources or both. This diversity increases the system's resilience by providing alternate modes of travel during a disruption and lesser impact in times of possible fuel shortages. These plans also prioritize mobility and accessibility which are important in the event of a crisis, especially for the section of the public that are transportation disadvantaged. Good mobility and accessibility also aid in evacuations and the transportation of resources during recovery efforts. Furthermore, the plan for State 1 supports adopting new technology and transportation demand management (TDM) strategies. TDM strategies are known to increase an agency's diversity and flexibility, as well as improve resource management and communication, thereby improving the agency's resiliency (VTI, 2010). The use of ITS and other technology to improve the efficiency and safety of infrastructure by offering increased protection and preservation, naturally increase system resilience. In addition, two of the agencies promote coordination, communication and cooperation within their agency, between their agency and other agencies, and also, between their agency and system users. This can work to increase the overall system efficiency and effectiveness -- thereby increasing resilience.

State 2's long-range transportation plan narrows itself by concentrating on only asset management and future surface transportation capacity expansion needs. It does not include any new policies that support system resiliency. On the whole, State 3 seems to be the best equipped and prepared for natural and man-made disasters, although there is still room for improvement.

To conclude this section, it is worthy to note that all three agencies implement projects that in one way or the other increase the system’s resiliency. For instance, the performance of seismic retrofits for vulnerable bridges by State 1 or the vulnerability assessments for bridges along international borders by State 3. These isolated strategies are commendable and must be continued but only contribute a fraction to the overall system’s resilience. Without a clear vision and a well-structured plan to tie all efforts of an agency together, many sections will eventually be overlooked creating loopholes in the system which may be problematic in the event of a major disruption. Second, it is general knowledge that all local and regional transportation plans are consistent with a state’s long-range transportation plan. Without resiliency as a priority in the STP, the series of plans that follow will also lack this.

# CHAPTER 5

# CONCLUSION

Transportation plays a major role in the quality of life of the people it serves. The failure of transportation systems during catastrophic events exacerbates the effects of such disasters by breaking the links between important life-line facilities, bringing mobility to a halt and hindering response efforts. Unfortunately, current transportation planning methods are deficient in elements that increase resilience. This thesis presents a framework to incorporate resiliency into the broader context of transportation planning. Such planning methods are now necessary due to the increase in future uncertainties concerning both natural and manmade catastrophic events.

This work first presents a brief overview of the impact past catastrophic climate-related events have had on certain transportation infrastructure, and the economic losses associated with those events. It then presents the concept of resiliency and how it can be applied to transportation planning through the resiliency framework. Last, three long-range transportation plans are assessed for elements of resiliency using the framework and some recommendations are made.

As of now, we are still unable to predict the occurrence of natural and manmade disasters, which leaves some element of uncertainty concerning the timing and intensity of such events. This implies that even with the implementation of certain resilience measures, we may never be fully protected from the effects of these events, but since the focus of resiliency is to "fail gracefully" and bounce back rapidly rather than "resist" such events, the effects of such disasters may be lessened from catastrophic to manageable by anticipating such failures (Foster, 1997; Fisher, 2013). The problem now is that resilience is usually an afterthought, only considered after a disaster has already occurred. For example, the New York City Governor's plans to invest $20 billion in a resiliency plan after Hurricane Sandy to protect New York from the negative impacts of climate change (Dillow, 2013).

With regards to state DOTs, the issue of inadequate funding is mostly the main reason for not adopting more resilient approaches and strategies. Other DOTs may also be averse to strategies that are novel or innovative, mostly because of their uncertainty about the benefits of resiliency, which may be attributed to uncertainty in the prediction of future catastrophic natural or manmade events. As such, further research is required in to evaluate the benefits and costs of resiliency planning in state DOTs, as well as aggregating data that provides evidence of the benefits of resiliency planning in order to make evidence-based decisions on investments. In the meantime, investments that increase a system's resilience may be funded through reallocation from other areas (DfT, 2011). This requires all future investments (including those that increase resiliency), to be assessed with the same evaluation criteria to justify such reallocations (DfT, 2011). To give resilience investments a wide range of potential financial support, it is important that they each have a broad range of benefits (Foster, 1997).

To conclude, it is important to develop federal policies that require critical asset vulnerability assessments at the state level and the development of subsequent strategies that increase resilience. However, with or without such policies state DOTs would still benefit from thinking about the application of resiliency frameworks, such as the one offered in this thesis, and assessing the costs and benefits of such measures to increase the agency's overall resilience.

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