A CONCEPTUAL FRAMEWORK FOR DEVELOPING SOCIOTECHNICAL TRANSPORTATION SYSTEM RESILIENCE

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A CONCEPTUAL FRAMEWORK FOR DEVELOPING SOCIOTECHNICAL TRANSPORTATION SYSTEM RESILIENCE

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To the children of the light.

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LIST OF SYMBOLS AND ABBREVIATIONS

ABAG	Association of Bay Area Governments
CDOT	Colorado Department of Transportation
DOT	Department of Transportation
EIS	Environmental Impact Statement
FAST Act	Fixing America's Surface Transportation Act
FDOT	Florida Department of Transportation
FHWA	Federal Highway Administration
GHG	Greenhouse Gas
GIS	Geographic Information System
IDOT	Iowa Department of Transportation
MAP-21	Moving Ahead for Progress in the 21st Century
MassDOT	Massachusetts Department of Transportation
MPO	Metropolitan Planning Organization
MSHA	Maryland Stage Highway Administration

MTA	Metropolitan Transportation Authority
MTC	Metropolitan Transportation Commission
NORPC	New Orleans Regional Planning Commission
ODOT	Oregon Department of Transportation
SLR	Sea Level Rise
STRF	Sociotechnical Transportation Resilience Framework
TAM	Transportation Asset Management

SUMMARY

Natural disaster statistics worldwide indicate an upward trend in the number of reported disasters. In the year 2000 alone, there were over 500 reported natural disasters, which caused at least ten fatalities; affected 100 or more people; and required international assistance or called for a state of emergency. According to the International Federation of Red Cross and Red Crescent Societies (IFRC), between 1991 and 2000, an average of 211 million people was either affected or died from a natural disaster. During that same decade, an average of 1,300 people was killed across the world every week. Such natural disasters are not only a humanitarian issue, but also an economic one and have a significant impact on the US economy. For example, between 2011 and 2013, transportation accounted for approximately $14.7 billion in disaster relief spending, ranking fourth highest among 19 departments. Additionally, Hurricane Sandy's recovery appropriation amounted to $60 billion.

Resilience, the ability of a system to maintain critical functions and prevent catastrophic failure during a disruption, and then recover rapidly, is now more than ever at the forefront of most critical infrastructure systems' discussions. A consensus has emerged among relevant stakeholders on the need for evolving long-standing planning approaches and operational methods into approaches with more resilient outcomes. The primary objective of this research is to therefore develop a framework for transportation system resilience planning that expands current transport resilience approaches by using a sociotechnical systems approach, one that considers human and organizational factors in addition to technical factors for system performance.

To develop the framework, this research adopts an inductive and multimethod approach. Data is systematically gathered and analyzed in two main phases. The first phase begins with an in-depth literature review and synthesis of transportation resilience as well as resilience theory and its applications to the built environment, social systems, economic systems and ecological systems. Next, a survey of selected transportation agencies is conducted to study resilience capacity building at transport agencies in order to extract an evolving maturity process for handling hazards and building system resilience using sociotechnical considerations. The second phase of this research then combines key concepts extracted from the resilience literature and the results of the survey to develop the sociotechnical transportation resilience conceptual and planning framework. The framework is then verified and demonstrated using practitioner reviews.

Findings from the research show that the concepts of stability at multiple equilibria found in ecological resilience present opportunities for expanding the current paradigm of transportation resilience thinking, evolving it from one based on single-equilibrium stability to multiple equilibria stability. The resultant framework, based on both the resilience literature and survey results, characterizes the relative levels of four types of transport agency capital (organizational, institutional, technical and financial capital) that contribute to sociotechnical system resilience and catalogues attribute-based strategies for developing resilience capacity systematically.

This research contributes to transportation resilience knowledge by extending the current paradigm of transportation system resilience planning from that of a single equilibrium conceptualization to multiple equilibria conceptualization. The research also characterizes different developmental stages of building transport resilience capacity using a sociotechnical approach. Finally, the resulting framework is a potentially beneficial tool for transportation decision makers involved in strategic or long-term resilience planning.

CHAPTER 1. INTRODUCTION

1.1 Background & Motivation

The world as we know it still exists because nature has proven to be resilient over the millennia (Fisher, 2013). In the study of behavior patterns of ecosystems, it has been observed 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 indication, “we are in the midst of an ecosystem collapse” (Fisher, 2013).

Natural disaster statistics worldwide indicate an upward trend in the number of disasters reported as shown in Figure 1.1 (EM-DAT, 2009). In the year 2000 alone, there were over 500 reported natural disasters, which caused at least ten fatalities; affected 100 or more people; required international assistance or called for a state of emergency (EM-DAT, 2015). According to the International Federation of Red Cross and Red Crescent Societies (IFRC), between 1991 and 2000, an average of 211 million people was either affected or died from a natural disaster (CRS, 2002). During that same decade, an average of 1,300 people was killed across the world every week (CRS, 2002).

Such natural disasters are not only a humanitarian issue, but also an economic one. Natural disasters have a significant impact on the U.S. economy, with their costs rising progressively as they increase in frequency and intensity. Figure 1.2 shows the number and costs (consumer price index adjusted, CPI) of billion-dollar disaster occurrences in the U.S. for the last three decades and their associated costs as reported by the National Oceanic

Administration (NOAA) (NOAA, 2017). The cost of these disasters to community quality of life and transportation infrastructure are also substantial. For example, between 2011 and 2013, transportation accounted for approximately $14.7 billion in disaster relief spending (Center for American Progress, 2013).

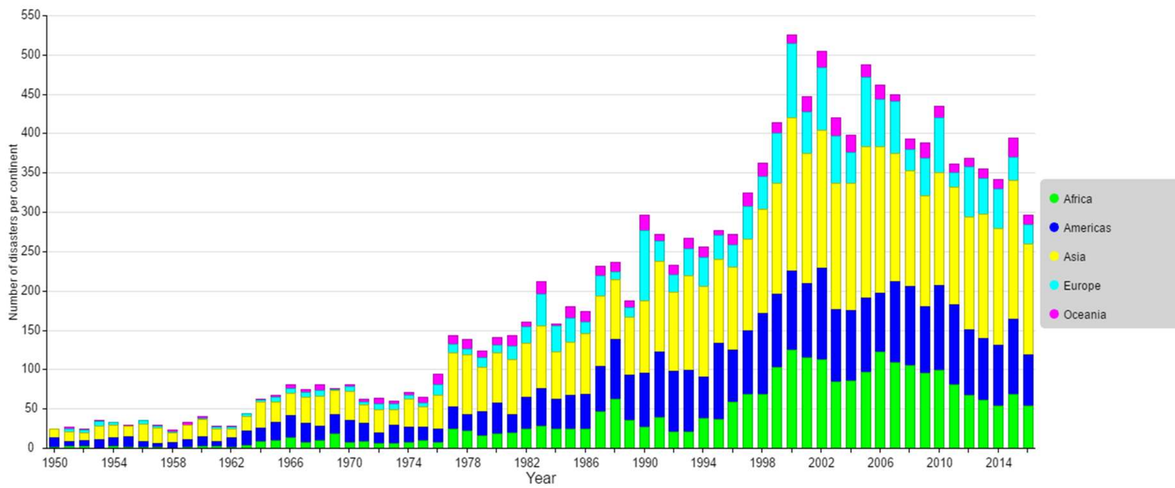

Figure 1.1 Global data trends show increase in natural disasters. (Source: EMDAT, 2017)

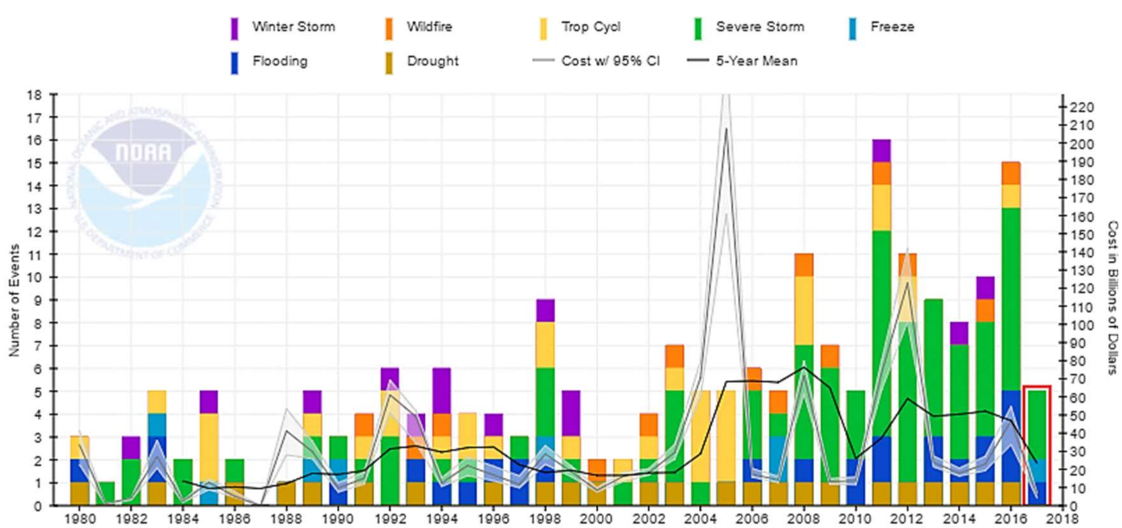

Figure 1.2 Number and costs of billion-dollar disaster event types by year. (Source: NOAA, 2017)

More specifically, the Federal Highway Administration (FHWA), by January 2012, had received Emergency Relief (ER) funding requests of about $2.9 billion for the repair and reconstruction of roads classified as federal highways that 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 in February 2013 allocated $287 million to the state of New York, of which $250 million was meant solely for Hurricane Sandy repair and reconstruction (FHWA, 2013).

Resilience, the ability of a system to maintain critical functions and prevent catastrophic failure during a disruption, and then recover rapidly, is now more than ever at the forefront of most critical infrastructure system discussions. A 2013 report by the Transportation Research Board (TRB), Critical Issues in Transportation, concluded that "[T]he performance of the transportation system is neither reliable nor resilient, yet transportation's role in economic revival and in global economic competition has never been more important" (TRB, 2013). This, in addition to the increasing frequency of catastrophic events due to extreme weather, aging infrastructure and terrorist attacks substantiate the need for evolving long-standing planning approaches and operational methods into approaches with more resilient outcomes.

Considering this formal traction, a consensus has emerged among relevant stakeholders on the need for enhanced transport system resilience. This has resulted in growing emphasis on, and sustained efforts in increasing system resilience for transportation and other built systems. For example, between 2010 and 2015, the FHWA sponsored 24 departments of transportation (DOTs) and metropolitan planning organizations (MPOs) to conduct climate change resilience projects which mainly sought to assess transport system vulnerabilities (Figure 1.3). Similarly, the Federal Transit Administration (FTA) also funded nine agencies in seven different locations to assess their system's vulnerability to climate change in 2011. Although the FHWA framework on which the DOT and MPO assessments are based on includes the integration of study results into decision making processes such as asset management, planning and project prioritization, many of the studies have not yet developed past the final report stage. In addition, the approaches used in these analyses are primarily technocentric (i.e. focused heavily on the systems' physical components), and therefore do not adequately account for other important system elements.

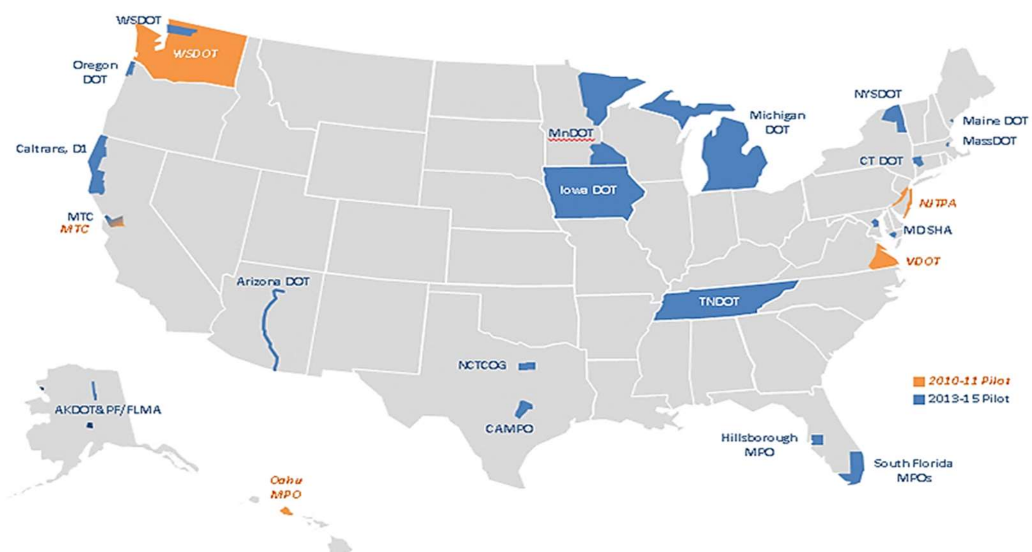

Figure 1.3 FHWA 2010-2011 Climate Change Vulnerability Assessment & 2013-2015 Climate Resilience Pilots. Source: FHWA (2017)

At the federal level, some policies and legislation have also been enacted with the aim of supporting infrastructure protection and resilience, albeit to varying levels of effectiveness.

For example, the 2015 national surface transportation legislation: Fixing America's Surface Transportation (FAST) Act, which formally emphasizes the need for resilience and reliability of the transportation system. Specifically, the planning process identified under the "Planning, Performance Measures, and Asset Management" section of the law includes a statement about MPO planning to ensure resilience, but fails to say what this constitutes (Trombino & Wright, 2016). Consequently, many transportation agencies still lack the necessary understanding, means and capabilities needed to begin addressing system resilience resulting in inadequate buy-in in many cases.

1.2 **Gaps and Opportunities**

Technocentric approaches being used by many transport agencies is seemingly intuitive and arises from the concept of *engineering resilience.* Engineering resilience focuses on a system's ability to *resist* external disturbances and return to its *pre-disturbance* state in the shortest possible time (Pimm, 1991). The idea is usually described in the literature using the resilience triangle shown in Figure 1.4. The size of the resilience triangle shows the extent of damage and time to full recovery, therefore, the more resilient the infrastructure is, the smaller its resilience triangle. Engineering resilience according to Pimm (1991) is therefore presented as only being stable at a single equilibrium; the system is inflexible to changes and fluctuations.

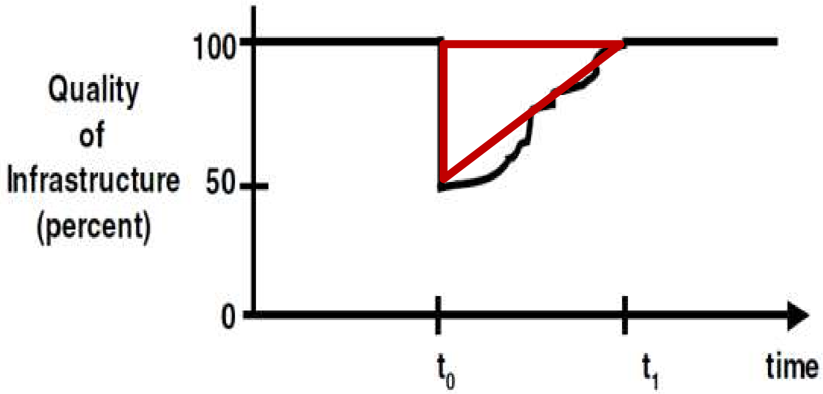

Figure 1.4 Resilience triangle showing 50% loss in functionality Source: Bruneau et al. (2009)

However, it is the view of this research work that the concept of a single equilibrium in engineering resilience does not suffice for two primary reasons. First, the increasing frequency and strength of natural hazards makes it impractical to try to engineer our infrastructure out of risk taking into consideration the necessary infrastructure renewal needed. Consider the example of the Netherlands. After the North Sea flood of 1953 that caused over 1800 fatalities and left over 100,000 residents homeless, the Dutch invested in large scale infrastructure that still protect their cities today. However, after the threat of another potential disaster in the early nineties caused by extremely high river tides, the Dutch realized that infrastructure alone was no longer an adequate solution and therefore embraced approaches other than purely combatting water. The country's approach therefore shifted from being only about hydraulic engineering works, to how the entire country is managed, "both physically and administratively" (Deltacommissie, 2008). The country's resilience strategy, has shifted from trying to *combat* water, to "exploring new opportunities that may improve the quality of life of residents, and to integrating their flood protection with nature, landscape and urban development" (Deltacommissie, 2008).

Secondly, returning to an original equilibrium state, as *engineering resilience* in the sense of Pimm (1991) proposes, may not always be a desirable outcome for certain populations, e.g., vulnerable populations, where original conditions already fall short of desires. For example, during Hurricane Katrina in 2005, one of the transport system failures was its inadequacy in providing transportation for transit dependent residents. According to Murdock (2005), although public officials were aware that approximately 100,000 residents of the City of New Orleans had no means of personal transportation, evacuation plans were inequitably focused on automobile evacuation (New Orleans, 2005). City buses set up to transport people to emergency shelters were unreliable, and neither public buses from the New Orleans Regional Transit Authority (RTA), nor trains were deployed to help evacuate transit-dependent residents from the city (Murdock, 2005). Consequently, transit-dependent members of the community who wanted to leave the city had to pay for commercial services – "a major barrier to many low-income residents" (Litman, 2006). In these situations, returning the transport system to its original equilibrium does not necessarily enhance its resilience.

This research therefore seeks to propose a shift from thinking about transportation systems in the context of *single equilibrium sys*tems to *multiple equilibria systems* and expand the transportation resilience approach. The concept of stability at multiple equilibria as seen in ecological resilience is based on a system's ability to *change in order to persist*. That is, ecological systems shift from one stable regime to another after a disturbance is experienced to ensure survival. The intent of this work is to show the practical value in adopting a multi-equilibrium approach for transportation resilience by developing different stability states (regimes) that agencies can systematically work toward. To do this, the transportation system needs to be viewed as *sociotechnical* in nature, i.e., one that "considers human, social and organizational factors, as well as the technical factors in the design of organizational systems" (Baxter and Sommerville, 2010). Broadening the concept of resilience from purely *technical* to *socio-technical* also enables us to explicitly address both technical and non-technical factors, processes and outcomes relevant to achieving increased system resilience.

Considering the experience of best practices in infrastructure resilience such as the Netherlands, and other system failures in U.S. cities, it can be hypothesized that as agencies mature in their dealings with hazards, they naturally move from purely technical to sociotechnical approaches. This research therefore seeks understand the extent to which agency experiences bear up to this statement by studying the evolution in their resilience approaches and extracting an evolving maturity process in handling hazards and building system resilience capacity. Consequently, this work proposes the use of an evolutionary approach which builds on other sociotechnical approaches found in the literature and also on theories from ecological resilience to develop a framework that advocates the joint optimization of different agency capital types (specifically, institutional, organizational, technical and financial) that can be achieved through incremental improvements to the system.

1.1 Research Objectives & Scope

Considering these gaps and opportunities, this research seeks to achieve the following objectives:

- Develop a conceptual framework for enhancing transportation system resilience using sociotechnical approaches
- Develop a maturity scale for sociotechnical system resilience through characterization of current transportation resilience practices, and identification of enhanced practices using the ecological resilience concepts
- Develop a planning tool based on the maturity scale for building resilience capacity in transport agencies using sociotechnical approaches
- Verify and demonstrate the application of the framework and tool using case studies and practitioner feedback

1.2 Research Methodology

The research adopts an inductive and multimethod approach in the development of the conceptual framework. Thus, data is systematically gathered and analyzed in two main phases. The first phase, shown in Figure 1.5, involves an in-depth literature review and synthesis, and transportation agency survey. The second phase then proceeds into the conceptual framework development, demonstration, review and finalization.

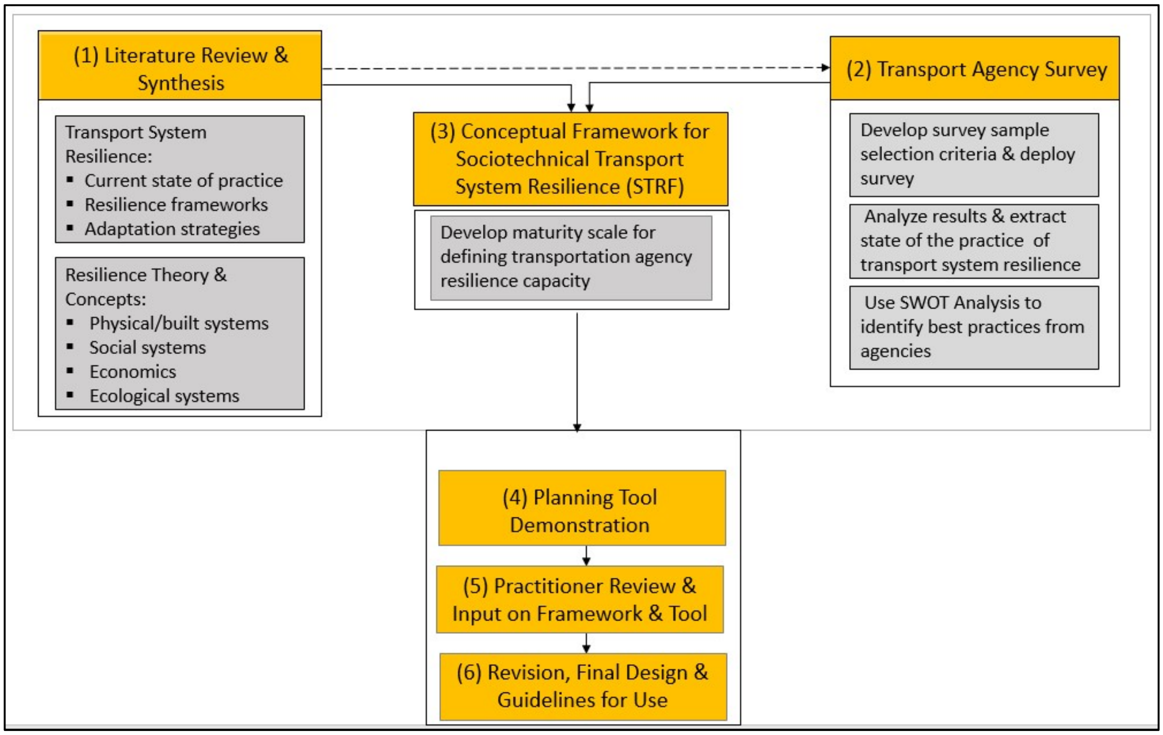

Figure 1.5 Research Design

1.2.1 Literature Review & Synthesis

This stage presents a review of three broad categories of literature: transport system resilience, resilience theory and resilience theory applications in fields outside transportation. The transport resilience literature includes peer-reviewed literature on frameworks for assessing and measuring system resilience, as well as literature on the current state of the practice. A summary and syntheses of the transport resilience literature is also presented identifying the main gaps for enhancement. The review of resilience theory then discusses its origins, related concepts and applications in ecological system, social/socioecological systems, economics and the built environment. Literature on built environments resilience captures resilience in physical infrastructure including energy and power systems. The literature review chapter concludes with a summary and synthesis of the resilience literature, extracting key characteristics of resilience and resilient systems, and identifying key concepts and opportunities for transport system resilience tailored toward the dissertation objectives.

1.2.2 Resilience Planning Survey

The next stage of the research involves the design and deployment of a transportation resilience planning survey. The purpose of the survey is to identify approaches currently being used by transportation agencies to address system resilience and to pinpoint major changes made in the past two decades to these approaches and the factors that caused them. Based on this information, the survey seeks to characterize the nature of transportation system resilience at selected agencies, and consequently, identify best practice strategies using a SWOT analysis. The results of this exercise are used to inform the development of the sociotechnical transport system resilience framework.

1.2.1.1 Survey Sampling Process and Agency Selection

The survey uses a type of purposive sampling technique for the agency selection process. Purposive sampling represents a group of *nonprobability* sampling techniques and is also known as judgmental, selective or subjective sampling (Laerd Dissertation, 2012). Generally, nonprobability sampling techniques rely on the judgement of the researcher in selecting the units to be studied. Unlike probability sampling techniques where the end goal is to make *generalizations* from the selected sample to a given population based on random selection, a purposive sample is "selected based on characteristics of a population and the objective of the study" (Crossman, 2016). For this research, the Maximum

Variation Sampling (MVS) technique, also known as heterogeneous sampling, is adopted. This technique is used to capture "variation in perspectives … [from study units that may] exhibit a wide range of attributes, behaviors, experiences, … and so forth [allowing one] to gain greater insights into a phenomenon by looking at it from all angles" (Laerd Dissertation, 2012). Figure 1.6 shows MVS as a subset of purposive and nonprobability sampling.

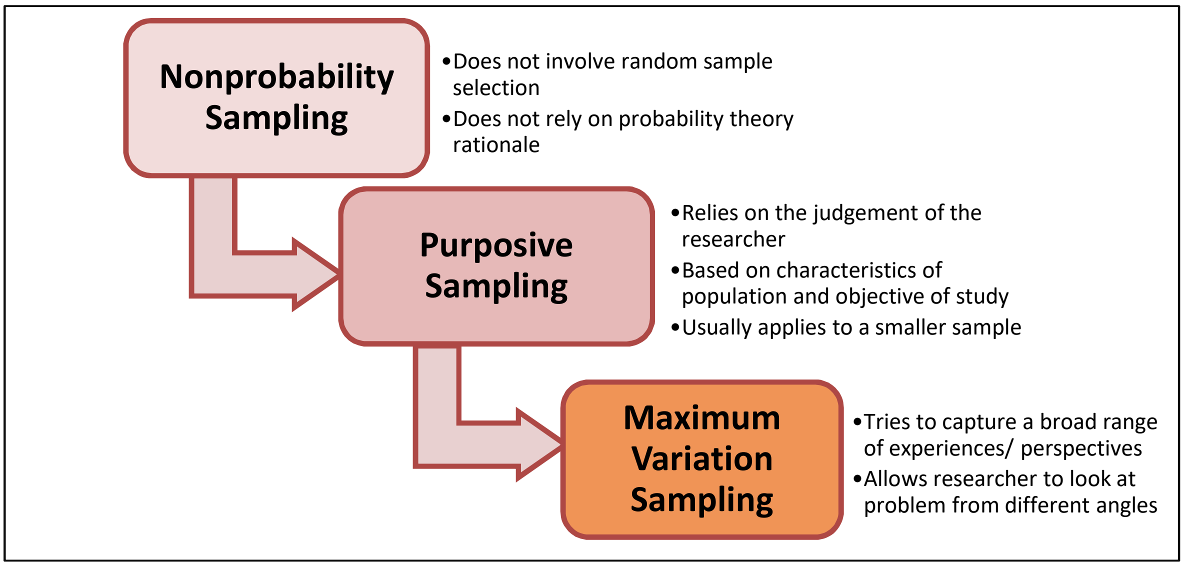

Figure 1.6 Sampling Technique Adopted in Research

Given the expected outcomes and objectives of this research, random selection of survey recipients would not be practical. Rather, survey recipients are specifically selected to represent the diversity of agency experiences encountered in resilience capacity building for transportation agencies. The two selection criteria are: (1) geographic location and hazard type, and (2) agency experience with disasters.

1.2.1.1.1 Hazard Type & Geographic Location

In general, hazards are either technological (man-made) or natural. Disasters caused by technological hazards are those that are "attributed in part or entirely by human intent, error, negligence, or involving a failure of a man-made system, resulting in significant injuries or deaths" ("Man Made Disaster", 2017). Natural hazards on the other hand refer to any naturally occurring phenomena that can cause harm to humans and built systems alike. This research primarily focuses on the latter hazard type. That is, natural hazards most likely to affect transportation systems such as climatological (e.g., drought and wildfire), geophysical (e.g., earthquake, tsunami, and volcanic activity), hydrological (e.g., flood, landslide, and avalanche) and meteorological (e.g., extreme temperatures, storm/surge, tornado, winter storm, etc.) and biological (e.g., disease epidemic, infestation) (IFRC, n.d.).

Moreover, geographic location plays a significant role in the hazards and risks transportation systems are exposed to (risks refer to the likelihood of hazards materializing). For example, many coastal areas are prone to sea level rise (SLR), storm surge and flooding from hurricanes while other inland areas more prone to tornadoes and flooding from extreme precipitation (including rainfall and winter precipitation). In addition, other parts of the country such as the west coast and northwest are prone to geophysical hazards such as earthquakes, landslides/mudslides and liquefaction. Table 1.1 below provides a summary of typical risks associated with the impacts of climate change for the different regions across the U.S. Additionally, Figure 1.7 provides a graphical representation of four different types of risks faced by areas across the continental U.S. Purposefully selecting survey recipients from each region provides the potential to solicit experiences from agencies with different hazard types that may allow transferability to agencies in similar regions facing similar hazards types.

Table 1.1 Typical Risks Associated with Different Regions

Region	Typical Risks
Northwest & West Coast	Sea level rise, storm surge, erosion, inundation, & increasing ocean acidity
Midwest & Great Plains	Extreme heat, & flooding; Rising temperatures
Northeast & Mid Atlantic	Heat waves, heavy downpours, & sea level rise
South & Southwest	Sea level rise, extreme heat; Increased heat, drought & flooding and erosion in coastal areas

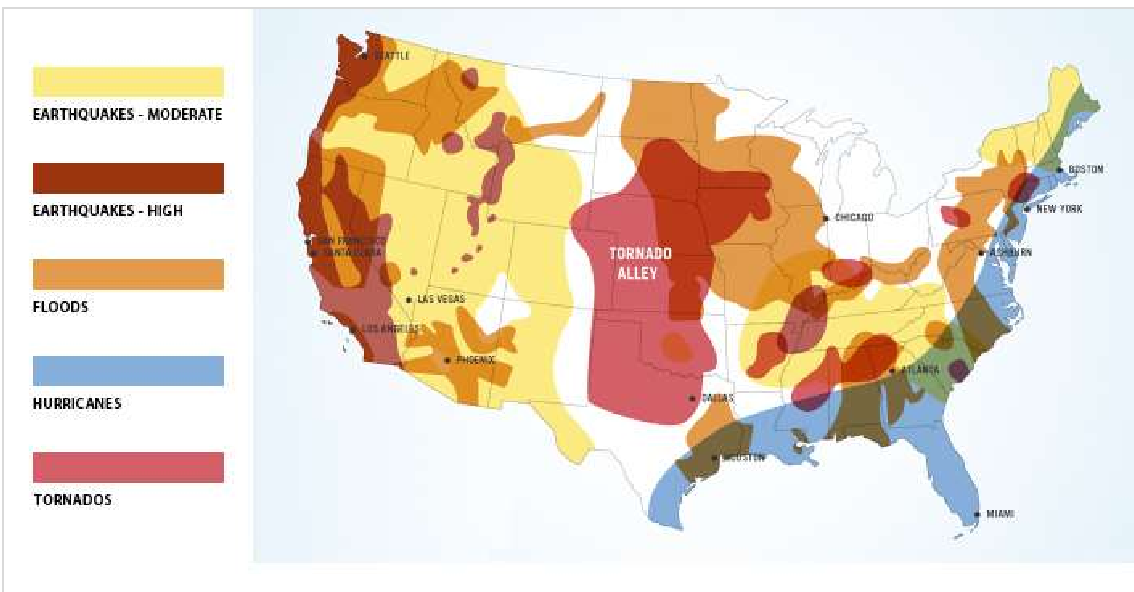

Figure 1.7 Map showing earthquake, flood, tornado and hurricane hazards in continental United States

(Source: Alert Systems Group, 2015)

1.2.1.1.2 Agency Experience

The second criterion used in selecting the cases is the relative experience agencies with building resilience capacity. Relative experiences of agencies were initially determined through a review of the state of practice literature. This criterion seeks to identify resilience approaches used by agencies with various threat levels and previous experience with system disruption. Specifically, this criterion seeks to help answer question of whether or not agencies that have experienced (or more frequently experience) system disruptions due to natural hazards have evolved further towards sociotechnical resilience approaches.

1.2.3 Framework Development

The second phase of this research begins with the development of the conceptual framework for sociotechnical transportation system resilience. The framework is developed by first incorporating key concepts drawn from the literature review to extend the current heavily technical practice to socio-technical, as well as input obtained from the survey on changes in different types agency capital. Next, a maturity scale for defining the resilience capacity for transportation agencies is developed and presented with the intent to define different stages of maturity an agency may go through based on its resilience capacity as a function of its different types of capital over time. The maturity scale is also designed to double as a self-assessment tool that agencies can use to identify where they fall on the scale to help them better plan toward higher levels system resilience using clear predefined targets. Agencies can therefore use the maturity scale as a tool for systematically progressing from one maturity level to the next.

1.2.4 Verification and Validation

The second phase of the research also involves a demonstration and review of the resulting tool by transportation industry practitioners. The review and feedback process is used for the framework and resulting tool's verification. The verification process is used to ensure that the tool meets the needs of its intended users. Generally, this process involves non-executable methods such as review. Validation on the other hand is meant to ensure that the tool produces the expected outcomes. Thus, validation of the framework and tool can only occur after it is adopted and used by transport agencies over an adequate period of time. Observations can then be used to evaluate the its effectiveness in producing resilient outcomes (i.e., through jointly optimizing agency capital using sociotechnical approaches). Considering the timeline of this research, validation falls outside its scope. However, verification through practitioner feedback provides the necessary quality assurance/quality control for initial adoption.

The verification process therefore constitutes a review by practitioners from four different transportation agencies: Arizona Department of Transportation (ADOT), Washington State Department of Transportation (WSDOT), New York Metropolitan Transportation Authority (MTA), and Atlanta Regional Commission (ARC). The first two agencies, ADOT and WSDOT, also provide a demonstration of the tool by conducting a self-assessment of their agencies' resilience efforts, in addition to reviewing the tool.

Output from the verification process are then incorporated into the refinement and finalization of the tool. The research then concludes with a set of guidelines for applying the conceptual framework and tool.

1.3 Organization of Dissertation

The rest of the dissertation is presented in the subsequent chapters as follows. Chapter 2 presents a review and discussion of literature relevant to this research and concludes with a synthesis of the literature identifying gaps and key concepts that serve as opportunities for meeting those gaps. Chapter 3 presents an overview of the survey participants and discusses the structure and organization of the survey questions. The chapter then proceeds to present an analysis of the survey responses in case study format. The case studies combine the survey responses with information obtained from reviewing agency-specific literature to present a synthesis of the strengths, weaknesses, opportunities and threats associated with different agency capital that influence system resilience capacity. Subsequently, the synthesis of the literature and case studies are used a basis for developing the conceptual framework for sociotechnical resilience in Chapter 4. Chapter 4 therefore presents the foundational concepts for the framework, along with a detailed description of the framework and the associated maturity scale (also the planning tool) and concludes with a summary. Chapter 5 discusses the verification process, that is, the practitioner review and demonstration process. Feedback from the review process are summarized and then used to finalize to the tool. The final chapter, Chapter 6, concludes the dissertation with a closing discussion on the main findings of the research as they relate to the survey objectives. The research contributions, limitations and potential future research are also discussed.

CHAPTER 2. LITERATURE REVIEW

2.1 Introduction

The literature review chapter is divided into two sections. The first section presents a review of transport system resilience literature beginning with a discussion of some prevalent threats to transport systems. This literature is then summarized and synthesized. The second section of the chapter reviews resilience theory, related concepts and their applications to each of the following areas: ecological systems, social/socioecological systems, economics, and the built environment. This literature is then summarized and synthesized to present (1) a conceptualization of how some resilience concepts apply to transportation systems at different geopolitical levels, and (2) a set of pathways for operationalizing these concepts from the resilience literature in transportation. The chapter concludes by identifying gaps in the transport resilience literature and opportunities for addressing them.

2.2 Transportation Systems Resilience

2.2.1 Transportation System Threats

In general terms, a threat or hazard is anything that could cause harm or danger. In the transportation system, a threat is anything that could potentially disrupt system functions. These could either be of natural causes like earthquakes, or of man-made causes like structural deficiency. Figure 2.1 shows some examples of the range of threats that transportation systems face. After the destructive impacts of events such as Hurricane Katrina and Superstorm Sandy, natural hazards, especially those related to climate change impacts or extreme weather, have become a critical issue for transport systems. In general, transportation engineers design infrastructure based on historical records. For example, culverts may be designed based on a 100-year storm (i.e., probability of occurring once every 100 years). However, as the frequency of previously thought high-impact-low probability events continues to increase, historical records are in many cases no longer sufficient to predict future risk. Climate change poses many significant threats for transportation systems including increased extreme precipitation and associated flooding, sea level rise (SLR), storm surge, and extreme heat. Some of these threats are briefly discussed in the following paragraphs as they affect many transportation systems in the U.S.

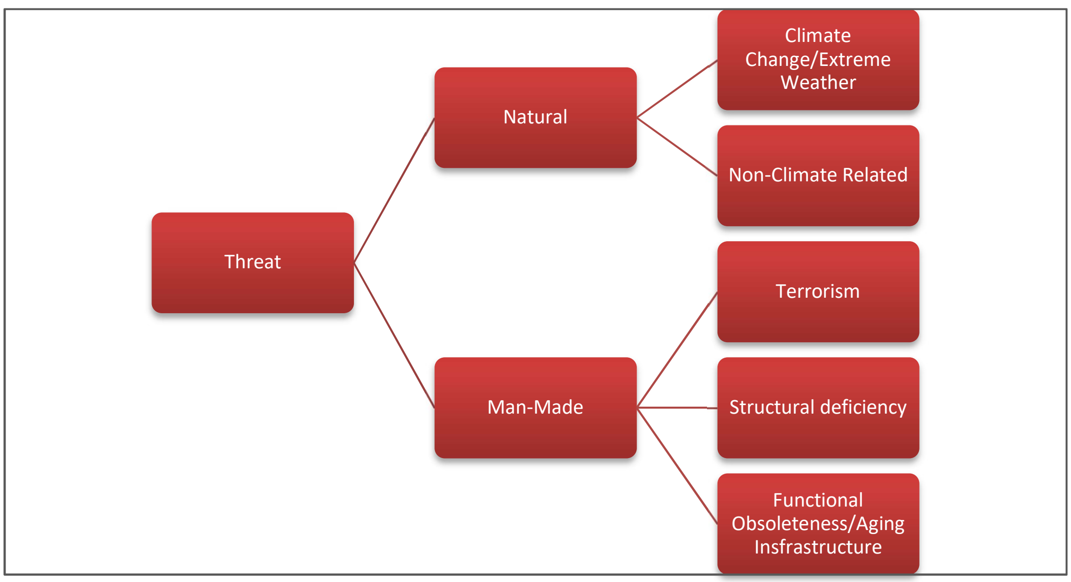

Figure 2.1 Types and Examples of Threats

2.2.1.1 Climate Change Related Threats

"Climate change is a long-term shift in the statistics of weather (including averages)" (NOAA, 2007). The resulting impacts of this is the warming of the globe, resulting in global sea level rise and more intense and frequent extreme weather events, with exact impacts varying across geographic regions. Since the early nineties, transportation agencies have worked towards *mitigating* (i.e. a focus on the causes of climate change such as reducing greenhouse gas emissions) the impacts of the transportation system on air quality mostly with funding from the Congestion Mitigation and Air Quality Improvement Program (CMAQ) established under the 1991 national surface transportation legislation: Intermodal Surface Transportation Efficiency Act (ISTEA). Because of recent events however, owners and operators of transportation infrastructure have begun to focus on the impacts of climate change and extreme weather on their systems.

2.2.1.2 Sea Level Rise (SLR):

Caused by glacial melting and thermal expansion of oceans, SLR threatens inundation of coastal transportation infrastructure. In addition to inundation, SLR can affect coastal erosion rates, ground water levels and environmental characteristics that affect material durability (Caltrans, 2011). Figure 2.2 shows a map of major Gulf Coast roadways that could be flooded by SLR in the next 50 to 100 years.

Figure 2.2 Major Gulf Coast roadways that could be flooded by SLR in the next 50 to 100 years. (Source: USGCRP, 2014)

2.2.1.3 Storm Surge, Intense Precipitation & Flooding:

Storm surge is "an abnormal rise of water generated by a storm, over and above the predicted astronomical tide" (NOAA, n.d.). This is primarily caused by winds associated with storms and hurricanes, although the exact level of surge is influence by several factors. According to the National Oceanic and Atmospheric Administration, (NOAA), the entire East coast and all locations along the Gulf coast are vulnerable to storm surge. Additionally, there are about 60,000 miles of coastal roads in the U.S. currently exposed to flooding from coastal storms and high waves (EPA, 2016). These hazards typically result in washed out or damaged roads and bridges, weakened soil under culverts and tunnels, and landslides, which result from inability of saturated soils to absorb more precipitation. Similarly, the number of extreme one-day precipitation events in the U.S. is on the rise as shown by data from NOAA in Figure 2.3. Such events consequently increase the flood rates and risk of potential damage to transport infrastructure.

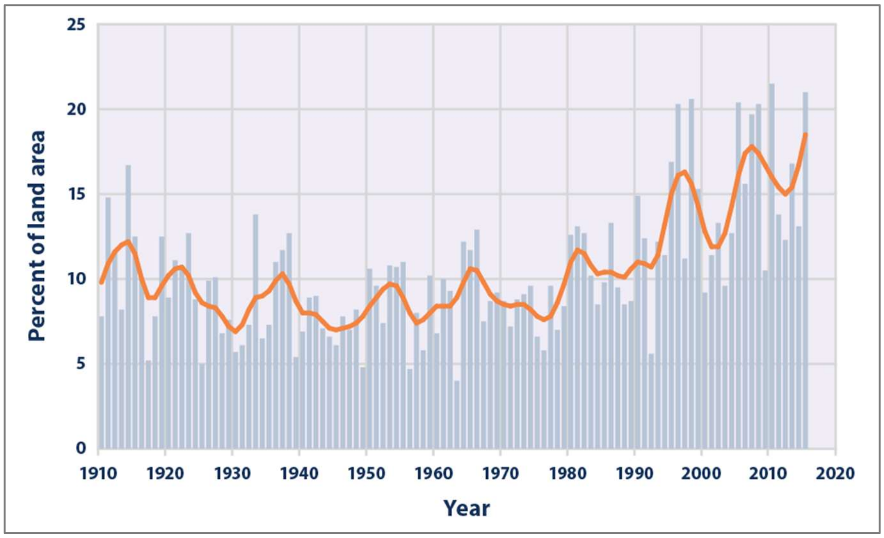

Figure 2.3 Extreme One-Day Precipitation events in the contiguous 48 States, 1910-2015. (Source: NOAA, 2016).

2.2.1.4 Extreme Heat

As a slow stressor, extreme heat can impact transportation systems in a number of ways. On roadways for example, high temperatures can lead to the softening and expansion, which can in turn cause rutting and potholes. On railroad tracks, buckling from expansion due to extreme heat can also lead to train derailments. Extreme heat can also affect bridge joints (TRB, 2008). Likewise, in a broader sense, extreme heat can potentially lead to increased project delays with its associated economic impacts for construction and maintenance activities because of limited construction activities, especially in high humidity areas (EPA, 2016).

With this general understanding of common threats faced by transportation systems, the next section introduces the state of the practice and research for transportation system resilience.

2.2.2 State of the Practice for Transportation System Resilience

Interest in transport resilience has gradually grown over years with a shift in focus from mostly studying the strength and resistance of infrastructure materials (e.g. subgrade and pavement materials) in the years prior to 2000, to research on freight and railroad security in the early 2000s. In the current state of the practice, transportation resilience is focused on assessing the impacts of climate change and extreme weather on transport infrastructure and its networks (see FTA, 2011; ICF International, 2013; Meyer et al., 2010; Testa et al., 2015; Espinet et al., 2015; and Dowds, 2015). Practitioners are consistently working with climate scientists to create data that is understandable and usable for infrastructure planning and design adaptation purposes. Beginning with the FHWA's Gulf Coast Study 1 in 2008, climate models and downscaling techniques are gradually becoming more accessible for regional and project-level adaptation endeavors as can be seen in Figure 2.4 (Choate & Bhat 2015). Subsequently, conducting threat, hazard and risk assessments in the transportation infrastructure field has also increased over the last few years across the country, and in states where such assessments are not being conducted, there is still an increased awareness of the possible risks to their systems. Specifically, assessments focused on quantifying the impacts of climate change on transportation infrastructure, by the use of vulnerability and risk indices, are continually being developed at the state level as part of Transportation Asset Management (TAM) (ICF International, 2013).

Transportation Asset management is "a strategic and systematic process of operating, maintaining, upgrading, and expanding physical assets effectively through their life cycle" (FHWA, 2015). It focuses on the use of improved and quality data in business and engineering practices for better resource allocation and decision making. The systems used in TAM serve as the main platform for climate change vulnerability assessments and infrastructure adaptation initiatives in transportation agencies. Specifically, TAM systems are being used to integrate climate change risk and/or vulnerability indicators with other asset information in databases to understand where the most vulnerable assets as well as public risks are located.

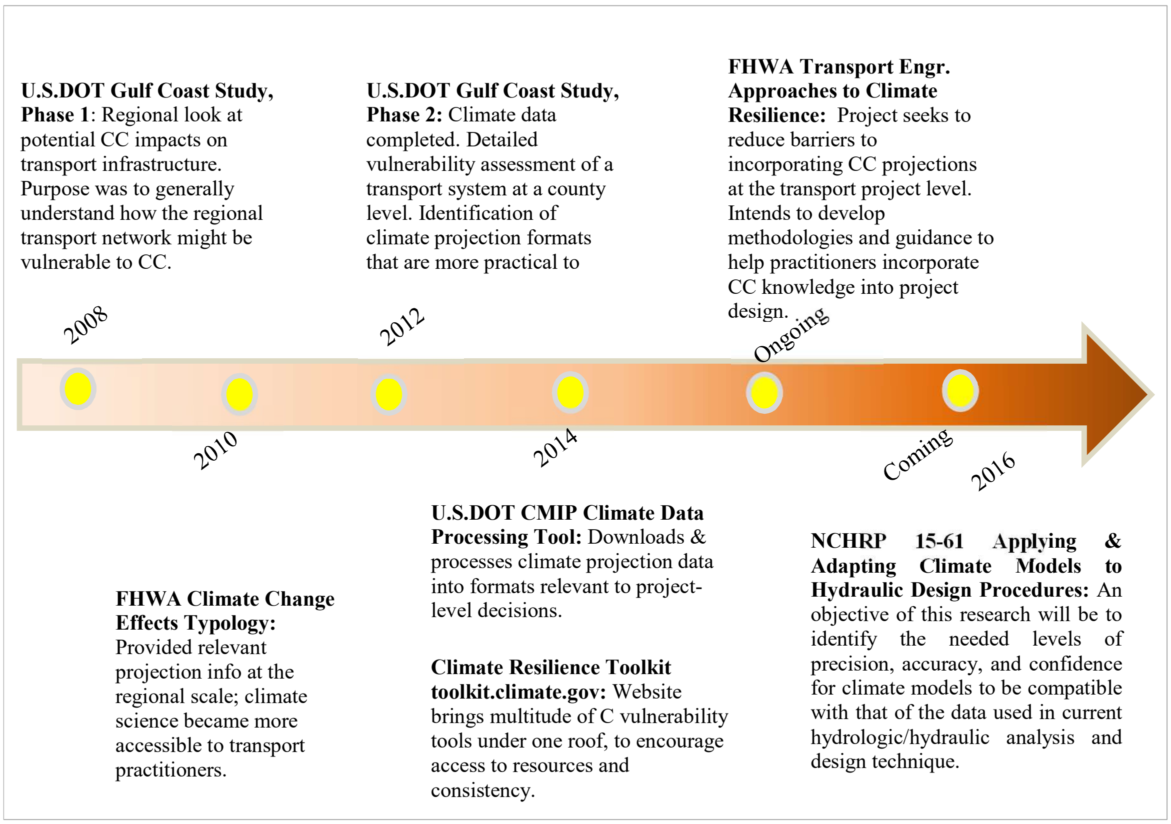

Figure 2.4 Timeline for climate change adaptation initiatives

Adapted from Choate and Bhat (2015)

For example, the Metropolitan Atlanta Rapid Transit Authority (MARTA) is incorporating climate change vulnerability into its asset management system by tagging assets that are sensitive to the impacts of climate change and subsequently factors this in resource allocation (FTA, 2011; Amekudzi et al., 2014). The MARTA climate change adaptation project was one of seven[1] pilot projects funded by the Federal Transit Administration (FTA) aimed at identifying and addressing climate change impacts on transit infrastructure, specifically those related to flooding and extreme precipitation, extreme heat, sea level rise, and tropical storms and hurricanes (FTA, 2014).

Similarly, the FHWA has also funded a number of climate change adaptation pilots. For example, the Virginia Department of Transportation (VDOT) has led efforts to assess the sensitivity of transportation assets to climate change impacts in the Hampton Roads metropolitan region. Asset scope was determined by: traffic volume, elevation relative to mean sea level, location on a maintenance priority route, and location on a hurricane evacuation route. This data was then used to develop an Excel-based prioritization model for climate change considerations. Similarly, the California Department of Transportation (Caltrans) with support from the FHWA conducted a study to analyze the potential vulnerabilities of state highways in four counties (as proof of concept) in order to prepare for the impacts of climate change, and to identify a range of adaptation options (Caltrans, 2014).

Some metropolitan transportation organizations (MPOs) have also begun planning for adaptation as part of the FHWA Climate Change Resilience Pilot projects. The Metropolitan Transportation Commission (MTC) in the San Francisco Bay Area analyzed transportation vulnerability to sea-level where the objective of the project was to provide transportation planners in the Bay Area with information for developing effective

[1] The other agencies involved in the pilot projects were San Francisco Bay Area Rapid Transit (BART), Chicago Transit Authority (CTA), Houston Metro, Tampa HART, and Island Transit (Gulf Coast), Los Angeles County Metropolitan Transport Authority (LACMTA), Southeastern Pennsylvania Transportation Authority (SEPTA), Philadelphia, and Central Puget Sound Regional Transit Authority (Sound Transit), Seattle.

adaptation strategies. The other state departments of transportation (DOTs) and MPOs involved in FHWA Climate Change Resilience Pilot projects include New Jersey DOT/North Jersey Transportation Planning Authority, Washington State DOT and the Oahu MPO (FHWA, 2015).

In terms of actual implementation, very few MPOs and DOTs use climate change adaptation and/or vulnerability as a factor for decision making. One of the few transportation agencies that does so is the Boston Region MPO. The Boston Region MPO incorporates resilience into project prioritization and selection by linking its interactive natural hazards mapping tool to the MPO's TIP (Transportation Improvement Program) projects database. The tool enables planners to determine projects that are located in areas exposed to flooding, storm surge, or sea level rise and factor that into the decision-making process (Boston Region MPO, 2013).

In summary, the current state of practice for developing transportation system resilience is to collect data that enables agencies assess the vulnerability and criticality of transport infrastructure to climate change. Agencies hope to eventually use the developed vulnerability and criticality metrics to inform project prioritization and resource allocation for various climate hazards such as storm surge, sea level rise, changing temperatures, changing rainfall and other risk factors. In addition, some agencies are also considering the use of climate data to understand the future vulnerability of planned projects under multiple climate scenarios using various climate models.

Despite the traction and growing emphasis on transport resilience, opportunities still exist to improve the current state of the practice. As mentioned earlier, many transportation agencies have not been able to cross over from the final report stage to actual implementation of recommendations although the FHWA framework being used in many of the resilience/climate change vulnerability studies includes the integration of study results into decision making as a step. In some cases, the infamous transportation trifecta (i.e., funding, political will and opportunity) is the cause and this research hopes to present some ways to overcome them. Secondly, these approaches are still largely focused on physical infrastructure (i.e., technocentric) placing less emphasis on the equally important practices, processes and human capital that affect the capacity of systems to produce resilient outcomes.

2.2.3 Transportation Resiliency Frameworks

In light of these developments, several researchers have developed various methodologies for measuring transport vulnerability and resilience which may be grouped into two broad categories. The first category comprises methods that use graph theory or a variation of it to assess vulnerability of transport networks based on their topological properties. For example, Ash and Newth (2007) use an evolutionary algorithm to evolve complex networks that are resilient to cascading failure. After an analysis aimed at finding the source of resilience for these networks, the authors reveal that topological regularities such as clustering, modularity and long path lengths are all vital in the design of robust networks. Ip and Wang (2009) also assess the resilience of transportation networks by using a quantificational resilience evaluation approach. This approach is based on the notion that survivability of any two nodes depends on the number of independent paths between them. Thus, the optimization model used in this work applies the weighted average number of passageways between a node and all other nodes in the network as the resiliency measure.

Along similar lines, Rosenkrantz et al. (2005) use the maximum number of path failures to a node that a network can tolerate as the surrogate resiliency measure for service-oriented networks and propose metrics for the quantification of resilience under node and edge failures. These metrics are based on both the topological structure of networks and manner of service distribution over the network, and also form a framework for determining the resilience parameters of a network, and for designing a network with a given degree of resilience. Lastly, Taylor and Susilawati (2012) measure changes to accessibility levels at different network states to assess network vulnerability. The authors compare levels of remoteness of localities within a study region on a basis of the extent or impact of network degradation on an accessibility/remoteness index.

The second category of methods provide a means for considering both the demand and supply side of the transport system to comprehensively assess the consequences of disruptions to users or society. In this area, Murray-Tuite and Mahmassani (2004) propose a bi-level formulation to identify vulnerable transportation links. The vulnerability index, a key component of the formulation, accounts for traffic flow, link capacities, travel times and availability of alternate routes. The vulnerability indices for all origin-destination pairs are aggregated to form a disruption index which is the measure of damage to a network that an entity (e.g. terrorist) might use to rank links as targets. Likewise, Scott et al. (2006) also present an approach to identify critical links and evaluate network performance by considering network flows, link capacity and network topology. This index is defined as the increase in user equilibrium travel time incurred because of a link closure.

Additionally, a number of frameworks for assessing transport system resilience have also been published in the literature. Tamvakis and Xenidis (2012) present a framework for assessing the resilience of transport systems utilizing the notion of entropy, i.e., transport system resilience is assessed based on the resilience of its component parts which exist at two levels - the micro and macro levels. The authors describe the micro level, as shown in Figure 2.5, as a level which comprises three segments: i) the physical system made up of infrastructure, vehicles, fuel, power systems, control communications, etc., (ii) the 'providing service' segment consisting of activities such as freight delivery, leisure travel, emergency responses, utility repair, commercial travel, etc., and (iii) the information system which consists of technological infrastructure that assists in the system's operation and control. Next, the macro level (Figure 2.6)* is described as comprising the external components of the system which include the government, customers, general public, competition, financial industry and supply industry. Thus, to evaluate the system's resilience, one must go through a series of processes that consists of first describing the system being addressed, evaluating its service level by collecting the appropriate data and then identifying its weaknesses.

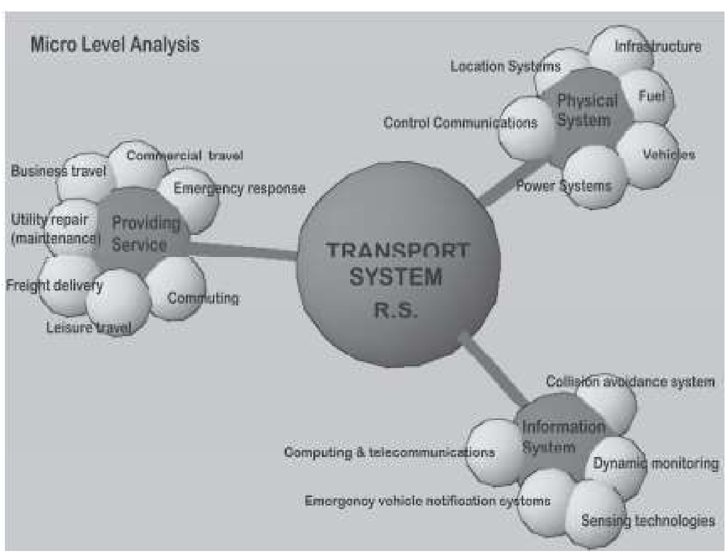

Figure 2.5: Micro level formed by internal components. (Source: Tamvakis and Xenidis, 2012)

* R.S. – Resilient System

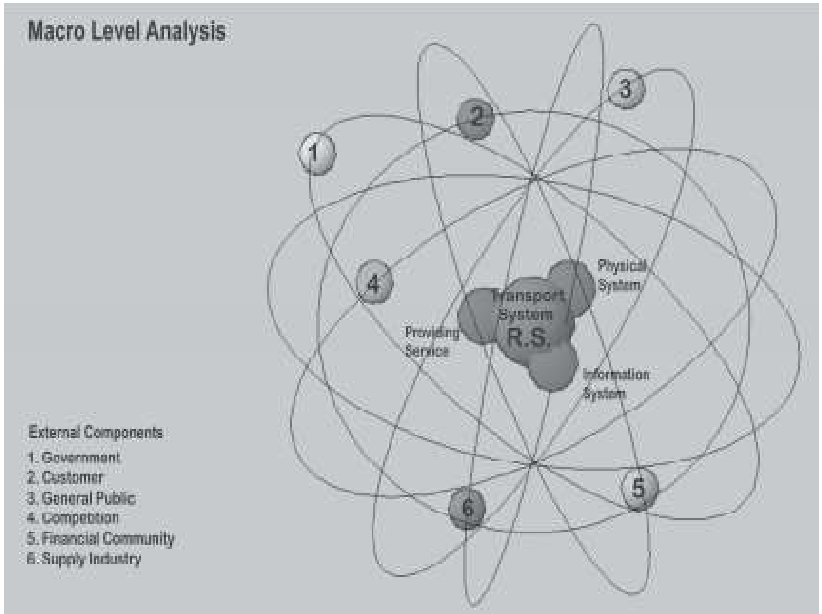

Figure 2.6: Macro level formed by external components.
(Source: Tamvakis and Xenidis, 2012)

In another framework developed by the U.S.DOT's Volpe National Transportation Systems Center, resilient transport infrastructure is described as consisting of three main attributes – robustness, adaptiveness, and consequence mitigation (Volpe, 2013). On this basis, researchers developed the 'risk-based layered defense' resiliency framework shown in Figure 2.7. This framework focuses on the conventional process for risk assessment, i.e., analyzing the likelihood and consequence of a particular threat, coupled with the principles of a layered defense. Thus, transport infrastructure becomes *robust* and *fault-tolerant* by having design-based components that give it a baseline of protection and using asset management practices to ensure a continuity of this protection. The infrastructure should also be capable of anticipating and preventing risks and limiting hazards by being *adaptable* and *resourceful*.

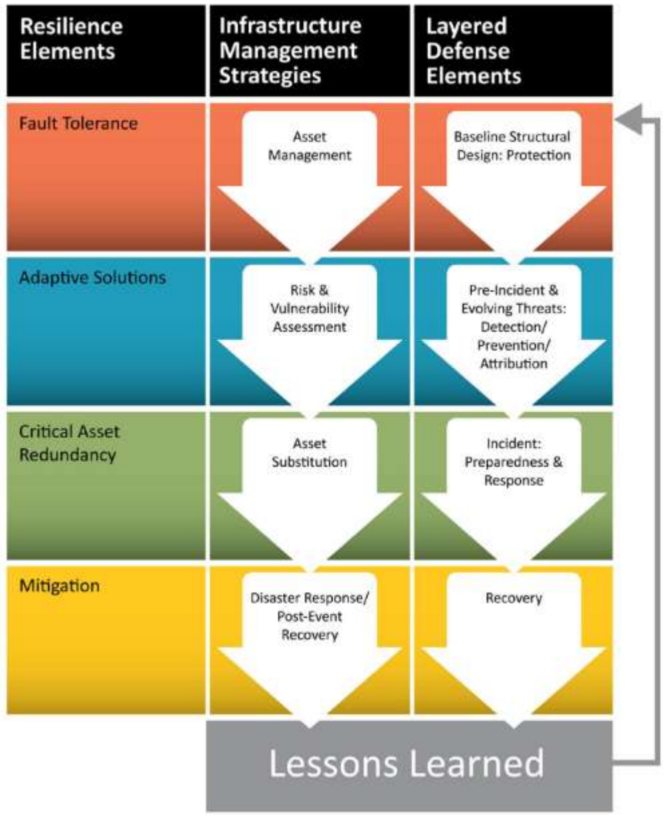

Figure 2.7 Risk-based layered defense infrastructure resiliency framework

In addition, the third element in the framework, critical asset redundancy, requires such an infrastructure system to be *flexible* to allow rapid reorganization, and *redundant* as means of providing spare safeguards and thereby avoiding single point failures. Finally, the resilient infrastructure should have response and recovery capability to mitigate the consequences of disruptive events. According to the authors, instituting this process will lead to a higher likelihood of the system meeting the three *resiliency performance criteria*: efficiency, sustainability, and survivability (Volpe, 2013), where efficiency is defined as an infrastructure system performing "its functions in order to meet its specified functional requirements at lowest cost"; sustainability is defined as "a resource-use pattern that meets today's needs while protecting resources for future use"; and survivability relates to an infrastructure being "capable of withstanding damages with minimal adverse impacts – lost lives, ecological impacts, structural damage – on the people, transportation operations, economy, and the environment" (Barami, 2013).

Also, Leu et al. (2010) present a resilience assessment framework, shown in Figure 2.8, that describes the transport 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. The framework presented by Leu et al. (2010) emphasizes the role of people and - through the service layer- the characterization of the transport network as part of several supply chains, and therefore the importance of measuring change and impact in all three transport layers for resilience assessment. In addition to the frameworks described, some other transport resilience frameworks proposed in the literature are summarized in Table 2.1.

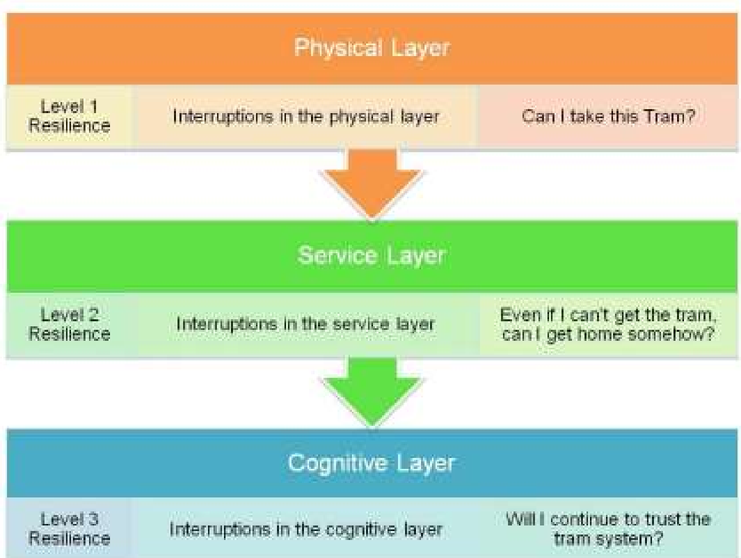

Figure 2.8 Three-layer resilience assessment framework (Source*:* Leu et al., 2010)

Table 2.1: Summary of work focused on measuring transport system resilience

Author	Proposed Methodology	
Serulle (2010)	Fuzzy systems approach for quantifying resiliency at pre-event conditions using measurable inputs that represent redundancy, cost, available capacity and accessible capacity.	
	Variables	Metrics
	Prevailing LOS Road density Average delay Average speed reduction Personal transportation cost Commercial/industrial cost Alternate infrastructure proximity Level of intermodality Network management	Highway Capacity Manual (HCM) Lane-miles/square-miles Hours or minutes %below speed limit Dollars/mile Dollars/mile Distance b/n key infrastructures/links Linguistic variable (low to high) Linguistic Variable (level 1 to level 5)
Croope et al. (2010)	Improving resiliency by using a 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:	
	Component	**Description**
	Spatial Decision Support System	Geographic Information System (GIS)/HAZUS-MH (FEMA application that uses GIS software to map & display hazard data and the results of damage & economic loss estimates for buildings and infrastructure caused by earthquakes, hurricane winds, & floods)
	Infrastructure Management System	FEMA benefit/cost analysis principles: net present value, avoided damages, etc. for highway asset management
	Management Information System	Based on resiliency concepts and principles
	The CIR-DSS is applied considering: — Physical infrastructure conditions (deterioration and maintenance dynamics) — Functional assessments (practices of estimating life-cycle cost) — Vulnerability and damage assessment within specified location Measures of *resilience and system performance* used were measured before, during, immediately following event, during recovery and after restoration. — Capacity in veh/hr/ln — Number of available lanes — Pavement condition index Measures may differ depending on available information	

Table 2.1: Summary of work focused on measuring transport system resilience (continued)

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. Measures transportation system resiliency using 2 components: — Static resiliency: ability of an entity to maintain function, measured in % of maximum disruption avoided by resilience behaviors. Where: o Max. Disruption = reduction in pax journeys for the attacked mode o Resilience behaviors = increase in pax journeys for alternate modes — Dynamic resilience: capability to recover rapidly to achieve a desired state, i.e. Speed of recovery beyond a normal speed measured in pax/km

2.3 Summary and Synthesis of Transportation Resilience Literature

Transportation resiliency frameworks in the literature have largely focused on algorithms to configure highway networks to be more robust – with characteristics of redundancy, modularity, efficiency, rapidity, diversity, etc. They have also focused on how vulnerable a system is from the standpoint of providing a sufficient supply of services to meet user demands. In addition, resiliency has been characterized as a function of system entropy, as a function of system redundancy, cost, and capacity; as a quadruple-layered hierarchy of attributes consisting of fault tolerance, adaptive solutions, critical asset redundancy and mitigation; and as a three-level layer consisting of interruptions in the physical layer, interruptions in the service layer, and interruptions in the cognitive layer. A few frameworks were found that focus on technical, organizational and institutional factors for improving transportation system resilience (Bruneau et al., 2003; Tierney & Bruneau, 2007; Ta et al., 2009; Vugrin et al., 2010). However, the literature shows that the implementation of some of these frameworks have still largely focused on the physical highway system and how it can be built better to withstand the impacts of major disruptions, both in research and in practice. This techno-centric approach to system resilience is valuable for learning about specific risk reduction measures; however, there is potential value in including the consideration of societal factors of transportation system resilience, alongside the technical. The socioeconomic influences and implications of transport system failure during catastrophic events, and the fact that many societies are largely dependent on the proper functioning of infrastructure systems such as transportation, indicates a broader perspective that formally addresses the organizational, institutional and financial, alongside the technical elements of transportation system resiliency will be more holistic and thus, potentially of incremental value to the status quo approaches.

Although some of the literature reviewed incorporates some of these broader factors, there is evidence that points towards unidentified opportunities still to be realized in enhancing current approaches. For example, recent FHWA climate resilience pilots show a difficulty for transport agencies to implement recommendations from studies conducted leading. It also shows little evidence that transportation agencies are proactively using transportation resilience performance metrics/factors in planning and decision making. The literature also shows that the underlying notion of resilience for current approaches are based on the concept of systems exhibiting resilience at a single equilibrium, which is indicative of the engineering resilience theory (to be discussed in subsequent sections).

To that end of tapping into unrealized opportunities, one can first look to the key principles from sociotechnical systems theory, which can be summarized in the following two statements (Walker et al., 2007):

- Joint optimization of social and technical factors for successful organizational performance
- Optimizing only one aspect increases the number of unpredictable, un-designed, non-linear and injurious relationships to the system's performance.

A sociotechnical approach to transportation system resilience is therefore particularly timely with the formal adoption of performance-based and risk-based transportation asset management in the 2012 national surface transportation law: Moving Ahead for Progress in the 21st Century (MAP-21), which is also continued in the 2015 Fixing America's Surface Transportation (FAST) Act. These laws are positioned to potentially promote the formal consideration of sociotechnical factors simultaneously with engineering and other factors in the planning and decision-making process.

In the subsequent sections, a review of resilience theory and its applications in social, ecological, economic and physical systems is presented, identifying transferable concepts that have the capacity to extent the current thinking of transportation system resilience.

2.4 Resilience Theory, Related Concepts & Applications

One of the earliest mentions of resilience theory is in the study of natural systems' behavior by Holling (1973). Holling's work, which is situated in ecology and socioecological systems, built the foundation for the resilience of complex adaptive systems and related concepts. Since then, resilience has been defined and applied in various ways in different fields. For an enriched understanding of resilience, the sections below discuss key resilience concepts that originated from ecological theory, and then discuss their applications to physical/built systems, economics, and social systems to set the stage for developing a more holistic concept of transportation systems resilience.

2.4.1 Ecological Systems and Resilience

Holling (1973) studied the behavior of natural systems by exploring ecological theory and different perspectives of the behavior of natural systems. In his work, he describes two kinds of ecological behavior: stability and resilience. Stability, represents a system's ability to return to a state of equilibrium after a disturbance. A stable system can therefore be characterized by the rapidity with which it returns to equilibrium and the associated levels of fluctuation. In addition, a system exhibiting stability has a range of possible movements that a disturbance can shift it into; within this range of possible movements the system will always return to its equilibrium after it is disturbed. This is its domain of stability or basin of attraction, the dimensions of which are defined by the thresholds of a set of controlling variables (Ludwig et al., 1997; Folke et al., 2010). Figure 2.9 shows a three-dimensional stability landscape for a system (shown as the ball) that has two basins of attraction. The number of basins of attraction for a particular ecosystem is defined by different combinations of ecosystem attributes. The dotted lines represent the thresholds, and the areas within the dotted lines represent the basins of attraction (a.k.a regime), their respective depths corresponding to the amount of perturbation required to shift each system from one regime to the other (OTP, 2015). An analogy could be made with the stability of a concrete beam. The stability of a concrete beam in a building is defined by a set of controlling variables, one of which is tensile stress. Thus, the beam's tensile strength is one of its thresholds, beyond which the beam will crack if it is not reinforced.

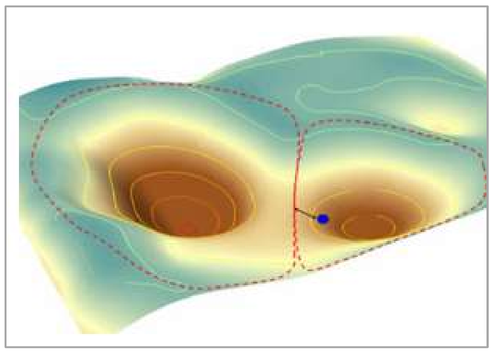

Figure 2.9 Three-dimensional stability landscape showing two basins of attraction

(Source: "Glossary", 2017)

The second ecological behavior, *resilience*, is concerned with the level of perturbation or disturbance that can be absorbed by a system before it is displaced from one state to another (Holling, 1973, 1986, 1992). Holling (1973) defines it as a "measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables". According to the author, resilient systems are still able to thrive in situations of high fluctuation.

Unlike systems that exhibit only stability which have a single equilibrium, resilient ecological systems have multiple points of equilibria thus, a fluctuation in system conditions simply causes a shift from one equilibrium state (regime) to another as opposed to a single equilibrium system which is pushed to failure. Holling's concept of multiple-equilibria systems forms the main difference between ecological resilience and engineering resilience in the sense of Pimm (1984; 1991) which stresses stability of a single equilibrium. Ludwig et al. (1997) further describe single state equilibrium as being present only in linear systems, or in nonlinear systems that are so close to stable equilibrium that a linear approximation is valid. Such systems always return to their original equilibria when displaced and can be described as globally stable. In contrast, resilience in the sense of Holling (1973) refers to nonlinear systems near the boundary of the basin of attraction. Such systems have multiple equilibria and exhibit local stability in each equilibrium state or regime (Ludwig et al., 1997). Relating this to transportation, we can therefore argue that for transport systems, returning to the original state is not always ideal in resilience capacity building. Thus, the intent of this work is to shift our thinking and views toward generating multiple-equilibria that involve multiple capital (the capital associated with system sustainability) rather than single equilibrium largely focused on technical capital.

2.4.1.1 Adaptive Cycles and Panarchy

The concepts described in the preceding paragraphs explain one of two main building blocks of ecological resilience, i.e. ecological systems have multiple stable states that are separated by thresholds. These thresholds are levels of certain "slow changing, controlling variables" beyond which a system is shifted into a different regime (equilibrium state) (Ludwig et al., 1997). The second relates to Holling and Gunderson's (2002) definition of ecosystem resilience: *"… the magnitude of disturbance that can be absorbed before the system changes its structure by changing the variables and processes that control* *behavior*." A better understanding of this is that, the system's resilience is not only related to the magnitude of the disturbance, but also, its **ability to change in order to persist** (i.e., adaptability). This very ability of the system to change in order to persist can be considered a fundamental criterion for resilient systems.

The adaptive cycle is a metaphor used to describe how some complex adaptive systems behave over time (Ludwig et al., 1997). Per Holling and Gunderson (2002), the adaptive cycle represents the waxing and waning of: (1) resource accrual or capital, (2) system connectedness, i.e. level of tightness of controlling variables, and (3) resilience. The changes to these three factors take place over the four stages of the adaptive cycle. Looking at Figure 2.10, the first phase of the adaptive cycle is called the rapid growth or exploitation phase. It is represented by the maximum rate of growth –r. During this phase, successful "system actors" make use of available resources and exploit all possible niches. The growth of the technology industry may be used as an example; with its rapid growth, new companies and entrepreneurs alike made use of available resources (whether knowledge, financial, etc.) to exploit new niches (e.g., Uber, Lift, zipcar, etc. are all examples of technology penetration into the transportation sector). At this stage, the system has weak connections, weak internal regulation, and high resilience.

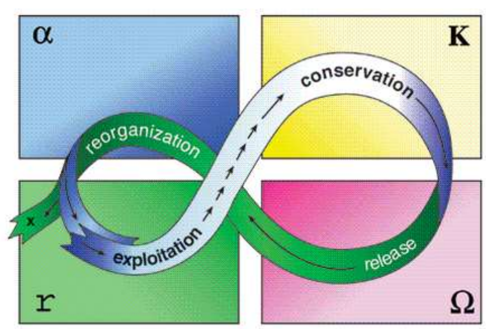

Figure 2.10: States of the Adaptive Cycle (Source: Holling, 2011)

The system then moves into the conservation (K) phase where interconnectedness increases, internal regulations are formed and become strong leading to little flexibility in the system. Novelty at this stage also starts to decline and leads to lower system resilience (Ludwig et al., 1997). The gradual decline creates local stability in the system but inadvertently leads to increased rigidity. The buildup of system rigidity through increasing interconnectedness leads to a sudden release of resources, a sort of "creative destruction", when some disturbance or shock destabilizes the system, plunging it into the release (Ω) phase (Schumpeter, 1943; Curtin and Parker, 2014). This disturbance breaks system connections, weakens internal regulations, and leads to the leakage of capital/potential from the system. This phase is usually briefer than the others. According to Holling and Gunderson (2002), the harshness of the release, depends on the length of the conservation phase, i.e. the longer the conservation phase, the harsher the release phase. The release phase is then followed by a period of "reorganization", also known as the α-phase. At this stage, new actors may come into the system; novelty, invention and experimentation also thrive.

The adaptive cycle can exist at different scales, temporally or spatially; the interactive dynamics of a system of nested adaptive cycles is known as *panarchy* (Holling and Gunderson, 2002). The adaptive cycle is presented by the authors as a metaphor with which hypotheses about a system's resilience, connectedness and potential/capital may be generated (Gotts, 2007; Holling and Gunderson, 2002). **Table 2.2** provides a summary of some of the important terms introduced in this section.

Table 2.2 Summary of ecological resilience terms (Source: Folke et al., 2010)

Term	Definition
Adaptability (adaptive capacity)	The capacity of actors in a system to influence resilience
Adaptive cycle	A heuristic model that portrays an endogenously driven four-phase cycle of social-ecological system and other complex adaptive systems. The common trajectory is from a phase of rapid growth where resources are freely available and there is high resilience (r phase), through capital accumulation into a gradually rigidifying phase where most resources are locked up and there is little flexibility or novelty, and low resilience (K-phase), then via a sudden collapse into a release phase of chaotic dynamics in which relationships and structures are undone (Ω), into a phase of re-organization where novelty can prevail (α). The r-K dynamics reflect a more-or-less predictable, relatively slow "foreloop" and the Ω – α dynamics represent a chaotic, fast "backloop" that strongly influences the nature of the next foreloop. External or higher-scale influences can cause a move from any phase to any other phase.
Panarchy	The interactive dynamics of a nested set of adaptive cycles
Regime	The set of system states within a stability landscape
Regime shift	A change in a system state from one regime or stability domain to another
Resilience	The capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure and feedbacks, and therefore identity, that is, the capacity to change in order to maintain the same identity
Social ecological system	Integrated system of ecosystems and human society with reciprocal feedback and interdependence. The concept emphasizes the humans-in-nature perspective
Specified resilience	The resilience "of what, to what"; resilience of some particular part of a system, related to a particular control variable, to one or more identified kinds of shocks
Domain of stability	A domain or basin of attraction of a system, in which the dimensions are defined by the set of controlling variables that have threshold levels (equivalent to a system regime)
Stability landscape	The extent of possible states of a system space, defined by the set of control variables in which stability domains are embedded
Threshold	A level or amount of a controlling, often slowly changing variable in which a change occurs in a critical feedback causing the system to self-organize along a different trajectory, that is, towards a different attractor

2.4.2 Built/Physical Systems and Resilience

The resilience of built systems is generally based on the concept of engineering resilience which Pimm (1984) defines as a system's ability to return to a steady state following a disturbance or perturbation (also O'Neil et al., 1986; Tilman and Downing, 1994; Tilman, 1996). **Resilience in this context focuses on a system's ability to withstand disturbances and the speed with which it returns to its original state.** A system in this context is said to have failed if a deviation from the expected value of external or internal influences (i.e., level of disturbance of perturbation) exceeds its absorptive capacity. Tamvakis and Xenidis (2012) define resilience as "… the ability of a system to react from stresses that challenge its performance", and Croope et al. (2010) as "the ability of a system to withstand or respond to changes". These definitions reflect the main ideas of resilience in physical/built systems: (1) ability to withstand a disturbance, i.e. resistance, and (2) the rate at which it recovers, i.e. rapidity of returning to pre-disaster conditions (stability). Thus, by controlling either the amount of infrastructure degradation that can occur, or the time it takes to reach full functionality after a disruption occurs, an infrastructure's resilience may be increased or lowered.

Several resilience frameworks have also been introduced in this area. The most comprehensive ones are those that are system-based. In earthquake engineering research, Bruneau et al. (2003) proposed the TOSE (technical-organizational-social-economic) framework for assessing resilience. The technical domain comprises all physical components of the system (e.g., highways and bridges). The organizational domain comprises the governing bodies or institutions in charge of the system (e.g., state DOTs and similar agencies). The social domain represents social groups and communities in contact with and hence, affected by the system. Lastly, the economic domain represents both local and foreign economies linked to the system. The TOSE framework has heavily influenced the physical/engineering resilience literature and assessment frameworks (e.g., Reggiani, 2012; Vugrin et al., 2010; Hughes and Healy, 2014). Tierney and Bruneau (2007) describe a resilient system as one that has *robustness*, the inherent strength or ability to withstand disasters without significant degradation; *redundancy*, the availability of back-up systems or the ability of system units to be substituted to perform other functions in order to maintain system functionality; *resourcefulness*, the extent to which a system can initiate solutions to address disruptions; and lastly, *rapidity*, which is the time it takes to restore a system's. Such an infrastructure system will ultimately have a reduced probability of failure, consequences of failure, and time to recovery (Bruneau et al., 2003; Reggiani 2012). Tierney and Bruneau's (2007) work, unlike many others in the area of physical and built systems resilience, places an emphasis on the social components of system resilience. The authors define resilience as "the ability of social units (e.g., organizations, communities, etc.) 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).

Work on freight system resiliency by Ta et al., (2009) introduces three dimensions that should be targeted by resilience strategies; the infrastructure, the user and the managing organization dimensions. Like 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 (Bruneau et al. 2003). The user dimension is made up of the individuals and organizations that use the system to transport people and goods. Lastly, the managing organization is the body in charge of the construction, maintenance and daily functionality of the infrastructure (Ta et al., 2009).

Vugrin et al. (2010) also present a resilience framework that attempts to expand on the TOSE dimensions by including two additional domains: environmental and ecological (Figure 2.11). These dimensions serve as channels through which targeted resilience strategies may be developed and applied for increasing a system's resilience. Lastly, Nemeth (2008) briefly explores resilience in terms of the linkages and interactions between systems and their environments. He extracts recurring themes from the Second Resilience Engineering Symposium which took place in France in 2006. Here, Nemeth (2008) describes resilience as the "generic ability to cope with unforeseen challenges, and having adaptable reserves and flexibility to accommodate those challenges". According to Nemeth (2008) the traits (characteristics) of resilience that emerged from the discussions were "experience, intuition, improvising, expecting the unexpected, examining preconceptions, thinking outside the box and taking advantage of fortuitous events".

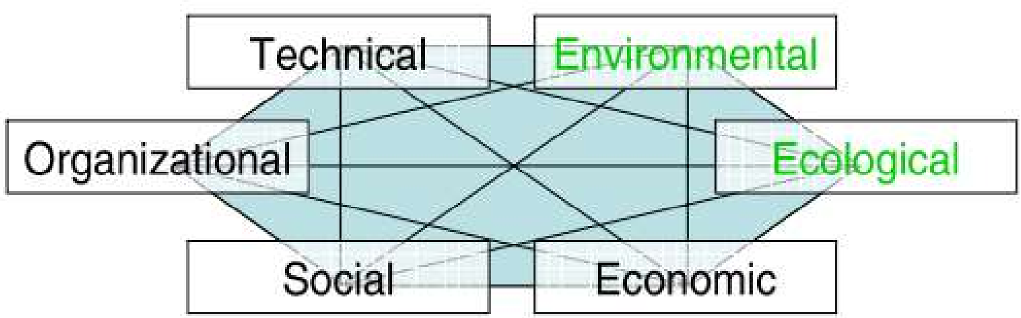

Figure 2.11 Domains for assessing system resilience by Vugrin et al (2010)

Now looking at the energy sector, specifically in the areas of electricity delivery and reliability, system resilience concepts are continually being applied. Research on defining, measuring and analyzing the resilience of energy systems was therefore also reviewed. Along these lines, an important consideration found in a report by Sandia National Laboratories on energy system resilience emphasizes the distinction between reliability and resilience by "constraining the definition of resilience to high-consequence, low-probability events" (Sandia, 2015). This very distinction is critical even for transportation systems where resilience efforts could easily be bloated to include planning for low-consequence, low probability events (e.g., car crashes and resultant congestion). Authors of this report also provide two fundamental concepts that risk-based frameworks should adhere to: (1) "resilience is defined with respect to disturbance(s) or threat(s)" and (2) "consequences relate to the social effects of system performance in addition to system performance itself" (Sandia, 2015). Consequently, a conceptual framework for developing resilience metrics for US electricity, oil and gas sectors is proposed as the Resilience Analysis Process (RAP). The RAP process outlines seven steps is as follows:

1) **Define resilience goals**: Determining a set of high-level goals for the system
2) **Define system and resilience metrics:** This determines scope of the analysis
3) **Characterize threats:** Includes assessing threat likelihood and intensity
4) **Determine level of disruption:** This is the amount of damage that occurs to the system
5) **Define and apply system models:** develop models that tie system damage to service levels

6) **Calculate consequence:** Convert system output levels produced from models into resilience metrics defined in Step 2.
7) **Evaluate resilience improvements:** Determine required improvements necessary for enhanced resilience. This may be a physical, policy or procedural change.

Summarily, implementation of this framework is meant to focus more on consequences (e.g. social welfare) rather than only system impacts. This approach to defining resilience metrics, that is, consequence-based rather than attribute-based, is constructive as it places the end user at the center of any analysis.

Another report on measuring the resilience of energy systems by Willis and Lea (2015) present a review of 154 resilience metrics used in the electricity, oil and natural gas sectors extracted from 58 reports and peer-reviewed papers. The authors first present a logic model with which the resilience metrics are organized. The model, shown in Figure 2.12 is developed on the premise that no single set of metrics can support decision making at all levels; however, when organized and presented using a logic model, decision making across levels can be made consistent (Willis and Lea, 2015). As one moves from the strategic to operational perspective, types of metrics should also change, moving from system inputs, capacities, capabilities, performance and outcomes.

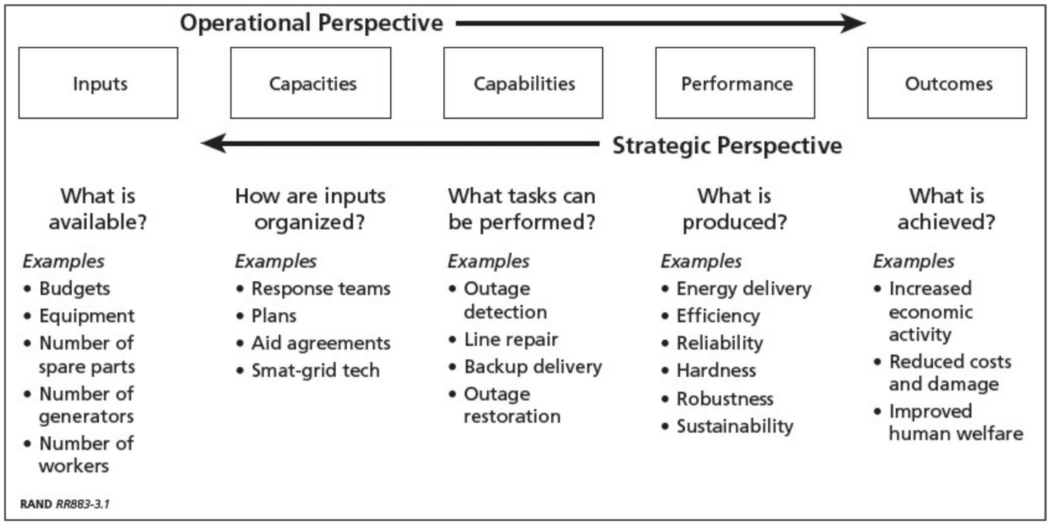

Figure 2.12 Logic model for organizing resilience metrics (Source: Willis and Lea, 2015)

The authors then go on to categorize the 154-identified metrics using three dimensions: resolution, type and maturity. The descriptions of the three dimensions are summarized in Table 2.3. Table 2.4 is an example of some of the resilience metrics categorized under the discussed framework. The framework provided by Willis and Lea (2015) give insight into important considerations for selecting resilience metrics and understanding that metrics need to be selected to suit specific tasks for different decision-making levels. Similarly, in developing resilience metrics for transportation systems, “inputs” and “capacities” should first be identified to support the strategic resilience goals of the system. These can then be distilled into “facility level” metrics that are more context-sensitive to each unit and enable the quantification of system outcomes in terms of social welfare.

Table 2.3 Summary of Willis and Lea (2015) categorization of energy sector resilience metrics

Metric Dimension	Description
Resolution	• Facility/system level • System/region level • Region/nation level
Type	• Inputs, • Capacities: Primarily resource allocation purposes • Capabilities, • Performance, • Outcomes: Primarily planning and evaluation purposes
Maturity	• Low: Metric mentioned in literature, but not consistently defined. If collected, sporadically or inconsistently • Medium: Well-defined methods for collection, but collected sporadically • High: Collected using well-defined methods and timescale for data collection is suitable

To summarize the literature on built system and physical resilience, many frameworks and evaluation methodologies have been developed and used. These applications of resilience can be said to be based on the principles of engineering resilience as presented by Pimm (1984). These generally seek to restore a system to its previous levels after a disruption in the least amount of time possible described by the resilience triangle (previously discussed in Chapter 1) (Bruneau et al., 2009). Resilience strategies in such systems are therefore designed to focus on particular areas of the disruption cycle, i.e., mitigation, preparedness, response, and recovery (Beenhouwer et al. 2003). Insights from this set of literature, especially from earthquake resilience (i.e., considerations beyond physical components, e.g., TOSE dimensions) and energy sector resilience (developing and categorizing metrics), can therefore be combined with concepts from other fields of study to give direction on enhancing transportation system resilience.

2.4.3 **Social/Socio-Ecological Systems and Resilience**

As in most systems, the need for resilience in social and socioecological systems arises from vulnerability. Vulnerability may be described simply as the potential for some form of loss. Alexander (2000) defines vulnerability as "the potential for causality, destruction, damage, disruption, or other forms of loss with respect to a particular element". Vulnerability may be faced by an individual or a community. Social vulnerability describes the situation where certain societal groups are more prone to loss than others as a result of characteristics such as class, ethnicity, gender, age, disability, etc. (Blaikie et al, 1994). The relationship between vulnerability and resilience is one that does not seem to show a clear consensus in resilience literature. While resilience is sometimes used as a *loose* antonym for vulnerability (Folke et al., 2002), Lucini (2013) objects to that notion. According to Lucini (2013), *social vulnerability and social resilience can exist in the same time and space*. This line of reasoning seems preferable when uncertainties, which are always present but cannot be planned for, are considered. This conceptualization of vulnerability as being able to coexist with resilience produces an image of a society which although vulnerable to the potential negative impacts of known and unknown factors, can still emerge resilient in the event of a disruption.

Table 2.4 Energy resilience metrics for electricity systems at the facility/system level (Source: Willis and Lea, 2015)

Inputs	Capacities	Capabilities	Performance	Outcomes
Energy feedstock (H) (McCarthy, Ogden, and Sperling, 2007)	**Communication/control systems/ control centers** (L) (Ward, 2013)	**Ancillary service** (L) (Bhatnagar et al., 2013)	**Coefficient of variation of the frequency index of sags** (M) (Shun et al., 2012)	**Load loss damage index**—damage caused by fire to the electrical system (M) (Lucia, 2012; Bagchi, Sprintson, and Singh, 2013)
Energy not supplied (L) (Brancucci Martínez-Anido et al., 2012)	**Electrical protection and metering** (L) (Ward, 2013)	**Hazard rate relating function**—altered hazard rate of component after a certain maintenance (M) (Wang and Guo, 2013)	**Control Performance Standard 2 violations**—one of the California Independent System Operator CIISO principal reliability standards (H) (Roe and Schulman, 2012)	
Energy storage (L) (Bhatnagar et al., 2013)	**Equipment positioning** (L) (Keogh and Cody, 2013)	**Line mitigation**—reroute electrical flows due to line overloading or "congestion" (L) (Roe and Schulman, 2012)	**Bulk electric system reliability performance indices** (M) (Billinton and Wangdee, 2006)	
Generators available (#) (H) (Roe and Schulman, 2012)	**Flow paths, line flow limits** (L) (Bompard, Napoli, and Xue, 2010)	**Load biasing**—major adjustments in automated dispatching software (L) (Roe and Schulman, 2012)	**Derated power**—rated power multiple with the reliability of the plant (M) (Voorspools and D'Haeseleer, 2004)	
Hydrophobic coating on equipment (L) (Keogh and Cody, 2013)	**Gen/load bus distribution** (L) (Bompard, Napoli, and Xue, 2010)	**Net-ability**—measures the aptitude of the grid in transmitting power from generation to load buses efficiently (L) (Bompard, Napoli, and Xue, 2010)	**Dropped/lost phase**—power quality metric (M) (Rouse and Kelly, 2011)	
Key replacement equipment stockpile (L) (Keogh and Cody, 2013)	**Reserve/spare capacity** (M) (Willis and Garrod, 1997; Molyneaux et al., 2012)	**Path redundancy**—assesses the available redundancy in terms of paths in transmitting power from a generation to a load bus based on entropy (L) (Bompard, Napoli, and Xue, 2010)	**Edge resilience trajectory**—relationship between reliability and resilience tracking a moving range of R^2 for the Control Performance Standard 2 (H) (Roe and Schulman, 2012)	
Redundant power lines (L) (Keogh and Cody, 2013)	**Substations (switchyards)—overhead lines** and **underground cables** are interconnected (L) (Ward, 2013)	**Protective and switching devices**—mean time to repair (M) (Yeddanapudi, 2012)	**Energy efficiency/intensity** (H) (Gnansounou, 2008; Molyneaux et al., 2012; Wang et al., 2012)	
Reinforced concrete versus wooden distribution poles (L) (Keogh and Cody, 2013)		**Protective and switching devices**—switching reliability (M) (Yeddanapudi, 2012)	**Failure rate** (M) (Wang and Guo, 2013)	
Siting infrastructure (L) (Keogh and Cody, 2013)		**Protective and switching devices**—mean time to switch (M) (Yeddanapudi, 2012)	**Flicker**—power quality metric (M) (Rouse and Kelly, 2011)	
Underground, overhead, undersea distribution/ cable lines (M) (Doukas et al., 2011; Rouse and Kelly, 2011)		**Viability of investments** (L) (McCarthy, Ogden, and Sperling, 2007)	**Harmonic distortions**—power quality metric (M) (Rouse and Kelly, 2011)	
Unique encrypted passwords for utility "smart" distribution (L) (Keogh and Cody, 2013)			**Overhead and underground line segments**—mean time to repair (L) (Yeddanapudi, 2012)	
Workers employed (#) (H) (McCarthy, Ogden, and Sperling, 2007; Keogh and Cody, 2013)			**Overhead and underground line segments**—permanent failure rate (L) (Yeddanapudi, 2012)	

In the study of societies, social resilience is seen to exist in the form of social capital. Lucini (2013) defines resilience from a sociological perspective as "the capacity of people in a group (formal and informal) to face up to disaster during the emergency and reconstruction time, starting from collective and individual resources made available for all people involved having needs to be satisfied through altruistic behavior and shared social relationships". In this work, social capital is "the whole of personal acquaintances, attitudes, competencies and skills belonging to a person" (Lucini, 2013). Taking this into consideration, we see that an individual's social capital is not constrained to only those skills and relationships possessed as a result of occupation or position in society. In addition, this form of social capital is useful both in their daily lives and ultimately in the event of a disaster. Lucini's approach to resilience shows how at a microscale, individuals contribute to the resilience of their communities. Along this line of thinking, Adger (2000) steps up a level and discusses the social capital of societies and communities, thus, presenting social resilience with an institutional context, where "institution" symbolizes formal institutions, as well as behaviors, rules and norms that govern a society (Adger, 2000). This author characterizes social resilience in this context is as "the ability of communities to withstand shocks to their social infrastructure". Adger (2000) proposes institutional change and economic structure, as well as demographic change as proxy indicators for examining social resilience. Another important feature about Agder's (2000) work is the distinction between resilience and other vulnerability-reducing approaches. According to the author, resilience should be viewed as *one* of the ways of combatting a system's known vulnerabilities; the others are mitigation and adaptation (Adger, 2000).

In Lorenz's (2010) discussion about the contribution of social science to interdisciplinary resilience research, he points out the similarities between social and ecological systems: "discontinuously changing, complex, multi-stable, self-organizing, and adaptive" (Lorenz, 2010). However, and most importantly, he also points out the most significant difference between social and ecological systems, which is the ability of social systems to self-organize at a higher level. This ability to self-organize at a higher level may be called the *symbolic dimension of meaning* (Luhmann, 2005), and describes the awareness social systems have of their existence in the broader environment, their ability to interpret and learn from the past, as well as the capability to be intentional about the future (Young et al., 2006). Lorenz (2010) defines social resilience in his work as "the internal ability of social systems to prevent and mitigate disastrous change". He identifies three components of social resilience which are all shaped by the *symbolic dimension of meaning*. These are the (1) adaptive capacity, (2) coping capacity and (3) participative capacity of social systems. Per the author, the latter two have mostly been disregarded in the literature in favor of adaptive capacity, which he defines as the "social ability of a system to establish new structure relationships… that subserve the persistence of the system in the case of major environmental change or incompatible system structures" (Lorenz, 2010).

Adaptive capacity, according to Folke (2006), should be interpreted in terms of both short and long term adaptability, i.e. short term response to crises, and long term transformability which is "the capacity to create a fundamentally new system when ecological, economic, or social structures make the existing system untenable" (Walker et al., 2004:5). In adaptability (short term), it is the *thresholds* of driving variables that may change. The response to the effects of these variables are altered as a result of using prior knowledge and experience. The system, however, remains in the same basin of attraction (Berkes et al., 2003). For social systems, adaptability requires that prior knowledge and experience are combined to adjust the response to crises, and continue within the same stability domain (Lorenz, 2010; Berkes et al., 2003). Transformability on the other hand, requires a change in some of the system's actual *driving variables* which in the sense of Lorenz (2010) creates new *structures of expectation* (elaborated on below). The relationship between adaptive capacity and resilience is another area in which researchers have different views. While Smit and Wandel (2006) in their work on community adaptation to climate equate the two concepts, others such as Gunderson (2000) and Carpenter et al. (2001), as well as Lorenz (2010) see adaptation as a component of social resilience.

The second component of social resilience discussed by Lorenz (2010), coping capacity, is essentially "a way of dealing with the failure of expectations in terms of meaning". This draws on the ability of social systems to maintain the continuity of their systems through finding meaning in the event of a loss. This abstract concept has the ability, in some cases, to completely change the expectations of societies. For example, a community that experiences frequent and devastation to certain environmental hazards (e.g., floods, fires, etc.) may gradually change their *expectation structures,* and over time may no longer regard such events as disasters, but rather as part of normal life and may develop mechanisms to ensure the persistence of that community (e.g. ephemeral cities in parts of Asia) (Greg Bankoff, 2007 in Lorenz, 2010).

Lastly, participative capacity relates to the extent to which a social system makes use of adaptive and coping capacities. It describes how different perspectives and expectation structures are integrated into solutions to enhance the ability of a whole society to be adaptive as well as to cope (Lorenz, 2010). According to Lorenz (2010), external beliefs and interventions imported into societies thought to be weak, poor, and passive inherently reduce the participative capacities of those local societies and subsequently also reduce their social resilience. Rather, the author argues that the initial stages of any external developmental cooperation or aid to devastated communities, must aim first at improving the adaptive and coping capacities. Lorenz (2010) therefore states that “decreased social resilience is nothing other than the blockage, erosion or devaluation of local knowledge and coping practices caused by unequal participative capacity”.

2.4.4 Economic Systems and Resilience

The concept and understanding of resilience in economics is diverse. The varying perspectives however, provide an opportunity to further enrich our understanding of resilience. One of such concepts addresses the core definition of resilience. According to Rose (2007), much of the confusion about resilience and the difficulty in operationalizing the concept stems from the issue of definition. Authors that have explored the concept have been prone to making resilience too broad, and using resilience as an umbrella term to cover all the ways of reducing vulnerability or hazard loss; for example, Mileti (1999) defines a resilient community as one that “can withstand an extreme event with a tolerable level of losses” and “takes mitigation actions consistent with achieving that level of protection.” Like Lucini, (2013); Blaikie et al., (1994), and Pelling, (2003), Rose (2007) disagrees with the idea that resilience is the opposite of vulnerability and that by reducing an entity’s vulnerabilities, its resilience is inherently strengthened. Instead resilience, as well as adaptation and mitigation are presented as some of the several ways of reducing an entity's vulnerabilities, with an emphasis on the distinction between resilience and mitigation.

Rose's (2007) work places emphasis on the need to understand that resilience is an outcome that occurs *after* a disruption, and not before, without dismissing the importance of mitigation, or resilience enhancing behaviors such as flexibility and redundancy. For example, Rose (2007) criticizes the choice of terminology in Bruneau et al.'s (2003) conceptualization of resilience. According to this author, economic resilience differs from the resilient system presented by Bruneau et al. (2003) in terms of the aspects and dimensions of such a system. Consistent with the notion that resilience is only active in the post disaster environment (i.e., response/recovery/reconstruction), the first aspect of a resilient system stipulated by Bruneau et al. (2003) - reduced probability to failures- is excluded since it pertains to actions and measures taken before the disruption and should therefore be captured by mitigation. However, Rose's conceptualization (2007) is possibly erroneous since reducing the probability of failure does not necessarily focus on preventing the disruptive event *itself* from happening or on reducing the probability of occurrence, but rather, the emphasis is placed on engaging in certain 'resilience-enhancing' measures that can prevent the *actual* system from failing. Failure here cannot be equated to the occurrence of the event, but the inability of the system to absorb it. However, Rose (2007) makes a good point where he suggests that resourcefulness and redundancy should be seen as the *means* to the *ends* of robustness and rapidity as described by Chang and Shinozuka (2004) in economic resilience literature.

Another concept in economic resilience literature is the bifurcation of resilience into static and dynamic resilience. Rose (2007) defines static resilience as "the ability of an entity or system to maintain function when shocked", and maintains that this primarily involves the demand-side of the system, i.e. the customers or users. Static resilience, in contrast to dynamic resilience, can be achieved without repair or reconstruction of the system, and is solely based on the ability of customers to efficiently use available resources. Dynamic resilience on the other hand, is "the speed at which an entity or system recovers from a severe shock to achieve a desired state"; this requires some level of repair and reconstruction from the supply-side (Rose, 2007). Lastly, this author presents three levels at which economic resilience can occur:

- Microeconomic level: This consists of the individual behavior of firms, households, or organizations;
- Mesoeconomic level: This consists of the economic sector, individual market, or cooperative group; and
- Macroeconomic level: This consists of all individual units and markets combined, in addition to their interacting effects.

In contrast to the approach of several authors to economic resilience including Rose (2007), Simmie and Martin (2010) completely reject resilience theories based on systems achieving equilibrium. The equilibrist versions of resilience propose either the notion of systems having (1) a single equilibrium, to which they return to after a disruption as in the case of engineering resilience, or (2) of multiple equilibria, in which case the system is displaced to a different equilibrium after a disruption (as in the case of ecological resilience). The authors argue instead that regional economies are better characterized using an evolutionary approach in which economies are constantly changing and do not have any equilibria[2]. Despite the obvious contradictory nature of this approach, the authors do agree on the need for some stability and admit that regional economies exhibit stability and self-organization (Martin and Sunley, 2006, 2007; Martin, 2010). Thus, Simmie and Martin (2010) propose that the most important attribute that a constantly changing, non-equilibrium regional economy possesses is its adaptive capacity. A useful insight from this approach is the shift in focus from a system's stability to understanding the actual nature of the change being experienced by the system. In seeking to understand the nature of changes experienced by regional economies, the authors argue that regional economies resemble complex adaptive systems[3], and thus, use the 'adaptive cycles' model from ecology as a framework for describing these changes. From this perspective, resilience is presented as an attribute that wanes and waxes, as the system goes through the different phases of the adaptive cycle.

2.5 Summary and Synthesis of Resilience Literature

The summary and synthesis section is presented in two parts: (1) a summary of the characteristics that describe resilient systems and an application of some concepts from resilience literature, and (2) a list of key themes found in the literature and the implications for transport system resilience and this research.

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[2] A better approach would be to say that regional economies have constantly changing equilibria since an entity cannot possibly be stable without an equilibrium.

[3] Key features of complex adaptive systems include: unfixed or pervious boundaries between the system and its environment due to constant exchanges; complex feedbacks and self-reinforcing interactions among components; and microscale interactions and behaviors, spurring macroscale spontaneous structures and dynamics.

2.5.1 **Characteristics of Resilient Systems & Other Concepts from the Resilience Literature**

The resilience of a system may increase or decrease depending on changes that affect the system's driving variables and should therefore be seen as a system attribute. From the literature, resilient systems may also be described as having certain traits. These include the need for persistence of the system through flexibility and diversity. Figure 2.13 has been developed to illustrate the relationships between three main resilience attributes identified (persistence, adaptability and transformability) in the literature and their corresponding characteristics.

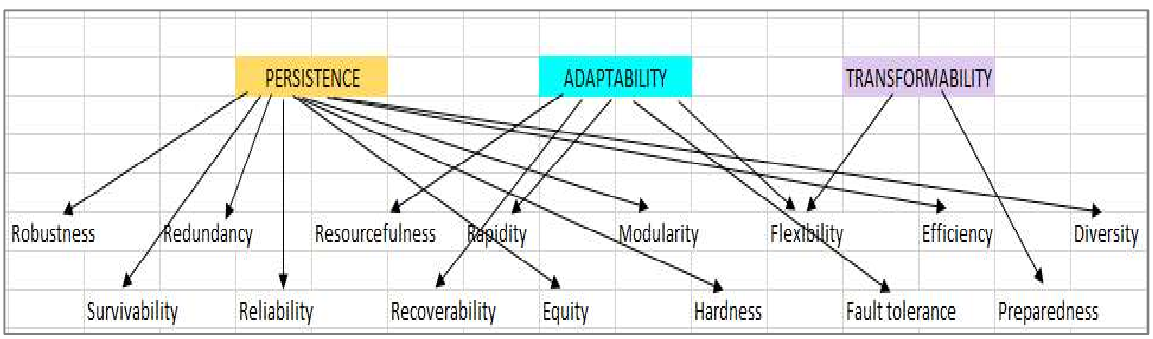

Figure 2.13 Three main attributes of a resilient system and their supporting characteristics

A resilient system also needs some degree of inherent strength to absorb the impacts of disturbances/perturbations, and adaptability and resourcefulness to consequently recover after a disturbance to either the original equilibrium (engineering resilience) or to a different equilibrium state (ecological resilience). This dissertation has an opportunity to extend the notions of engineering resilience more toward that of ecological resilience from the standpoint of finding a new regime after a disturbance.

Resilience differs from resistance (i.e., structural mitigation) which focuses only on the robustness of a system. System robustness is still crucial for resisting the impacts of extreme events and increasing the system's chances of survival. However, when a resilient system is overwhelmed by a perturbation and resistance fails, resilience enables the system's functions to decline gracefully avoiding catastrophic consequences. Resilience therefore complements mitigation (Wein and Rose, 2011).

In a sociotechnical system like transportation, the tendency is to focus on the physical components of the system without including much of other system elements. While the physical components are extremely important, other system elements, especially abstract ones such as business processes, social capital (both formal and informal, and including collaborative networks), should not be neglected. The resilience of a system is therefore characterized by its ability to persist, i.e., maintain critical functions as a result of its adaptive capacity in the form of either adaptability or transformation (Olson et al., 2006).

Adaptability in the transport system can take many forms. It includes modifying physical infrastructure in an attempt to control its behavior during an extreme event, as well as integrating the impacts of climate change during planning. Adaptability involves devising strategies to maintain the current levels of service, and attempting to reduce the impacts of adverse events (Olson et al., 2006). In adaptability, the thresholds of certain system drivers are changed, thereby increasing or decreasing the system's basin of attraction. Transformation on the other hand would require the creation of new system configurations. This occurs when certain factors force changes in the system's state variables. Such changes include the addition of new state variables, or the replacement of some state variables. In the socio-ecological context, such transformations are usually the result of:

(1) some ecological crises, (2) changes in the system's social components such as values or resources, and (3) economic or political change (Scheffer et al., 2003; Aberbach and Christensen, 2001; in Olsen et al., 2006). According to Folke et al. (2010), these transformations may be *deliberate* (initiated by the people involved) or *forced* (imposed by changing environmental or socioeconomic conditions), with forced transformations more likely to occur at larger scales and beyond the influence of local actors. Deliberate transformations on the other hand, may be initiated at multiple scales and usually lead to gradual transformations – such deliberate transformations require resilience thinking.

Several other concepts identified in the literature may be applied to enhance the scope and strength of transportation resilience thinking; from ecological system resilience: resilience as a function of adaptive behavior, single-equilibrium versus multiple-equilibria states; from social system resilience: vulnerability, adaptive capacity and participative capacity; and from economic resilience: a multi-scaler approach to resilience, and static versus dynamic resilience. Table 2.5 provides examples of how these respective concepts may be applied to develop transportation system resilience and offers some operational pathways.

Table 2.5 Application of Ecological, Social and Economic Resilience Concepts to Building Transportation System Resilience Capacity

Concept	Application to Transportation System Resilience	Operational Pathway
Resilience as a function of adaptive behavior (Ecological systems)	- **Expand** choices for improved mobility and accessibility to allow for adaptive choices during or after a disruption. - **Create** redundancy within system to allow for adaptive choices.	- **Expand** modes/modal availability (Multimodalism) - **Improve** seamlessness between the modes (Intermodalism)
Single-Equilibrium and Multiple-Equilibria States (Ecological Systems)	- **Conceptualize** Transportation System with Multiple-Equilibria over time linked to different states that afford communities different levels of quality of life and infrastructure resilience readiness. o An understanding that in communities where infrastructure resilience readiness is not at a relatively high level the general desire will be to move to a higher state of equilibrium after a disruption (e.g., MTA after SuperStorm Sandy) o An understanding that in communities where there are relatively lower infrastructure levels of service and community quality of life, there is a general desire not to return to the former state but to move to a higher state after a disruption. (E.g., New Orleans after Hurricane Katrina)	- Transportation and other planning and decision making must anticipate infrastructure renewal (not simply replacement) after disruptions in areas where infrastructure resilience readiness has not been achieved. - Transportation and other planning and decision making must anticipate infrastructure upgrading (not simply replacement) after disruptions in areas where minimum infrastructure standards have not been achieved. - **Plan** for resiliency based on envisioning of socio-infrastructure scenarios, states or regimes that are likely to result from different kinds of possible disruptions. **Develop** organizational, institutional and technical capacity to ensure a minimum standard of functionality of the society in those states with pathways for returning the socio-infrastructure system to its original or a higher state.
Vulnerability (Social Resilience)	- **Consider** vulnerability explicitly as related to communities to lead to considerations of local and system resilience, both of which are needed to characterize system-wide resilience – leading to minimum resilience standards, spatially and temporally.	- **Determine** local and system resilience as inputs to transportation planning, decision making and the development of transportation improvement program.

Table 2.5 Application of Ecological, Social and Economic Resilience Concepts to Building Transportation System Resilience Capacity (continued)

Concept	- **Application to Transportation System Resilience**	- **Operational Pathway**
Adaptive Capacity (Social Resilience)	- **Identify** situations when *transformation* is a better approach to resilience than *adaptability* during development of resilience-enhancing policies and strategies.	- **Question** past underlying assumptions that have led to unfavorable outcomes. - **Capitalize** on windows of opportunity (e.g., teaching moments from natural or man-made disasters) to redefine driving factors of transport systems using transformative laws, policies and approaches.
Participative Capacity (Social Resilience)	- **Apply** implication of participative capacity that community involvement in the transportation planning and decision-making process will influence community resilience for the better in the long run.	- **Determine** minimum standard and quality of public involvement for various communities within jurisdiction, and identify ways to achieve these minimum standards in the transportation planning and decision making process.
Static and dynamic resilience (Economic resilience)	- **Consider** transportation resilience as not only preventing system failure in event of perturbation, but also, if necessary, allowing system to fail in a way that is not catastrophic, as well as recover rapidly.	- **Focus** equally on provision of short-term safeguards and resources that prevent catastrophic failure and maintain certain service levels for users, as well as strategies for long-term recovery of system.
Adaptive Cycles at multiple scales (Ecological and Economic Resilience)	- **Consider** the interactive dynamics of the transport system at different spatio-temporal and geopolitical scales, and assess factors that increase or decrease resilience, capital stocks and flexibility.	- **Capture** institutional learning from past experiences and share lessons learned including effective strategies and resources. - **Determine** and make use of federal-level and state/regional-level partnerships that promote inter-jurisdictional cooperation.

Besides these the concepts identified in Table 2.5, other interesting lessons can be gleaned from also applying the following concepts to the transportation system: social capital (social resilience), deliberate transformations (social resilience), panarchy and hysteresis (ecological resilience), which can be used to describe the interactive dynamics of a system which exists at multiple scales (Gunderson and Holling, 2002). Similarly, transportation systems exist at multiple scales. Three of the common geopolitical scales can be described with language from Rose's (2006) work in economic resilience, that is, the *macro*, *meso* and *micro* scales.

The macroscale can be used to describe the highest level of governance in the transportation system. For this context, it refers to the federal or national level. System actors at this level include decision makers in charge of setting and providing support for strategic national direction/agenda. Leadership at this stage is critical as it involves decisions that drive the meso- and micro-scales such as those affecting funding, national goal attainments, or inter-jurisdictional boundaries/barriers (e.g., between DHS/MPOs, DHS/DOTs, DOTs/MPOs, etc.). However, it is fair to state here that leadership executed at the macroscale may also be driven by leadership at the mesoscale and microscale. This is because, in many cases, decisions resulting in policy or regulation at the macro level are a culmination of existing efforts and activity at the two lower levels. Thus, *deliberate transformations* (social resilience) at this level can still have organic roots. As already discussed in the literature, *transformability* can be said to be a fundamental characteristic of resilience. In certain situations of policy failure, environmental crises or even fiscal crises for instance, *transformation*, rather than adaptability, is the key approach to ensure resilience (Olsen et al., 2006). Unlike adaptability which seeks to maintain a system's trajectory by improving certain components, transformation requires that the underlying assumptions behind key state variables or system drivers be questioned and redefined when needed (Hordijk et al., 2014).

Furthermore, the ability to enact radical transformations at the macro level is a tool that is sometimes necessary but rarely used. Although this stream of thought may seem difficult to adopt, decision makers are likely to be successful when they take advantage of windows of opportunity. That is, where "…*a problem is recognized, a solution is available, the political climate makes the time right for change, and the constraints do not prohibit actions*" (Kingdon, 1995). Kingdon (1995) argues that the confluence of problems, solutions, and politics creates a positive environment for significant changes to occur.

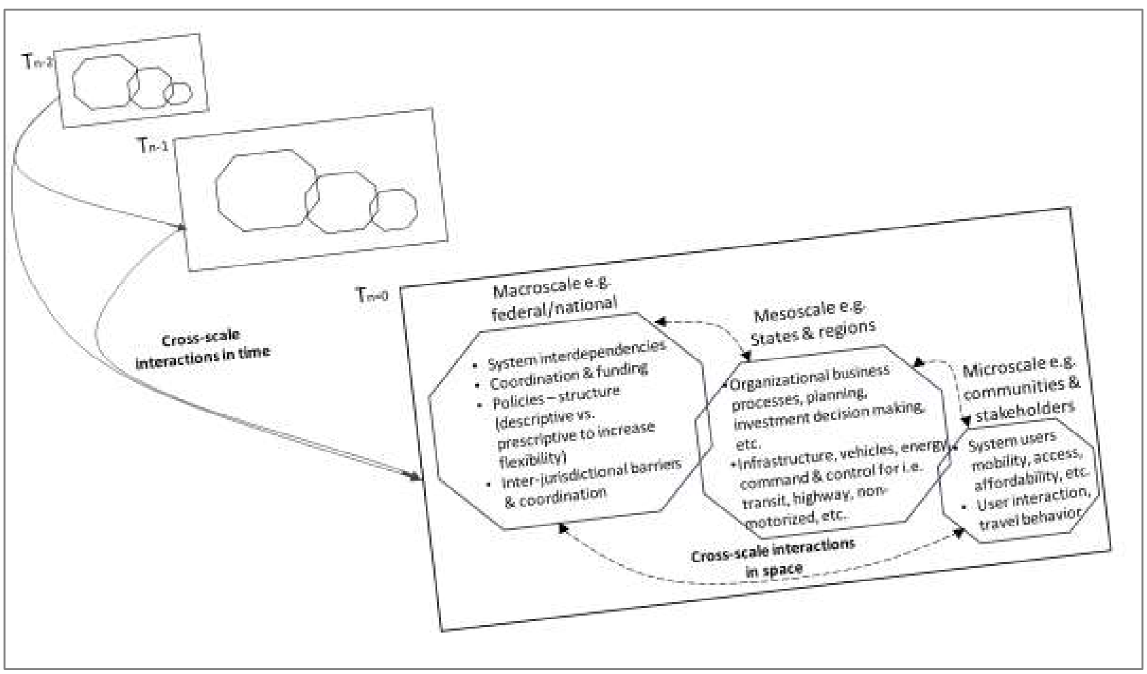

Figure 2.14 Diagrammatic representation of extracted concepts in resilience literature to the transportation system

The Netherlands provides an example of a transformative macroscale intervention. The country's new Delta Committee's[4] approach to adaptation has shifted from being only about 'hydraulic engineering works', to how the entire country is "managed, both physically and administratively" and to "present an integrated vision for the Netherlands for centuries to come" (Deltacommissie, 2008) that impacts overall community quality of life. Over the decades, there has been a tremendous shift in the program's strategy – from adaptability to transformation. The course of transformation taken up by the Delta Committee is seen as the only means of ensuring persistence due to predicted future sea level rise and fluctuations in river discharge. Now, instead of focusing only on building stronger and higher levees and sea walls to combat the water, the Dutch now embrace the water, and are finding means of working with water. They are "exploring new opportunities that may improve the quality of life of residents, and integrating their flood protection with nature, landscape and urban development" (Deltacommissie, 2008). To learn from the Dutch example, decision makers at the macro level (and in some cases, the meso level) may need to question assumptions underlying the way in which the transport system is planned, designed, operated and maintained.

The second scale that may be identified comprises the state and regional levels, and is the primary focus of this dissertation. The mesoscale includes state and regional agencies such as departments of transportation (DOTs), metropolitan planning organizations (MPOs), transit agencies, local governments, etc. This level is critical for the implementation of adaptability and transformation. Transport agencies serve as the owners and operators of transport infrastructure and are thus, the first point of contact for strengthening the system's

[4] The committee that heads the country's flood protection program

infrastructure (which consists of infrastructure, vehicles, energy supply, and command and control). In addition to ensuring physical resilience, this level can also initiate deliberate transformations in terms of enhancing business processes by exploring answers to the following questions: When is a radical transformation a better option than adaptability? Have there been missed windows of opportunity in past? What were the consequences? What strategies can we use to ensure that future windows of opportunity are fully taken advantage of?

In addition, meso level actors may also work toward taking better advantage of social capital: intentionally harnessing social capital can be done through formal networks that already exist in such institutions. The response to and recovery from extreme events primarily depends on the processes in place and the people that implement them. If the social capital in institutions are considered as assets in asset management practice, then this capital would be subject to performance measurement and management. This could be done through assessing the social network performance at agencies such as DOTs (both with respect to internal and external stakeholders), and tracking its performance and evolution over time. When this is done, organizational network structures that contribute to effectively harnessing social capital, as well as those that inhibit system resilience can be identified and improved. Similarly, collaborative networks, whether emergent, self-organizing or ad-hoc, play an important role in system resilience. Collaborations between transport agencies and emergency management groups (local, state & federal), as well as local and regional planning entities, etc., foster the environment for effective communication by facilitating information flows and sharing. Such an environment also allows collaborators to brainstorm creative solutions to problems by bringing together "nodes of expertise of significance" (Olsson et al., 2006). For example, transit agencies can work with emergency management agencies to better coordinate the transport of transit dependent individuals during evacuations.

The third and final scale that may be identified is the microscale, which consists of communities and stakeholder groups that directly consume services provided by the transportation system. The behavior of system actors at this level with respect to transport system interactions should guide the design and development of resilience strategies. Building social capital using elements of social resilience, that is, adaptive, coping and participative capacity, will strengthen the overall system during crises. According to Lorenz (2010), each social system (group) is inherently linked to other social systems/groups, and thus, enhancing one social group's participative capacity, inevitably diminishes another's participative capacity. Thus, equity becomes an important factor when considering social resilience since power inequalities hinder the achievement of social resilience. Lastly, micro level resilience can be enhanced through developing social capital within pre-existing groups, communities and individuals. According to the literature, this may be accomplished through (1) taking advantage of existing capital within networks, and (2) building more capital through interactions/interventions from the macro and meso scales (Lucini, 2013; Adger, 2000).

2.5.1.1 Cross-Scale Interactions in Space & Time

Drawing on the concepts of panarchy and hysteresis, cross-scale interactions within the transport system can also be examined. As stated previously, panarchy describes the interactive dynamics of a set of hierarchical systems. Hysteresis, as used in economics literature, describes what Setterfield (2010) calls *selective memory path dependence*, where a few selected events in the system's past, permanently affect the system's future path and output. Figure 4.1 represents this concept through the interactions between the three levels, and asserts that these cross-scale interactions in time and space play a vital role in system resilience.

First, in terms of the influence and impacts across scales, larger scales affect smaller ones in ways that are usually lasting (Simme and Martin, 2010). For example, 2012's MAP-21 establishes a performance-based framework that transportation agencies at the state, metropolitan and local levels are required to adhere to. Second, the smaller scales also affect larger ones, and per Simmie and Martin (2010), this is usually during the release phase (of the adaptive cycle) i.e., the phase in which a major disruption or event occurs that causes network connections and regulations to break down, resources to seep out of the system, and resilience to be is truly tested. For instance, a community whose social values are gradually shifting in terms of sustainability and environmental preservation, through advocacy, may be able to initiate a deliberate transformation at the micro level. Although this transformation may be slow, persistent advocacy for more sustainable forms of transport, e.g., bike and pedestrian infrastructure, or use of alternative fuels, may affect decisions of transport agencies or local governments. This change in values by the system users may cause infrastructure owners to also shift towards providing sustainable transportation solutions over time.

Using the concepts of hysteresis and interactions in time, decision makers at all levels can strategically identify factors from past events, whether directly or indirectly, that shaped the current trajectory (desirable or not) of the system. Perhaps, a past funding crisis may have led to certain tasks in the maintenance program being suspended. As a result, the occurrence of an event that should not have caused a catastrophic failure based on the system's prior trajectory resulted in one. Time interactions also mean that decision makers, especially at the meso and micro levels, benefit from prioritizing the maintenance and management of institutional memory. More likely than not during disasters, standard operating procedures are either nonexistent or become difficult to follow. In such cases, in addition to the physical resilience of the system, individuals and groups tap into their social capital (e.g. skills, knowledge, experience, networks, etc.) to ensure that the system does not degrade further and to restore it as rapidly as possible. However, since social capital also resides in the individuals or groups of individuals in the organization or agency, the resilience of the system may be reduced when such people leave. By understanding that system interactions occur in space, as well as in time, agencies can start to work towards enhanced strategies for retaining institutional memory.

2.5.2 Gaps and Opportunities: Key Concepts and Implications for Transport Resilience

This section identifies gaps in current approaches to transport system resilience and opportunities for enhancing the capacity of transport systems to produce more resilient outcomes. After reviewing resilience literature in transportation systems as well as systems in other fields of study, certain key concepts emerge and their implications for transportation system resilience are discussed in the subsequent sections.

2.5.2.1 Gaps: Single Equilibrium Resilience No Longer Suffices

i. The increasing frequency and intensity of natural hazards make it impractical to try to engineer ourselves out of risk. The necessary infrastructure renewal needed to create improved design standards to address the increasing frequency and strength of natural hazards would be nearly impossible to meet. Take the Netherlands for example, after the 1953 North Sea Flooding that led to about 1,800 fatalities, the country began to greatly enhance their flood defenses (i.e., increasing levee and dike heights) and sought to predict and control nature ("North Sea Flood", 2017). However, after another round of devastating floods in the 1990s, a paradigm shift in flood protection occurred. This birthed the concept of "room for rivers" where the emphasis was no longer placed on constricting water, but rather, learning to live with water. Learning from the Dutch example, the intent of this research is to create a conceptual framework that shifts our thinking and views from a single equilibrium resilience approach toward generating multiple equilibria that involve the multiple capital associated with system sustainability.

ii. For the most vulnerable populations, returning to an original equilibrium state is not always the most desirable outcome as the original state in many cases may not have met their needs. For example, during Hurricane Katrina in 2005, although public officials were aware that approximately 100,000 residents of the City of New Orleans had no means of personal transportation, evacuation plans were inequitably focused on automobile evacuation (New Orleans, 2005). City buses set up to transport people to emergency shelters were unreliable, and neither public buses from the New Orleans Regional Transit Authority (RTA), nor trains were deployed to help evacuate transit-dependent residents from the city (Murdock, 2005). Consequently, transit-dependent members of the community who wanted to leave the city had to pay for commercial services – “a major barrier to many low-income residents” (Litman, 2006). The transport system failure experienced was a result of the homogenous treatment of system users. The disparateness of modal access and socioeconomic status of transport system users was overlooked contributing to the subsequent transport system failure. Returning to this original state, is therefore not desirable.

2.5.2.2 Opportunities: From Single Equilibrium to Multiple Equilibria

i. Consideration the aforementioned points, this research seeks to explore and identify benefits of shifting the current approach to transportation resilience from Pimm (1984; 1991) to Holling (1973) thinking. There is practical value in considering and adopting a multi-equilibrium approach from ecological resilience thinking with shifting regimes; developing step-up regimes that may be accessed either through *forced* or *deliberate* action (Folke et al., 2010), and planning for such regimes to enable them to be accessed at the right time (either forcibly or deliberately).
ii. The concepts of stability and regimes can be used as a paradigm for a system maturing in resiliency where the objective will be to determine what types and relative levels of capital (institutional, organizational, financial, technical) can constitute maturing regimes for system resiliency and explore strategies for attaining these regimes.

iii. The concept of the next attainable regime (either proactively/deliberately) with some institutional intervention or reactively (forcibly) after some natural or man-made intervention.

iii. Considering the experience of international best practices such as the Netherlands, and considering system resilience failures in the U.S., we can hypothesize that as agencies mature in their dealings with hazards, they will naturally move from purely technical to sociotechnical approaches. Thus, to investigate this, selected agencies can be surveyed to explore the extent to which their experiences bear up this, and to study their evolution in order to extract an evolving maturity process in handling hazards and building transportation system resilience capacity using sociotechnical approaches.

iv. In expanding the engineering resilience approach, the intent is to move toward an approach that formally incorporates human/social capital elements together with the technical, focusing on organizational, institutional and financial capital.

CHAPTER 3. SURVEY RESULTS &ANALYSIS

3.1 Introduction

This chapter presents an overview of the survey used as the data collection instrument and analyzes the results in a case study format. The purpose of the survey, as stated earlier, is to collect data on existing resilience efforts being implemented by transportation agencies. Data from the survey results will then be drawn from to inform the development of the framework premised on the foundational concepts of multiple equilibria, shifting regimes and evolution toward sociotechnical resilience capacity building.

The chapter begins by providing an overview of the agencies surveyed and the survey questions used in the research. This is followed by an analysis of the survey results combined with data collected from literature searches are then presented in a case study format. Finally, the chapter ends with a synthesis of the case studies highlighting strengths, weaknesses, opportunities and threats to transport resilience efforts being implemented by the agencies surveyed.

3.2 Overview of Agencies

To determine the critical factors for developing the socio-technical systems resilience framework, a case study analysis was conducted. A purposive sample survey was conducted to collect information on agency approaches for building resilience capacity. In some cases, the survey yielded little information, therefore document reviews were conducted to supplement the responses and create a better picture for resilience within the state or region. Transportation agencies targeted were departments of transportation

(DOTs) and metropolitan planning organizations (MPOs). In addition, some local government agencies and associations of local government agencies were also included to provide a holistic view of transportation resilience by including stakeholders that oversee planning, providing and maintaining the transportation system.

Fourteen agencies were contacted to partake in the survey. Out of this number, 11 agencies responded (78.5% response rate). The 11 responding agencies are in the following states: California, Colorado, Florida, Iowa, Louisiana, Maryland, Massachusetts, Texas and Oregon (shown in Figure 3.1). The three agencies that could not respond are in New York, California and Louisiana. As discussed in Chapter 1, agencies selected to participate were chosen to provide a range of experiences across the US's various geographic regions. Table 3.1 provides the details of the agency representatives including names, agency names and job titles.

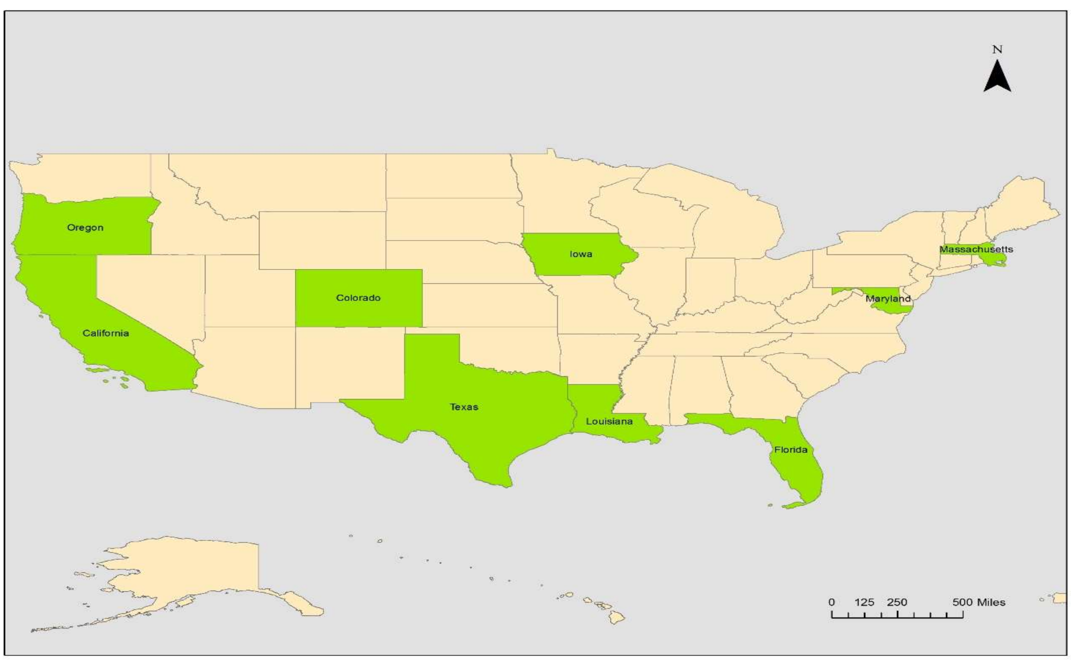

Figure 3.1 States represented in resilience planning survey

Table 3.1 Details of responding agencies

State	Survey Contact	Agency	Job Title
California	Stephanie Hom	Metropolitan Transportation Commission (MTC)	Transportation Planner
	Michael Germeraad	Association of Bay Area Governments (ABAG)	Resilience Planner
Colorado	Will Johnson	Colorado Department of Transportation (CDOT)	Performance and Asset Management Branch Manager
Florida	Dennis Smith	Florida Department of Transportation (DOT)	Growth Management Coordinator
	James Cromar,	Broward MPO	Director of Planning
Iowa	Tamara Nicholson	Iowa Department of Transportation	Office Director, Location and Environment
Louisiana	Meredith Soniat	New Orleans Regional Planning Commission (NORPC)	Sustainability Planner
Maryland	Elizabeth Habic	Maryland State Highway Authority (MSHA)	Climate Change Program Manager
Massachusetts	Steven Miller	Massachusetts Department of Transportation (MassDOT)	Supervisor, Environmental Management and Sustainability
Oregon	Bruce Johnson	Oregon Department of Transportation (ODOT)	State Bridge Engineer
Texas	Jory Dille	North Central Texas Council of Governments (NCTCOG)	Senior Transportation Planner

3.3 **Overview of Survey Questions**

Survey questions were designed to capture a broad range of resilience planning factors in transportation systems based on the literature review. Thus, the survey was categorized under four main headings: technical capital (includes built), organizational capital, institutional capital and financial capital. The four types of capital were informed by the Performance Mosaic developed by Amekudzi-Kennedy (2016) which describes different types of capital that drive performance in infrastructure systems as shown in Figure 3.2. The categories are described below.

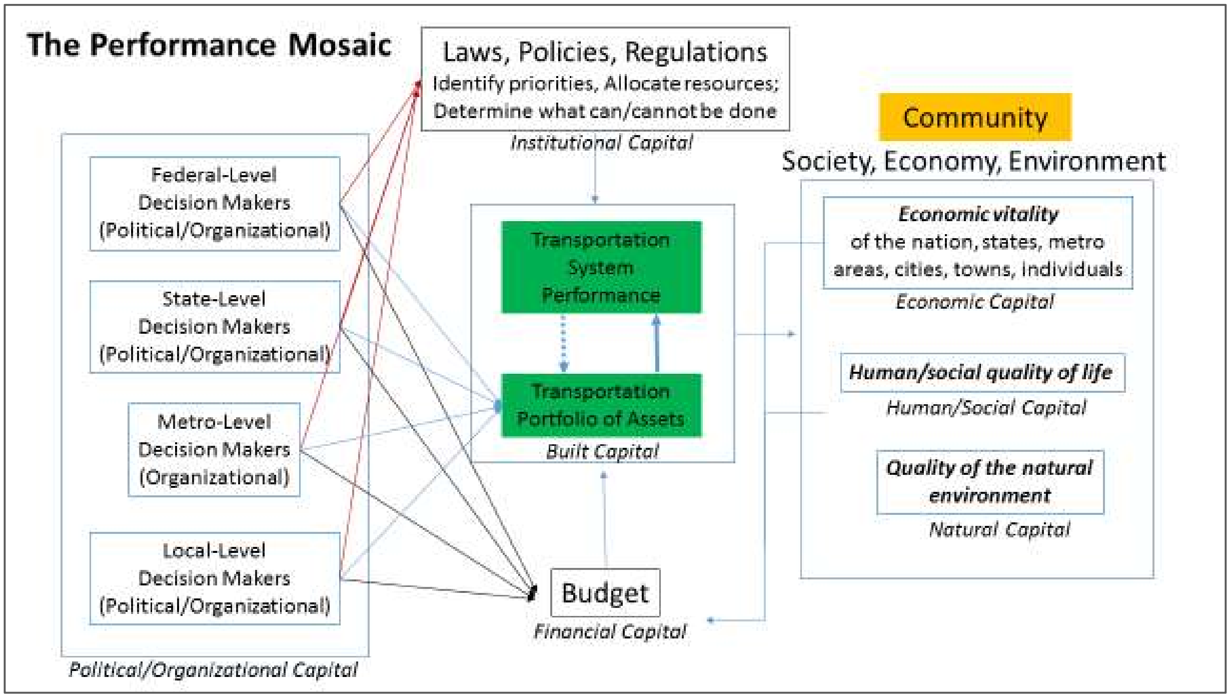

Figure 3.2 The Performance Mosaic

3.3.1 Institutional Capital

Institutions refer to the structures, mechanisms or tools put in place to govern behavior of a group of people such as a society or community. In this context therefore, institutional capital refers to the laws, policies, regulations, standards or codes put in place to guide the provision and management of transportation systems. Having institutional capital that promotes resilience is necessary in all stages of an infrastructure's lifecycle. For example, the planning stage may include regulations that guide the steps to be followed (e.g., requiring a risk analysis for potential climate change impacts) for new infrastructure projects. Other examples include the National Protection Policy Directive (NPPD) signed into law in 2013 by President Obama that calls for owners of critical public infrastructure to ensure the safety and resilience of their infrastructure, and the FAST ACT, the 2015 national surface transportation re-authorization which calls for more effort towards enhancing the resilience of transportation infrastructure.

3.3.2 **Organizational Capital**

In simple terms, organizational capital refers to the processes and practices that enable an organization to fulfill its purpose. It is an intangible resource that, when leveraged, provides competitive advantage to organizations. That is, such capital ultimately determines the quality and extent of service provision by organizations as it "enables both tangible and intangible resources … to be productive" (Lev et al., 2016). According to Lev et al., (2016), organizational capital comprises four non-mutually exclusive elements: human capital, processes and practices, knowledge and expertise, and lastly, values and norms. The intangible nature of this type of capital makes it difficult to quantify. Therefore, for the purposes of this research, focus is placed on attempting to address the first three elements (human capital, processes and practices, and knowledge and expertise) and how they influence resilience capacity.

3.3.3 **Technical Capital**

A subset of organizational capital, this research explicitly pulls out technical capital to refer to the technical knowledge and expertise required to enhance the resilience of an agency's portfolio of physical assets. Examples of such knowledge and expertise include the technical capabilities agency staff possess to perform risk analyses for system components or agency infrastructure monitoring capabilities that enhance emergency response.

3.3.4 **Financial Capital**

Financial capital, in this context, refers to the financial resources available to transportation agencies to pursue activities that enhance system resilience. It also includes how existing resources are prioritized in order to reform existing practices or pursue new initiatives directed toward system resilience.

3.4 **Analysis of Survey Responses**

3.4.1 **Colorado DOT**

3.4.1.1 Background

The state of Colorado is the 8th largest state in the US in terms of land area covering approximately 103, 718 sq. miles and a 2016 population estimate of about 5.5 million. The Colorado Department of Transportation (CDOT) manages over 23,000 total lane miles of highway and 3,447 bridges, in addition to overseeing 35 mountain passes and monitoring over half the avalanche paths in the state (CDOT, n.d.a). The agency has an annual budget of approximately 1.4 billion and also manages federal grants for transit operators and airports to the tune of about \$11 million and \$41 million respectively (CDOT, n.d.a). The main transportation planning stakeholders in the state include its 15 Regional Planning Commissions (comprising 10 rural Transportation Planning Regions and five Metropolitan Planning Organizations), the Transit and Rail Advisory Committee (TRAC), and the Freight Advisory Council (FAC) (CDOT, n.d.b).

3.4.1.2 Survey Responses

The Performance and Asset Management Branch Manager answered survey questions for the Colorado Department of Transportation (CDOT). With over 10 years of experience at the agency, Mr. Johnson is one of two agency employees in charge of resiliency efforts at the agency. He has also seen an evolution in the way the agency addresses system resilience over the last decade as a result of the impact of a catastrophic event. For Colorado DOT, resilience is *the ability to withstand*.

3.4.1.2.1 Institutional Capital

For the agency, the FAST ACT provisions for resilience will hopefully guide its direction in future initiatives. Survey answers point toward conducting assessments of transportation assets and looking at the role of resilience in project selection and prioritization.

3.4.1.2.2 Organizational Capital

The agency does not have strategic objectives or goals specific to resilience; however, it has an active Geohazard Management Program. Also through CDOT's Geohazard Management Plan, the agency monitors and reports on program accomplishments. Threats identified under this program include landslides, sinkholes, floods and erosion, etc., and the program involves corridor risk reduction as well as emergency response and hazard management. The plan also uses asset management practices for resource allocation.

CDOT is also currently undergoing change in the area of decision making. For example, the agency is in the process of developing a multi-objective decision analysis process where resilience is being looked at as a potential measure. When asked about how the agency manages institutional learning with regards to disaster/extreme event planning and management, Mr. Johnson stated that the agency is in the process of assessing training needs.

In terms of collaborations, the agency helps coordinate the development of the state's Emergency Management Plan. The Colorado Flood Recovery Office and the Office of Emergency Management have both been useful partnerships in the agency's efforts.

3.4.1.2.3 Financial Capital

A process is underdevelopment that reflects the desire to build system resilience through agency budget allocations. However, CDOT is the only DOT among those reviewed in this research to acquire state funding for its resilience assessment. The State's Transportation Commission (11 member governor appointed board of commissioners) approved funding for the I-70 pilot project in July 2016. The I-70 pilot project's goal is to "quantify and improve system resilience in advance of future events to better prepare CDOT and reduce future losses" (Kemp et al., 2016). The agency hopes that this project will help inform how it complies with MAP-21's mandate, which requires agencies to develop and apply risk-based asset management processes. This comes in the wake of significant damage of CDOT infrastructure from "floods, fire, rockfall and other physical events" (Kemp et al., 2016).

Also worth noting is the agency's new approach to risk and resilience which outlines two kinds of replacement of assets damaged during unplanned disruptions including disasters: in-kind and betterment replacement. In-kind replacement is expected to be paid for by federal funds whereas betterment replacement will have to be funded by the agency.

3.4.1.2.4 Technical Capital

According to the survey responses, Colorado's transport system has experienced multiple major disasters over the last two decades (more than 10). Threats faced by the state's transportation system include rockfall, flooding, extreme heat/drought, and wildfire. However, the agency has not yet conducted any risk or vulnerability assessments, but is planning on doing so in the future. CDOT is currently working with Applied Engineering Management (AEM) Corporation to develop a new risk and resilience approach to be used with the new Federal Emergency Response (ER) Manual.

As stated earlier, CDOT is working on conducting risk and resiliency assessment pilot on its I-70 corridor. The pilot study will utilize a method that was already used on the Glenwood Springs rockfall event and was developed as part of the Flood Recovery Program. For the Glenwood Springs event, it was used in an analysis of mitigation measures that could be potentially implemented on that corridor. The analysis approach, developed with Applied Engineering Management (AEM) involves the following steps:

i. Developing an inventory of assets on the corridor
ii. Calculating the probability of different threats impacting those selected assets
iii. Estimating the resulting damage
iv. Identifying assets most critical to system operations
v. Developing and recommending improvement strategies which could include alternate maintenance or adapting assets to identified threats.

3.4.1.3 Summary

Colorado DOT seems to have a good foundation for developing mature resilience practices. By having an active rockfall hazard management program, the agency is already well versed with risk management. Incorporating this into the agency's broader asset management program will be an effective way to begin strategically planning for resilience. For example, using rockfall hazards as a starting point, the agency can broadly explore what resilience to rockfall hazards means to the entire system. CDOT can identify different types of agency capital that can build resilience capacity and help fulfil the program's goals of risk reduction, emergency response and hazard management. We also see some elements of movement toward a sociotechnical approach in that the agency is developing a multi-objective decision making method that may incorporate resiliency as a criterion.

In terms of financial and technical capital, the CDOT approach provides interesting information about funding. By identifying the two types of replacement, i.e., in-kind and betterment, the agency is better placed to better respond to crises. For example, in a situation where system vulnerabilities are well understood, the occurrence of a disaster, say a bridge deck failing, provides the opportunity for betterment as long as there has been forethought. In the absence of this kind of proactivity, the pressure to replace or repair infrastructure in the least amount of time greatly overshadows the need to enhance resilience capacity. Thus, in many cases, infrastructure is replaced to its prior state, which may not necessarily be the most desirable state. To conclude, CDOT listed three statements as failings, shortcomings or ineffective practices to avoid. They are as follows:

i. Approaching resilience strictly as a standards and engineering issue - not a planning issue.
ii. Not funding assets based on criticality.
iii. Not funding redundant corridors.

3.4.2 **Florida DOT & Broward MPO**

3.4.2.1 Background

The State of Florida has the nation's second longest coastline with low-lying and highly developed coastal areas (Cambridge Systematics, 2015). As such, the state's transportation infrastructure has been impacted by repeated flooding from severe storms and storm surge. In the last decade alone, Florida has experienced 12 FEMA declared disasters caused by hurricanes, severe storms, tropical storms, tornadoes and flooding (FEMA, n.d.).

3.4.2.2 Survey Responses

Planning, designing, and operating our infrastructure to ensure it is able to withstand and bounce back from physical threats – including natural hazards."
-Dennis Smith, FDOT

Responses from Florida were provided by the Director of Planning at the Broward MPO and the Growth Management Coordinator from the Florida Department of Transportation. The Director of Planning is one of two agency employees in charge of resiliency efforts at the MPO.

3.4.2.2.1 Institutional and Organizational Capital

Both the MPO and DOT have seen changes in their approaches to resiliency. The evolution came about as a result of three factors: (1) impact of a catastrophic event, (2) greater awareness of threats, and (3) greater understanding of system resilience. For FDOT, this change is reflected in the recent update to the Florida Transportation Plan which now includes a goal to support agile, resilient, and quality transportation infrastructure. Florida DOT is the only agency represented in the survey to use a clear strategic approach for addressing transportation resilience. The plan includes the following objectives:

- "Adapt transportation infrastructure and technologies to meet changing customer needs
- Increase the resiliency of infrastructure to risks, including extreme weather and other environmental conditions" **(**FDOT, 2015)

The stated objectives are also accompanied by a set of strategies. Examples of these strategies are provided below.

- Innovation: Retrofitting, adapting or providing more diversity in areas where critical infrastructure is located to "reduce vulnerability to extreme weather and other environmental conditions" (FDOT, 2015)
- Collaboration: "Coordinate with local governments when making major infrastructure investment and development decisions to consider the risks of investing in areas vulnerable to extreme weather, flood risks, and other environmental conditions, including consideration of areas identified as priorities

for mitigation of risks or adaptation of infrastructure in regional and local plans" (FDOT, 2015).

- Data & Processes: "Implement FDOT's Transportation Asset Management Plan and expand this plan over time to include all modes; Encourage local governments and other modal providers to develop asset management plans; Incorporate the risks of extreme weather and other environmental conditions into long-range planning, project development, design, operations, and asset management decisions for all modes" (FDOT, 2015).

Finally, bridge and pavement condition (and "other infrastructure") are the selected indicators for assessing resilience according to the strategic plan. The FTP's Implementation Group is required to develop benchmarks, which will also include resilience benchmarks, to be implemented within a 5-25-year timeframe.

For Broward MPO, survey responses suggest that strategically planning for resilience may become a reality in order to comply with FAST ACT provisions[5]. This may begin as early as 2017 as part of the 2045 Long Range Transportation Plan Update. According to the MPO representative, there is currently an attempt to use agency's long-range planning to try to minimize the range of future impacts. The MPO representative also stated that no major changes have occurred in decision making, but the new information is expected in the upcoming year.

[5] The 2015 FAST ACT does not actually require agencies to strategically plan for resilience. It only requires agencies to include resilience considerations in planning.

Having said that, Broward County developed a Climate Action Plan published in 2015 that lists several action items. Among the transportation-related actions is one directed at "coordinating transportation-related adaptation policies across jurisdictional boundaries and ensuring alignment amongst broader planning and plan implementation efforts" (Broward County, 2015).

A resilient system "has the capacity to accommodate the impacts of extreme weather/climatic events and can return to functionality in a timely manner" - James Cromar, Broward MPO.

With regards to collaboration and resilience efforts in southeast Florida, partnerships between Broward MPO, FDOT and other municipal partners have been helpful in the region's resiliency efforts. Currently, Southeast Florida, being a highly vulnerable area may be leading the way for state level efforts. Per the survey responses, FDOT supports local government resiliency planning initiatives through its district offices. Broward MPO staff also actively pursue opportunities to share the agency's experiences through peer exchanges, webinars, ribbon-cutting ceremonies and technical meetings. According to them, spreading the word helps to "expand the network of the informed".

When asked about managing institutional learning related to disaster/extreme events, the survey respondent referred to FDOT's in-house Emergency Management Office. The office is part of the Florida State Emergency Response Team (SERT) and leads Emergency Support Function (ESF) 1 & 3 at the State EOC. The purpose of the emergency support function is to "provide, in a coordinated manner, the resources (human, technical, equipment, facility, materials and supplies) of member agencies to support emergency transportation needs during an emergency or disaster …" (ESF, 2010). According to the

FDOT response, exercises and training are offered at the Emergency Management Office to support response efforts. As for the MPO, the following quote by the agency representative shows how the agency seems to be learning from the experience the importance of strengthening organizational capital for resilience efforts.

"In several cases, the intergovernmental coordination turned out to be based on individuals more than on institutions. Specifically, there were agency staff on technical committees who participated based on personal interest and not on assigned roles. When these individuals moved to new organizations, the agencies they previously represented did not consistently assign replacement staff to take their places. This left us in a scramble too often."

3.4.2.2.2 Technical Capital

Florida's transport system has been impacted by at least one major disaster in the last decade and about four more within the period of 1996-2005 according to the survey responses. As a result, two separate studies that included the Broward, Miami-Dade, Monroe, and Palm Beach Counties, as well as Hillsborough County. Both studies were supported by the FHWA and sought to assess the impact of climate change on the regional transport network. Threats identified in the assessment were sea level rise (SLR), storm surge, extreme precipitation and related flooding. The assessment covered transportation assets only, i.e., highways, railroads, and bridges.

Both studies used the Sea Level Scenario Sketch Planning Tool developed by University of Florida's GeoPlan Center. The tool uses data on sea level trends and tidal datums from NOAA and U.S. Army Corps of Engineers methods. Transportation network data from FDOT and LiDAR (Light Detection and Ranging) elevation data were also used. Results from the assessment provided the study team with relative costs of adaptation for sample strategies on the six facilities assessed.

Broward County plans on conducting a follow up study that will focus on county and local roads only. At Hillsborough County, results from the study were incorporated into outreach efforts for the region's 2040 transportation plan update.

3.4.2.2.3 Financial Capital

Broward MPO is in the process of discussing how resiliency may become a project prioritization criterion along with the more traditional criteria such as safety, congestion, mobility, equity, etc. In the event of unplanned disruptions, the MPO finds emergency funds which sometimes leads to delays for other projects.

3.4.2.3 Summary

The Southeast Florida region has already faced many of the dire impacts of climate change. Although this has stressed the region's infrastructure and economy among others, the MPO representative stated in the survey that this has resulted in many political conflicts being side-stepped and more focus placed on resolving existing issues. Thus, we see a particularly strategic approach with the Florida transportation agencies. The first feature that shows an evolution towards a sociotechnical approach is FDOT's incorporation of goals and objectives for extreme weather resilience. This approach goes beyond asset specific adaptation goals, and more broadly defines what a resilient system looks like for Florida, that is a shift from asset-based to system-based resilience. Additionally, objectives and strategies developed are broad enough to be implemented across different asset types as well as modes. The use of **existing structures** (i.e., State Transportation Plan) **to articulate the agency's agenda for resilience**. In terms of human capital, formation of the FTP Implementation Group meant to handle both short and long term implementation of the plan shows institutionalization of the resilience thinking at the agency. This is because, the group will handle resilience goals and objectives in addition to all goals in the plan. This approach also enables the group to strategically plan implementation in a way that maximizes the co-benefits of strategies that build resilience capacity and those directed at other goals. We still see remnants of the technocentric approach in this case and opportunities to further embrace sociotechnical thinking in the selected indicators for system resilience. The selected indicators, bridge and pavement condition, are actually reliability metrics. Conflating reliability and resilience in itself is a risk. The risk being that, improving reliability does not always improve resilience. In addition, reliability improvements do not get to the heart of resilience, which focuses on a system's response after a disruption.

For the MPO, we see systematic progression in building institutional and organizational capital for climate change resilience. In the region's Climate Action Plan, we see an objective to coordinate transportation policies across the different jurisdictional boundaries to ensure alignment with broader goals. This high-level approach ensures that efforts in different sectors are not duplicated, or worse, in opposition to each other. The Broward MPO also stated a desire to identify and incorporate resilience capacity considerations into its Long-Range Transportation Plan (LRTP) update. The MPO's experience with building resilience capacity also seems to have showed firsthand the importance of institutionalizing various processes. Hopefully, the agency can build on the lessons learned and continue to make progress in this area. Finally, the MPO is working towards improved financial capital as it is thinking of how best to make project resiliency a prioritization criterion that is not viewed as a separate objective, but included in the existing process as part of multiple objectives.

3.4.3 **Iowa DOT**

3.4.3.1 Background

Iowa's public road system is ranked 13th highest in the U.S. in terms of mileage with over 114,000 lane miles of roads. The Iowa DOT manages eight percent of the total roads in the system, but this number accounted for 62% of all vehicular traffic in 2012. In 2008, Iowa suffered from catastrophic floods that resulted in 85 of its 99 counties being designated as federal disasters. The flooding resulted in about $19 million in damages to interstates, U.S. routes and state routes, and an additional $43 million to county roads in 92 counties (ASCE Iowa, 2015). Figures 3.3-3.5 show Iowa DOT photographs of road damage from the 2008 floods. The year 2008 is not the only calendar year Iowans remember as catastrophic: 1993, 2010, and 2011 also came with significant catastrophic floods (ASCE Iowa, 2015; EPA, 2011). The 2011 floods caused an estimated $46 million in total damages (ASCE Iowa, 2015).

Figure 3.3 Photograph showing I-80 overtopping caused by floods. Source: FHWA (2015)

Figure 3.4 IA 1 Flood damage by Cedar River. Source: FHWA (2015)

Figure 3.5 I-80 overtopping at Cedar River. Source: FHWA (2015).

3.4.3.2 Survey Responses

Tammy Nicholson is the Office Director for Location and Environment at Iowa DOT. Ms. Nicholson has been at the agency for over 10 years and heads a team of five that head agency initiatives related to resilience in addition to their other responsibilities. According to Ms. Nicholson, Iowa DOT is in the early stages of defining what resilience means to the agency. At this stage, the agency plans to evaluate the impacts of projects on the climate and the impacts of climate change and extreme weather on its projects to identify infrastructure vulnerabilities. Currently, the agency is involved in assessing the vulnerability of bridge and highway assets to extreme weather events. IDOT plans to expand this analysis to other stages of the infrastructure lifecycle from *planning* through to *operations*. Based on the survey responses, resilience champions are mainly responsible for the agency's current direction. Other factors that also led to this change are (i) impact of catastrophic event, (ii) greater awareness of threats and (iii) greater understanding of system resilience.

3.4.3.2.1 Institutional and Organizational Capital

Iowa DOT has not yet addressed system resilience in its strategic planning. However, the agency is in the process of forming a Resiliency and Sustainability Team to formally address resiliency issues. The team, which is currently informal, will also work on addressing institutional learning with regards to disaster/extreme event planning and management. At the state level, a number of flood mitigation initiatives can be identified. In 2012, Iowa's General Assembly established the Iowa Flood Mitigation Board which is responsible for creating the state's Flood Mitigation Program. The Flood Mitigation

Program also serves as a funding source for public entities who wish to pursue flood mitigation projects. The state is also one of 12 states nationwide recognized by FEMA to have an Enhanced State Mitigation Plan, meaning that the plan is comprehensive enough to manage increased funding to reach mitigation goals (State of Iowa, n.d.).

In terms of collaboration**,** Iowa DOT is exploring how its efforts can fit into a larger state effort by collaborating with agencies such as the Department of Agriculture and the Department of Natural Resources.

3.4.3.2.2 Technical Capital

Like other states that participated in FHWA's resilience pilots, Iowa DOT used a risk-based approach in its first infrastructure vulnerability assessment. The assessment sought to identify extreme precipitation and flooding vulnerabilities to the agency's bridge and highway assets within two river basins in the state (South Skunk River and Cedar River). No interdependencies were covered in this study. Objectives of the analysis were to:

- "Collect information, monitor, predict, and evaluate the performance of existing highway structures and roadway embankments with respect to flood inundation during severe rainfall events.
- Determine relevant precipitation metrics in climate projections for transportation infrastructure calculations.
- Quantify the sensitivity of simulated streamflow to projected precipitation change.
- Conduct an assessment of bridge vulnerability to simulated streamflow change using an integrated asset database and bridge-monitoring software application called BridgeWatch.

- Provide adaptation strategies for climate change impacts and review design policy to incorporate climate change." (Anderson et al., 2015).

Table 3.2 provides a summary of the agency's vulnerability assessment methodology along with a summary of study's findings.

Iowa DOT hopes to integrate findings from its vulnerability study into its BridgeWatch Program. The agency also hopes to create real time alerts that maintenance staff can use from a combination of the BridgeWatch data, USGS gauge data and Next-Generation Radar data. Iowa DOT hopes to conduct further vulnerability analyses on other agency assets and explore policy guidelines for bridge scour assessments (for floods with a return period of more than 500 years). Lastly, the agency may also explore incorporating climate considerations in policy analysis and cost-benefit analysis.

3.4.3.2.3 Financial Capital

Iowa DOT is in the process of developing criteria for project prioritization that would include project resiliency. Additionally, assets affected by extreme events are repaired or renewed using ER funding form FHWA.

3.4.3.3 Summary

Iowa DOT has suffered significant asset damage and financial loss because of past flooding. We also see that the agency's approach to resilience differs slightly from other states, in that, the agency seems to be giving systematic thought to how to build resilience capacity and shows evidence of developing in a sociotechnical way.

Table 3.2 Summary table showing summary of Iowa DOT vulnerability assessment methodology

Step	Data/Analysis
Asset Inventory	• Iowa DOT's asset database already contains information for the following bridge characteristics: - "age of the structure, elevation of roads and low beams, critical streamflow thresholds, scour vulnerability, current plan of action when the bridge is threatened by high streamflow, soils information, past damage from extreme streamflow, and maintenance records" (Anderson et al., 2015). • The project team further developed streamflow rating curves using data from USGS.
Climate Data	• Annual peak flow data – USGS • Historic data – NOAA stage IV precipitation analysis, historic daily precipitation measurements • Streamflow simulation – using downscaled climate models at 22,781 grid points for 1960-2100
Streamflow modeling and Future flood estimation	• CUENCAS hydrological model (river networks analysis tool) • Calculated % of absorbed rainfall and % of runoff • USGS protocol (modified version) used to estimate streamflow quantiles
Credibility analysis	• Analyzed degree of simulation errors for climate model precipitation data • Compared streamflow simulation error to climate change induced streamflow changed predicted
Vulnerability and risk assessment	• Assessed vulnerability of bridges to overtopping and scour • Potential bridge and roadway exposure to high streamflow determined qualitatively
Findings	• Based on analysis of climate impacts, each pilot location's streamflow exposure exceeds current design standards • Increased frequency of highway overtopping and bridge scour projected
Identified adaptation strategies	• Grade raise of 2ft to survive a 200-year flood to be incorporated into planned work for the identified interstate bridges.

Beyond conducting a vulnerability study of agency assets, as seems to be the first step with most agencies, IDOT is also intentionally addressing human capital needs, moving from needing resilience champions to formalizing a team (Resiliency and Sustainability Team) to handle resilience-based issues in the agency. The agency is also giving systematic thought to how to expand resilience considerations to a larger portion of its infrastructure lifecycle, from planning to operations. Thinking about resilience using an infrastructure lifecycle approach provides room to strategically identify capacity building strategies in other capital areas to support infrastructure resilience. We also see sociotechnical resilience thinking in the integrated approach the agency is using by exploring how Iowa DOT's efforts fit into the broader state efforts and thereby working with the Departments of Agriculture and Natural Resources.

Lastly, IDOT also shows the emerging effective practice in terms of financing resilience initiatives (similar to Colorado DOT). In this area, the agency plans to develop a set of project prioritization criteria, which will include resilience in addition to other traditional focus areas such as safety and cost. This approach to building resilience capacity is possibly more financially feasible than identifying alternative sources of funding to "address resilience". This approach is also at a higher level of maturity than efforts to identify separate funding for resiliency initiatives, as it has a better chance of being institutionalized into existing decision making processes. The examples described show a gradual shift from purely an asset adaptation focus to resilience thinking. There is still opportunity for growth. As the agency continues to build capacity in these capital areas, a more strategic approach that is also reflected in IDOT documents such as the TAMP, LRTP and TIP will provide guidance and direction on subsequent steps towards meeting resilience goals in a systematic way.

3.4.4 **Maryland (MD) DOT**

3.4.4.1 Background

The Maryland Department of Transportation comprises the following: State Highway Administration (SHA), MD Transit Administration, Motor Vehicle Administration, MD Port Administration, MD Aviation Administration, MD Transportation Authority and The Secretary's Office. The SHA manages about 17,824 miles of roads and over 2,500 bridges within the state (MDOT, n.d.; NOAA 2017). The survey responses for MDOT were provided by Elizabeth Habic, the Climate Change Program manager at Maryland State Highway Administration (SHA).

3.4.4.2 Survey Responses

3.4.4.2.1 Institutional and Organizational Capital

Champion efforts and political will have been the main drivers behind the agency's resiliency initiative. The main initiative being the inclusion of sea level rise mapping for project review and some decision making at the planning and design stage. There are also ongoing vulnerability assessments aimed at incorporating such considerations into planning and asset management. According to the survey response, implementing resiliency strategies at the agency has not caused major changes in decision making, but it has raised awareness.

The agency does not currently have strategic goals or objectives for addressing system resilience, however, it believes the FAST Act's provisions will reinforce the need to conduct vulnerability assessment and incorporate findings into project planning and design. Passage of Maryland's House Bill 514 is also a driver for resilience efforts as the bill requires annual reporting of agency efforts towards resiliency. Thus, political will and champion efforts are seen to be the main drivers for change in the way MDSHA addresses system resilience.

In terms of planning resources, MDSHA develops or helps coordinate the development of the Emergency Management Plan, Evacuation Plan, Communication Plan and Recovery Plan regarding the state's highway system. The agency has also collaborated with Silver Jackets and the Maryland Commission on Climate Change (MCCC) in its resilience building efforts. Silver Jackets is a national organization that "facilitate[s] collaborative solutions to state flood risk priorities" (Silverjackets, n.d.). Furthermore, the agency shares data and communicates about ongoing efforts with other state and local entities as a way of unifying overall resilience efforts. Lastly, MDSHA manages institutional learning through mentorship and training.

"A system that can handle a certain amount of stress without failure or can bounce back quickly and [possesses] the redundancy to ensure uninterrupted connectivity."–Elizabeth Habic, MDSHA

3.4.4.2.2 Technical Capital

According to MDOT responses, the agency has experienced an average of three natural disasters each decade from 2016 to 1986. The agency in 2014 conducted vulnerability assessment for highways and bridges partially funded by the FHWA. System threats identified included hurricanes, sea level rise (SLR), extreme precipitation and flooding. The assessment also covered agency coordination on dams and water release during an extreme event. The study assessed assets in Anne Arundel and Somerset counties and hoped to achieve the following two objectives:

i. "Assess the vulnerability of SHA's transportation assets to climate variables or stressors;

ii. Review and consider design strategies, best management practices, planning standards, and other ways to support the adoption of adaptive management solutions to improve the resiliency of Maryland's highway system." (FHWA, 2014)

Table 3.3 provides a summary of the assessment methodology used in MDSHA's climate resilience study. The agency hopes to eventually integrate such analyses into its asset management and planning process.

Table 3.3 Summary table showing SHA vulnerability assessment methodology

Process Step	**Data Source/Analysis Type**
Collect **asset information** including historical exposure and impacts	• SHA engineers and planners • Asset data warehouses (SHA and national) • Road closure information • Emergency evacuation route status • Drainage asset databases • Corresponding GIS data
Map climate scenarios for 2050 and 20100	• Partner – Salisbury University Eastern Shore Regional GIS Cooperative (ESRGC) - Light Detection and Ranging (LiDAR) elevation data incorporated - SLR projections - Coastal flooding modelling for storms - Surge inundation maps - Riverine flooding modelling
Identify **asset exposure**	• GIS used for: - SLR projections; sea, lake and overland surges from hurricanes (SLOSH) models (FEMA 100-year floodplain boundaries
Detailed **vulnerability assessment**	• Bridges **– U.S. DOT Vulnerability Assessment Scoring Tool (VAST)**. Provides asset level exposure, sensitivity, adaptive capacity, and preliminary vulnerability score. • Roads – **Hazard Vulnerability Index (HVI)** by SHA and ESRGC. Used to evaluate SLR and flooding vulnerability (based on road functional class, evacuation route designation, and extent and depth of projected flooding). • Small culverts and drainage conveyances – unable to conduct risk assessments due to lack of data.
Adjustment of calculated **scores** and **identification of risk areas**	• VAST Tool indicators ranked (by project team and SHA engineers) resulting in weights that better suit Maryland • VAST and HVI scores mapped to identify high risk areas
Develop site specific **adaptation measures**	• Further detailed assessments may be need to be carried out • Evaluation of resiliency, costs and environmental impacts of adaptation alternatives
Important Lesson	• Identifying resiliency issues during NEPA is too late to address the problems

3.4.4.2.3 Financial Capital

Like many agencies, MDOT does not have separate funds for resiliency efforts. Any recovery work is paid for with FEMA emergency funds. Also worth noting is that the survey response reinforces the need for a strategic approach to system resilience. According to the agency representative, needs are usually identified too late to incorporate resilience. For example, identifying resilience issues during the NEPA (National Environmental Policy Act) stage, i.e., environmental assessment, is too late to address issues.

3.4.4.3 Summary

At MDSHA, we see that the agency is in the initial stages in terms of building organizational capital for transport system resilience. Progress in efforts have primarily been as a result of champion efforts. This has also led to raised awareness within the agency. This is necessary but not sufficient when compared with Iowa DOT's approach of instituting a formal team. Also, although state-level legislation exists that requires annual reporting of climate resilience efforts, not having agency-specific resilience goals or objectives hinders the agency's ability to address some of the problems identified such as where in the transportation planning process resilience needs should be addressed. As correctly indicated on the survey, an ad-hoc approach to resilience often results in resilience needs being identified too late in the project lifecycle for such needs to be incorporated. From previous responses, we see that utilizing existing agency structures (e.g., planning documents) allows the agency to articulate its vision for system resilience and systematically work towards it. However, the survey responses from MSHA show signs of the agency possibly incorporating the risk-based approach used in its vulnerability and risk analysis to its asset management plan and other project planning. If this is done, resilience thinking can be institutionalized within the agency.

A second sign that shows progress towards a more sociotechnical approach is found in an objective that guided the agency's vulnerability study: "review and consider design strategies, *best management practices*, *planning standards*, and *other ways to support the adoption of adaptive management solutions* to improve the resiliency of Maryland's highway system" (FHWA, 2014). This objective provides an excellent example of looking beyond an asset's strength to include other types of agency capital that can support resilience (e.g. management practices, planning standards).

3.4.5 **Massachusetts DOT**

3.4.5.1 <u>Background</u>

The Massachusetts DOT oversees the state's highway, transit, aeronautics, and motor vehicle registration. This includes 5,000 bridges and 9,500 lanes miles of state highways maintained by MassDOT, 19 rail lines and 170 bus routes operated by MBTA (Massachusetts Bay Transit Authority), and 15 regional transit agencies among others (MassDOT, 2016).

In the Massachusetts, coastal communities are most vulnerable to the state's main hazards which include intense precipitation, flooding, erosion and sea level rise. Table 3.4 below shows future relative sea level rise estimates for Boston, MA using 2003 as the beginning year of analysis. Values were calculated by adjusting global sea level rise scenarios to better reflect conditions in Boston, which includes adjusting for local vertical land movement (subsidence).

Table 3.4 Relative sea level rise estimates for Boston, MA. Source: CZM (2013)

Scenario	2025		2038		2050		2063		2075		2088		2100	
	ft	m	ft	m	ft	m	ft	m	ft	m	ft	m	ft	m
Highest	0.49	0.15	1.08	0.33	1.81	0.55	2.80	0.85	3.92	1.19	5.33	1.63	6.83	2.08
Intermediate High	0.36	0.11	0.73	0.22	1.19	0.36	1.80	0.55	2.47	0.75	3.32	1.01	4.20	1.28
Intermediate Low	0.24	0.07	0.43	0.13	0.65	0.20	0.92	0.28	1.21	0.37	1.55	0.47	1.91	0.58
Lowest (Historic Trend)	0.18	0.06	0.29	0.09	0.39	0.12	0.50	0.15	0.60	0.18	0.71	0.22	0.81	0.25
Range	0.31	0.09	0.79	0.24	1.42	0.43	2.30	0.70	3.32	1.01	4.62	1.41	6.02	1.83

The state has also been impacted by catastrophic hurricanes in the past with the three worst being (1) Hurricane Bob in 1991 (causing about $39 million in damages to the state), (2) Hurricanes Carol and Edna in 1954 (sustained winds of 80-100 mph and storm surge of over 14 feet in some areas), and (3) the Great New England Hurricane in 1938 (18-25 foot tides in some areas and strongest wind speed of 121 mph) (Commonwealth of Massachusetts, 2017).

With such recorded events in the state's past and recent, although less devastating, floods in the state, Massachusetts is working towards creating more resilient communities. The survey for MassDOT was filled out by Steven Miller. Steven Miller has worked at MassDOT for over 10 years and is currently the Supervisor for the Office of Environmental Management and Sustainability. He works with a team of seven who all have additional responsibilities.

3.4.5.2 Survey Responses

3.4.5.2.1 Institutional and Organizational Capital

Resilience is "the ability to anticipate, prepare for, and adapt to changing conditions, and withstand, respond to, and recover rapidly from disruptions."
– Steven Miller, MassDOT

For MassDOT, political will has played a positive role in the agency's approach toward climate change. Political capital at the state level led to the Massachusetts Global Warming Solutions Act and Massachusetts Executive Order (EO) 569. Similar capital at the agency has driven work to enhance its resilience capacity. Other factors that influenced the evolution in the agency's resilience approach are champion efforts, impacts of catastrophic event and a greater awareness of threats.

Two agency level policies promote agency actions and form the institutional capital required to drive resilience improvement. Firstly, MassDOT has a series of initiatives, some which involve collaborating with other MA agencies, aimed at informing asset management, to "better understand inland and coastal flooding, and to reassess resources" (Miller, 2016). Secondly, the agency has a strategic objective to identify flood-prone locations and use such information to support project design and maintenance activities. According to Mr. Miller, the MassDOT Highway uses an "initiative tracking sheet" to monitor and report progress in this area.

In terms of transportation planning, the agency representative believes that FAST ACT provisions will promote climate change consideration in project planning. At the moment, MassDOT does not yet explicitly address transport resilience in its planning documents;

however, progress in this area is being made. The agency also collaborates with external partners on its resilience initiatives. These partners include: FHWA, NOAA, US EPA Region 1, USGS, Army Corps of Engineers (ACOE), MA Energy and Environmental Affairs (EOEEA), MA Office of Coastal Zone Management (CZM), MA EPA, Boston Harbor (now known as The Boston Harbor Association), City of Cambridge, City of Boston, MA GIS, MassPort, MA Water Resources Authority (MWRA), MA Department of Conservation and Recreation (DCR), Woods Hole Oceanographic Institute, Boston Water and Sewer, and the MA Bay Transportation Authority (MBTA).

In addition to these efforts, progress is being made toward learning about different tools used to develop future climate scenarios for planning. According to Mr. Miller, the process of translating future climate scenarios into inputs for emergency planning and management is somewhat difficult.

3.4.5.2.2 Technical Capital

Massachusetts experiences regular disruptions in the transportation system, as results from the survey indicate. MassDOT conducted a risk assessment as part of FHWA's climate resilience pilots. Partners included NOAA, EPA, USGS, ACOE as well as other state and local agencies and NGOs. The study assessed the impacts of sea level rise and extreme storm events on the on the I-93 Central Artery/Tunnel (CA/T). The study sought to do the following:

i. Create an inventory of assets on the I-93 CA/T
ii. Conduct vulnerability assessment of CA/T to sea level rise and extreme storms
iii. Identify adaptation strategies to reduce vulnerabilities

MassDOT learned some lessons from the study that can inform future analyses. First, the study team encountered some GIS-related challenges. This ranged from data incompatibility to finding staff with sufficient GIS expertise (FHWA, 2017). The study team also found that site visits used to supplement digital datasets yielded more robust data for the analysis, and buy-in from a range of MassDOT staff. Lastly, the team used asset identifiers that were consistent with MassDOT's asset management database. This will enable the team integrate results from the vulnerability assessment to the agency's asset management database, providing useful information for future investment decisions (FHWA, 2017).

Next steps for the agency include reviewing and sharing the assessment's findings with some MassDOT district staff and the City of Boston, and assessing engineering feasibility of the identified adaptation strategies. The team also intends to update emergency response procedures for the CA/T. According to the survey response, conducting the vulnerability study is causing a gradual change in the agency's general decision-making approach.

3.4.5.2.3 Financial Capital

At MassDOT, there is no specific budget for resilience enhancement. Funding resilience strategies are currently done on a case-by-case basis. That is, resilience considerations are either considered during design or when a specific need arises. Consequently, the agency uses a risk-based approach during project prioritization to ensure resilience. The two factors currently in use are (1) proximity to coast and (2) locations that routinely flood. Repairs, renewal and recovery of assets affected during disruptive events are funded by disaster declarations. Lastly, Mr. Miller stated that insurance underwriters are currently interested in how assets can be protected from damage.

3.4.5.3 Summary

MassDOT shows several examples of what it looks like to institutionalize resilience thinking in an agency and evolution towards a sociotechnical approach. Firstly, champion efforts and political will at the agency seem to provide an environment where resilience enhancing strategies can be developed. For example, the agency is progressively working to understand how inland and coastal flooding can inform its asset management program. The agency already flags flood prone locations for design considerations and maintenance activities. We also see progress in resilience thinking as the agency is learning about ways it can harness various types of tools for climate planning. Although, resilience considerations are not yet explicitly addressed in planning documents, progress in this area seems to only be a factor of time. Next, by using asset identifiers that are consistent with the agency's current asset management database in conducting the agency's climate vulnerability assessment, the study team created the means for the study results to be integrated into management practices. The intentionality of this approach shows a higher likelihood of using such risk-based approaches to inform future investment decisions. Lastly, MassDOT seems to have moved more rapidly to incorporate resilience considerations in their existing decision-making process by assessing flooding risk and SLR risk. As indicated in the survey, these efforts have been the result of the agency having a greater awareness of threats, impact of catastrophic event, champion efforts and political will.

With the practical examples of moving towards institutionalizing resilience thinking in the agency, MassDOT could further move this progress along by starting to incorporate such actions into planning documents. Using existing processes such as the long range plan, asset management plan, and the transportation improvement plan can help the agency to strategically address different types of capital in its resilience capacity building and rely less on efforts of resilience champions within the agency.

3.4.6 Metropolitan Transportation Commission (MTC) and the Association of Bay Area Governments (ABAG)

3.4.6.1 Background

Located in northern California, the San Francisco Bay Area is a nine-county region with a population of over 7 million projected to grow to 9 million by 2040. The combined economy of the Bay Area (i.e., Alameda, Contra Costa, Marin, Napa, San Francisco, San Mateo, Santa Clara, Solano and Sonoma counties) is about $300 billion making it the 21st largest economy in the world (MTC, 2013). Correspondingly, the area encompasses the major metropolitan areas San Jose, San Francisco and Oakland.

The Bay Area's roadway system consists of 620 miles of freeways, 800 miles of state highways, and 1900 centerline miles of local roadways that are maintained by the local governments. A history of seismic activity and a long coastline are both factors that have influenced the Bay Area's posture towards transport system resilience. Main stakeholders involved in initiatives that focus on identifying vulnerabilities and planning for system risks include the California Department of Transportation (Caltrans), the Metropolitan

Transportation Commission (MTC), the Association of Bay Area Governments (ABAG), the San Francisco Bay Conservation and Development Commission (BCDC), and the San Francisco Bay Area Rapid Transit (BART). These agencies collaborate at different levels by sharing ideas, resources and expertise to build system resilience.

Similar to other parts of the state, the Bay Area is prone to a combination of geophysical, climatological and meteorological hazards. Earthquakes that have occurred in the Bay Area have resulted in perhaps the nation's most destructive impacts in terms of seismic activity. The region has seven main fault lines, namely, the San Andreas, Calaveras, Concord-Green Valley, Greenville, Hayward, Rodgers Creek, and Sand Gregorio Faults. Historically, seismic activity in the region has followed what closely resembles a cycle of some sort. For example, the second half of the 19th century saw frequent earthquakes with magnitudes of 6.0 or higher occurring at a rate of once every four years (USGS, 2016). This was followed by period of low activity right after the destructive 1906 San Francisco (7.8 magnitude) earthquake which damaged about 80% of the city and caused at least 3000 fatalities. The Loma Prieta earthquake (6.9 magnitude) then followed this period of low activity about 83 years later causing 63 fatalities and about 3,000 injuries (Morrison, 2014). Although the frequency of seismic activity in the Bay Area has not returned to that of the latter 1800s, scientists believe that the stresses that continue to build could lead to more frequent and intense earthquakes in the future (USGS, 2016).

The Bay Area is also prone to seal level rise. According to National Research Council projections, the Bay Area's sea level could rise by 12-14 inches by 2050; and by as much as 36-66 inches by the end of the century (BCDC, 2016).

3.4.6.2 Survey Responses.

"Urban resilience is the capacity of individuals, communities, institutions, businesses, and systems within a city to survive, adapt, and grow no matter what kinds of chronic stresses and acute shocks they experience".

–Michael Germeraad (Rockefeller Foundation Definition)

Michael Germeraad, a Resilience Planner from ABAG[6], the council of regional governments, and Stefanie Hom, a Transportation Planner from the regional MPO, MTC, answered questionnaires for the Bay Area online and by phone respectively. The two representatives have a combined average experience of 9.5 years working with the agencies and while Ms. Hom's role is not exclusively dedicated to resilience planning, Mr. Germeraad's is a dedicated position. The details of their roles and position are provided in Table 3.5.

Table 3.5 Details of agency representatives

Survey Question	Michael Germeraad	Stefanie Hom
Position, Agency	Resilience Planner, ABAG	Transportation Planner, MTC
Years at Agency	2-5 years	6 years
Dedicated Position	Yes	No, additional responsibilities
Part of a team? [number]	Yes [5 members but they have additional responsibilities]	N/A

3.4.6.2.1 Institutional Capital

Both respondents did not identify agency level institutional capital that affects transportation resilience. However, state level policies affect both agencies. The State of

[6] ABAG is not a transportation agency and does not own transport assets. It acts a convening body, technical hub, and research body that supports individual and coordinated local government action.

California has taken strategic steps over the last few years to address resilience. Executive Order S-13-08, which was signed in November 2008 by Governor Schwarzenegger, directed state agencies to develop the state's first strategy that would identify and prepare for climate change impacts (CNRA, n.d.). The Executive Order also requested that a committee be formed by the National Research Council (NRC) to assess sea-level rise to assist state efforts. Also under this Executive Order, a stipulation requires a range of sea level rise scenarios to be used during the planning phase for all construction projects in areas considered to be vulnerable to sea level rise (Executive Order, 2010).

A second initiative that has shaped California's planning landscape is Senate Bill 375. The legislation became law in January 2009 with the aim of reducing GHG emissions that result from cars and light trucks. The legislation requires an integration of transportation, land-use and housing planning to provide more efficient communities, reduce single-occupant-vehicle (SOV) travel and eventually reduce GHG emissions (SCAG, n.d.). California's work on emissions reductions and development of the Climate Adaptation Strategy are coordinated by the state's Climate Action Team. The team's membership comprises secretaries of state agencies, heads of agency boards and departments, and is led by the California EPA Secretary.

3.4.6.2.2 Organizational Capital

Questions in this section sought to understand the agencies' general approaches to building resilience covering the human capital available as well as business processes and practices. Michael Germeraad is part of a team which grew from having one member to five over the past five years. Mr. Germeraad's position is solely dedicated to resilience planning, but his teammates have additional responsibilities at the agency. According to the survey responses, the resilience team's growth has legitimized resilience efforts to an extent, making it "become more integrated into the overall agency decision making process." (Germeraad, 2016). This has also provided more exposure and resources from the senior leadership within the agency.

In addition to growth in human capital (i.e., the resilience team), ABAG's approach to system resilience has also seen an evolution because of a greater understanding of system resilience. According to Mr. Germeraad, the program was best described as a hazard mitigation program that focused on addressing acute shocks. However, over the last five years, the program has become more integrated by building various partnerships. This has provided greater connectivity within regional business lines and allowed them to better address *urban resilience,* i.e., housing affordability, equity, sustainability, and economic development, among others.

For us being resilient means being able to better respond to acute shocks and chronic stresses and to transform following a disruption. People should be able to still get where they need to go – Stefanie Hom, MTC

At the MTC[7], initiatives related to system resilience are carried out by transportation planners. This is not uncommon. As with several other transportation agencies, there is no dedicated role for resilience planning. According to Ms. Hom, resilience initiatives at MTC started gaining traction about 3-4 years ago, with the start of the climate initiative program.

[7] The MTC is currently in the process of merging with ABAG, therefore questions remain about MTC's future role in resilience. At the same time, due to maturity of the resilience topic within ABAG, the new merged agency structure will be influenced.

This mainly involved mitigation initiatives such as demand management, car sharing, and shuttle services that were aimed at reducing greenhouse gas (GHG) emissions.

Currently, neither of the two agencies have direct policies, regulations, or strategic objectives that promote transport system resilience. Even so, ABAG is working towards strategically addressing resilience and has begun with the agency mission statement: *"The ABAG Planning and Research Department works with local governments and stakeholders to develop and implement innovative solutions for issues involving land use planning, housing, transportation, environmental climate change, earthquakes and* ***disaster resilience****, and economic equity."* In addition, a significant portion of ABAG's work relates to policy dissemination at the local level. The agency therefore tracks jurisdictions that adopt resilience related policies. Despite the lack of strategic planning documents for resilience at ABAG and the MTC, California Department of Transportation (Caltrans) has begun to strategically plan for resilience. A survey response from Caltrans was not received; however, a literature search revealed information about Caltrans' strategic approach to resilience.

The Caltrans Strategic Management Plan for 2015-2020 has a strategic objective to "*improve economic prosperity of the State and local communities through a resilient and integrated transportation system*" (Caltrans, 2015). One of the stated performance measures for this objective is a Resiliency Score which is to be developed and adopted by the December 2017. The score comprises three components:

- Climate change resiliency (e.g., sea level rise and flood vulnerability)
- System resiliency (e.g., adaptability during emergencies and disasters)

- Financial resiliency (e.g., "ensure funding considering maintenance, operations, modernization, disasters, financial stability, etc.") (Caltrans, 2015).

The Caltrans plan is another example that shows how transportation agencies are giving systematic thought to how transport resilience can be viewed using a multidimensional perspective.

In terms of collaboration, both ABAG and the MTC have collaborated to different extents with Federal Emergency Management Agency (FEMA) Region IX, U.S. Geological Survey (USGS), Bay Conservation and Development Commission (BCDC) and others. In addition, ABAG has a strategic partnership with the Rockefeller Foundation's 100 Resilience Cities, an initiative to "help cities around the world become more resilient to the physical, social, and economic challenges that are a growing part of the 21st century" ("100 Resilient Cities", 2017).

3.4.6.2.3 Financial Capital

Current system resilience efforts at ABAG are funded almost entirely by grants. The team actively searches for grants to fund regional work. They also provide resources for partner cities that need to make the case to decision makers for funding. Similarly, MTC's initiatives are also grant funded with sources included the BCDC, Caltrans, FHWA and a local regional fund.

3.4.6.2.4 Technical Capital

According to the survey results, the Bay Area has experienced at least eight natural disasters in the last three decades that resulted in at least one of the following: ten or more people were reported killed, 100 or more were people affected, a declaration of a state of emergency or a call for international assistance was issued. At least one of these events happened within the last decade (2006-2016) and three in the decade before that (i.e. 1996-2005). In light of this, some risk/vulnerability assessment have been conducted to assess climate change related impacts. Both ABAG and the MTC have worked with strategic partners including the Federal Emergency Management Agency (FEMA), the California Governor’s Office of Emergency Services (CalOES), the Environmental Protection Agency (EPA), San Francisco Bay Conservation and Development Commission (BCDC), and the California Department of Transportation (CalTrans) to consider highway, railway and bridge assets. The region was a part of FHWA’s 2010-2011Climate Change Vulnerability Assessment Pilot Project and the 2013-2015 Climate Resilience Pilot Program. The MTC was among the first round of vulnerability assessment pilots conducted by FHWA because of the Adapting to Rising Tides (ART) initiative already being conducted in the region by the BCDC and the National Oceanic and Atmospheric Administration (NOAA) Coastal Services Center. The MTC, CalTrans, and BCDC then joined FHWA’s efforts to conduct a vulnerability and risk assessment as part of ART.

The project was conducted in Alameda County, one of the region’s eight counties with an objective to “enable the Bay Area’s transportation planners to craft effective adaptation strategies based on improved vulnerability and risk assessment practices, and to deploy and test the FHWA conceptual model and provide FHWA with recommendations for evolving the model” (FHWA, n.d.). The study followed the following methodology:

i. Refine asset inventory & sensitivity assessment
ii. Conduct seismic vulnerability assessment

iii. Develop inundation maps
iv. Assess vulnerability
v. Assess risk
vi. Develop risk profiles
vii. Review adaptation options

In terms of considering interdependencies in the studies conducted, ABAG leveraged resources from a report on the San Francisco's lifeline infrastructure. This report, created for earthquake resilience, qualitatively discusses the connections between 11 infrastructure systems: water and wastewater, electric power, natural gas, telecommunications, highways and roads, ports and waterways, transit systems and railroads (Barkley, 2009).

The vulnerability assessment produced some lessons for the agencies involved. First, the study team had problems identifying relevant data and deciding on the most useful formats for analyses. The team also encountered problems with data disparities between study sites. While some areas had enough data, other less studied areas did not and resulted in less in-depth analyses along various stages of the project (Caltrans, 2014). Another useful lesson learned was that the study did not produce any surprises in terms of asset vulnerabilities. The results mostly matched information gathered from maintenance staff and other stakeholders. Therefore, for areas where vulnerabilities are well understood, more value may be obtained from conducting site specific or asset specific assessments. Lastly, the entire study involved significant public engagement, especially for identifying possible adaptation strategies. This was necessary to cater to the various stakeholders affected by transportation vulnerabilities in the area (Caltrans, 2014).

3.4.6.3 Summary

The Bay Area agencies are an example of how resiliency efforts within an agency evolve over time as a result of increase in institutional capital. The survey responses explicitly highlight the role of SB 375 in spurring action towards climate change mitigation. At MTC, the travel demand mitigation program focused on emissions reduction directly evolved to include sea level rise adaptation efforts. At ABAG, work previously solely focused on hazard mitigation (specifically, earthquake hazards) evolved over time to become an integrated resilience program. For ABAG, this was a result of a greater understanding of system resilience. We see here that also this led to greater investments into resilience capacity building as the agency increased its resilience staff over the five-year period.

Now, although Caltrans was not included in the survey responses, the brief agency review shows the use of a strategic approach (i.e., identifying objectives and associated performance measures) in its resilience efforts. Also, the collaboration between ABAG, MTC and Caltrans (including FHWA, BCDC, etc.) to conduct vulnerability studies within the San Francisco Bay Area show resulted in interesting insights. Specifically, the use of public and stakeholder engagement to identify adaptation strategies for the vulnerabilities identified shows a commitment to understand how adapting vulnerable infrastructure will affect the surrounding communities.

Considering the number of major transport system disruptions indicated in the survey response, California's history with catastrophic earthquakes, as well as the growing understanding of potential climate change impacts in the region, the level of organizational and institutional capital developed alongside progress in technical capital among the

California agencies supports the notion that agencies with more experience dealing with hazards evolve towards sociotechnical approaches.

3.4.7 **New Orleans Regional Planning Commission (NORPC)**

3.4.7.1 Background

The City of New Orleans has a 2014 population of 384,320 forming 83% of its pre-Katrina population (City of New Orleans, 2015). Current identified threats include floods, storm surge coastal erosion, subsidence, winter storms, extreme temperatures, tornadoes, and tropical cyclones among others. In addition, New Orleans is vulnerable to sea level rise of as much as 4.3 feet by the year 2100, the highest estimate anywhere in the world (City of New Orleans, 2015).

3.4.7.2 Survey Responses

"I think of a system that can bounce back from acute disasters (hurricanes) and that can deal with gradual stresses (sea level rise)" – Meredith Soniat, NORPC

Meredith Soniat responded to the survey for the New Orleans region. She is a Sustainability Planner at the New Orleans Regional Planning Commission (NORPC), the MPO for the Jefferson, Orleans, Plaquemines, St. Bernard, St. Tammany and Tangipahoa parishes. Hurricane Katrina was a landmark disaster that the City of New Orleans is still trying to learn from. One important fact is that the recovery process changed the way the agency addresses system resilience. According to Ms. Soniat, it caused the agency to become better aware of threats to the city and propelled a greater understanding of system resilience.

3.4.7.2.1 Institutional and Organizational Capital

Meredith Soniat has been at the agency for more than five years and is currently part of a team of two that leads resiliency efforts at the agency. They however have additional responsibilities at the agency. At the moment, NORPC does not have any strategic goals or objectives for enhancing system resilience. When asked about agency policies that promote resilience, the agency representative referred to the agency's complete streets policy. The policy requires projects to be evaluated for the inclusion of bicycle and pedestrian facilities, and also to be evaluated for the incorporation of green infrastructure. Furthermore, Ms. Soniat stated that the FAST Act's provisions for resilience in general transportation planning may encourage a broader incorporation of green infrastructure projects. In terms of project prioritization, a "yes" or "no" classification for environmental sustainability is used for projects included in the agency's plans. Furthermore, anecdotal evidence of resilience consideration during project prioritization alluded to a case-by-case consideration for projects. For example, when the city's Interstate 10 highway flooded after an extreme event, roadway elevation became a priority for that segment of highway.

Next, the survey also sought to understand how the agency's resilience efforts fit into state level efforts. According to the survey response, NORPC directly works with cities for policy implementation. Once a policy is successful, the agency can recommend it to be incorporated into state-level plans. For example, the City of New Orleans recently developed a draft green infrastructure toolkit, including typical details for certain green infrastructure treatments. The agency representative is now working to share those details with the state and to receive feedback for next steps. In terms of collaboration, the New Orleans Water Collaborative has been a helpful partner in the NORPC's resilience building efforts. The agency also participates in the development of a FEMA Hazard Mitigation Plan.

3.4.7.2.2 Technical Capital

Based on the survey responses, NORPC has not yet been involved in any assessments involving vulnerability or risk of the transportation system. However, there is a focus on combining green and gray infrastructure in storm water management as a means of accommodating changing weather patterns. According to the survey responses, “living with water” is now a common jargon in discussing storm water issues.

Again, the City of New Orleans is a participant in the Rockefeller Foundation 100 Resilient Cities initiative, which has conducted a preliminary resilience assessment of the city. As part of this assessment, a high-level overview of the region’s critical transport components is presented including rail, ports and bridges. Similarly, the New Orleans Hazard Mitigation Plan mainly focuses on the transport of hazardous materials and how to mitigate consequences of accidents. Neither plans discuss in-depth transport system vulnerabilities and strategies for enhancing transport resilience.

3.4.7.2.3 Financial Capital

The NORPC is a planning agency and therefore does not own any assets. However, like other agencies, funding programs or initiatives specifically directed at building resilience are an issue currently being overcome by coordinating with agencies such as the Federal Emergency Management Agency (FEMA), the Hazard Mitigation Grant Program (HMGP), and the Coastal Protection and Restoration Authority (CPRA).

The HMGP is a grant program run from the Governor's Office of Homeland Security & Emergency Preparedness (GOHSEP) which funds hazard mitigation measures proposed by Local Governments, Tribal Agency, State Agencies, Private Nonprofits and individuals. However, individuals must submit applications through a local agency. Applications for HMGP funds can only be submitted within 12 months of a Presidentially declared disaster and funding is dependent on the total amount of assistance to be made available by FEMA for disaster recovery (GOHSEP, 2017).

Unlike HMGP, CPRA is a not a grant program. it is a state entity established as the only agency with the "mandate to develop, implement, and enforce a comprehensive coastal protection and restoration Master Plan" for Louisiana's coast. The agency collaborates with both the Department of Transportation and Development (DOTD) and the Department of Natural Resources among others to work on an integrated approach to coastal restoration and hurricane protection (CPRA, 2013).

3.4.7.3 Summary

In summary, the New Orleans region has suffered from the devastating impacts of hurricanes in the past and is working towards resilience. From this review however, the focus of transportation planning initiatives seem focused on sustainability initiatives. Although such efforts contribute to resilience capacity building, more strategic efforts towards building the system's resilience capacity could be beneficial. More collaboration between the MPO and the numerous ongoing efforts in other sectors such as housing, and business development, could lead to the development of strategies with co-benefits in multiple sectors.

Other insights gleaned from the survey responses relate to identification of measures of effectiveness and harnessing existing agency technology. Currently, the agency seems to implicitly measure resilience using rapidity factors. That is, the survey response stated that resilience is addressed by how quickly roads can be reopened or electricity turned back on. Since the two factors have been identified, officially recognizing them as measures of effectiveness and getting them into standard operating procedures is key. This may prevent reliance on common sense judgement during disruptions. Next, the benefits of existing agency technology can be harnessed for preliminary transport resilience planning. After Hurricane Katrina, GIS was used to identify signal locations and overlay them with information of city locations that were inundated enabling the agency to focus efforts on restoring power and function to signals in unflooded areas. This example shows that capability exists to conduct preliminary vulnerability assessments of the city's transport infrastructure. The key would be to identify and partner with entities that can provide technical support for modelling various system threats.

3.4.8 North Central Texas Council of Governments (NCTCOG)

3.4.8.1 Background

The NCTCOG serves as the MPO for a 16-county region that includes Dallas and Fort-Worth, the main urban centers. The region's population is 6.5 million and is expected to grow to 10 million by 2035 (NCTCOG, 2016). To set the transportation policy for the region, the MPO has an independent body called the Regional Transportation Council (RTC). Some of the RTC's primary duties include developing transportation plans and programs as well as allocating federal, state and regional transportation funds ("Regional Transportation Council", 2016).

3.4.8.2 Survey responses

A resilient system is one that "has the ability to function efficiently when dealing with extreme events."- Jory Dille, NCTCOG

Survey responses were filled Jory Dille, a Senior Transportation Planner at the North Central Texas Council of Governments (NCTCOG). Mr. Dille has been at the agency between five to ten years and works with three other employees as part of a team that work on resiliency efforts in addition to other responsibilities. According to the survey response, the agency has become better aware of threats facing their system and have also developed a greater understanding of system resilience. Over the last decade, the agency has experienced a change in the way it addresses resilience; there is now more focus on asset management.

3.4.8.2.1 Institutional and Organizational Capital

According to the survey results, NCTCOG does not have policies or regulations that promote transport resilience; nonetheless, the agency responses indicate a strategic objective for addressing resilience. Although a specific resilience objective for the NCTCOG was not stated in the survey response and could not be identified through a review of the agency's current long range plan or strategic plan, evidence of some resilience capacity building was present was found. In an early effort to evaluate the MPO's planning efforts NCTCOG used the Infrastructure Voluntary Evaluation Sustainability

Tool (INVEST) developed by FHWA to score one of its former long-range plans, Mobility 2035. This produced results highlighting opportunities for growth in areas including asset management and infrastructure resilience. The current transportation plan, Mobility 2040, acknowledges these opportunities and alludes to progress in resilience building, but no explicit evidence of this is found in the plan (progress in asset management is clearly identified) (NCTCOG, 2016).

Lastly, with regard to the FAST Act, the agency hopes that the law's provisions for resilience will prompt agencies to use a more performance based approach to planning.

3.4.8.2.2 Technical Capital

In reviewing literature NCTCOG literature, three attributes stood out in terms of technical capital that can enhance system resilience. First, NCTCOG has been making systematic progress towards adopting asset management principles in its project planning. The agency's Capital/Operations Asset Management (Cap-Main) program combines these principles with a strategic design and performance-oriented approach for planning corridor improvements (NCTCOG, 2016). As of now, there's no evidence of resilience considerations in this process, but its presence can enhance the agency's capacity towards developing a data-driven approach for resilience planning.

Secondly, NCTCOG has well developed Geographic Information Systems (GIS) program that promotes the cooperation of GIS professional within its jurisdiction. The agency organizes bi-annual meetings that bring major stakeholders (e.g., universities, local governments) within the region and GIS market together (e.g., data vendors). The collaboration also enables interested parties within the region to pool funds for purchasing high-quality data. Access to this kind of technical expertise and data both within the agency and through its collaborators creates many opportunities for the agency to incorporate risk data (e.g., downscaled climate projections) into project planning.

Finally, NCTCOG conducted a vulnerability study that concluded in 2015 with funding from the FHWA and support from the City of Dallas, Fort Worth Transportation Authority and the University of Texas at Arlington. The study the vulnerability of regional transportation assets (roads, passenger rail, airports) to extreme heat, rainfall and flooding, drought, and the urban heat island effect. The objectives of the study were to:

- “Assess and categorize vulnerabilities of vital transportation assets.
- Determine potential effects of impacted segments or facilities on asset performance, mobility, economy, and quality of life.
- Develop and pilot an assessment process that can be replicated throughout the NCTCOG region, Texas, and in other Great Plains States that experience similar climatic, geologic, and hydrologic conditions” (FHWA, 2016a).

The main findings from the study showed the potential of road, rail and airport assets to damage from extreme heat and flooding. These includes an increase in mean August temperatures to highs of 94 degrees Fahrenheit and daily extremes that could exceed 120 degrees Fahrenheit. The study also revealed an increase of about 40% in severe thunderstorms occurring in the spring. The resulting potential transportation impacts include inundation of 636 miles of roadway by a 100-year flood, with 17 of those miles classified as critical and estimated to reach 44 miles by 2035 (FHWA, 2016a).

Following this study, the agency hopes to integrate the findings into its planning process. Specifically, to incorporate vulnerability into project development and prioritization to inform subsequent transportation plans. It also plans using such climate projects to inform asset management (FHWA, 2016a).

3.4.8.2.3 Financial Capital

The survey results yielded little information about the financial processes involved with resilience capacity building. Similar to many other agencies, NCTCOG has not yet identified a systematic way of funding resilience strategies. Consequently, resilience is not considered in project prioritization or selection.

3.4.8.2.4 Summary

NCTCOG is in the early stages building sociotechnical transport resilience. The survey responses show much room for growth in all four capital areas. However, in the short term, the low hanging fruit for enhancing resilience capacity is to take advantage of the agency's existing technical capital and to work outwards from there. In particular, NCTCOG has an opportunity to build on its Cap-Main and GIS programs. Although system risks (such as those resulting from extreme weather or climate change) are not explicitly incorporated into NCTGOC's Cap-Main process, the systematic nature of the process combined with the use of good data for corridor planning, provides a ripe opportunity for extension to include resilience considerations. Furthermore, the agency's strength in GIS applications and GIS data create an environment where resilience thinking can eventually thrive.

3.4.9 **Oregon DOT**

3.4.9.1 Background

Oregon DOT owns and maintains over 8,044 miles of state highway and about 2,666 bridges. The agency also supports and provides funding to transit agencies, and oversees (to a limited extent) the state's railroads (Oregon DOT, 2009). In the last decade, ODOT has experienced two major disasters and at least eight in the preceding two decades (1986 - 1996) before that.

The survey for ODOT was filled by Bruce Johnson, a State Bridge Engineer, who has worked at the agency for over 10 years. According to Mr. Johnson, the most significant change at the agency that affects system resilience is in seismic functional design for bridges.

3.4.9.2 Survey Responses

3.4.9.2.1 Institutional and Organizational Capital

"Resilience means the transportation system would be usable by emergency responders and the public within 72 hours after a major event." – Bruce Johnson, ODOT

In April 2011, the State of Oregon adopted House Resolution 3. This directed the Oregon Seismic Safety Policy Advisory Commission (OSSPAC) to "to lead and coordinate preparation of an Oregon Resilience Plan that reviews policy options … and makes recommendations on policy direction to protect lives and keep commerce flowing during and after a Cascadia earthquake and tsunami" ("Oregon Resilience", 2013a). The decision led the OSSPAC to set up eight task groups focused on assessing the infrastructure impacts of a 9.0 Cascadia earthquake, defining acceptable timeframes for service restoration, and recommending strategies (to be implemented within the next 50 years), including policy options, required to achieve those resilience targets. The eight task groups cover transportation, water and waste water, energy, critical/essential buildings, information and communications, business and work force continuity, coastal communities, and a magnitude 9.0 earthquake/tsunami scenario review group. The final plan released in 2013 was a result of 169 volunteers, no extra funding and a one-year schedule.

The Transportation Task Group for the Oregon Resilience Plan was led by Mr. Bruce Johnson from Oregon DOT. The established resilience goal for the transportation network is to "*facilitate immediate emergency response, including permitting personnel to access critical areas and allowing the delivery of supplies, and … to restore general mobility within specified time periods for various areas of the state*" ("Oregon Resilience", 2013b). The Group, tasked with assessing the resilience levels for highways, rail, airport, water ports and transit, followed the set objectives from the OSSPAC.

In terms of ODOT specific capital, the agency has a design policy that contributes towards overall capacity. This is the Seismic Functional Design Criteria, which focuses on the physical robustness of the agency's infrastructure. ODOT also coordinates the development of an Emergency Management Plan for the state. With regard to other organizational capital, ODOT does not have specific strategic objectives for addressing system resilience; however, since the DOT oversees the setting of the state's highway resilience policy, progress in this area may be reviewed to an extent by following updates on the Oregon Resilience Plan. ODOT may benefit from formally integrating its State Resilience Plan involvement with its agency strategic plan. This will allow for better monitoring and accountability of progress. Lastly, the agency collaborates with the state's Department of Geology and Mineral Industries (DOGAMI).

3.4.9.2.2 Technical Capital

As stated earlier, Bruce Johnson from Oregon DOT led the Transportation Task Group, which conducted vulnerability studies for the Oregon Resilience Plan. Analyses that covered highway and bridge assets provided more details on impacts of earthquakes and land/mudslides than it did for other modes such as rail, airports and water ports. The assessment also looked at interdependencies between transportation, liquid fuel and communication. Partners for this study included USCG, Department of Aviation, local agencies, consultants and the state rail/transit division.

The vulnerability assessments conducted were based on technical studies where possible. In the absence of such information, analyses were based on engineering judgement based on factors including construction year, seismic code at time of design and construction, conditions assessment and a resilience performance comparison of similar facilities in other areas (or parts of the world) ("Oregon Resilience", 2013b). For the highway network, a detailed assessment of the state's highway network was conducted, highlighting potential earthquake impacts to critical corridors and road segments. The group also established resilience targets at three levels and prioritized facilities into tiers. Figure 3.6 shows the highway priority levels and overall resilience targets used in the vulnerability assessments.

A detailed analysis for the rail network has not yet been conducted and securing funding for a possible analysis in the future would be problematic because the rail lines are privately owned. The study team therefore made generalizations about possible impacts based on experiences from other regions. At the end of the state-led effort however, the Task Group recommended that detailed vulnerability studies and gap analyses be conducted for rail and air transportation, and river and coastal ports. Figure 3.7 shows part of the results section from Oregon DOT's vulnerability assessment.

Highway Priority	Resilience Targets
•**Tier 1** - Backbone system, i.e., access to vulnerable regions, major population centersm vital areas for rescue & recovery operations	•**Minimal** - for use by emergency responders, repair crews, vehicles transporting food & critical supplies
•**Tier 2** - Larger network, i.e., access to most urban areas & major commercial operations	•**Functional** - Not yet full capacity, some restrictions, but enables economic services, e.g., some freight traffic
•**Tier 3** - More complete transport network	•**Operational** - up to 90% capactiy restored, level of service fully restored, allows school and work trips

Figure 3.6 Oregon Resilience Plan Transportation Targets

Oregon DOT also conducted a second regional vulnerability assessment and adaptation options study of climate change and extreme weather impacts on certain highway corridors. Hazards included in the assessment included landslides, coastal erosion, and storm surge. The study was partly funded by the FHWA. Other partners included the following:

- Oregon State University (OSU)
- Oregon Climate Change Research Institute
- Oregon Department of Geology and Mineral Industries (DOGAMI)
- Oregon Department of Land Conservation and Development (DLCD)
- Other local partners and stakeholder

Like other FHWA funded vulnerability studies, the assessment was guided by FHWA's Vulnerability Assessment Framework. The study involved about 300 miles of highway and proceeded using the following steps:

- "Analysis of projected climate changes and sea level rise
- Qualitative assessment of vulnerabilities and risks from climate impacts,
- Baseline data collection and adaptation strategies developed for high-risk sites,
- Benefit-cost analysis, and,
- Review of regulatory constraints" (FHWA, 2014).

By the end of the study, assessment results showed that nearly all ODOT routes identified as vital for emergency response and economic activity, i.e., Lifeline Routes, are vulnerable to projected climate change impacts (FHWA, 2014). The study team also identified regulatory constraints (e.g., standards and permit applications with multiple agencies) that would make adapting coastal infrastructure difficult. The main risk identified is the possibility of ODOT taking the path of least resistance, which may not always be the best course of action.

TARGETS TO ACHIEVE DIFFERENT LEVELS OF RECOVERY:	
Minimal: (A minimum level of service is restored, primarily for the use of emergency responders, repair crews, and vehicles transporting food and other critical supplies.)	R
Functional: (Although service is not yet restored to full capacity, it is sufficient to get the economy moving again—e.g. some truck/freight traffic can be accommodated. There may be fewer lanes in use, some weight restrictions, and lower speed limits.)	Y
Operational: (Restoration is up to 90% of capacity: A full level of service has been restored and is sufficient to allow people to commute to school and to work.)	G
ESTIMATED TIME FOR RECOVERY TO 60% OPERATIONAL GIVEN CURRENT CONDITIONS:	S
ESTIMATED TIME FOR RECOVERY TO 90% OPERATIONAL GIVEN CURRENT CONDITIONS:	X

Comparison of Target States and Estimated Time for Recovery

Infrastructure Facilities	*Event Occurs*	*0 – 24 hours*	*1 – 3 days*	*3 – 7 days*	*1 – 4 weeks*	*1 – 3 months*	*3 – 6 months*	*6 – 12 months*	*1 – 3 years*	*3+ years*
Central Oregon Zone										
▶ OREGON STATE HIGHWAY SYSTEM										
State Highway System - Tier 1 SLR [1]			R	Y	G			S	X	
Roadways			R	Y	G/S		X			
Bridges			R	Y	G		S	X		
Landslides			R	Y	G			S	X	
State Highway System - Tier 2 SLR			R		Y	G			S	X
Roadways			R		Y	G/S		X		
Bridges			R		Y	G		S	X	
Landslides			R		Y	G			S	X
State Highway System - Tier 3 SLR				R		Y	G		S	X
Roadways				R		Y	G/S		X	
Bridges				R		Y	G		S	X
Landslides				R		Y	G		S	X
State Highway System - Other Routes					R		Y	G	S	X
Roadways					R		Y	G	X	
Bridges					R		Y	G	S	X
Landslides					R		Y	G	S	X
▶ AIRPORTS & AIR TRANSPORTATION										
Tier I - Oregon Airports System										
Redmond Municipal Roberts Field Airport - FEMA		R	S		Y	G	X			
Klamath Falls Airport		R	S		Y	G	X			
FAA Facility			R	Y	G					
▶ OREGON RAIL TRANSPORTATION										
UPRR										
CA/OR State Line to Bieber Line Jct. (Klamath Falls)			Y	G	S	X				

Figure 3.7 Sample output from Oregon DOT vulnerability assessment. (Source: "Oregon Resilience", 2013b)

3.4.9.2.3 Financial Capital

Currently, the agency does not have funding to promote resilience initiatives; however, a long-term funding plan for resilience considerations has been prepared and is waiting on approval from the legislature. As stated earlier, the earthquake vulnerability study was conducted using volunteer hours, and the climate change impacts study was funded by FHWA.

3.4.9.3 Summary

In summary, we see that the nature and type of threats faced by Oregon has created a general sense of awareness resulting in state-led resilience efforts. We also see that this awareness as well as previous disruptive events have caused ODOT to make actual changes in its functional and operational seismic design standards. The agency has also taken steps outside state-led efforts to conduct a vulnerability and risk analysis of climate impacts to its system. This study went beyond only identifying impacts and subsequent adaptation strategies by also identifying possible regulatory constraints that may be encountered during the implementation of physical adaptation features to coastal infrastructure. This feature shows a movement towards strategically identifying factors beyond those that *directly* affect physical infrastructure and hence show evidence of movement toward a sociotechnical approach.

3.5 Synthesis of Case Studies: Summary of Strengths, Weaknesses, Threats and Opportunities

3.5.1 Institutional Capital

From the analysis of the survey results, we form a picture of practices and approaches being used at some specific agencies. Two categories emerge that may be used to describe the posture of cases analyzed. Agencies in the first category of cases have a *proactive* posture. Such agencies have some form of institutional capital, whether at the state, regional or local level, to promote resilience. The second category have a *reactive* posture. Particularly, these agencies try to take advantage of crises to make changes that increase resilience capacity. According to Kingdon (1995), *Windows of opportunity* become available when "... a problem is recognized, a solution is available, the political climate makes the time right for change, and the constraints do not prohibit actions". From the results of the survey, all but three agencies (Maryland, Texas, and California) referred to an impact of a catastrophic event as the main reason for the change in their agency's approach to resilience.

3.5.1.1 Maryland's Executive Orders and Legislation

Of the three agencies that did not cite the "impact of a catastrophic event" as a reason for the agency's current trajectory in terms of resilience capacity building, two have some form of state-level institutional capital directed at greater system resilience. The State of Maryland in May 2015 passed a House Bill 514 which expanded the Maryland Commission on Climate Change (MDCCC) and further solidified its role as a state entity. The legislation was not born overnight. On the contrary, it a result of Maryland's steady and consistent action in response to climate change mitigation and adaptation. The commission was first established in 2007 by Governor O'Malley to develop the state's Climate Action Plan that would provide advice on climate change mitigation and adaption. This was followed by an Executive Order (EO) in 2012 that directed state agencies to consider the risks of coastal flooding and sea level rise in the design of capital projects. Specifically, the EO calls for the Department of General Services (DGS) to update architectural and engineering that govern state structure (both new and rebuilt structures). The DGS' order is prescriptive and requires state structures to be two or more feet above the 100-year base flood level (Georgetown Climate Center, 2013). In addition, the 2012 mandate calls for the Department of Natural Resources in collaboration with the MDCCC, local governments and other agencies to develop citing and construction guidelines for new and rebuilt state structures including public infrastructure improvements such as roads, bridges, and sewer systems (Georgetown Climate Center, 2013). Later in 2014, Governor O'Malley issued another EO which strengthened the MDCCC and subsequently led to the 2015 legislation (Executive Order 01.01.2014.14, n.d.). The bill requires annual reporting of climate change resilience. It also requires state agencies to review planning, regulatory, and fiscal programs in order to identify strategies that enable integration of greenhouse gas goals and climate change impacts including sea level rise, storm surge, and flooding, increased precipitation and temperature, and extreme weather events. Thus, the Maryland State Highway Administration's (and Maryland DOT) work towards increasing transportation system resilience was born out of state-level institutional capital. It should however, be noted that the legislation does not provide any funding towards the State Highway Administration's initiatives. Agencies are expected to work within their current budgets. Figure 3.8 provides a timeline of the Maryland's state actions.

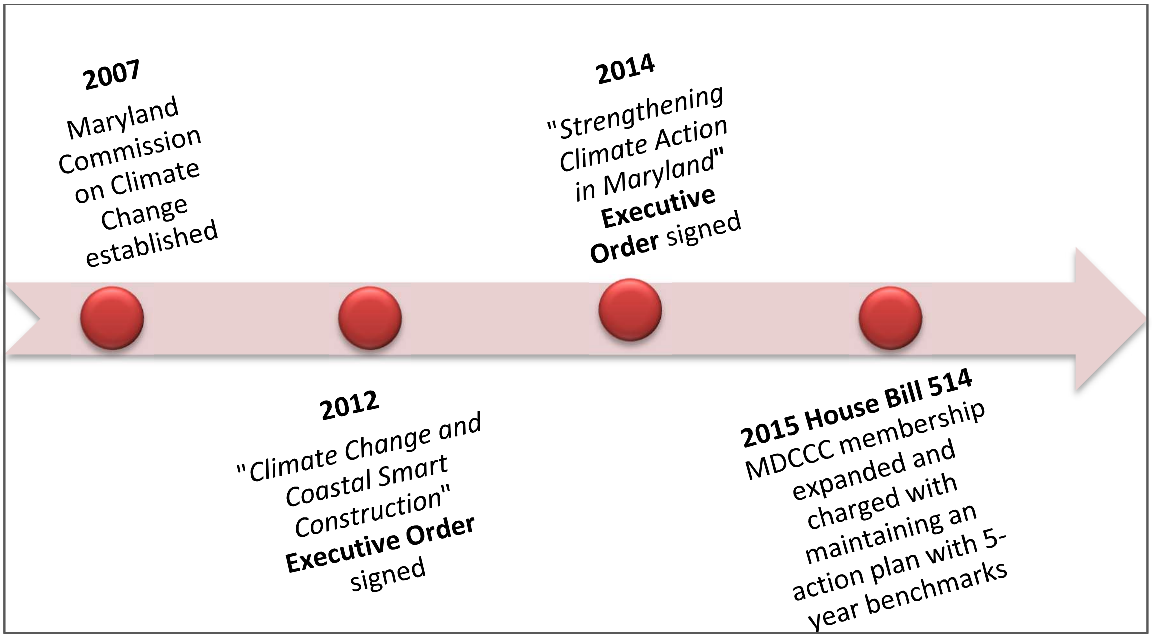

Figure 3.8 Timeline highlighting the development of Maryland's institutional capital for climate change resilience

3.5.1.2 <u>California's Executive Orders</u>

Similar to Maryland, California's progress has been marked by consistent efforts in building state-level institutional capital. California has a number of Executive Orders related to climate change albeit focused on mitigation. The two Executive Orders that go beyond GHG mitigation are EO s-3-05 (in 2005) and EO s- 13-08 (in 2008), both signed by Governor Schwarzenegger (California Climate Change, 2011). The earlier EO signed in 2005 focuses more on emissions reduction by setting GHG targets although it also calls for the preparation of a plan that addresses mitigation and adaptation strategies for impacts on public health, water supply, agriculture, coastline, forestry, etc. It does not specifically call out transportation infrastructure.

The second EO that incorporates adaptation signed in 2008 more specifically calls out transportation infrastructure by requiring the preparation of a report that outlines sea level rise (SLR) vulnerability and an adaptation strategy to those impacts. It also calls for guidance on land-use planning for SLR and other climate change impacts. Furthermore, the EO more broadly requires all state agencies to consider infrastructure vulnerability to SLR, assess and attempt to reduce expected risks, and increase resilience during the planning phase for construction projects being planned in areas vulnerable to SLR. It is worth noting though that provisions are made in Executive Order s-13-08 for projects with Notices of Preparation already filed, routine maintenance projects, or those that were already programmed for construction funding for the five years following the Order (California Climate Change, 2011). California Climate Adaptation Strategy was finalized in 2009 and a subsequent update was released in 2014.

3.5.1.3 Massachusetts' Executive Order

Incidentally, Massachusetts is a state that both selected "impact of catastrophic event" as the reason for the DOT's current work in resilience, and also has a state Executive Order for establishing a climate change strategy. Executive Order 569, signed in September 2016 by Governor Baker, has many similarities to those of California and Maryland. In addition, however, it calls for proactive efforts by state agencies/authorities, municipalities, and regional planning agencies to use adaptation and resiliency measures to address the impacts of climate change. This includes providing guidance for changes needed in current plans, by-laws, regulations and policies (Executive Order 569, 2016). Furthermore, the EO requires that efforts towards this end define "clear goals, expected outcomes, and a path to achieving results" (Executive Order 569, 2016). The final distinguishing element of

Massachusetts' EO as compared to the others is that the EO requires a Climate Change Coordinator to be designated by each Executive Office Secretary. This individual is to be an existing employee of the secretariat and is to serve as the point of contact for all mitigation, adaptation and resiliency efforts. The Coordinator is to assist in the development of the state's Climate Adaptation Plan; conduct a vulnerability assessment of assets to climate change and extreme weather for the respective Executive Office and for each agency within that Executive Office (within two years of the Order); identify adaptation strategies; and finally, incorporate those results into "existing policies and plans for the Executive Office and its agencies" (Executive Order 569, 2016).

The strength of this EO is in its prescriptive nature. By requiring a designated role, stated goals, outcomes and strategies, and specifying a timeline for some of the required activities, state agencies are provided with a clear direction of steps to follow in the process. Nonetheless, the Order still provides agencies ample room for creativity and innovation during implementation.

3.5.1.4 Linkages between Windows of Opportunity and Deliberate Transformations

The three states, Maryland, California, and Massachusetts provide examples of how *deliberate transformations* in the form of state-level institutional capital can serve as a driver for transportation agencies to initiate proactive efforts for enhancing system resilience. This is not meant to detract from the fact that connections exist between and among states that have experienced some major disruptive events (*reactive posture*) and those that have taken *proactive* action towards increasing resilience (e.g., Massachusetts). Connections exist, but some states are still more proactive than others (e.g. Louisiana vs.

Massachusetts). Using the adoption of climate action plans by states as another example, it can be inferred from current progress that coastal states are more likely than others to have finalized and adopted state-level adaptation plans (Figure 3.9). While understanding the detailed extent of this relationship is beyond the scope of this research, it is safe to say that progress towards enhancing system resilience is spurred by states becoming more aware of threats to their systems, their vulnerabilities and the consequences of inaction. As can also be seen from Figure 3.9[8], not all states that have experienced catastrophic/major disruptive events have adopted adaptation plans[9] (e.g., Texas, Louisiana, and South Carolina). Finally, although system resilience goes beyond climate change mitigation/emissions reduction initiatives, what these three states show is that places that have the existing groundwork may more readily/easily evolve into holistic resilience efforts/programs.

[8] Alaska has adopted a state-level adaptation plan. Hawaii's adaptation plan is to be completed by the end of 2017, however, local/regional plans exist

[9] It should also be noted that not all states that have adopted adaptation plans are successfully following through to achieve the plans' stated goals (Georgetown Climate Center, n.d.).

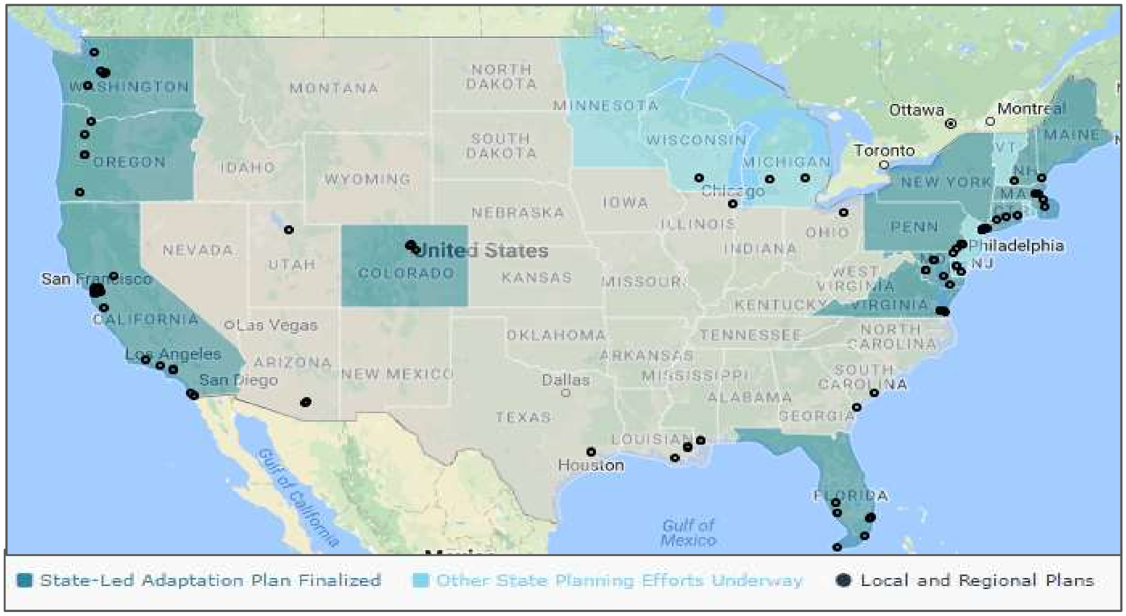

Figure 3.9 Map showing states in continental US that have finalized and adopted adaptation plans. (Source: Georgetown Climate Center, n.d.)

3.5.2 Organizational Capital

Another important theme extracted from the survey results relates to the human capital, policies and processes within agencies for matters regarding system resilience. Firstly, with regards to human capital, it is understandable that not all agencies may have the necessary resources to have dedicated personnel. However, having an individual or group responsible for coordinating resilience efforts is essential during the initial stages of "resilience maturity" at agencies. As the resilience initiatives at agencies continue to grow, roles and responsibilities become institutionalized and would no longer rely on championing efforts by a few interested employees. A quote from the Broward MPO further explains this: *"In several cases, the intergovernmental coordination turned out to be based on individuals more than on institutions. Specifically, there were agency staff on technical committees* *who participated based on personal interest and not on assigned roles. When these individuals moved to new organizations, the agencies they previously represented did not consistently assign replacement staff to take their places. This left us in a scramble too often."* In addition, practices are more easily assimilated into standard operating procedures when institutional learning is prioritized, which assigning roles and responsibilities does.

Of the agencies surveyed, ABAG is the only one to have dedicated personnel for coordinating resilience issues. The MD SHA has a Climate Change Program Manager that coordinates the agency's resiliency efforts, but this individual also has additional responsibilities. Iowa DOT is also in the process of forming a Resiliency and Sustainability Team that will formally address system resilience within the agency. Table 3.6 sheds light on the various job titles for the agency personnel in charge of coordinating resilience efforts.

Table 3.6 Agency titles for personnel designated to coordinate resilience efforts

Agency	Resilience Designee
CDOT	Performance and Asset Management Branch Manager
FDOT	Growth Management Coordinator
Iowa DOT	Office Director for Location and Environment
MDSHA	Climate Change Program Manager
MassDOT	Environmental Management and Sustainability, Supervisor
Oregon DOT	State Bridge Engineer
ABAG	Resilience Planner
MTC	Transportation Planner
NCTCOG	Transportation Planner
New Orleans	Sustainability Planner

Similar to the impacts that state-level legislation and Executive Orders have on resilience building, is the institutional capital that agencies have in the form of policies, standards or regulations for agency-wide operations. Few of these were identified from the survey results although some agencies had other important attributes. Strategically addressing resilience may provide the initial impetus for some work in this area. The survey sought to identify which agencies have taken a strategic approach toward enhancing system resilience. The responses show that agencies are at different levels in terms of resilience planning. For example, ABAG has no stated strategic objective, but it's mission statement, "[t]he ABAG Planning and Research Department works with local governments and stakeholders to develop and implement *innovative solutions for issues involving land use planning, housing, transportation, environmental climate change, earthquakes and disaster resilience, and economic equity,*" alludes to the agency's commitment to the Bay Area's resilience (ABAG, 2014). There is therefore an opportunity to align the mission with strategic goals, objectives, performance measures, decision criteria and other elements within the planning and decision-making process to strengthen resilience building capacity.

On the other hand, the Florida Transportation Plan, which covers all modes of transportation, provides a goal and supporting objectives for achieving "agile, resilient and quality transportation infrastructure" (FDOT, 2015). The listed objectives are followed by emphasis areas for achieving the stated objectives. Lastly, three indicators are selected for this objective: bridge, pavement and *other* infrastructure condition. This plan serves as a good example for ways in which resilience thinking can be incorporated into strategic planning. That is (1) identifying a clear goal, (2) selecting objectives to follow through with, and (3) identifying indicators to measure progress. The first two steps form the visioning process of the performance-based planning process, but opportunities also exist to improve plan effectiveness and system performance by also incorporating feedback mechanisms. This consists of setting targets, tracking progress and reporting successes.

Not clearly articulating the three processes (target setting, tracking, and reporting) in the FTP or alluding to them could prevent consistent and systematic progress.

The Caltrans Strategic Management Plan for 2015-2020 is another example of how resilience can be considered strategically and also offers evidence of how understanding the nature and severity of threats (in this case climate change impacts) influences the urgency to action and nature of approach used. The plan lists a strategic objective and associated performance measures for assessing resilience at Caltrans (the Resiliency Score is still in development) (Caltrans, 2015).

California and Florida are not the only states working toward a strategic approach to transportation system resilience. Agencies like Colorado and Iowa DOT both stated that they've begun to consider how to incorporate resilience considerations into decision making. Colorado DOT is currently developing on a multi-objective decision analysis methodology in which resilience will be incorporated as a decision criterion. Similarly, MassDOT currently uses flooding information to inform project design and maintenance activities. The agency uses a project's *proximity to coast* and location in *flood prone areas* as factors in project prioritization.

In all the latter examples, we see that the agencies are working toward incorporating resilience thinking into business processes but have not yet completely achieved it. Incorporating resilience efforts into existing structures also promotes institutional learning which in turn ensures that agencies maintain and build on past knowledge, preventing resource waste from effort duplication and supports consistent progress towards resilience capacity. Consequently, long range planning, transportation asset management planning and the Transportation Improvement Program are all established means that can be used in this regard. Additionally, as shown by the FTP and Caltrans examples, progress in using existing structures seem to be higher in those agencies that have experienced significant disasters and associated losses or have developed a sense of urgency from a greater understanding system threats and potential consequences. The Caltrans and FTP approaches are examples that other agencies can learn from. However, opportunities still exist to enhance the resilience planning process.

3.5.2.1 Role of Performance-Based Planning in Planning for Resilience

As stated earlier, the FTP incorporates resilience considerations in its plan, but does not completely adopt performance-based planning process in the approach. Performance based planning is "an approach to applying performance management principles to transportation system policy and investment decisions" (Middleton and Regan, 2015) and is required by law (MAP-21) for MPOs and state DOTs. However, the seven national goals that this process is required to feed into do not explicitly include system resilience. Nonetheless, the Fixing America's Surface Transportation Act (FAST ACT) signed into law in December 2015 expands the scope of MPO planning considerations to include strategies/projects that improve transportation system resiliency and reliability (FHWA, 2016b). Therefore, agencies can assume a proactive posture towards incorporating resilience thinking into performance-based planning by building on an approach similar to the Caltrans approach. A strategic approach also allows agencies to more intentionally align resilience planning efforts with broader efforts such as hazard mitigation planning and comprehensive transportation planning. The performance-based planning process is summarized below (Middleton and Regan, 2015):

- *Visioning*: The first step of the process will require agencies to define what resilience means for their systems. For example, for the MTC, resilience means being able to better respond to acute shocks and chronic stresses and to transform following a disruption. This should be followed by goals and objectives that will help realized the agency's vision. It is important for this step to capture the needs of a diverse group of stakeholders.
- *Performance measures*: Agencies should then identify performance measures that can be used to assess its progress. Generally, performance measures are categorized as input, output, or outcome measures. Performance measures selected should be holistic, i.e., cover different types of agency capital and should also match the scale of use.
- *Target setting and identifying priorities*: Corresponding targets should be set for performance objectives. Targets must be prioritized into short, medium and long term to enable efficient use of resources.
- *Monitoring and evaluation mechanisms*: Mechanisms which require review and reporting of progress towards building resilience capacity are essential for agencies to achieve desired outcomes. Regular evaluations provide information that feeds back into the other elements of performance based planning. This could include reviewing performance measures for efficacy, adjusting priorities or changing targets.

3.5.3 Technical Capital

In this research, technical capital refers to the technical knowledge and expertise an agency has and how it uses it to protect its physical assets. From the survey results, we see many similarities in the way agencies build this type of capital for resilience capacity. One such strategy mostly used in the early stages of exploring resilience at an agency is conducting vulnerability or risk analyses. These studies usually follow similar set of steps that end with the identification of strategies for enhancing an asset or piece of infrastructure. Now, three main opportunities can be identified to enhance this process and are discussed below.

Firstly, once strategies for enhancing resilience capacity for assets are identified during a vulnerability/risk study, further investigation could be conducted into which other capital areas would affect those outcomes. That is, identifying which other capital areas that when jointly enhanced with the physical adaptation strategy would yield more holistic and effective results with lasting impact. Needless to say, this provides a means of conducting a project-level analysis using a sociotechnical approach. Figure 3.10 shows an example adaptation strategy using a raised bridge deck and going through some sample questions that could be asked as one explores related enhancements in the three other capital areas (institutional, organizational and financial). Evidence of this approach is seen in Broward County MPO's vulnerability study. Here, the study results included relative costs for the sample adaptation strategies recommended. Therefore, the team could review the recommended strategies and include related improvements from additional capital areas that will support the physical adaptation. Again, in Oregon's climate vulnerability study, regulatory constraints that would make adapting coastal infrastructure difficult were identified (i.e., standards and permit applications with multiple agencies), albeit solutions to the identified constraints were not also identified.

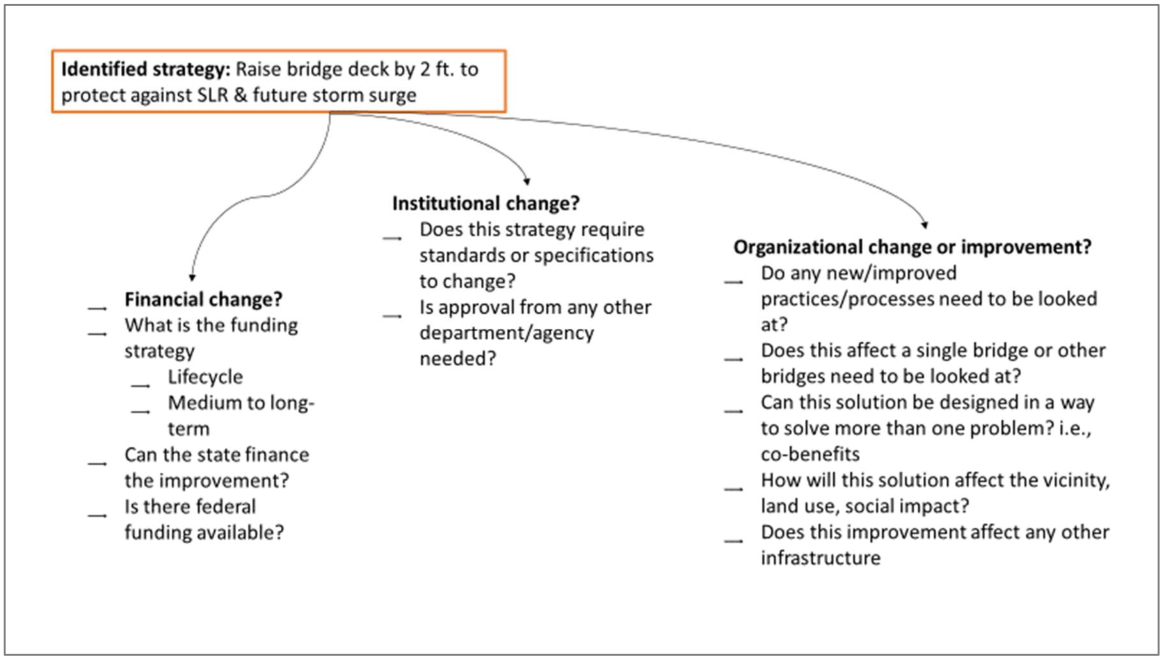

Figure 3.10 Project-level analysis using a sociotechnical approach

Secondly, in selecting metrics for assessing resilience, a cue can be taken from the literature on energy resilience. When majority of metrics or the main metrics selected for assessing a system's resilience are *outcome* or *social welfare* metrics, social needs of a community are taken more into consideration (Sandia, 2015). Accessibility metrics, for example, are often able to capture the transport system's impact on social welfare, as opposed to *purely* system performance measures. An example of such a metric is the number of people able to work "X" number of days after a catastrophic event. This metric can be contrasted to the FTP's resilience metrics of bridge and pavement condition in its effectiveness to put social welfare at the forefront of resilience discussions. The outcomes-based approach is seen in Oregon's transport system vulnerability study as shown in the case study (FHWA, 2014).

Once such outcome metrics are identified, one can then backtrack to identify the capacities necessary to fulfill that outcome. It is important to note that the scale at which outcome metrics are most useful is the project-level, as opposed to the system level where the unknown variables far exceed the known system variables.

Finally, another important characteristic observed from MassDOT that promotes institutionalization of resilience efforts is the use of asset identifiers consistent with the agency's asset management database. This strategy, among others, is contributed to the ongoing change in the agency's general decision-making approach, and this is what should ultimately occur for all agencies.

3.5.4 **Financial Capital**

With regard to financial capital at transportation agencies for enhancing resilience capacity, having separate funding is not the popular approach. This makes sense from the standpoint of integrated performance-based planning and decision-making. Even in cases where Executive Orders or legislation is present, as is the case for Maryland and Massachusetts, agencies are required to work within their current budgets to pursue resilience enhancing strategies. When survey respondents were asked about how repairs, renewal and recovery of assets affected during disruptions are funded, FHWA/FEMA emergency relief /disaster funding was the prevalent answer. For Colorado DOT, a new approach to risk and resilience, which is still under development, differentiates between types of treatment for assets damaged during extreme events: *in-kind* versus *betterment* replacement. According to the agency, in-kind replacement is to be paid for with federal funds and any betterment will have to be funded using alternative funding. Colorado DOT also recently petitioned the state's Transportation Commission (an 11-member board of governor appointees) and received funding approval to conduct a risk assessment on its I-70 corridor.

Unlike Colorado DOT that sought state funding for its risk assessment, nine out of the 11 responding agencies used federal funds, either partially or fully, to fund their vulnerability and/or risk assessments. This outcome is not surprising. According to the ABAG representative, almost all resilience work is funded by grants. Massachusetts DOT on the other hand funds resilience strategies on either a case-by-case basis, i.e., during the design stage or when a need arises. Further along in addressing funding is Oregon DOT, which stated that the agency has prepared a long-term funding plan and is waiting on approval.

Due to the funding issue, many agencies find partners with similar interests to collaborate with on resilience projects. This approach does not only allow agencies to pool funds, it also allows them to bring together nodes of expertise on such projects. Sharing data, personnel and other resources results in effective processes and better outcomes as all collaborators have a stake in the said outcome. Table 3.7 lists organizations the transportation agencies surveyed have partnered with in their resilience enhancing efforts.

Table 3.7 Agency Collaborations for physical resilience

Agency	Partners
Bay Area	FHWA, Adapting to Rising Tides, BCDC, NOAA Coastal Services Center, CalTrans District 4
FDOT/Broward MPO	Miami-Dade County, Monroe County, Palm Beach County, FHWA
MDSHA	FHWA
MassDOT	FHWA, NOAA, EPA, USGS, ACOE, local agencies & NGOs
Oregon DOT	USCG, Dept. of Aviation, local agencies, consultants, state rail/transit division
NCTCOG	FHWA, UTA
Iowa DOT	FHWA

3.6 Summary of Survey Findings

This chapter presented the nine case studies involving 11 transportation related agencies. The case studies presented analyses of the various resilience capacity building strategies being implemented and showed evidence of how these agencies are evolving toward sociotechnical approaches in certain aspects of their efforts. Specifically, the agencies were analyzed using a capital-based approach, thus, efforts towards enhancing system resilience were categorized under institutional, organizational, technical and financial capital.

The cases were then synthesized to extract key characteristics and unique attributes that promote sociotechnical resilience thinking at agencies across the four capital types. For institutional capital, agencies like MDSHA, MassDOT, ABAG and MTC, that have the presence of some state or agency policies produced associated benefits in other capital areas. For example, MTC's resilience worked was birthed out of pre-existing efforts on greenhouse gas emissions reduction programs, which was in turn directly a result of the passage of Senate Bill 375. This momentum eventually resulted in joint efforts among Bay Area agencies and Caltrans to conduct vulnerability assessments of transportation infrastructure in order to develop strategies for adaptation. Similarly, MDSHA's capability of monitoring and reporting progress towards resilience efforts, which shows maturity in organizational capital, is directly linked to the agency's responsibility to annually report such efforts to the state's Commission on Climate Change (MDCCC) and the passage of House Bill 514. Finally, another strategy that contributes towards the development of institutional capital identified in the cases was from ABAG. This was the presence of efforts to align/coordinate resilience planning across sectors. Now, the difficulty in achieving this attribute in certain types of transport agencies does not go unnoticed. For example, as an association of local governments, ABAG is uniquely placed to play the role of convener and coordinator. However, this can also be achieved in MPOs and to a lesser extent, at DOTs.

In terms of organizational capital, agencies considered to be at higher levels of maturity are those that showed evidence or progress towards incorporating resilience considerations in existing agency structures (e.g., asset management plan, long range plan, etc.). Again, agencies at higher levels of maturity had dedicated or designated individuals formally recognized by the agency working on resilience programs. This was also related to creating buy-in and an understanding of resilience thinking within the agency. This in turn contributes to institutionalizing resilience thinking within the agency showed by looking at a project's lifecycle (planning, construction, operation, maintenance, renewal and/or decommissioning) and making decisions at each stage that promote the creation of resilient outcomes.

Finally, for technical and financial capital, many of the surveyed agencies had similar characteristics in terms of strategies adopted and capabilities possessed. Technical capital varied from high-level qualitative vulnerability studies in some agencies, to in-depth and risk based analysis of vulnerabilities in other agencies. Agencies such as MassDOT also show process integration by actively involving their asset management programs and linking asset data to vulnerability and risk information developed. This was however the exception and not the rule. Most agencies conducted studies as separate projects (mostly because these were pilot studies), outside regular agency business activity and not yet impacting their current asset management processes. Similarly, agencies surveyed that showed presence of resilience initiatives mostly relied on external grants or volunteer agency hours to fund such activities. Some agencies have also begun to fund initiatives on a case by case basis. Nonetheless, a sentiment that resonated through almost all the survey responses, was the desire to eventually incorporate resilience considerations in project prioritization. Some agencies stated that such prioritization processes were either in development (e.g., Broward MPO, Colorado DOT and Iowa DOT) or already existed (e.g., MassDOT and NORPC). Incorporating resilience in project prioritization for funding or in lifecycle cost analysis for asset management were considered higher levels of maturity than other strategies for enhancing financial capital.

The subsequent chapter presents a framework developed using both key concepts from the literature identified in Chapter 2, as well as the agency key attributes identified in this chapter. Attributes and strategies identified across the four capital types are presented in the subsequent chapter in a form of a maturity scale. The maturity scale orders these attributes and strategies in a way that shows systematic progression from one stage to another.

CHAPTER 4. DEVELOPMENT OF THE SOCIOTECHNICAL TRANSPORTATION RESILIENCE FRAMEWORK (STRF)

4.1 Introduction

This chapter describes the second phase of this research. It presents the development of a framework for transportation resilience planning using a sociotechnical approach (i.e., one that formally considers human, organizational and institutional factors in addition to technical factors in its design). The chapter then proceeds to describe feedback received from three transportation agencies asked to apply and review a self-assessment tool developed from the framework. The chapter ends by presenting a revised framework and tool based on the practitioner input.

4.2 Conceptual Framework Design

4.2.1 Foundational Concepts

From the literature, this framework adopts the concept of stability at multiple equilibria found in ecological resilience, which is founded on the idea of shifting system regimes. Therefore, transport system resilience in this context is based on this fundamental criterion: the ability of a system to change in order to persist (as per Holling and Gunderson, 2002). The inquiry on agency resilience experience was therefore based on the main research question exploring whether as agencies mature in their dealings with hazards, they naturally move from largely technical to sociotechnical approaches. In other words, do agencies located in communities or states that have experienced catastrophic events resulting in loss of life or significant damage to property naturally evolve toward sociotechnical approaches as compared to agencies that have not experienced such events nor been impacted by teaching moments from others' disasters? Subsequently, the following questions guided the framework development (as discussed in Chapter 2):

- Do transportation agencies and the systems they oversee have adaptive cycles?
- Do agencies that have dealt with major natural disasters show some adaptive behavior with regime shifts? If so, what do these shifts look like? How can these regime shifts be characterized in terms of capital-based regimes?

Using the concepts of stability and regimes (previously discussed in Chapter 2) in an expanded paradigm for an agency's maturity in resilience capacity building, the survey was developed and used to study an agency's resilience capacity building in order to extract an evolving maturity process for handling hazards and building system resilience in a sociotechnical manner. The survey results were therefore used to determine the types and relative levels of capital (institutional, organization, technical and financial) that can constitute maturing regimes for system resilience. These maturity regimes (next attainable regime) may be accessed either through *forced* or *deliberate* action, where forced actions are those initiated reactively because of some external condition or circumstance (e.g., natural or man-made intervention). Deliberate actions on the other hand, are those initiated proactively by the will of system actors (in this case, transport agencies). Thus, to reach the next attainable regime, there is the need for forced or deliberate action.

4.2.2 **Framework Description**

The sociotechnical resilience framework is presented in two parts: Figure 4.1 and Table 4.1. Figure 4.1 is a diagrammatic representation of the concepts presented in the framework and should be viewed for a conceptual understanding, whereas the details of the maturity scale are provided in Table 4.1. Both the figure and the table show four types of agency capital that affect system resilience (institutional, organizational, financial and technical capital). In Figure 4.1, capital types are represented by the first initial of each capital type, and maturity stages (regimes) are represented by subscripts. In the table, columns represent capital types and the rows represent maturity stages. The following points provide important considerations for using the framework:

1. The four stages represent a gradual progression in maturity in terms of the resilience capacity of agencies, sociotechnically. It is also important to note that the framework is not intended to measure or rate an agency's resilience; rather, it serves as a scale which agencies can use to assess the relative maturity of their resiliency-building endeavors, and systematically work toward enhancing their resilience capacity by reaching for the next desirable stage.
2. The different capital types in each stage do not necessarily occur simultaneously. In assessing an agency's position on the maturity scale, one may find that the agency may be at Stage 1 in terms of its Financial Capital, but Stage 2 in terms of the development of its Organizational Capital. Thus, an agency can invest in progressing within a particular capital type based on its predetermined strategic priorities, and based on its strengths, weaknesses, opportunities and threats.
3. The stages described do not constitute a rigidly prescribed process for enhancing system resilience capacity; therefore, while some agencies may mature by progressively moving from one stage to the subsequent one, others may leapfrog

from one to the next, based on agency priorities, available resources for growth, damages from disasters, and other factors.

4. Lastly, the framework is meant to be a tool that agencies use to assess the maturity of resilience capacity building in their agencies; thus, it also doubles as a gap analysis and planning tool, that may be used to assess growth opportunities in the different capital areas and develop guidance on next-level objectives for resilience capacity building. on what attributes to aspire to.

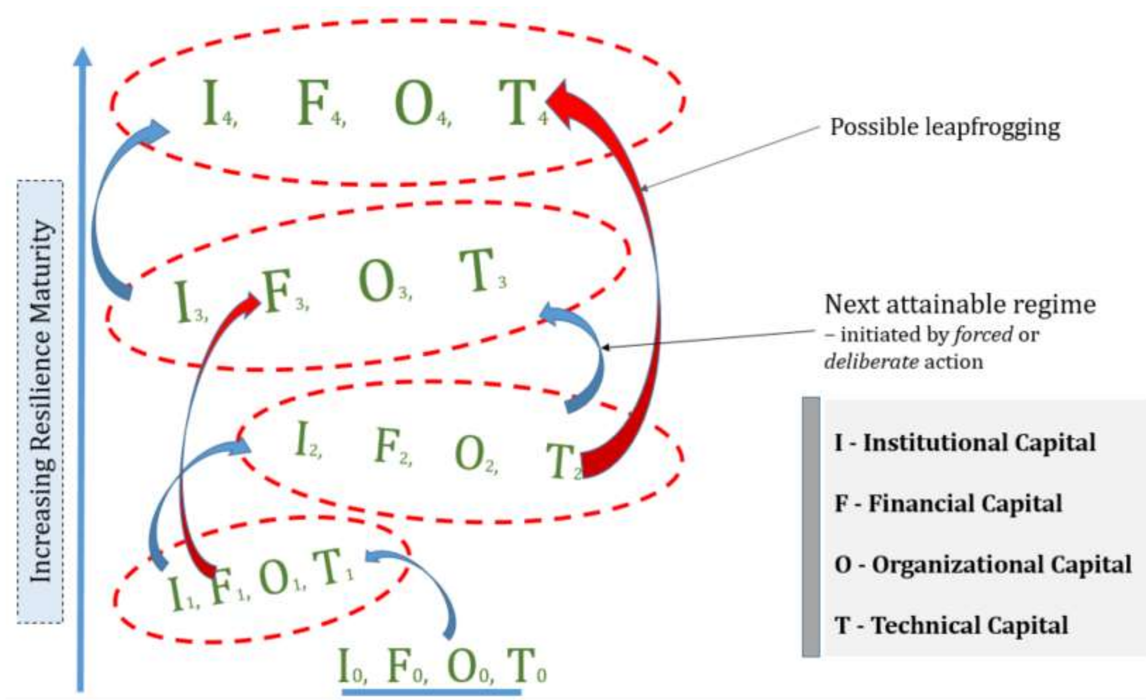

Figure 4.1 Diagrammatic Representation of Sociotechnical Transportation Resilience Framework (STRF)

Table 4.1 STRF Review Table

	Institutional	Organizational		Technical	Financial
		Human capital	Business processes & practices		
Stage 1	- No formal agency policies explicitly address system resilience - Sustainability policies may be present at agency. E.g., NORPC - No external state policies present that impact transport agency	- Champion efforts present to raise awareness in agency	- Plans that address aspects of resilience may be present. E.g., initial climate action plans such as Broward County Climate Action Plan, 2010 - High level resilience planning, e.g., general impacts study, general state-wide resilience planning - Emergency response and recovery processes present	- Awareness of hazards (e.g., climate impacts) and taking initial steps to mitigate. E.g., travel demand management (TDM), developing and instituting green /sustainability design	- No institutionalized approach/process for considering financial implications/needs for resilience - Use of external grants/funds for initiatives
Stage 2	- Some hazard specific policies that enhance resilience - External state action influences agency posture and actions. E.g., executive order, legislation, state resilience committee or other external requirements.	- Champion efforts still critical - Political will garnered at agency, i.e., senior leadership support	- Resilience priorities identified; however, may not be explicitly stated in agency planning documents, e.g., MassDOT - Hazard specific plan(s) or program(s) developed with detailed impacts analysis and adaptation strategies identified, e.g., ABAG-earthquakes, CDOT – Geohazard mgnt. Program. - May include some level of external collaboration with strategic partners	- Resilience focus on infrastructure hardening - May have conducted or planning to conduct pilot study on risk or vulnerability for certain assets - Active asset management program, but does not explicitly incorporate resilience considerations	- Initiatives still rely on grants - May secure some state legislature funds for initiatives, e.g., CDOT

Table 4.2 STRF Review Table (continued)

	Institutional	Organizational		Technical	Financial
Stage 3	- Guidance developed for changes in current plans, regulation or policies to support resilience thinking at agency (or state) (e.g. EO 569, MA) - Framework provided for possible institutional barriers (including inter-agency barriers) that may be faced in implementing resilience building strategies (*ODOT-barriers identified)	- Raised employee awareness - Formal, dedicated or designated person/team responsible for resilience planning or initiatives., e.g., Formal team-ABAG & Iowa DOT, designated person – MassDOT, Broward MPO	- Resilience considerations incorporated into project planning, e.g., hazard mapping - Monitoring and reporting of initiatives adopted, e.g., MassDOT - Coordination and/or unification of efforts with external agencies, e.g., ABAG	- Concrete steps taken to incorporate resilience considerations into existing asset management program, e.g., results of risk/vulnerability studies	- Case by case consideration of funding for adaptation strategies, e.g., MassDOT
Stage 4	Alignment of transport resilience planning and resilience planning in other sectors (e.g., land-use, housing, etc.) to streamline efforts and realize co-benefits.	- Champion effort no longer needed - Buy-in and understanding of resilience thinking established throughout agency - Formal agency positions (partial/full) dedicated to building resilience capacity within agency.	- Strategic goals and objectives for resilience capacity clearly identified - Resilience thinking institutionalized at agency, i.e., resilience considerations incorporated into project development process (i.e., planning, construction, operation, maintenance, renewal/decommissioning) - Resilience thinking reflected in main agency plans: o Asset Management Plan (TAMP) o Long Range Plan (LRTP) o Transport Improvement Plan (TIP)	- Resilience considerations go beyond direct transport assets, i.e., supporting infrastructure, (e.g., IT, ancillary assets) and subsystems/interdependent systems (power, water, etc.)	- Resilience considered in lifecycle costs analysis - Resilience considerations included in project prioritization in addition to other priorities such as safety, costs, etc. e.g., CDOT (in development)

4.2.3 **Linking Capital Types to Resilience Attributes**

From the resilience literature discussed, many characteristics of resilient systems were identified including robustness, redundancy, flexibility, rapidity, resourcefulness, preparedness, etc. It was also discussed that the many characteristics can be traced to three main attributes: persistence, adaptability and transformability. In reviewing the maturity scale presented in the previous section, we can draw inferences about the various capital types and maturity stages, and their relationships to these resilience attributes and characteristics. Figure 4.2 shows a tree diagram of the four agency capital types investigated in this research and their relationships to various resilience attributes discussed in the literature.

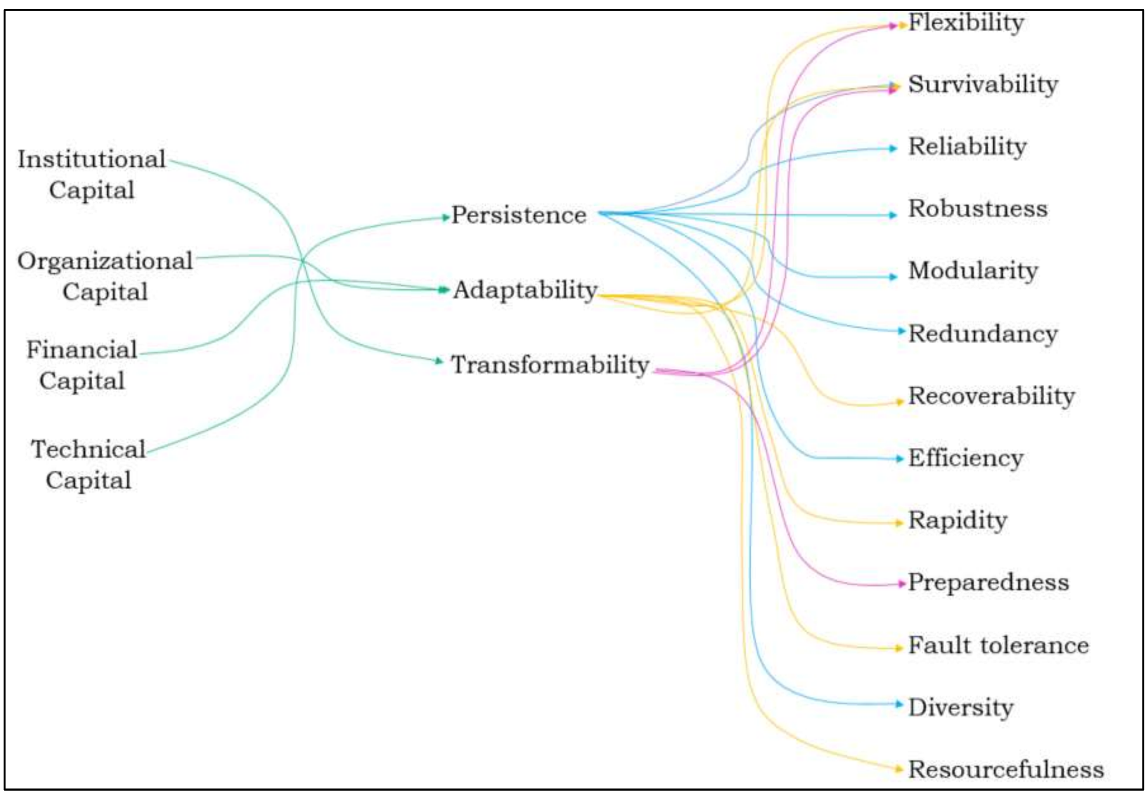

Figure 4.2 Tree diagram showing agency capital mapped to resilience attributes

The rate at which uncertainty overwhelms an organization is related more to its internal structure than to the amount of environmental uncertainty" (Carvajal, 1983).

Firstly, intuitional capital that enhances system resilience provides the regulatory environment that enables transformability, which ultimately shows a system's possession of flexibility, preparedness and survivability. Flexibility in the sense that, an agency's institutional capital supports the enactment of changes that allow for movement from one stage (regime) to another when existing conditions are no longer desirable. This also ultimately ensures survivability of the system. Lastly, transformability promotes preparedness by means requiring the necessary regulatory structures to support deliberate and forced transformations.

Secondly, adaptability, a core principle in both socio-technical systems theory and resilience theory, is enhanced by building organizational and financial capacity. Carvajal (1983) puts it this way: "the rate at which uncertainty overwhelms an organization is related more to its internal structure than to the amount of environmental uncertainty." Organizational and financial capital translate into many of the main attributes of system resilience, including resourcefulness, rapidity, fault tolerance and flexibility.

Lastly, technical capital builds resilience capacity by promoting system persistence. That is, ensuring that the system can absorb a certain level of baseline stress. Working towards persistence means, system actors ensure robustness, redundancy, efficiency, and diversity among others. Thus***, persistence is about maintaining what you have despite external forces; adaptability is about maintaining service provision despite internal and external change; and transformability is about ensuring survival by enacting change***.

4.2.4 **Agency Capital and Resilience Maturity**

4.2.4.1 Institutional Capital

At the early stages of resilience maturity, institutional capital does not explicitly address system resilience. However, existing policies, e.g., sustainability, may be present that contribute to resilience capacity. For example, although the New Orleans Regional Planning Commission (NORPC) does not explicitly address resilience in this way, there is a heavy focus on green practices and sustainability initiatives, which can contribute to resilience capacity. Colorado DOT is also another example of stage 1 institutional capital with no mention of resilience related policies at the agency level.

As the agency progresses in building institutional capital (stage 2), some hazard specific policies may be put in place that contribute to resilience capital (e.g., Oregon's seismic functional design criteria). However, these policies may not be multidimensional and only address certain needs. Keeping in line with sociotechnical system theory that advocates for joint optimization of system components for organizational performance, policies designed to build resilience through institutional capital should address the technical and organizational sides of the issues they seek to address. Stage 2 also includes agencies located in states or regions with regulatory structures that influence agency posture (such regulatory environments do not necessarily mean a top-down impact, as we are cognizant of the fact that many state and federal policies are the result of efforts at lower levels). Although such transportation agencies may not have explicit policies, they are affected by legislation, executive orders or other external factors, which lead them to take action in building resilience capacity. Examples include Iowa's Flood Mitigation Program created in 2012, as well as executive orders passed in California EO in 2008 and Maryland in 2012.

As the agency continues to mature (i.e., Stage 3), explicit guidance that supports resilience thinking in the agency is developed. Such guidance provides direction for the necessary changes in current plans or policies that need to occur. Massachusetts' EO 569 signed in 2016 by Governor Baker directs state agencies (including the DOT) to provide such guidance for its current plans, by-laws, regulations and policies (EO 569, 2016). Although full implementation of this has not yet occurred at MassDOT, once completed, will have a relatively higher level of institutional capital. Lastly, stage 4 describes what many communities aspire to – aligning inter-sectoral resilience initiatives and planning to streamline efforts and achieve co-benefits.

4.2.4.2 Organizational Capital

Based on the data collected in this research, the initial stage of resilience maturity at transportation agencies is characterized by a general awareness of infrastructure resilience propagated by a champion. This individual's work may not necessarily be a delegated role; however, interest in the area and understanding the needs of the organization causes this individual to start to work on resilience building initiatives at the agency. Such agencies in the early stages also generally have emergency response and recovery procedures already in place, as is necessary for most public agencies. Mostly notably, agencies at stage 1 will have an initial plan that addresses aspects of system resilience. The most common is the climate action plan. Such plans are usually the first step for many agencies and may contain information on possible hazards that could impact the transport system and potential consequences of such events. An example is the Broward County Climate Action Plan published in 2008. The Metropolitan Transportation Commission (MTC) in the Bay area was also at stage 1 about three to four years ago when its primary focus was on meeting greenhouse gas emissions reduction targets. The MTC instituted mitigation initiatives such as travel demand management programs, car sharing and shuttle services.

Over time, the MTC's organizational capital matured to stage 2 with the identification of resilience priorities. Shifting from only mitigation to include adaptation, the agency began to work on addressing the threats of sea level rise in the region. Colorado DOT (CDOT) is another example of a stage 2 agency. Although the agency does not have an explicit resiliency plan with associated goals and objectives, it has an active geohazard management program. CDOT does possess stage 1 attributes having a high-level, state-produced climate action plan and a resiliency framework (both published in 2015). However, these documents only give a high-level view of climate change impacts on transportation. A detailed transportation resiliency study has not yet been conducted. By stage 2, political will at the agency is usually garnered with support from its senior leadership. Champion efforts still critical here.

By stage 3, agencies have started to incorporate resilience considerations into project planning. MassDOT, for example, does this by mapping hazards in its asset management program. MassDOT has also identified resilience priorities, although these are not documented in its planning documents. The MDSHA has also began to use sea level rise mapping for project review and some decision making at the planning and design stage.

In terms of human capital, MassDOT has a designated person, i.e., supervisor for the Environmental Management and Sustainability Office.

By stage 4, champion efforts are no longer needed as such roles will have become formalized, e.g., ABAG, or in the process of being formalized (e.g., Iowa DOT). There is also buy-in and an understanding of resilience thinking throughout the agency. Employees no longer view resilience efforts as separate initiatives outside their work, but as an integral part of the way the agency plans, operates and maintains its system. Strategic goals and objectives are also clearly identified and articulated in the agency's main planning documents. There is also evidence of resilience thinking in the project development process (i.e., planning, construction, operation, maintenance and renewal/decommissioning).

4.2.4.3 Technical Capital

From the literature and case studies reviewed, technical capital seemed to be the most common entry point for agencies starting to build up resilience capacity. The initial stage, stage 1, is characterized by an awareness of potential system threats and taking initial steps to mitigate them. As the agency matures, there is a shift from solely focusing on sustainable/green design practices to an inclusion of infrastructure hardening to common threats (stage 2). Agencies at stage 2 may have also conducted or planning to conduct vulnerability or risk assessments for parts of their infrastructure. The focus here is solely on ensuring that infrastructure can withstand the impacts of known threats when they occur. Agencies at stage 2 may also have active asset management programs, but do not explicitly incorporate resilience considerations. Many of the DOTs reviewed fall into this category. These are agencies that have perhaps conducted some risk assessments through pilot projects and are working towards translating the study results into strategies that can be implemented in their asset management programs. Examples include Maryland State Highway Authority (MDSHA), Oregon DOT and Iowa DOT.

MassDOT is shows the characteristics of a stage 3 agency in terms of technical capital. The agency is taking concrete steps to incorporate resilience considerations into its asset management program. The agency also exhibits attributes of good institutionalization. In conducting its risk assessment, the agency used asset identifiers that are consistent with its current asset management system, making it easier to integrate results from the study into the current system.

Finally, by stage 4, resilience considerations go beyond direct transportation assets. The agency starts to incorporate supporting infrastructure (e.g., IT and ancillary assets), subsystems and interdependent systems (e.g., power, water, etc.). Resilience considerations at this stage are also incorporated throughout the infrastructure lifecycle.

It is important to note that although the four capital areas may develop at different paces over time, developing technical capital simultaneously with institutional, organizational and financial capital is necessary to achieve the benefits of joint capital optimization. A comparable amount of growth in the other capital areas will further strengthen and institutionalize technical capital growth.

4.2.4.4 Financial capital

Financial capital mainly deals with an agency's ability to use its financial resources to build resilience capacity. During the early stages of developing this type of capital, an agency typically has not identified an approach or process of considering the financial implications of resilience capacity building. As the agency becomes more aware of potential system threats, efforts to secure external funds through grant programs or other means may begin to take place. At stage 2, the agency still relies almost entirely on grants (e.g. ABAG), but may also work toward securing state funds (e.g., Colorado DOT). Over time, and as other capital areas grow (e.g., technical capital), the agency may move to stage 3 where it begins to use some internal funds towards resilience initiatives. This could be a case by case approach where the agency considers funding for individual projects based on some critical identified needs (e.g., MassDOT). Eventually, the agency starts to incorporate resilience considerations in lifecycle cost analysis of projects and would then be at stage 4. Also at stage 4, the agency may develop a systematic and integrated decision-making process for prioritizing projects that includes resilience considerations where necessary.

It is important to note that although movement from one stage to another within a capital type is not exclusively tied to movement in other capital types, some cases would require progress in closely related areas in order to progress from one stage to another. For example, movement from stage 3 to stage 4 of financial capital would require an agency to assess lifecycle costs of projects and assess any resilience implications. However, for this to be possible, an agency would need to have a mature asset management program since a lifecycle approach to managing assets/infrastructure is a characteristic of good asset management.

4.3 Generalizability versus Transferability

Generalizability refers to the "extension of research findings and conclusions from a study conducted on a sample population to the population at large" (Barnes et al., 1994-2012). That is to say, generalizability of research findings allows predictions to be made based on the outcomes that particular research. Thus, generalizability requires large amounts of data, which quantitative research enables, to produce sound predictions. Transferability, on the other hand, is not related to making predictions or conclusions about certain populations, rather, it describes "the process of applying the results of research in one situation to other similar situations" (Barnes et al., 1994-2012). Transferability is a process performed by the readers of research. Readers compare the contexts of research their situations and determine whether enough similarities exist to infer from the findings. The survey on which the framework was based utilized a non-probabilistic sampling technique and therefore, generalizations cannot be make from its results. However, the MVS technique adopted allowed agency selection to cover different contexts including geographic locations, threats faced, and agency type. The variations present in the survey participants allow for *transferability* of survey findings from agency to the other. Additionally, because of the diversity in agencies selected, strategies and attributes catalogued in the maturity scale cover different approaches used for resilience enhancements. In situations where certain attributes do not apply, such as in the case of an MPO that does not own any physical transport assets, value can still be obtained from assessing attributes across other capital categories.

4.4 **Summary**

This chapter presented the development of a planning framework for enhancing transportation system resilience using sociotechnical approaches. Foundational concepts underpinning the framework and a detailed description of the framework were also presented. Finally, a discussion of how organizational, institutional, technical and financial capital affect system resilience at difference stages of development was presented, providing examples from the experiences of actual transportation agencies in the U.S.

The next chapter provides an account of the framework application to another set of transportation agencies as well as a discussion of practitioner feedback on the framework's usefulness and opportunities for improvement.

CHAPTER 5. FRAMEWORK DEMONSTRATION & REVIEW

5.1 Introduction

This chapter presents the demonstration and review of the Sociotechnical Transportation Resilience Framework (STRF) by practitioners from three transportation agencies. The STRF table was presented in the form of a self-assessment tool and required reviewers to indicate which attributes in the different stages and capital areas that applied to their agencies. After conducting the exercise, the reviewers were asked following questions:

1) How useful is this tool to you/your agency as a guide for resiliency planning?
    a. In the near term
    b. In the long term
2) What attributes/factors can be added or removed to strengthen the tool's usefulness?
3) In your opinion, what additional stages should be included to improve the tool?
4) Please provide any additional comments you think will be useful for finalizing this tool

The subsequent sections in this chapter present a discussion of the STRF output and feedback from each of the three agencies, as well as a revised STRF table that takes the provided practitioner feedback into account.

5.1.1 **Arizona Department of Transportation (ADOT)**

5.1.1.1 Overview

The Arizona Department of Transportation's (ADOT), assets are required to function from sea level to about 6000 feet above sea level, and also withstand temperatures of below zero degrees Fahrenheit to over 120 degrees Fahrenheit. In addition to extreme heat and freeze-thaw cycles, ADOT's assets are exposed to flooding, rockfall and wildfire threats (Tao and Leary, 2013).

The review for ADOT was conducted by Steve Olmstead, the Innovative Programs Manager in ADOT's Environmental Planning Section. In addition to assisting ADOT's construction program, Mr. Olmstead administers project teams for resilience. This includes extreme weather and climate adaptation, sustainable transportation and partnerships between ADOT and USGS focused on developing risk-based assessment mechanisms for asset management, hydrologic modelling and hydraulic engineering design.

5.1.1.2 Self-Assessment

Figure 5.1 shows a summary of the output obtained from ADOT's self-assessment using the STRF table (Table output shown in Appendix B). It shows that ADOT identified as being at Stage 3 for institutional capital. This means that ADOT has developed guidance for changes to be implemented in current plans, regulation or policies to support resilience thinking at the agency.

Stage 3 for institutional capital also means that ADOT has identified possible institutional barriers that may be faced in implementing resilience strategies and has either developed or is working toward the development of a set of solutions to address them.

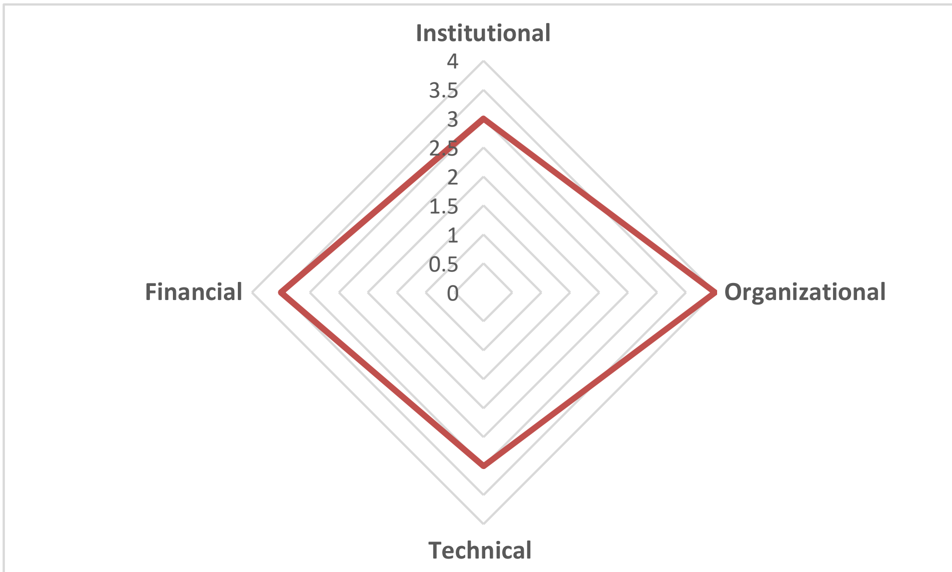

Figure 5.1 Relative capital levels for resilience capacity at ADOT

ADOT's organizational capital can be described as Stage 4 since it meets all but two attributes for stages 3 and 4. These were (1) coordination and/or unification of efforts with external transportation or non-transportation agencies, and (2) champion efforts no longer needed. Thus, although not fully not fully realized, ADOT's organizational capital is well into Stage 4. It also means that resilience thinking has been institutionalized at the agency. The agency has taken a lifecycle approach to building resilience capacity and has incorporated resilience considerations into existing structure at the agency (i.e., Asset Management Plan, Long Range Transportation Plan, etc.). ADOT established a formal Resilience Program within the agency in 2016 to provide strategic direction for enhancing the resiliency of ADOT's transportation system and help the agency cope with the ever-increasing cost of threats. The program was tasked with incorporating resilience considerations into existing criteria used throughout the infrastructure lifecycle (i.e., planning, design, construction, operations, and maintenance), identifying or developing a decision-making resilience framework, and building on past climate adaptation efforts from 2014 and 2015. ADOT's Resilience Program therefore set out to achieve the following initial goals:

- "Centralize the concerns encompassing the unknown, erratic and abrupt incidents of storm water and its contributors of flooding, overtopping, system hotspots and hydraulic-related failures under one managing entity to hone efforts
- Introduce extreme weather adaptation into agency and engineering design processes, as well as, establish current transportation asset sensitivity to extreme weather incidents
- Identify scientifically informed climate data downscaling as it relates to transportation systems" (Olmstead and Lester, n.d.)

At stage 3 in terms of technical capital, the agency has taken concrete steps to incorporate resilience considerations into its existing asset management program. Progress in this area can be traced back to 2013, when ADOT submitted problem statement (research idea) to AASHTO's Center for Environmental Excellence. The document was titled "Integrating Climate Change and Extreme Weather Uncertainty into a State DOT Transportation Asset Management Plan – An Initial Process Development." Since then, ADOT has consistently worked on developing technical capital using asset management principles. For example, ADOT worked with consultants (Cambridge Systematics) in 2015 to develop a batchprocessing technique for downscaling climate data more efficiently and incorporate identified risks into decision models (Georgetown Climate Center, 2015). In 2015, ADOT also participated in the National Cooperative Research Program (NCHRP) Project 25-25, titled *Integrating Extreme Weather and Adaptation into Transportation Asset Management Plans* (Meyer and Flood, 2015). This contributed to the agency's efforts in using asset management for resilience capacity.

Lastly, in terms of financial capital, ADOT is described as being at Stage 3, working towards Stage 4. At ADOT, resilience is considered in the lifecycle cost analysis of projects; however, it is yet to be fully incorporated in project prioritization process along with other traditional priorities (e.g., mobility).

5.1.1.3 Practitioner Feedback

Feedback from review process was positive and suggestions for improvements were also provided. With regard to the tool's usefulness for resiliency planning, the reviewer described the different levels/thresholds of participation, assessment, implementation and institutionalization as well disseminated and beneficial for executive decision makers to be used for long-term planning. He also expressed that the framework and tool is a good foundational discussion piece for resilience interdependency amongst different industries.

In terms of factors/attributes that can be removed or added, the reviewer commented about the practicality or extent that interdependent infrastructure systems (power, water, transportation, etc.) would coordinate at the state level. He did note that analyzing cascading and interdependent systems is useful but that would require the governor's office to catalyze such an effort. Secondly, the reviewer suggested including attributes that account for efforts towards developing scientifically downscaled climate data for asset management out to years 2050/2100. Furthermore, an additional stage, Stage 5, was suggested to recognize progressive work at the global scale. This would recognize adoption of European Union (EU) resilience building strategies, for example, as presented at the 2016 US/EU transcontinental symposium on adapting transportation to climate change impacts.

Lastly, the following statement was provided as closing comments from the ADOT reviewer: "ADOT is a leading practitioner of these activities nationwide and recognized globally for our specific area of expertise – that of blending risk, science, technology, and engineering. To respond to you, projects focus on 'human and organizational factors in addition to technical factors' ADOT has progressed to the point of incorporating national partners, statewide partners, senior administration, planning, design, construction, maintenance, and operations. But we have more room to grow in the use of two areas – organizational and financial." (Olstead, 2017). This statement captures ADOT's progress with using sociotechnical factors and shows that the agency has recognized the capital areas, financial and organizational, where opportunities to enhance are present.

5.1.2 **Washington State Department of Transportation (WSDOT)**

5.1.2.1 Overview

The Washington State Department of Transportation (WSDOT) owns and manages over 7,000 centerline miles of roadway, over 8,500 bridges, 22 ferry terminals, four freight rail lines and 16 airports. Some of these assets are exposed to earthquakes, tsunamis, wildfires, drought, storms and flooding. The review for WSDOT was conducted by Carol Lee Roalkvam, the Environmental Policy Branch Manager.

5.1.2.2 Self-Assessment

Figure 5.2 shows a summary of the output results obtained from WSDOT. The completed table showing details of capital levels can be found in Appendix B. From the tool's output, WSDOT's institutional capital is best described as stage 3, although the agency check off only one of the two stage attributes. Stage 3 for WSDOT means that the agency has hazard specific policies for resilience and guidance has been developed for changes to current plans or policies. This includes a seismic risk reduction policy and program. Between 1991 and 2013, WSDOT invested approximately $150 million in bridge retrofits to withstand earthquake hazards (WSDOT, 2015).

There is also external action that influences the agency's posture and actions toward resilience, an example of which is the Resilient Washington State Initiative, developed to develop a framework for statewide earthquake resilience (EMC, 2010). The state also convened the Resilient Washington Subcabinet with the intent to better prepare for disasters. The subcabinet's tasks include among others, to identify data and information for better preparedness and response, and also to "develop actions that can be coordinated across state agencies, local jurisdictions and federal partners to reduce risk and improve response in the event of an earthquake or tsunami" ("Resilient Washington" n.d.).

To continue to develop institutional capital at WSDOT, the agency can begin to align its resilience planning with efforts in other sectors, identifying possible institutional barriers or challenges that could hinder implementation of resilience strategies.

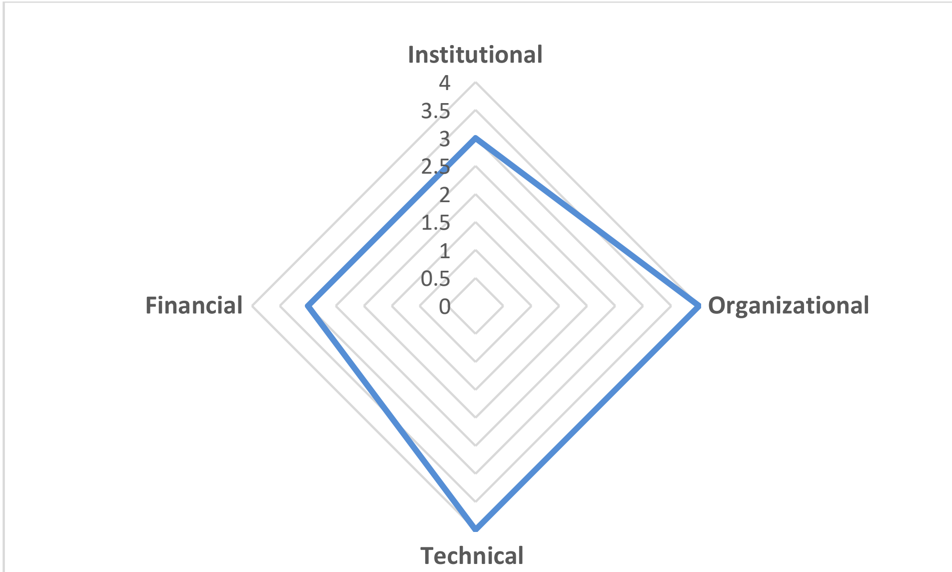

Figure 5.2 Relative capital levels for resilience capacity at WSDOT

WSDOT's organizational capital is at Stage 4. WSDOT has identified a clear resilience goal in its 2014-2017 strategic plan. This goal, listed as a strategy that contributes to overall environmental stewardship, is to ensure that plans and major capital projects developed during the 2013-2015 biennium and undergoing environmental review (i.e., NEPA EIS and EA level) consider climate change and extreme weather vulnerability. The goal also requires that strategies to improve resilience for the identified vulnerabilities be documented (WSDOT, 2016). This is a key attribute as it directly ensures that all major projects and plans are reviewed for resilience. The results also show that resilience thinking is institutionalized at the agency, that is, resilience considerations are incorporated into project development. This attribute is evident from the resilience goal discussed. Lastly, the agency has formal positions (partial/full) dedicated to building resilience capacity. Again, although organizational capital is at stage 4, areas of growth still exist since there is neither monitoring and reporting of resilience capacity building initiatives, nor coordination of efforts with external agencies; both of which are stage 3 attributes.

For technical capital, WSDOT efforts align with stage 4. Here, the reviewer indicated the presence of an integrated state strategy; however, the extent of detail and coordination between state agencies unclear. The agency also has an active asset management program with concrete steps taken to incorporate resilience considerations. In fact, WSDOT is considered an industry *shining star* in terms of efforts in this area. In WSDOT's first vulnerability assessment, which was partly funded by FHWA, the agency followed a sort of "decentralized" model based on going to all districts and interacting with maintenance staff about asset vulnerabilities for the entire system. The stakeholder-based qualitative model has since been replicated by other agencies (M. Culp, personal communication, June 14, 2017; FHWA, 2014). WSDOT's second resilience project with FHWA resulted in the development of a process for considering extreme events (specifically hydraulic data) in transport planning (Climate Change, 2017).

Moving on to financial capital, WSDOT is at stage 3. An institutionalized process or approach for considering financial implications of resilience has not yet been developed. Notwithstanding this, the agency is able to fund resilience enhancing strategies on a case by case basis, although some initiatives still rely on external grants.

5.1.2.3 Practitioner Feedback

The reviewer from WSDOT provided insightful feedback about the tool's ease of use. In her opinion, the instructions attached to the tool did not provide enough information making it difficult to understand the tool itself. Additional comments provided suggest that tool needs to be improved to ensure that it can be used without an in-depth understanding of the concepts employed in the tool's development by clearly defining the main terms used.

The reviewer also did think there was much added value in providing a snapshot of a prior year's efforts by filling out a second table as was suggested by the tool's instructions. Her experience, the work to promote climate resilience since 2008 is ongoing. This means being constantly educated and re-educated. Also, in her experience, the key factor at her agency has been leadership support. Executive leadership from the state or federal level (i.e., governor/president) is less consequential.

Furthermore, the reviewer from WSDOT's response suggest removing the attribute "champion efforts no longer needed" from stage 4 because such efforts are required at all times. This comment suggests that even with formal agency positions dedicated to resilience capacity building, champion efforts could still be needed and an individual in this position may still need to act as a *champion* to promote efforts. This also highlights a need to provide a clear definition of the term *institutionalization* to potential tool users. Finally, the framework could be modified to reflect the progressive nature of developing employee awareness on resilience issues. According to Ms. Roalkvam, such awareness needs to constantly fed otherwise, it is lost within the agency.

5.1.3 **Atlanta Regional Commission (ARC)**

5.1.3.1 Overview

The Atlanta Regional Commission (ARC) is the metropolitan planning organization for the Atlanta region and develops the long-range transportation plan for the 20-county Atlanta region. The agency also conducts regional planning and intergovernmental coordination for the smaller 10-county region, which includes community development, water resources management, and service provision for the elderly and disabled (ARC, n.d.). David D'Onofrio, the Air Quality and Climate Change Principal Planner at ARC, provided the last review for the STRF.

5.1.3.2 Self-Assessment

Figure 5.3 shows a summary of the relative capital levels for ARC (actual output may be found in Appendix A). The output from ARC provides an interesting insight into resilience capacity building at an MPO that does not own assets. For institutional capital, the agency has sustainability policies as well as formal agency policies that explicitly address system resilience. Possession of the latter attribute indicates Stage 4 growth (having 50% of attributes in Stage 4), however, there is significant leapfrogging from Stage 1 to Stage 4, which may be accompanied by some disadvantages. Stages 2 and 3 of institutional capital show two things: (1) an understanding of system-specific vulnerabilities and the consequent changes needed to be implemented, and (2) an enabling external regulatory environment that also promotes resilience thinking. By not systematically growing from one stage to the next in institutional capital, there is a risk of existing institutional capital not being fully effective. Ultimately, institutional capital is meant to provide the foundation on which other capital types can develop sustainably. Therefore, the full benefits of Stage 4 institutional capital may not be realized.

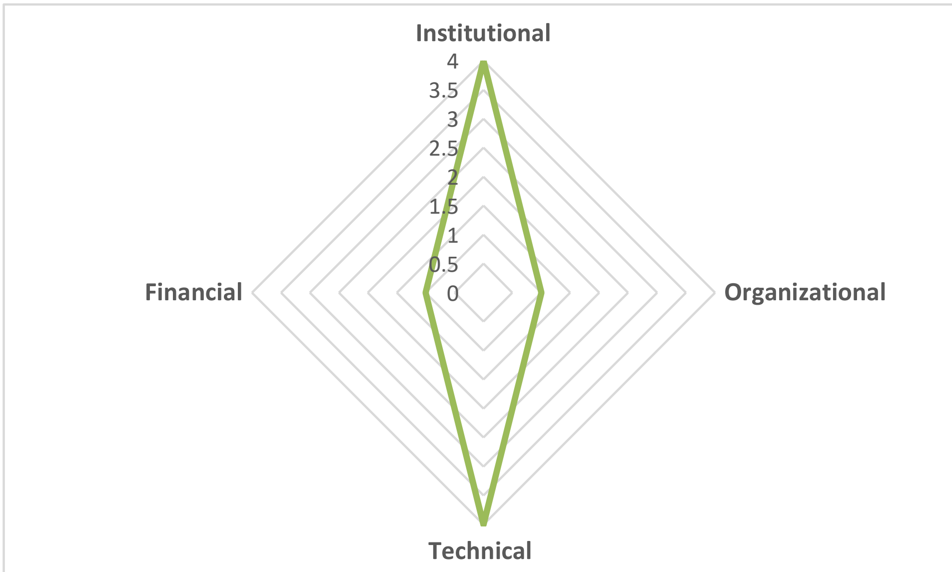

Figure 5.3 Relative capital levels for resilience capacity at ARC

In terms of organizational capital, the ARC's maturity can be described as Stage 1 since this is the only stage at which the agency possesses 50 percent of attributes. At this stage, the agency has existing champion efforts at the agency and plans that address aspects of system resilience, e.g., climate action plan. It is worth noting that resilience priorities have also been identified at the agency but have not been stated in official planning documents. The agency also has a formal, dedicated or designated person responsible for resilience planning/initiatives.

Similar to institutional capital, ARC exhibits significant leapfrogging for technical capital. The self-assessment results indicate that ARC is at Stage 4 for technical capital. Given that the agency does not own any assets, not all the attributes apply. However, certain attributes not related to assets must still be developed (e.g., possession of detailed hazard information). Finally, the STRF output shows that ARC is in the early stages of financial capital development and therefore at Stage 1.

In summary, the STRF output for ARC indicates higher levels of institutional and technical capital, and lower levels of organizational and financial capital maturity. The disproportionate nature of growth is a likely indicator of the risks of leapfrogging. Systematic growth from one stage to the next is therefore preferable.

5.1.3.3 Practitioner Feedback

Mr. D'Onofrio is an at the ARC. In his opinion, providing tasks to help agencies move towards resilience is important and a checklist is an effective means of letting agencies know what they should be doing or working towards. However, the STRF can still be improved in a number of ways. First, the *introduction* to the tool should be refined to better communicate what the different stages represent and why an end user should be interested in developing the four types of capital. Also, certain terms like "champion efforts" need to be *defined* to ensure a baseline of understanding before undertaking the assessment. Lastly, a *consistent sentence structure* within each box would reduce confusion and improve readability.

5.1.4 **State of New York Metropolitan Transportation Authority (NY MTA)**

The final STRF reviewer, Michael Salvato, is from the State of New York Metropolitan Transportation Authority (NY MTA). The MTA is the largest transportation provider in North America, covering a region of approximately 15.3 million people and an average weekday passenger ridership of 8.8 million. The agency manages a wide range of assets including bridges, tunnels, railroads, railcars and buses, among others.

Mr. Salvato is the Director and Program Executive for Enterprise Information, Asset Management and Strategic Innovation at the State of NY MTA. He also serves as Vice President for the Institute of Asset Management, an organization that aims to advance the interests of asset managers in the US and beyond. According to Mr. Salvato, the MTA uses a sociotechnical approach for its risk-based asset management program. They focus on practices, processes, human capital, and technological capital which includes data, information, IT and engineering systems.

The representative from NYMTA provided a review without applying the STRF tool. Concerning resilience planning, Mr. Salvato suggests that a good approach is to be top-down without being too descriptive. That is, guidance such as standards and knowledge should flow from upper management down to the field, but still allow enough flexibility in actual implementation to create buy-in and promote innovation. Thus, a capabilities approach or assessing the capacity to act, which is the structure of the STRF, is a good approach.

For organizational capital, the STRF needs to assess organizational *capability to manage risk*, the *resources to manage risk* and *information* available for managing risk. Thus, the first point of improvement for the tool is to increase the focus on data and information – both availability and management—for technical capital. Secondly, with regard to administering the tool, assessments should be carried out by multiple individuals within an agency to ensure a holistic picture. In many cases, the general knowledge of one person only extends to the boundary of his or her sphere of influence. By having multiple people fill out the tool, knowledge lacking from one person's account may still be captured. Therefore, Mr. Salvato suggests the following three points of view to be captured at each agency:

i. A high-level contact with a good understanding of the agency's capabilities,
ii. A planning department representative, and
iii. A representative from either engineering or operations departments, or from both.

Mr. Salvato also shared information on the Hitchin Framework for Systems Engineering (shown in Figure 5.3), and on an MTA organizational culture assessment on assessing risk as it relates to safety, reliability and resilience (Hitchins, 2000). He hoped this information would further inform the STRF's revision.

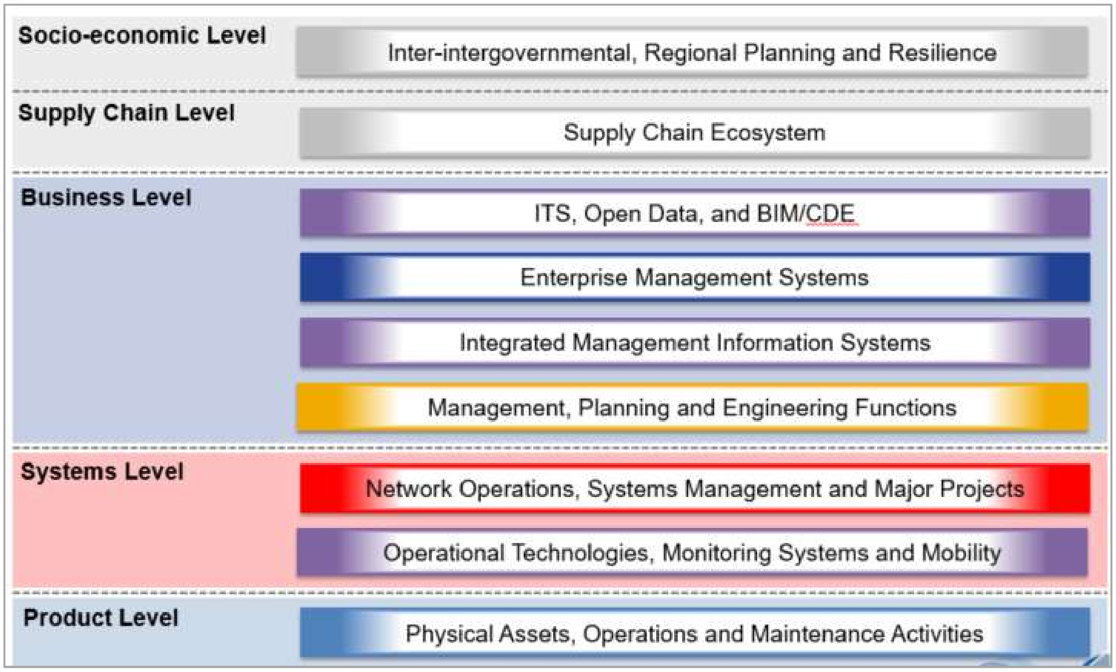

Figure 5.4 Hitchen Framework for Systems Engineering. (Source: Salvato and Glecker, 2017)

5.2 Summary of Practitioner Feedback

Feedback from the four reviewers suggest that the STRF could be a useful tool for resilience planning within transportation agencies upon refinement. Given the timeframe of this research not all the feedback received was integrated into the finalized tool (e.g., concepts from the Hitchin framework). The following revisions were therefore made to the STRF tool in order to realize its full potential:

i. Definition of terms

ii. Expansion of technical capital attributes to highlight possession and use of data and information to inform decisions (e.g., downscaled climate data, good quality asset/infrastructure information)

iii. Inclusion of attributes from an international perspective
iv. Revision of introduction to better describe maturity stages, capital types and articulate tool benefits
v. Revision of assessment process (i.e., use of multiple personnel versus one individual)
vi. Revision of sentence structure within boxes

The finalized STRF table is shown below in Table 5.1 and the revised tool is found in Appendix C.

Table 5.1 Revised STRF Table

	Institutional Capital	Organizational Capital	Technical Capital	Financial Capital
Stage 1	☐ Agency policies for sustainability may be present	☐ Champion efforts present to raise awareness in agency ☐Plans that address aspects of resilience may be present. e.g., initial climate action plans ☐ High level resilience planning present, e.g., qualitative/general impacts study, general state-wide resilience planning ☐ Emergency response and recovery processes present	☐ Awareness of hazards (e.g., climate impacts) and taking initial steps to mitigate	☐ Use of external grants/funds for initiatives
Stage 2	☐ Some hazard specific policies that enhance resilience present ☐ Mitigation policies present at agency, e.g., greenhouse gas mitigation ☐ External state action influences agency posture and actions. E.g., executive order, legislation, state resilience committee or other external requirements.	☐ Champion efforts still critical ☐ Political will garnered at agency, i.e., senior leadership support ☐ Resilience priorities identified; however, may not be explicitly stated in official agency planning documents ☐ Hazard specific plan(s) or program(s) developed with detailed impacts analysis and adaptation strategies identified ☐ Some level of external collaboration with strategic partners present	☐ Resilience focus on infrastructure hardening ☐ May have conducted or planning to conduct pilot study on risk or vulnerability for certain assets ☐ Active asset management program, but does not explicitly incorporate resilience considerations	☐ Initiatives still rely on grants ☐ May secure some state legislature funds for initiatives

Table 5.2 Revised STRF Table (continued)

<table>
<tr><th></th><th>Institutional Capital</th><th>Organizational Capital</th><th>Technical Capital</th><th>Financial Capital</th></tr>
<tr><td>Stage 3</td><td>☐ Guidance developed for changes in current plans, regulation or policies to support resilience thinking at agency (or state)

☐ Framework provided for addressing possible institutional barriers (including inter-agency barriers) that may be faced in implementing resilience building strategies</td><td>☐ Raised employee awareness on resilience issues at agency
☐ Formal, dedicated or designated person/team responsible for resilience planning or initiatives
☐ Resilience considerations incorporated into project planning, e.g., hazard mapping
☐ Monitoring and reporting of resilience capacity building initiatives/activities adopted
☐ Coordination and/or unification of efforts with external transportation or non-transportation agencies</td><td>☐ Information on system vulnerabilities collected and documented e.g., downscaled climate data
☐ Detailed data and information on hazards present
☐ Concrete steps taken to incorporate resilience considerations into existing asset management program, e.g., results of risk/vulnerability studies</td><td>☐ Case by case consideration of funding for adaptation strategies by agency</td></tr>
<tr><td>Stage 4</td><td>☐ Formal agency policies explicitly address system resilience

☐ Alignment of transport resilience planning and resilience planning in other sectors (e.g., land-use, housing, etc.) to streamline efforts and realize co-benefits.</td><td>☐ Formal agency positions (partial/full) dedicated to building resilience capacity within agency

☐ Strategic goals and objectives for resilience capacity clearly identified

☐ Adoption of adaptive strategies outlined to achieve resilience goals

☐ Resilience thinking institutionalized. i.e., resilience considerations incorporated into project development process (i.e., planning, construction, operation, maintenance, renewal/decommissioning)

☐ Resilience thinking reflected in main agency plans: Asset Management Plan (TAMP), Long Range Plan (LRTP), Transport Improvement Plan (TIP)</td><td>☐ Resilience considerations go beyond direct transport assets, i.e., supporting infrastructure, (e.g., IT, ancillary assets) and subsystems/interdependent systems (power, water, etc.)</td><td>☐ Resilience considered in lifecycle costs analysis of projects

☐ Resilience considerations included in project prioritization process where necessary in addition to other priorities such as safety, costs, etc.

☐ Institutionalized approach/process for considering financial implications/needs for resilience</td></tr>
</table>

CHAPTER 6. CLOSING DISCUSSION

6.1 Summary of Research Findings

Transportation systems are faced with a plethora of threats that continue to evolve and grow over time. Natural threats such as those posed by the impacts of climate change and extreme weather are also increasing in intensity and extent of damages as indicated by data from NOAA (2017). These threats combined with the probable occurrences of catastrophic disruptions from terrorist events or infrastructure failure due to aging and structurally deficient infrastructure has spurred great attention to the area of system resilience and how to achieve it. Resilience, the ability of a system to maintain critical functions and prevent catastrophic failure during a disruption, and then recover rapidly, is now at the forefront of most critical infrastructure discussions. Different types of transportation agencies are also interested in the resilience discussion because of its implications to the systems they plan, operate and manage, and the capabilities for service provision after major disruptive events.

To bridge this gap, the transportation field in both research and practice, has worked towards realizing more resilient outcomes by developing various methodologies, frameworks and approaches. In transportation research, graph theory based models such as those by Ash and Newth (2007), Ip and Wang (2009), Rosenkratz et al., (2005), and Taylor and Susilawati (2012) assess transport resilience using various optimization techniques to assess network properties based on the topological properties of networks (e.g., weighted or unweighted nodes and links/ intersections and streets). Other process based models (e.g., Croope et al., 2010, Cox et al., 2010, Serulle, 2010, etc.) seek to assess system resilience by attempting to capture both demand and supply sides of transportation. Consequently, resilient transportation systems have been characterized as having redundancy, robustness, modularity, efficiency, rapidity, diversity, resourcefulness, etc. The literature also shows that the implementation of some of these frameworks are largely focused on the physical highway system and how it can be built better to withstand the impacts of major disruptions, both in research and in practice. Additionally, although some of the literature reviewed also incorporates some broader factors (such as organizational and institutional considerations), the current experiences of transportation agencies with resilience capacity building is evidence that unidentified opportunities exist and are yet to be recognized and capitalized upon.

The literature on resilience applications in ecological, socioecological, and economic systems provide such opportunities. Specifically, the concepts of system stability at a single equilibrium, and system resilience at multiple equilibria through regime changes are pivotal for the current conceptualization of transportation system resilience. Stability, represents a system's ability to return to a state of equilibrium after a disturbance and can therefore be characterized by the rapidity with which it returns to equilibrium. Resilient ecological systems, on the other hand, have multiple points of equilibria, and thus, a fluctuation in system conditions simply causes a shift from one equilibrium state (regime) to another. These two types of ecological behavior described by Holling (1973) form the main difference between ecological resilience and engineering resilience in the sense of Pimm (1991) (i.e., engineering resilience is based on system stability at a single equilibrium).

This research therefore sought to shift the current conceptualization of transportation system resilience by developing a framework based on the foundational concepts of system resilience at multiple equilibria accessed via regime changes. A transportation resilience survey was therefore developed and deployed to a purposive sample to obtain information on transportation agency experience with developing resilience capacity with the premise that agencies with more experience in dealing with hazards and/or major disruptive events, evolve towards more sociotechnical approaches over time.

The survey results show evidence of sociotechnical approaches at agencies that have experienced major system disruptions such as ABAG/MTC (technical and organizational capital), Iowa DOT (organizational and technical capital), and FDOT/Broward MPO (organizational and technical capital). The results also show similar changes in resilience approaches in agencies that may not have experienced major system disruptions, but have developed a greater understanding of system threats and potential consequences for their systems. These agencies can be described as having a *proactive* posture and include agencies such as MassDOT (institutional, organizational, technical and financial capital) and MDSHA (institutional, organizational and technical capital). Thus, although agency experience is a factor in evolving resilience efforts towards sociotechnical approaches, a greater awareness and understanding of system threats may also be a factor. We also observe that agencies described as *proactive* also have some sort of state level policy, law or regulation that promotes that behavior.

In addition to these insights, the survey showed different levels of organizational capital for resilience building at transport agencies. This includes staffing, strategic planning, monitoring and reporting, coordination and collaboration, and a reflection of resilience thinking in main planning documents. Similarly, institutional capital development was distributed between agency-level efforts and state-level efforts (discussed in preceding paragraph). At the agency-level, few agencies reflected this in their survey responses (ODOT and ABAG). Technical capital development at the agencies surveyed was characterized by initial maturity stages of general threat awareness and non-risk-based asset management, to higher maturity levels of collection of (or possession of) detailed data and information on system assets and potential threats for the purposes of risk/vulnerability analyses. In some cases, agencies had either incorporated this data (to various extents) to their asset management systems, as in the case of MassDOT, or were planning to do so. Lastly, similar to institutional capital, few resilience strategies were identified for financial capital. Agencies mostly rely on grants to fund initiatives, which is not unexpected considering the nascent nature of resilience efforts at most agencies. Agency responses also showed a desire to develop decision-making and project prioritization processes that incorporate resilience.

These strategies and system attributes identified across the different capital types were combined with the concept of system resilience at multiple equilibria to develop a framework and maturity scale for developing institutional, organizational, technical and financial capital for transport resilience capacity building. The maturity scale, which doubles as a self-assessment and resilience planning tool, was verified by means of demonstration and practitioner reviews from Arizona DOT, Washington State DOT, New York MTA and the ARC. The verification process revealed certain enhancements, which were consequently incorporated to the tool, were needed to ensure an easier understanding of the tool's use and benefits.

6.2 Recommendations

Transportation agencies at any stage in the resilience development capacity process may use the framework as a planning tool to outline both short and long term targets and goals for enhancing transportation system resilience. It is recommended that agencies plan towards systematically progressing along the maturity scale rather than leapfrogging to effective accrue the benefits of joint capital optimization. Additionally, it is recommended that agencies engage multiple employees at different levels and divisions within the agency when conducting the self-assessment to provide a holistic picture of the agency's capabilities. Obtaining employee buy-in is therefore crucial to the success of this process. Creating a business case for resilience within an agency by linking resilience considerations to improvements in some day-to-day agency activities presents the case for resilience in terms of what matters most the agency.

Finally, after the STRF output is obtained from a self-assessment, the agency must prioritize its resilience goals and targets based on the agency's strategic priorities, available resources, and the potential co-benefits to be accrued across capital areas.

6.3 Research Contributions

This research makes three main contributions to the knowledge and understanding of transportation resilience. Firstly, while the literature on transport system resilience as it relates to conceptualization and measurement is vast, this research presents a novel conceptualization of resilience in transport systems by extending the current paradigm from that of a single equilibrium conceptualization to a multiple equilibria conceptualization. This conceptualization shifts the current thinking from a concentration of resources on physical system hardening and a focus on returning to pre-disruption state, to one that seeks change in order to persist.

Secondly, the research combines the concepts of stability regimes, capital asset management and sociotechnical systems theory to explicitly conceptualize different developmental stages of building resilience capacity in transport systems through *joint optimization* of institutional, organizational, technical and financial capital within an agency. The approach therefore emphasizes the interdependence of the four capital types for organizational performance and achieving resilient outcomes. This is important because the common approach for transportation agencies interested in building resilience capacity is to focus mostly on improving robustness of physical infrastructure, offering less attention to organizational aspects of resilience building.

Finally, the STRF provides a means for transport agencies to assess progress towards building resilience capacity. It is potentially beneficial for decision makers involved in strategic or long-term resilience planning to assess gaps and growth areas, strategically plan for the *next attainable regime,* and allocate the needed resources to systematically achieve the desired capabilities.

6.4 **Limitations and Future Research**

The framework developed has a number of limitations that ought to be discussed. These limitations, however, do not detract from the benefits of the framework and some limitations are also directly linked to future research. As stated earlier, the transportation resilience survey used Maximum Variation Sampling (MVS), a type of purposive sampling technique in the selection of agencies to survey. This non-probabilistic method of sampling means that broad generalizations cannot be made about the results of the survey, and by extension, about transportation agency resilience efforts. However, the strength of MVS is its ability to allow the researcher to capture a variation in perspectives on a topic and present different angles of an issue. By creating variation of the types of agencies selected (DOTs, MPOs, and local governments), as well as geographic locations and hazards faced, the survey was able to capture the experiences of transportation-related agencies across a broad spectrum. Therefore, the survey output fed into the development of a framework that captures a wide range of agency experiences and can thus be utilized by various agencies in their efforts to build resilience capacity.

Next, the process of using check boxes in the STRF tool may present slight ambiguities when interpreting results for agencies that possess attributes scattered across the different stages. Here, there may be difficulty in determining which stage they fall in. However, when the original intent of the tool is revisited, one realizes that the purpose is not to rank or score agencies, but to provide information on opportunities for building capacity. Thus, in such cases, an agency may identify with the highest stage in which it possesses 50 percent or more of attributes. This can point the agency to what other opportunities exist for improvement.

This potential challenge also poses an opportunity for future research into the tool's design and administration process. The current tool can be developed into a web-based tool with an improved user interface that automatically indicates which stage an agency is in and lists the strategies for improvement. Another closely related area for further research is identifying and cataloguing detailed strategies that agencies can implement to achieve the capacities indicated by each capital attribute. The improved web-based tool can then include a list of possible strategies for implementation with the tool results.

Another area of further research is investigating the correlations between the four agency capital areas. Research into the correlations between capital types and the extents to which increasing one input affects other capital types would create value for strategic planning. This can be done over time as more data is collected from continued use of the framework by agencies. Subsequently, validation studies can be conducted to evaluate the effectiveness of the proposed tool in providing guidance for enhancing resilience capacity for transportation systems.

Finally, further research into other types of institutional capital in enhancing resilience can be investigated. This includes defining institutional capital to include social institutions (e.g., community capital) in addition to laws and regulations and investigating the contributions of such social institutions in the community recovery process.

APPENDIX A

STRF Outputs from Framework Verification

Table A.1 Arizona DOT STRF Output

	Institutional Capital	Organizational Capital	Technical Capital	Financial Capital
Stage 1	☐ No formal agency policies explicitly address system resilience ☐ Sustainability policies may be present at agency ☐ No external state policies present that impact transport agency	☐ Champion efforts present to raise awareness in agency ☐Plans that address aspects of resilience may be present. e.g., initial climate action plans ☐ High level resilience planning, e.g., general impacts study, general state-wide resilience planning ☐ Emergency response and recovery processes present	☐ Awareness of hazards (e.g., climate impacts) and taking initial steps to mitigate. E.g., travel demand management (TDM), developing and instituting green /sustainability design	☐ No institutionalized approach/process for considering financial implications/needs for resilience ☐ Use of external grants/funds for initiatives
Stage 2	☐ Some hazard specific policies that enhance resilience ☐ External state action influences agency posture and actions. E.g., executive order, legislation, state resilience committee or other external requirements.	☐ Champion efforts still critical ☐ Political will garnered at agency, i.e., senior leadership support ☐ Resilience priorities identified; however, may not be explicitly stated in official agency planning documents ☐ Hazard specific plan(s) or program(s) developed with detailed impacts analysis and adaptation strategies identified ☐ Some level of external collaboration with strategic partners present	☐ Resilience focus on infrastructure hardening ☐ May have conducted or planning to conduct pilot study on risk or vulnerability for certain assets ☐ Active asset management program, but does not explicitly incorporate resilience considerations	☐ Initiatives still rely on grants ☐ May secure some state legislature funds for initiatives

Table A.1 Arizona DOT STRF Output Continued

Stage 3	☒ Guidance developed for changes in current plans, regulation or policies to support resilience thinking at agency (or state) ☒ Framework provided for possible institutional barriers (including inter-agency barriers) that may be faced in implementing resilience building strategies	☒ Raised employee awareness on resilience issues at agency ☒ Formal, dedicated or designated person/team responsible for resilience planning or initiatives ☒ Resilience considerations incorporated into project planning, e.g., hazard mapping ☒ Monitoring and reporting of resilience capacity building initiatives/activities adopted ☐ Coordination and/or unification of efforts with external transportation or non-transportation agencies	☒ Concrete steps taken to incorporate resilience considerations into existing asset management program, e.g., results of risk/vulnerability studies	☐ Case by case consideration of funding for adaptation strategies by agency
Stage 4	☐ Alignment of transport resilience planning and resilience planning in other sectors (e.g., land-use, housing, etc.) to streamline efforts and realize co-benefits.	☐ Champion efforts no longer needed ☒ Formal agency positions (partial/full) dedicated to building resilience capacity within agency ☒ Buy-in and understanding of resilience thinking established throughout agency ☒ Strategic goals and objectives for resilience capacity clearly identified and strategies outlined to achieve them ☒ Resilience thinking institutionalized at agency, i.e., resilience considerations incorporated into project development process (i.e., planning, construction, operation, maintenance, renewal/decommissioning) ☒ Resilience thinking reflected in main agency plans: • Asset Management Plan (TAMP) • Long Range Plan (LRTP) • Transport Improvement Plan (TIP)	☐ Resilience considerations go beyond direct transport assets, i.e., supporting infrastructure, (e.g., IT, ancillary assets) and subsystems/interdependent systems (power, water, etc.)	☒ Resilience considered in lifecycle costs analysis of projects ☐ Resilience considerations included in project prioritization process where necessary in addition to other priorities such as safety, costs, etc.

Table A.2 WSDOT STRF Output

	Institutional Capital	Organizational Capital	Technical Capital	Financial Capital
Stage 1	☐ No formal agency policies explicitly address system resilience ☒ Sustainability policies may be present at agency ☐ No external state policies present that impact transport agency	☒ Champion efforts present to raise awareness in agency ☒ Plans that address aspects of resilience may be present. e.g., initial climate action plans ☒ High level resilience planning, e.g., general impacts study, general state-wide resilience planning ☒ Emergency response and recovery processes present	☒ Awareness of hazards (e.g., climate impacts) and taking initial steps to mitigate. E.g., travel demand management (TDM), developing and instituting green /sustainability design	☒ No institutionalized approach/process for considering financial implications/needs for resilience ☒ Use of external grants/funds for initiatives
Stage 2	☒ Some hazard specific policies that enhance resilience ☒ External state action influences agency posture and actions. E.g., executive order, legislation, state resilience committee or other external requirements.	☒ Champion efforts still critical ☒ Political will garnered at agency, i.e., senior leadership support ☒ Resilience priorities identified; however, may not be explicitly stated in official agency planning documents ☒ Hazard specific plan(s) or program(s) developed with detailed impacts analysis and adaptation strategies identified ☒ Some level of external collaboration with strategic partners present	☐ Resilience focus on infrastructure hardening ☒ May have conducted or planning to conduct pilot study on risk or vulnerability for certain assets ☒ Active asset management program, but does not explicitly incorporate resilience considerations	☒ Initiatives still rely on grants ☐ May secure some state legislature funds for initiatives

Table A.2 WSDOT STRF Output Continued

Stage 3	☐ Guidance developed for changes in current plans, regulation or policies to support resilience thinking at agency (or state) ☐ Framework provided for possible institutional barriers (including inter-agency barriers) that may be faced in implementing resilience building strategies	☐ Raised employee awareness on resilience issues at agency ☐ Formal, dedicated or designated person/team responsible for resilience planning or initiatives ☐ Resilience considerations incorporated into project planning, e.g., hazard mapping ☐ Monitoring and reporting of resilience capacity building initiatives/activities adopted ☐ Coordination and/or unification of efforts with external transportation or non-transportation agencies	☐ Concrete steps taken to incorporate resilience considerations into existing asset management program, e.g., results of risk/vulnerability studies	☐ Case by case consideration of funding for adaptation strategies by agency
Stage 4	☐ Alignment of transport resilience planning and resilience planning in other sectors (e.g., land-use, housing, etc.) to streamline efforts and realize co-benefits.	☐ Champion efforts no longer needed ☐ Formal agency positions (partial/full) dedicated to building resilience capacity within agency ☐ Buy-in and understanding of resilience thinking established throughout agency ☐ Strategic goals and objectives for resilience capacity clearly identified and strategies outlined to achieve them ☐ Resilience thinking institutionalized at agency, i.e., resilience considerations incorporated into project development process (i.e., planning, construction, operation, maintenance, renewal/decommissioning) ☐ Resilience thinking reflected in main agency plans: • Asset Management Plan (TAMP) • Long Range Plan (LRTP) • Transport Improvement Plan (TIP)	☐ Resilience considerations go beyond direct transport assets, i.e., supporting infrastructure, (e.g., IT, ancillary assets) and subsystems/interdependent systems (power, water, etc.)	☐ Resilience considered in lifecycle costs analysis of projects ☐ Resilience considerations included in project prioritization process where necessary in addition to other priorities such as safety, costs, etc.

2

Table A.3 ARC STRF Output

	Institutional Capital	Organizational Capital	Technical Capital	Financial Capital
Stage 1	☒ Agency policies for sustainability may be present	☒ Champion efforts present to raise awareness in agency ☒Plans that address aspects of resilience may be present. e.g., initial climate action plans ☐ High level resilience planning present, e.g., qualitative/general impacts study, general state-wide resilience planning ☐ Emergency response and recovery processes present	☒ Awareness of hazards (e.g., climate impacts) and taking initial steps to mitigate	☒ Use of external grants/funds for initiatives
Stage 2	☐ Some hazard specific policies that enhance resilience present ☐ Mitigation policies present at agency, e.g., greenhouse gas mitigation ☐ External state action influences agency posture and actions. E.g., executive order, legislation, state resilience committee or other external requirements.	☒ Champion efforts still critical ☐ Political will garnered at agency, i.e., senior leadership support ☒ Resilience priorities identified; however, may not be explicitly stated in official agency planning documents ☐ Hazard specific plan(s) or program(s) developed with detailed impacts analysis and adaptation strategies identified ☐ Some level of external collaboration with strategic partners present	☐ Resilience focus on infrastructure hardening ☒ May have conducted or planning to conduct pilot study on risk or vulnerability for certain assets ☐ Active asset management program, but does not explicitly incorporate resilience considerations	☐ Initiatives still rely on grants ☐ May secure some state legislature funds for initiatives

Table A.3 ARC STRF Output (Continued)

	Institutional Capital	Organizational Capital	Technical Capital	Financial Capital
Stage 3	☐ Guidance developed for changes in current plans, regulation or policies to support resilience thinking at agency (or state) ☐ Framework provided for addressing possible institutional barriers (including inter-agency barriers) that may be faced in implementing resilience building strategies	☒ Raised employee awareness on resilience issues at agency ☒ Formal, dedicated or designated person/team responsible for resilience planning or initiatives ☐ Resilience considerations incorporated into project planning, e.g., hazard mapping ☐ Monitoring and reporting of resilience capacity building initiatives/activities adopted ☐ Coordination and/or unification of efforts with external transportation or non-transportation agencies	☒ Information on system vulnerabilities collected and documented e.g., downscaled climate data ☐ Detailed data and information on hazards present ☐ Concrete steps taken to incorporate resilience considerations into existing asset management program, e.g., results of risk/vulnerability studies	☐ Case by case consideration of funding for adaptation strategies by agency
Stage 4	☒ Formal agency policies explicitly address system resilience ☐ Alignment of transport resilience planning and resilience planning in other sectors (e.g., land-use, housing, etc.) to streamline efforts and realize co-benefits.	☐ Formal agency positions (partial/full) dedicated to building resilience capacity within agency ☐ Buy-in and understanding of resilience thinking established throughout agency ☐ Strategic goals and objectives for resilience capacity clearly identified ☐ Adoption of adaptive strategies outlined to achieve resilience goals ☐ Resilience thinking institutionalized. i.e., resilience considerations incorporated into project development process (i.e., planning, construction, operation, maintenance, renewal/decommissioning) ☐ Resilience thinking reflected in main agency plans: Asset Management Plan (TAMP), Long Range Plan (LRTP), Transport Improvement Plan (TIP)	☒ Resilience considerations go beyond direct transport assets, i.e., supporting infrastructure, (e.g., IT, ancillary assets) and subsystems/interdependent systems (power, water, etc.)	☐ Resilience considered in lifecycle costs analysis of projects ☐ Resilience considerations included in project prioritization process where necessary in addition to other priorities such as safety, costs, etc. ☐ Institutionalized approach/process for considering financial implications/needs for resilience

APPENDIX B

STRF Self-Assessment and Planning Tool

Transportation Resilience Self-Assessment and Planning Tool

Introduction

The STRF framework for resilience planning in transportation agencies uses a sociotechnical approach, that is, those that consider human and organizational factors in addition to technical factors, for resilience planning. The framework is based on foundational concepts from the resilience of ecological systems; specifically, defining and adopting a multi-stage approach to building resilience capacity. The framework is also structured by using a capital asset management approach and therefore focuses on enhancing a transport agency's *institutional*, *organizational*, *technical* and *financial* capital for building resilience capacity.

Furthermore, development of the Sociotechnical Resilience Framework was premised on the notion that as transport agencies mature in their dealings with hazards, they naturally move from largely technical to more sociotechnical approaches. The various capital attributes for each capital type were therefore extracted from both resilience literature and the relative experiences of U.S. transportation agencies involved in building resilience capacity.

Tool Description and Use

1. The four stages represent a gradual progression in maturity in terms of the resilience capacity of agencies. It is important to note that the framework is not intended to measure or rate an agency's resilience; rather, it serves as a scale that agencies can use to assess the progress of their resiliency building endeavors, and

systematically work toward enhancing their resilience capacity by reaching for the next desirable stage on the maturity scale.

2. The different capital types in each stage do not necessarily occur simultaneously. In assessing an agency's position on the maturity scale, one may find that the agency may be at Stage 1 in terms of Financial Capital, but Stage 2 in terms of the development of its Organizational Capital. Thus, an agency can invest in progressing within a capital type based on its predetermined priorities.
3. The stages described do not constitute a rigidly prescribed process for enhancing system resilience capacity; therefore, while some agencies may mature by progressively moving from one stage to next subsequent one, others may leapfrog from one to the next, based on agency priorities and available resources for growth.
4. Lastly, the framework is meant to be a tool that agencies can use to assess their progress in building resilience capacity within their agencies and identify growth opportunities in terms of what attributes to aspire to or will constitute appropriate strategic goals in different timeframes.

What to do for this exercise

Identify the current resilience capacity building stages for your agency by placing checkmarks on each attribute that best describes your agency's efforts. To collect the best type of information, it is advised that the exercise be carried out by persons from the following three categories:

- High level position with a good understanding of agency capabilities

- Planning division
- Operations or Engineering division

Table B.1 Definitions

Concept	Definition
Resilience	The ability of a system to maintain critical functions and prevent catastrophic failure during a disruption, and then recover rapidly, is now at the forefront of most critical infrastructure discussions
Organizational capital	Resourcefulness of the managing agencies in the case of infrastructure systems. It includes plans, processes, procedures or practices that increase an organization's resilience capacity
Institutional capital	Comprises laws, policies and regulations that determine what can be done in a particular system
Financial capital	This refers to the amount of financial resources available to an agency. This is reflected in budgets and impacts the prioritization of activities and projects
Technical capital	Comprises the portfolio of assets an agency owns, including their individual and combined performance, as well as the technical knowledge and expertise required to enhance the resilience of an agency’s portfolio of physical assets
Resilience champion	Individual at an agency that advocates for resilience awareness and promotes the adoption behaviors that result in more resilient outcomes

Table B.2 STRF Planning Tool

	Institutional Capital	Organizational Capital	Technical Capital	Financial Capital
Stage 1	☐ Agency policies for sustainability may be present	☐ Champion efforts present to raise awareness in agency ☐Plans that address aspects of resilience may be present. e.g., initial climate action plans ☐ High level resilience planning present, e.g., qualitative/general impacts study, general state-wide resilience planning ☐ Emergency response and recovery processes present	☐ Awareness of hazards (e.g., climate impacts) and taking initial steps to mitigate	☐ Use of external grants/funds for initiatives
Stage 2	☐ Some hazard specific policies that enhance resilience present ☐ Mitigation policies present at agency, e.g., greenhouse gas mitigation ☐ External state action influences agency posture and actions. E.g., executive order, legislation, state resilience committee or other external requirements.	☐ Champion efforts still critical ☐ Political will garnered at agency, i.e., senior leadership support ☐ Resilience priorities identified; however, may not be explicitly stated in official agency planning documents ☐ Hazard specific plan(s) or program(s) developed with detailed impacts analysis and adaptation strategies identified ☐ Some level of external collaboration with strategic partners present	☐ Resilience focus on infrastructure hardening ☐ May have conducted or planning to conduct pilot study on risk or vulnerability for certain assets ☐ Active asset management program, but does not explicitly incorporate resilience considerations	☐ Initiatives still rely on grants ☐ May secure some state legislature funds for initiatives

Table B.2 STRF Planning Tool (continued)

	Institutional Capital	Organizational Capital	Technical Capital	Financial Capital
Stage 3	☐ Guidance developed for changes in current plans, regulation or policies to support resilience thinking at agency (or state) ☐ Framework provided for addressing possible institutional barriers (including inter-agency barriers) that may be faced in implementing resilience building strategies	☐ Raised employee awareness on resilience issues at agency ☐ Formal, dedicated or designated person/team responsible for resilience planning or initiatives ☐ Resilience considerations incorporated into project planning, e.g., hazard mapping ☐ Monitoring and reporting of resilience capacity building initiatives/activities adopted ☐ Coordination and/or unification of efforts with external transportation or non-transportation agencies	☐ Information on system vulnerabilities collected and documented e.g., downscaled climate data ☐ Detailed data and information on hazards present ☐ Concrete steps taken to incorporate resilience considerations into existing asset management program, e.g., results of risk/vulnerability studies	☐ Case by case consideration of funding for adaptation strategies by agency
Stage 4	☐ Formal agency policies explicitly address system resilience ☐ Alignment of transport resilience planning and resilience planning in other sectors (e.g., land-use, housing, etc.) to streamline efforts and realize co-benefits.	☐ Formal agency positions (partial/full) dedicated to building resilience capacity within agency ☐ Strategic goals and objectives for resilience capacity clearly identified ☐ Adoption of adaptive strategies outlined to achieve resilience goals ☐ Resilience thinking institutionalized. i.e., resilience considerations incorporated into project development process (i.e., planning, construction, operation, maintenance, renewal/decommissioning) ☐ Resilience thinking reflected in main agency plans: Asset Management Plan (TAMP), Long Range Plan (LRTP), Transport Improvement Plan (TIP)	☐ Resilience considerations go beyond direct transport assets, i.e., supporting infrastructure, (e.g., IT, ancillary assets) and subsystems/interdependent systems (power, water, etc.)	☐ Resilience considered in lifecycle costs analysis of projects ☐ Resilience considerations included in project prioritization process where necessary in addition to other priorities such as safety, costs, etc. ☐ Institutionalized approach/process for considering financial implications/needs for resilience

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