DEVELOPMENT OF THEORY AND METHODOLOGIES TO ASSESS ADAPTIVE RESILIENCE IN INFRASTRUCTURE SYSTEMS

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DEVELOPMENT OF THEORY AND METHODOLOGIES TO ASSESS ADAPTIVE RESILIENCE IN INFRASTRUCTURE SYSTEMS

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Dedicated to all women in my life who personify resilience and whose shoulders I have had the privilege to stand on.

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LIST OF ABBREVIATIONS

AR	Adaptive Resilience
AR-CMM	Adaptive Resilience- Capability Maturity Model
ART	Adapting to Rising Tides
ASCE	American Society of Civil Engineers
B/C	Benefit/Cost Ratio
BCA	Benefit Cost Assessment
BSOPM	Black-Scholes Options Pricing Model
CAEP	City Assisted Evacuation Program
CGT	Constructivist Grounded Theory
CMM	Capability Maturity Model
DAP	Dynamic Adaptive Planning
DCF	Discounted Cash Flow
DM	Decision Making
DMDU	Decision Making under Deep Uncertainty
DOTs	Department of Transportation
EBB	Economic Benefit of the Bridge

ESAI	Emergency Service Availability Index
EU-VRi	European Virtual Institute for Integrated Risk Management
FAST	Fixing America's Surface Transportation
FEMA	Federal Emergency Management Agency
FHWA	Federal Highway Administration
FTA	Federal Transit Administration
GDOT	Georgia Department of Transportation
GEV	Generalized Extreme Value
HSIP	Highway Safety Improvement Program
IPCC	International Panel for Climate Change
IRB	Institutional Review Board
MAP 21	Moving Ahead for Progress in the 21st Century
MCS	Monte-Carlo Simulation
MPO	Metropolitan Planning Organization
MRT	Modified Resilience Triangles
NCHRP	National Cooperative Highway Research Program
NJ	New Jersey
NOAA	National Oceanic and Atmospheric Administration

NPV	Net Present Value
RADT	Risk-Adjusted Decision Trees
RCP	Representative Concentration Pathways
RDM	Robust Decision Making
ROA	Real Options Analysis
RT	Resilience Triangle
SLR	Sea Level Rise
SOS	System of Systems
TFI	Transit Functionality Score
TSMO	Transportation System Management and Operations
USGCRP	U.S. Global Change Research Program

SUMMARY

With the growing frequency, intensity, and consequences of disasters, developing resilience in infrastructure systems is increasingly recognized as critical to maintaining and enhancing system performance. Evolving trends in climate change, population growth, and urbanization make it essential to build adaptive capacity as a critical element of resilience, to enable systems to re-organize, or adapt to changing future conditions. This research focuses on answering two questions: (1) What capabilities of transportation systems foster adaptive resilience, how are they connected to system goals, and how can they be incorporated in planning for more resilient systems? (2) How can we evaluate the benefits of applying adaptive resilience approaches in planning for transportation systems?

The overall research methodology follows a mixed-methods sequential approach, where qualitative methods are applied to identify, define, and categorize the adaptive resilience capabilities of transportation systems, followed by a quantitative methodology developed to assess the benefits of adaptive resilience initiatives over the life cycle of infrastructure systems. An Adaptive Resilience Capability Maturity Model (AR-CMM) is developed using a quasi-grounded theory approach, involving iterative literature reviews and expert interviews to identify the adaptive resilience capabilities of transportation systems and their connections with system goals. The AR-CMM assesses the maturity level of any transportation agency on 16 identified adaptive resilience (AR) capabilities of transportation systems. The capabilities are categorized into three themes and assessed over a five-level maturity scale. To enable benefits quantification of initiatives that can enhance the maturity levels of the identified AR capabilities, a Modified Resilience Triangles (MRTs) approach is developed, which can be used to evaluate the long-term benefits of adaptive resilience investments in infrastructure systems under future uncertainty.

The application of the MRTs approach is demonstrated using three case studies, where investments have focused on different aspects of adaptive resilience enhancement in various infrastructure systems. The results from all three case studies demonstrate the increasing benefits of adaptive resilience strategies over a long time frame due to deep uncertainty, ongoing learning and the evolving nature of resilience strategies.

This research expands existing infrastructure resilience theory by developing a portfolio of capabilities of transportation systems that enable adaptive resilience in the systems; and by developing the Modified Resilience Triangles approach, thereby extending the theory on resilience assessment to include impacts of adaptive resilience on the long-term resilience of infrastructure systems. The AR-CMM provides a framework for transportation agencies to evaluate and enhance their adaptive resilience maturity levels. Application of the MRTs approach provides practitioners in any infrastructure field with an enhanced approach for assessing the value of resilience investments, thereby offering a tool that can be used to demonstrate the business case for adaptive resilience to uncertain future conditions. The AR-CMM along with the MRTs approach can be used to incorporate adaptive resilience formally in transportation system planning frameworks, enabling more reliable and cost-effective performance.

CHAPTER 1. **INTRODUCTION**

1.1 Motivation

"Despite established definitions and models guiding research and applied work for the last 20 years, recent massive losses due to infrastructure failures raise the question: ***Are the ways people thinking about resilience producing resilient infrastructure systems?"*** (Eisenberg 2018)

Transportation infrastructure design and practices guide and are guided by land-use development, city planning, and business district growth, hence impacting the functioning of these mega-systems. The implications of investment in non-resilient & non-adaptable transportation infrastructure can thus be significant to society as most of these investments are irreversible and have significant directional impacts on the overall societal system.

In general, infrastructural development does account for extreme weather protection in some form or the other. Traditionally, this has been done using safety factors incorporated into the design standards of the infrastructure, safeguarding it from a probabilistic risk limit (e.g., 50-year return period event). These limits are identified using historical data on events like precipitation, temperature, and flood inundation (Meyer 2007). But the recent climate change events and the unpredicted extreme events in the past few years has led to the understanding that the estimates we have for climate change are changing at a much faster rate than anticipated. Using historical data to predict the future is no longer a viable option (Chester and Allenby 2018). This essentially makes the static design safety standards obsolete. This poses even bigger threats to public infrastructures as they are designed for a significantly long lifecycle, and once built, they are generally hard to modify in terms of critical design elements, introducing path dependencies. The long life cycle makes the assets susceptible to extreme events that are highly uncertain and unpredictable based on current knowledge, and the fixed-design aspects make it difficult for the system to adapt. For example, a bridge designed for a fixed value of flood level (which was identified based on prior 50-70 years of data), has a good chance of flooding as the historical estimates are no longer valid. Also, once built with a static design, it is difficult to change the design for any other flood level without rebuilding the bridge in its entirety and hence incurring a significant and avoidable financial loss.

The significant impact of transportation infrastructure assets on the overall economy and the increasing uncertainty in climate change leads to a need to plan for future uncertainty in order to minimize the costs of the extreme events while keeping the economy running.

Recent developments in understanding the effects of climate change have led transportation agencies to look critically into resilience to safeguard their assets from potential extreme events. This interest is generally in conflict with other demands like increasing population and the need for system expansion, as the overall public budget is constrained (Levy and Herst 2018). Given that the benefits of resilience and adaptation are primarily based on the reduced damage from potential extreme events, it is difficult to quantify and present them in an objective term equivalent to the direct benefits obtained from investment in projects that serve current demands (Levy and Herst 2018).

The motivation of this research is to bridge the gaps in resilience understanding with respect to transportation infrastructure systems, develop methodologies that can be used to understand and characterize the adaptive resilience maturity of a transportation system, and identify and assess the benefits of enhancing adaptive resilience maturity in any infrastructure system, thereby providing a means to develop a business case for proactive incorporation of adaptive resilience in transportation planning.

1.2 Research Overview

1.2.1 Research Problem

The current understanding of resilience concepts and their application in the transportation domain has proved insufficient in creating resilient systems (Eisenberg 2018). The frameworks applied in practice do not necessarily reflect the complete resilience perspective that has been developed in theory.

The theoretically accepted definition of resilience across all domains involves the following key elements: 1) Planning & Preparation, 2) Absorption, 3) Recovery, and 4) Adaptation (Bhamra et al. 2011; Hosseini et al. 2015; Martin-Breen and Anderies 2011; Wan et al. 2018). However, in infrastructure practice, especially in transportation, more focus is placed on the first three elements. The literature from other fields where resilience has been studied extensively, such as ecology, economy, and social resiliency, indicates the importance of adaptability in any system for it to remain resilient, particularly in a rapidly changing environment. Adaptation, one of the critical pillars of resiliency, is not as much present in the current practice of infrastructure system resilience, particularly in transportation.

The current transportation system in practice identifies risk identification, shock absorption, and quick recovery (back to normal) as the critical elements of a resilient system (Bruneau et al. 2003; Wan et al. 2018). While all these factors are essential, they are not sufficient to define the resiliency of a system. Adaptability is often omitted in resiliency measures and applications, which is also evident in its low representation in the resiliency literature for built systems (Figure 1-1).

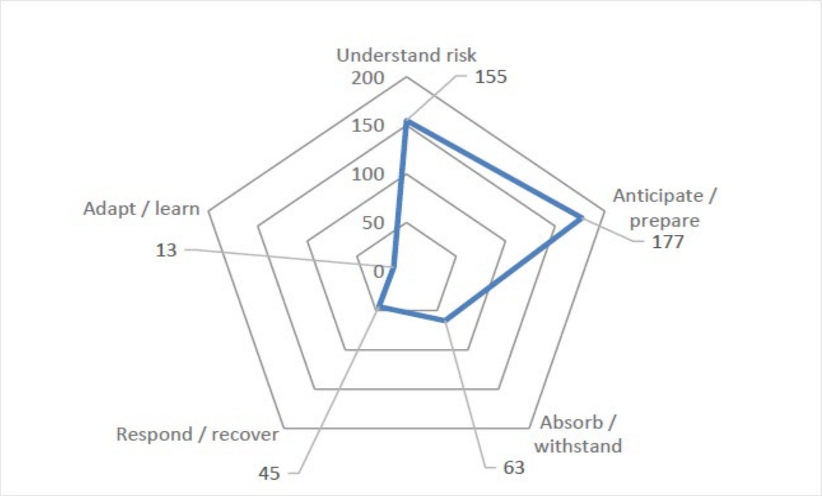

Figure 1-1: Distribution of the literature found for each phase of the resilience cycle for built systems (Jovanović et al. 2018)

A critical reason for the lack of adaptation elements in the transportation system is the lack of quantifiable performance metrics for adaptation. Adaptation is not easily quantified—yet public investment decision making has historically favored objective and measurable processes to evaluate and fund projects. In the US transportation system, federal funding is generally distributed based on the overall asset valuation of the state/regional agency (FHWA 2016c). The valuation framework currently being followed only looks at the condition-based value of the asset (Amekudzi-Kennedy et al. 2019). This undervalues the assets with adaptive capacity and favors investment in non-adaptive assets to avoid the added costs. This is becoming a major issue due to the increasing uncertainty associated with future climate scenarios and extreme events, intensifying the need to develop adaptive resilience in infrastructure systems. At the same time, there is still a lack of objective measures to evaluate them against other competing investment needs.

There is a need to reanalyze the foundational concepts of resilience, trace the evolution of definitions of resilience for built systems (and other systems), and identify and fill the gaps with respect to incorporating adaptive resilience into transportation planning.

1.2.2 Objective and Scope

The objective of this research is to identify the adaptive resilience capabilities of transportation systems and develop an approach to evaluate the impacts of incorporating adaptive resilience in infrastructure systems.

While the identification of adaptive resilience capabilities and development of the maturity model is scoped for the transportation infrastructure system, the adaptive resilience benefits assessment methodology can be applied to other infrastructure systems as well.

1.2.3 Research Questions and Hypothesis

The two main research questions that this research attempts to answer are:

(1) What are the capabilities of transportation systems that foster adaptive resilience, how are they connected to the system goals?

(2) How can we evaluate the benefits of using adaptive resilience approaches in transportation system planning?

This research hypothesizes that adaptive resilience approaches enhance the long-term benefits of resilience investments in transportation systems.

1.2.4 Research Framework

The research framework follows a three-phase approach. The first phase focuses on preliminary testing of the research hypothesis by capturing the value of dynamic adaptive planning on a selected project-level case study—the next two phases on theory development and application. The second phase includes identifying a portfolio of adaptive resilience capabilities of transportation systems and developing a capability maturity model to assess the maturity level of the identified adaptive resilience capabilities for any transportation system. The third phase focuses on the development of the Modified Resilience Triangles methodology- an approach to quantify the life-cycle benefits of improving the maturity of the adaptive resilience capabilities of infrastructure systems under uncertainty. The third phase also includes applying the developed MRT methodology on three separate case studies to validate the research hypothesis. The three phases are presented as research articles in Chapters 3, 4, and 5. Table 1-1 presents the research overview, including the specific research questions and the methods used in each chapter.

Table 1-1: Research Overview

Chapter	Research Question(s)	Research Method(s)
Chapter 3	Does adding flexibility in resilience planning lead to better returns over the life-cycle of an infrastructure asset?	Real options theory inspirited risk-adjusted decision trees- used to compare dynamic vs. static plans
Chapter 4	What are the capabilities of transportation systems that demonstrate adaptive resilience?	Inductive theory development using grounded theory approach – Iterative literature review and expert interviews
Chapter 5	How can we evaluate the long-term benefits of using adaptive resilience approaches in transportation system planning under uncertain future conditions?	Inductive theory development using grounded theory approach. Case study based demonstrations of the developed methodology

1.3 Methods

The research follows a mixed-methods approach. Chapter 3 reviews resiliency, especially the adaptive nature of resiliency which deals with the uncertainty of future events. Exploring the adaptive element in the resiliency domain, the paper presents Dynamic Adaptive Planning (DAP) as a potential planning strategy to develop robust long-term plans for infrastructure resilience, which are not stationary and can handle deep uncertainty. The importance of accurate economic valuation of such methods, where uncertainty handling has a value, is presented. An illustrative example highlights the economic value of using dynamic adaptive plans compared to static plans, exemplifying the value of flexibility in deeply uncertain situations. The chapter follows an Embedded Design (Creswell and Clark 2010) as presented in figure 1-2(a), where qualitative data on the different plans for building resilience for the given infrastructure asset is embedded with the quantitative data related to the costs and benefits of the different plans, in order to allow for interpretations based on the collective qualitative and quantitative data. The detailed methodology of data collection for the two parts of the embedded design is presented in Chapter 3. The work presented in chapter 3 has been published as a peer-reviewed paper in the Transportation Research Record (Singh et al. 2020).

In Chapter 4, the paper uses a constructivist grounded theory (CGT) approach to identify the capabilities of transportation systems that support adaptive resilience and to develop a maturity model to reflect different levels of adaptive resilience maturity in a transportation agency. The chapter follows a Taxonomy Development Model of Exploratory Research Design, emphasizing the qualitative methods (Creswell and Clark 2010). The model is presented in figure 1-2(b). Here, qualitative data collected from literature review and expert interviews is used to develop a taxonomy of adaptive resilience capabilities in transportation systems and used as a basis for the development of a CMM that can be applied for quantitative data collection. The qualitative theory can then be used to interpret the collected quantitative data. Chapter 4 presents the theory developed using qualitative data. The preliminary application of the developed methodology for quantitative data collection and interpretation is presented in the Appendix.

Chapter 5 introduces an approach to assess the benefits of adaptive resilience investments by examining the long-term benefits of continuous adaptation of a system under future uncertainty. The approach builds on the resilience triangle approach, which has been applied widely in the infrastructure field to quantify resilience. The chapter presents the changes made to the existing resilience triangle approach, introduces the methodology of the Modified Resilience Tringles (MRT) approach, and demonstrates its application using three case studies of adaptive resilience strategies implemented in different infrastructure systems across the US. The chapter follows an Instrument Development Model of Exploratory Design, emphasizing quantitative methods (Creswell and Clark 2010). The model is presented in figure 1-2 (c). Here qualitative data on resilience assessment approaches is collected through literature review, through which the MRT instrument is developed. The instrument is then implemented and validated using quantitative data from the three case studies. The detailed methodology for developing the instrument and specific quantitative methods for the instrument implementation for each case study are presented in chapter 5.

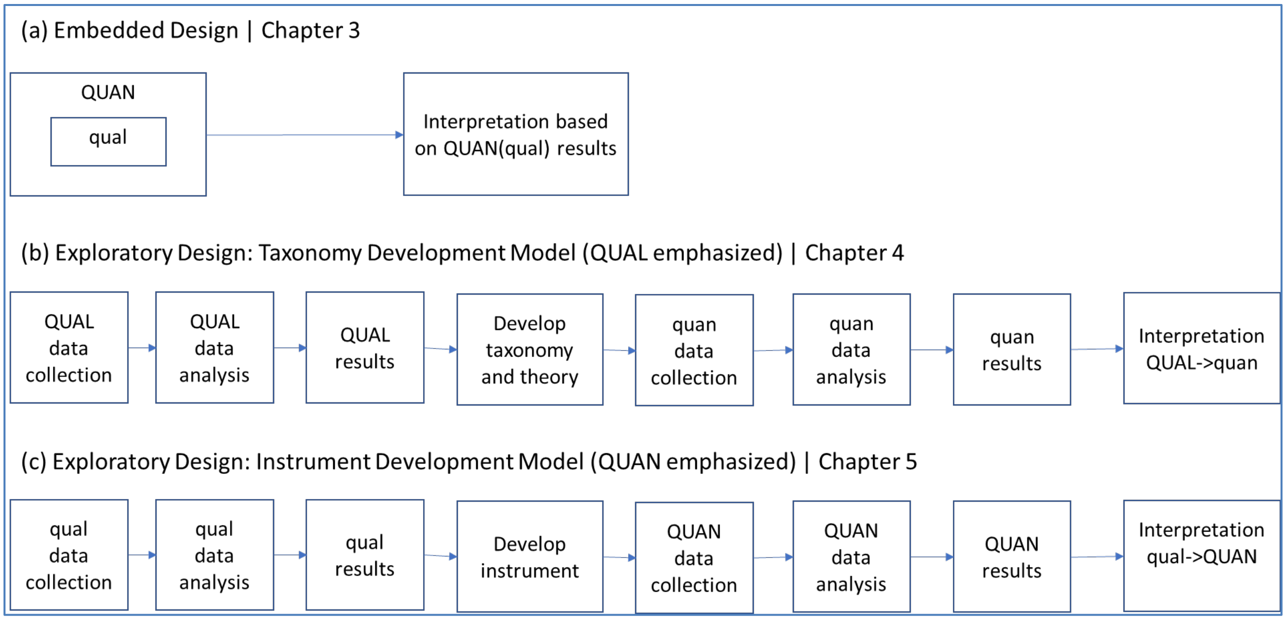

Figure 1-2: Research Design Methods used in different chapters of the dissertation (Creswell and Clark 2010)

1.4 Dissertation Format

This dissertation follows a journal article format, where Chapters 3, 4, and 5 are stand-alone articles. Chapter 2 provides additional background based on a literature review of the key concepts of the dissertation. Chapters 3, 4, and 5 have been submitted as articles, and Chapters 4 and 5 are currently under review with separate peer-reviewed journals. Chapter 2 is a published article (Singh et al. 2020). The author respectfully requests that any citations of the work presented in Chapters 3, 4, and 5 refer to the existing or eventual published versions of the work rather than this dissertation. References for each of the three journal articles are included in the respective chapters. Chapter 6 summarizes the theoretical and practical contributions of this dissertation and suggests directions for future research. Appendices are included at the end of this dissertation to report details of the IRB approval and additional research that would not fit within the journal articles due to space limitations.

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CHAPTER 2. **BACKGROUND**

2.1 Disasters

Life on the planet since it has existed has been shaped by perturbations occurring at different levels of impact in the regular system. Various extinction events throughout history have shifted the life system on earth, with some life forms getting extinct and other surviving (Grant et al. 2017). Each such change has forced life on earth to adapt in order to survive. Such perturbations can span 100 years (yet be sudden in terms of geological time) or occur in a very short period of time but still have a tremendous impact (Grant and Grant 2014). In any such cases, being resilient and adaptive is the key to sustainability. The concept applies to built systems just as it does to natural systems.

Disasters can be categorized by their cause of origin, duration, and potential of occurrence (Berren et al. 1980). Events such as earthquakes, floods, and hurricanes are considered natural disasters, while terrorist attacks, structural failure if infrastructure systems account for human-made disasters. Recent impacts on human interventions on the natural systems have blurred the line between natural and human-made disasters due to significant impacts of human activities on natural phenomenon such as climate change (Chester et al. 2019; Shaluf 2007). Disasters could also be distinguished based on their duration. While focus of disaster management has generally been on sudden disasters such as earthquakes, fires, and hurricanes occur for a very short period of time, while disasters such as famines and pandemics such as COVID-19 could last for years and are termed as creeping disasters (Boin et al. 2020; NASA 2000). The consequences and potential of occurrence of disasters has been continuously increasing, demonstrated by a general upward trend in number of billion-dollar events over the last few decades (Adam B. Smith 2019; NOAA 2021).

Of special interest in this research are sudden natural disasters, that are now exacerbated by anthropogenic factors. Disasters such as earthquakes, hurricanes, floods, volcanic eruptions, landslides, and fires have significant impacts on built systems, society, and the economy of the affected region. The impacts range from loss of life, food scarcity, emotional aftershock, critical infrastructure failure, and disruptions to the economy (Childfund International 2013). According to United Nations Office for Disaster Risk Reduction (UNISDR), “between 1998 and 2017, climate-related and geophysical disasters killed 1.3 million people and left a further 4.4 billion injured, homeless, displaced or in need of emergency assistance.” (UNISDR 2018). These trends emphasize the need to develop resilience in our natural and build systems.

2.2 Resilience

The word Resilience originates from Latin *resiliens,* which means ‘to bounce back.’ The use of the word spans multiple disciplines. Initially used in ecology (Holling 1973, 1985), the term is widely used in psychology, business management, political science, sociology, urban planning, international development (Martin-Breen and Anderies 2011), and in engineering fields such as metallurgy (Callister 2003), supply chain management (Sheffi 2005), strategic management (Hamel and Välikangas 2003), safety engineering (Hollnagel et al. 2006), and disaster preparedness (Bruneau et al. 2003). Extended over multiple and diverse domains, the definition and use of the word also varies. An extensive review of the definition of resilience (Bhamra et al. 2011; Hosseini et al. 2015; Martin-Breen and Anderies 2011; Sun et al. 2018) suggests that the concept has some common attributes spread across different domains and has some fixed distinctions specific to each domain.

- Across all fields, resilience entails the concepts of "capability and ability of an element to return to a stable state after a disruption" (Bhamra et al. 2011). Categorizing the fields in four different dimensions - Technical, Organization, Social, and Economic, each dimension requiring four common properties - Robustness, Rapidity, Redundancy, and Resourcefulness (the 4 Rs), eventually leads to a resilient system that is reliable, has a faster recovery, and has lower consequences from a disruption (Bruneau et al. 2003; Sun et al. 2018). These eleven aspects are presented in figure 2-1.

Figure 2-1: The 11 dimensions of resilience (Adapted from Bruneau et al. 2003 and Sun et al. 2018)

Holling (1996) defines two faces of resilience: engineering resilience and ecological resilience. Engineering resilience is defined in literature by its characteristics of "bouncing back faster after expected stress, enduring greater stresses, and being disturbed less by a given amount of stress."(Martin-Breen and Anderies 2011). This form of resilience concentrates on a single-equilibrium point, and resistance to disturbance and speed of return to the original state are used to measure resiliency. In contrast, the other face, ecological resilience, allows the system to move to a different equilibrium regime, as long the system sustains itself (Holling 1996). Engineering resilience relates well to the idea of building infrastructures that can handle large stresses and are expected to return quickly to normal once the stress is removed.

Martin-Breen and Anderies (2011) also segregate resilience based on whether the subject of resilience is an isolated object or a system. The resilience attributed to an isolated object is here referred to as engineering resilience, the same as defined by Holling. System resilience extends the engineering resilience paradigm to consider interdependent and interactive components that make up a system. Hence, resilience here is defined as the property of maintaining the system function in the event of a disturbance (Martin-Breen and Anderies 2011; Pregenzer 2011).

The traditional definition of resilience, especially in the engineering domain, primarily focused on the system being “strong, static, and resistant to change” (Tiernan et al. 2018). The resilience triangle approach (Figure 2-2), initially presented by Bruneau and others (Bruneau et al. 2003), presents a method for quantifying resilience by representing ‘loss of functionality or discomfort.’ With this approach, a smaller reduction in performance (robustness) and a faster recovery indicates a resilient system. The model is extensively applied in infrastructure systems, especially in measuring the resilience of built systems & supply chains towards natural disasters such as earthquakes (Bevilacqua et al. 2017; Bruneau et al. 2003; Yu et al. 2014).

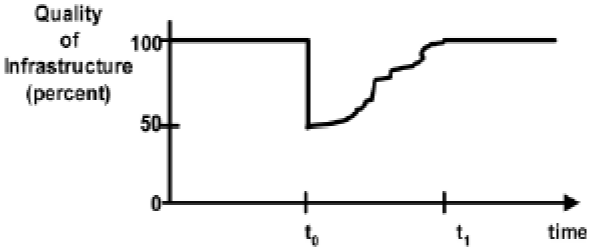

Figure 2-2: Resilience triangle - Measure of seismic resilience - conceptual definition (Bruneau et al. 2003)

Holling defines three characteristics of engineering resilience that need to be critically evaluated while assessing its application to complex systems. It indicates that engineering resilience is based on the following three assumptions:

(1) There is only one equilibrium
(2) The object returns to the same state after a disturbance it can handle
(3) The types of disturbances are expected (Holling 1996; Martin-Breen and Anderies 2011)

These assumptions have been challenged in recent years with changing paradigms of disruptions in the system. With the changing rates of natural disasters and their increasing impacts on risk-based planning, the question of whether a robustness and resistance-based, risk-oriented approach is the best model of resilience for infrastructure systems (Eisenberg 2018).

Complex Adaptive System Resilience differs from engineering and system resiliency by focusing on adaptive capacity or adaptability (of a complex system). Martin-Breen and Anderies (2011) define this as

> "It is not just adaptation—change—in response to conditions. It is the ability of systems—households, people, communities, ecosystems, nations—to generate new ways of operating, new systemic relationships. If we consider that parts or connections in

> systems fail or become untenable, adaptive capacity is a key determiner of resilience. Hence in complex adaptive systems, resilience is best defined as the ability to withstand, recover from, and reorganize in response to crises. Function is maintained, but system structure may not be." (Martin-Breen and Anderies 2011)

A review of disaster resilience themes from 2012-2017 indicates that the new definition of a resilient system is the one that is flexible, is able to adjust to stress, and that has adaptive capacity, and can undergo a transformational change in the face of extreme stress (Tiernan et al. 2018). Studies also present a modified version of the resilience triangle attempting to indicate the adaptive capacity of systems by emphasizing the 'building better' scenario (Häring et al. 2017; Tang and Heinimann 2018). Figures 2-3 and 2-4 from the above two literature sources indicate this shift.

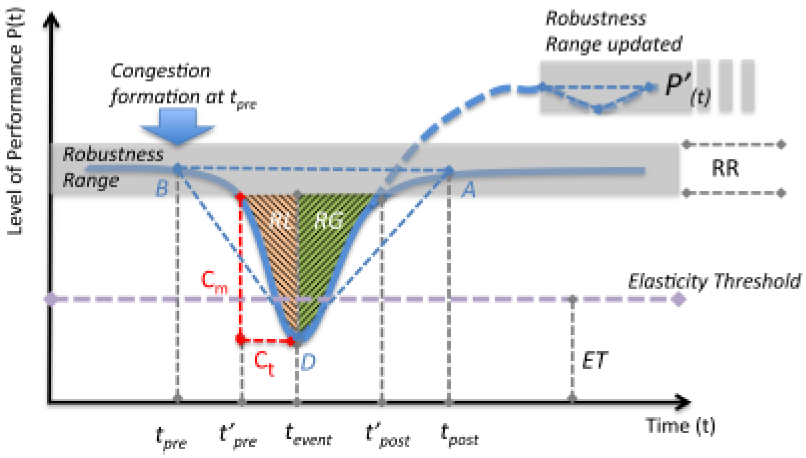

Figure 2-3: Traffic congestion resilience model, incorporating resilience gain section (P'(t) performance level) as increased performance after the recovery phase. (Tang and Heinimann 2018)

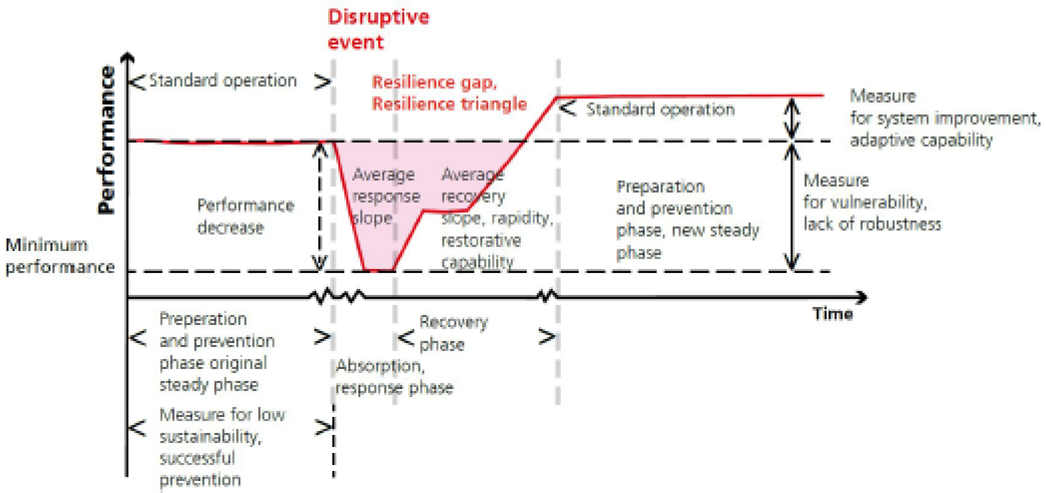

Figure 2-4: Resilience quantities derived from the time-dependent system function performance curve in case of bounce back with improvement (bounce back better). (Häring et al. 2017)

2.3 Adaptive Resilience

Adaptation is essentially an adjustment in the face of change (Martin-Breen and Anderies 2011). In most of the literature, it is directed towards positive change. In the ecology literature, the word is defined as a change or the process of change by which an organism or species becomes better suited to its environment (Engle 2011). It is a key concept in evolutionary science and is also widely used in psychology. Climate change literature defines adaptation as “adjustments in ecological-social-economic systems in response to actual or expected climatic stimuli, their effects or impacts” (Smit et al. 2000). Adaptive capacity (or adaptability) is characterized as a property of complex adaptive systems defined as “the ability of a (human) system to adjust to climate change (including climate variability and extremes), to moderate potential damages, to take advantage of opportunities, or to cope with the consequences”(Climate-ADAPT n.d.). Essentially, the adaptive capacity of a system allows it to implement sustainable adaptations.

Adaptive capacity has been referenced in vulnerability and resilience frameworks separately, and Engle (2011) (Engle 2011) reviews both the literature to assess the property and its impacts on sustainability research. In the vulnerability literature, adaptive capacity is one of the three basic elements, the other two being sensitivity and exposure. Figure 2-5 presents the role of adaptive capacity in influencing the vulnerability of a system. In climate change and extreme weather literature, exposure relates to the susceptibility of an object or system to a particular hazard, and sensitivity refers to the degree to which a system or species is affected by the exposure. Adaptive capacity modulates the two features to reduce the vulnerability of the object/system.

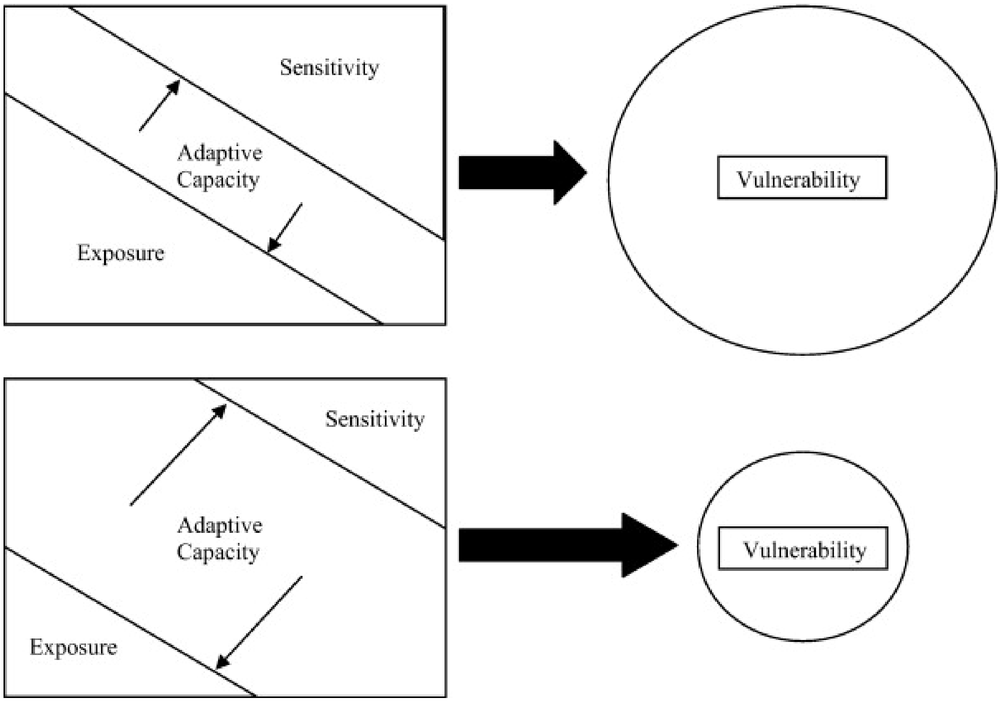

Figure 2-5: A basic depiction of adaptive capacity's role in influencing vulnerability. Adaptive capacity affects a system's vulnerability through modulating exposure and sensitivity. (Engle 2011)

In the resilience literature, as pointed out above, adaptive capacity (or adaptability) is the capability of the system to improve resilience by facilitating its movement to another equilibrium state and by facilitating transitions or transformations of the system when needed (Engle 2011).

Engle (2011) connects resilience and vulnerability through adaptive capacity, as presented in Figure 2-6.

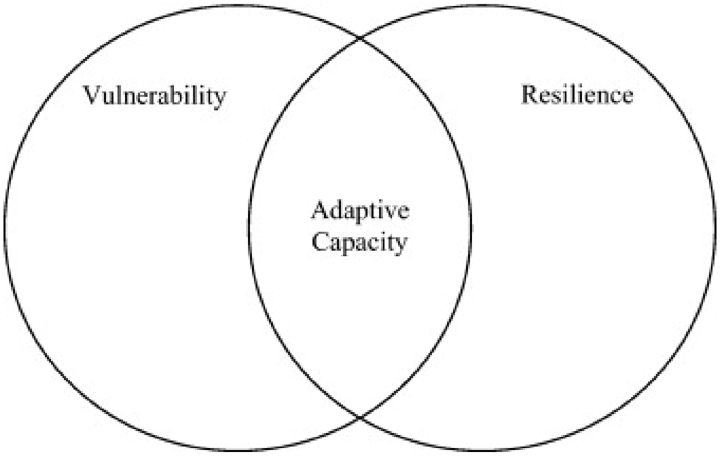

Figure 2-6: Vulnerability and resilience frameworks as linked through the concept of adaptive capacity.(Engle 2011)

While resilience and vulnerability are separate concepts, both support the prioritization of management practices, assets, and institutions to better react to stresses. The vulnerability literature leads to the development of risk-based planning. The application of adaptive capacity in linking resilience and vulnerability literature can support a movement from purely risk-based planning framework to an adaptive resilience-based planning framework, the desired direction for mega-systems in the face of uncertain climate change.

Adaptive capacity and the shift from single-equilibrium focus to multi-equilibrium have been emphasized in recent studies (Amoaning-Yankson 2017; Martin-Breen and Anderies 2011). Amoaning-Yankson (2017) reasons this by stating that the concept of engineering infrastructure out of risk is not practical in the current era given the variable frequency and strength of natural hazards (Amoaning-Yankson 2017). Martin-Breen and Anderies (2011) conceptualize this approach as 'Embracing Change.'

> "One slogan of resilience thinking is "Embracing Change." One part of this is accepting that change in response to adversity is itself normal. Fighting against it, as well, can actually cause a decrease in resilience. Try to keep everything the same, and the chance of future catastrophe can actually increase." (Martin-Breen and Anderies 2011)

While adaptive capacity has gathered the attention of resilience researchers across the globe, its use in practice, especially in infrastructure systems, is not very advanced so far (Eisenberg 2018). Given the varied use of resilience across multiple domains, it currently serves as an umbrella word in practice covering risk-based planning, climate-change impact assessment, emergency planning, and green-urban development (Amoaning-Yankson 2017; Lizarralde et al. 2015).

A study done by the European Virtual Institute for Integrated Risk Management (EU-VRi) on the analysis of existing assessment approaches, indicators, and data sources of smart critical infrastructures concluded that the majority of resilience frameworks emphasize understanding risk and anticipating/preparing for emerging risks over absorption and recovery. The focus on adaptive capacity or transformation is the least evident (A. Jovanović et al. 2018). Figure 2-7 shows the study results, presenting the distribution of the studied literature over the different dimensions of resilience.

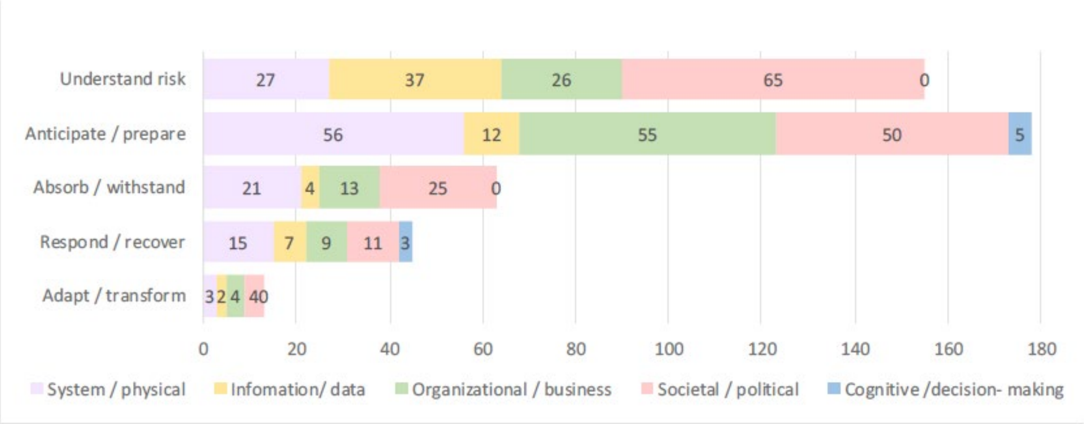

Figure 2-7: Number of candidate indicators in each phase and dimension of the SmartResilience matrix (A. Jovanović et al. 2018)

Understanding risks and anticipating threats are generally the first logical steps to making a system more resilient. Recent FHWA resilience pilots also focus strongly on better vulnerability assessment of the assets (Rodehorst et al. 2018). Several state agencies in the US have developed their vulnerability assessment frameworks to identify the critical assets that need attention. As was discussed before, withstanding or absorption of shock is a common solution pathway considered in the infrastructure industry, which has led to a prevalence of engineering resilience practices. The three phases of resilience (understanding risk, anticipation, and absorption) attempt to reduce the uncertainty associated with either the exposure (understanding risk) or with the consequence (withstand/absorb) to a certain extent. Response, recovery, and adaptation/transformation inherently acknowledge uncertainty and do not necessarily focus on just reducing the hazard's risk. Instead, they work at reducing the impacts of the hazard, even if it means shifting the original system characteristics (transformation). In this research, adaptive resilience is defined as ‘a way of incorporating resilience in a system that fosters flexibility and agility across all the complex system components.’ Under this definition, any efforts to support the planning and preparation, absorption, response, and recovery of a system against a disruption are to be done ‘adaptively,’ i.e., with intentional incorporation of flexibility and agility in the different aspects of resilience of the system accounting for uncertainties related to future disruptions.

2.4 Uncertainty

Uncertainty is generally defined as “limited information about past, present or future events”(Wall et al. 2015). In civil engineering, the concept is divided into two types, one evolving from natural variability (aleatory uncertainty), and the other evolving from lack of knowledge (epistemic uncertainty). Wall and others (2015) categorize uncertainty levels from a spectrum to four defined levels, between two extremes of complete certainty and total ignorance:

- Level 1: One where uncertainty is acknowledged, but is not given enough importance in planning and is generally handled by sensitivity analyses.
- Level 2: Where uncertainty is defined in statistical terms. Here it is generally handled by using probability-based single forecasts.
- Level 3: Where probability allocation is not possible, and scenarios and potential plausible futures are used to plan for the uncertainty.
- Level 4: Deep uncertainty, where the only information is known, is that we lack the information. It is also termed as recognized ignorance and applies to black swan events, which have catastrophic impacts on society. (Wall et al. 2015)

The first two phases of resilience involve understanding/predicting and responding/preparing to resolve or work with Level 1 & Level 2 uncertainties. Using a discount rate and doing sensitivity analyses are examples of working with level 1 uncertainty in future demand. Creating barriers and design manuals with conservative safety factors for a specific level of an extreme event (e.g., 100-year return period flood and 5-percentile temperature extreme limit) are examples of working with predictable Level 2 uncertainty.

Adaptation, adaptive capacity, flexibility, and transformability work with the last two levels of uncertainty, as they focus less on attempting to reduce the uncertainty; instead they work with or plan for the uncertain future.

Climate change and disaster management have long been handled at uncertainty Level 1 or 2. Risk-based planning aims to reduce the risk and consequences but assumes that the level of risk and consequences are known beforehand or can be estimated at reasonable confidence levels. However, recent changes warrant these uncertain events to be considered at level 3 or 4 uncertainty. "Reliance on probabilistic likelihood to identify, assess, and respond to uncertain climate change risks is problematic since the emission scenarios upon which climate projections are based are assigned no measure of likelihood."(Wall et al. 2015)

As adaptive resilience is most useful in situations with higher levels of uncertainty, the possibility of the reduction of loss because of a system's adaptive resilience depends on the occurrence of an extreme event. Hence, the benefits associated with adaptive resilience also involve the same levels of uncertainty as the disruption itself and are therefore difficult to quantify or assess. This is a significant challenge for incorporating adaptive resilience in infrastructure systems, as without an appropriate understanding of the benefits provided by the added adaptability, there is no quantifiable business case for investing in adaptive resilience to prepare for a highly uncertain future. Although researchers acknowledge that in these changing times, adaptation is critical, the means to evaluate resilience investments still follow a risk-oriented approach. The majority of the major infrastructure projects, especially transportation infrastructure projects being publicly funded, are the most affected by this challenge, as without a proper objective business case for investment in adaptive resilience where benefits can be clearly identified and presented, it is increasingly difficult for policymakers to invest funds from taxes on adaptation measures, over other projects with better benefit-cost ratios based on standard BCA tools.

The next three chapters follow a format for journal papers, with each chapter answering different aspects of the research questions presented in Chapter 1. The next chapter focuses on preliminary hypothesis testing, and uses a case study approach to assess the value of flexibility in transportation planning. The subsequent two chapters focus on theory development and application, with Chapter 4 presenting the AR-CMM (Adaptive Resilience – Capability Maturity Model) and Chapter 5 presenting the MRT Assessment approach. Chapter 6 concludes the dissertation with the contributions of this work to theory and practice and an outline of future work followed by complete references and appendices.

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CHAPTER 3. VALUING FOR FLEXIBILITY IN TRANSPORTATION PLANNING

Singh, P., B. Ashuri, and A. Amekudzi-Kennedy. Application of Dynamic Adaptive Planning and Risk-Adjusted Decision Trees to Capture the Value of Flexibility in Resilience and Transportation Planning. Transportation Research Record, Vol. 2674, No. 9, 2020, pp. 298–310. https://doi.org/10.1177/0361198120929012.

3.1 Abstract

Transportation infrastructure around the world is under stress to perform with ever-changing climate scenarios, unpredictable disasters, and stress on resources stemming from rapid urbanization and population growth. Current approaches to developing resilience applied to the transportation system focus primarily on engineering resilience, and do not explicitly deal with deep uncertainties arising from climate change. This paper reviews adaptation, a critical aspect of a resilient system in an uncertain and changing environment, as applied in the transportation resilience literature. It compares and contrasts the status of adaptive resiliency in transportation with that in other fields to highlight gaps and research opportunities. The paper then presents Dynamic Adaptive Planning (DAP) as a method to deal more effectively with deep uncertainty in decision making and offers an approach that combines economic analysis with DAP to enhance decision making under external uncertainties, such as natural disasters, with financial constraints. It presents a case study of the San Francisco-Oakland Bridge to demonstrate the economic benefits of DAP. This paper provides transportation practitioners with guidance on the application of DAP and understanding the economic benefits of such an approach to decision making in various settings including emergency response planning, long range planning, maintenance and renewal planning, and operations planning. The paper also identifies future research combining financial theory with dynamic adaptive planning as important in developing more robust decision-making frameworks for handling deep uncertainty.

Keywords: Resilience**,** Dynamic Adaptive Planning, Economic Analysis, Robust Decision Making

3.2 Introduction

Natural disasters have always disrupted the regular workings of the society, but the recent escalation in the frequency and impacts of natural disasters is forcing decision makers to understand the necessity and urgency for a shift in traditional decision-making processes, accounting better for existing deep uncertainties associated with the changing climate and other dynamic factors. Damages from disasters in the U.S. in 2017 broke the 2005 record exceeding $300 billion in cumulative cost. The same year was also one of the highest billion-dollar disaster counts so far, tied with the year 2011 (NOAA n.d.). A major part of the impact comes from the transportation system, where it is of critical importance to overcome the disaster impacts quickly, in order to provide immediate evacuation and which is a critical means to get the economy functioning again. This also makes the transportation system at once critical and vulnerable to disasters impacts, as its breakdown can significantly escalate losses and damages.

The complex distribution of the transportation system geographically, jurisdictionally, and by mode choice makes it difficult to have a single policy plan for all disaster events. Different funding sources and changing political environments may also have noteworthy impacts on policy development. With these constraints in place and given that the decisions in this system tend to be primarily irreversible and long-term, there is a lot of pressure on policy makers to make sound decisions. The US transportation system has always incorporated climate impacts in the planning, but resides on the concept of *stationarity*, the idea that the historic trends give a fair indication of the future (Rodehorst et al. 2018). This concept has been challenged recently with the disrupting frequency and intensity of extreme events. It is becoming increasingly difficult to determine future changes in temperature, rainfall, sea-level rise (SLR), and other climate stressors with only historic data, especially with the unpredictability of how climate change will unfold based on human activities, and given that humans continue to have a substantial impact on its direction (Rodehorst et al. 2018). Resiliency to extreme events is hence a useful concept to understand and apply for a better transportation system.

This paper reviews resiliency, and especially the adaptive nature of resiliency which deals with the uncertainty of the future events. Exploring the adaptive element in the resiliency domain, the paper presents Dynamic Adaptive Planning (DAP) as a potential planning strategy to develop robust long-terms plans for infrastructure resilience, plans that are not stationary and can handle deep uncertainty. We then further present the importance of accurate economic valuation of such methods, where uncertainty handling has a value. An illustrative example is presented to highlight the economic value of using dynamic adaptive plans compared to static plans, exemplifying the value of flexibility in deeply uncertain situations.

3.3 Resilience

The word resilience originated from the Latin word "resiliere" meaning to "bounce back'' and has gained prominence across multiple fields, particularly with the quest to create more resilient systems as natural and man-made disasters have increased. The concept has been researched in a broad range of areas, from psychology to material science (Martin-Breen and Anderies 2011), with more than 70 definitions in the literature. In a general sense, the word implies "the ability of an entity or system to return to normal condition after the occurrence of an event that disrupts its state" (Hosseini et al. 2015). Several definitions have been offered in different fields, with some overlap in terms of "concepts such as robustness, fault-tolerance, flexibility, survivability, and agility, among others."(Hosseini et al. 2015).

A detailed review of definitions of resilience can be found in (Bhamra et al. 2011; Hosseini et al. 2015; Martin-Breen and Anderies 2011). These reviews suggest the following key elements about resilience:

- The broad use of the concept has led to a variety of definitions and interpretations, and a conclusive single definition is not present.
- The definitions "vary between two extremes"(Fisher 2015) - One extreme defining resilience as the ability of a system to bounce back after stress, and the other defining resilience as "the capacity of social-ecological systems to adapt or transform in response to unfamiliar, unexpected and extreme shocks" (Carpenter et al. 2012).
- Common recurring themes include 'perturbation' and 'recovery', and the theme of adaptation within resilience has been interpreted differently across domains (Tiernan et al. 2018).

The two extremes can be represented by Holling's definition and the American Society of Civil Engineers' (ASCE) definition, depicting the contrast in how resilience has been interpreted. Holling, in the ecological sciences field, provides one of the earliest definitions of resilience: "Resilience determines the persistence of relationships within a system and is a measure of the ability of these systems to absorb changes of state variables, driving variables, and parameters, and still persist."(Holling 1973).

In the built systems field, the ASCE defines resilience as "the capability to mitigate against significant all-hazards risks and incidents and to expeditiously recover and reconstitute critical services with minimum damage to public safety and health, the economy, and national security."(ASCE 2013).For built systems, resilience is generally characterized as the ability to ‘quickly’ recover from a perturbation (generally referred to as long-term resilience), and/or the capacity to ‘absorb’ the impacts and retain the functionality (generally referred to as short-term resilience). This is evident in the frameworks most used in incorporating resilience in infrastructure domains. The 4-R framework presented below was used by Bruneau and others in a number of studies to define resilience of infrastructure towards seismic hazards (Bruneau et al. 2003; Minsker et al. 2015).

Four Rs of Resilience (adapted from Minsker et. al. (Minsker et al. 2015)):

- **Robustness**: ability of the system to withstand a given level of stress and/or demand
- **Redundancy**: measure of the inherent substitutability
- **Resourcefulness**: measure of the capacity to mobilize resources in the event of disruption
- **Rapidity**: measure of the capacity to contain losses or prevent further degradation in a timely manner

Bruneau also presented the resilience triangle, which has been used extensively to measure the resilience of infrastructure systems(Bruneau et al. 2003). The 4-R framework and the resilience triangle indicate that the capacity to ‘absorb shocks’ and ‘rapidly recover’ are considered the key aspects of resilience. This framework has been the conceptual basis for multiple quantitative frameworks developed later to quantify resilience (Ayyub 2015; Sun et al. 2018). The difference between the two extremes is explained by Holling highlighting the difference between Engineering Resilience and Ecological resilience (Holling 1996). Holling explains that the traditional definition (engineering) focuses on efficiency, constancy, and predictability, while the other (ecological) focuses on persistence, change and unpredictability. This is demonstrated with the single-equilibrium (I) and multi-equilibria (II) approach to resilience, as illustrated in **Figure 3-1** (Amoaning-Yankson 2017; Holling 1996).

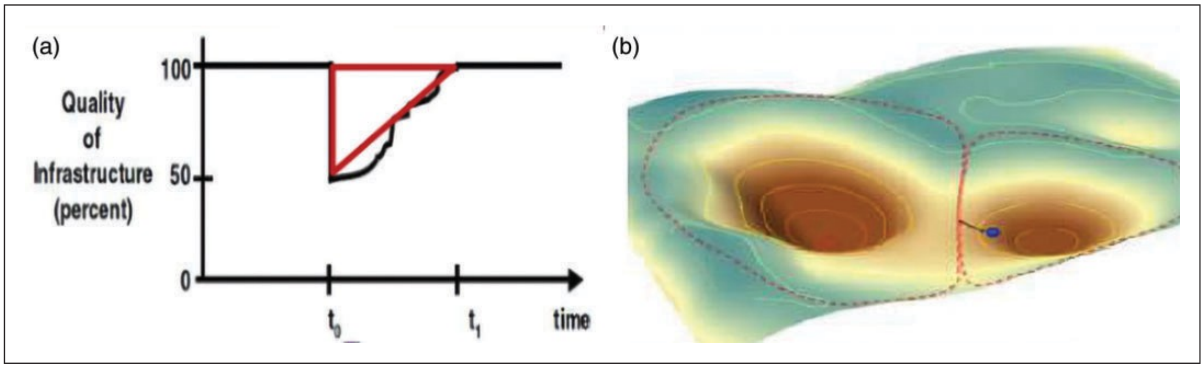

Figure 3-1: Single equilibrium resilience triangle framework: (I) by Bruneau versus multi-equilibria-resilience approach; and (II) by Holling.

The single-equilibrium (I) approach suggests a return to the same state as before the perturbation, while a multi-equilibria (II) approach, with multiple basins of attractions where the system can be headed after a perturbation, suggests a change in the system properties as a response to a perturbation - adapting to the new settings if needed.

3.4 Adaptive Resilience and Dynamic Adaptive Planning Approach

The current resiliency frameworks used for built systems and especially transportation systems have been criticized as being primarily being focused on ‘engineering resilience’(Wang 2015), and relying on the predictive capacity of the models to accurately predict the future (Wall et al. 2015).This criticism highlights two main issues: First, focusing on engineering resilience prepares the system to stay in a single equilibrium regime. Considering the resiliency triangle approach, in the ideal situation where we are able to prepare a system for a given perturbation to have a small resiliency triangle, we are then not prepared for any other perturbation, nor the same perturbation at a higher intensity. The 4-R approach doesn't account for adaptive capacity or flexibility of the system. This system essentially equates resiliency to stability of the system. This disregards the opportunity of the system to move to a different, and possibly better regime. In transportation systems, this translates to, for example, strengthening the floodgates to prevent roadway flooding, quickly reconstructing the bridges with better materials after a disaster etc., hence focusing on the structural features of the system. But with recent disasters, their impacts, and the failures associated with focusing on infrastructural hardening (Eisenberg 2018), an important distinction is being drawn between engineering resilience and socio-technical resilience in the built systems literature. Walls et al. and Wilbanks et al. argue that ultimately "services and not structures are what are important to users and decision makers"(Wall et al. 2015; Wilbanks and Fernandez 2014). Given that the service provided by transportation systems is the efficient movement of people and goods from one location to another, strictly strengthening a particular structural infrastructure restricts thinking in terms of ideas around multi-modal transportation, other alternative modes for the service, and, other opportunities that deviate from the norm.

Second, it is increasingly difficult to achieve the given ideal state of future prediction, as timing and impacts of disasters incorporate significant uncertainties. The majority of climate change prediction models use historic data with selected future scenarios to predict future events. The use of probability distributions of extreme events such as floods, earthquakes etc. has been considered misleading due to reasons such as sparse data, cognitive bias of underestimating the impacts of expected events, and future climate factors that are changing and unpredictable in triggering these events (Carpenter et al. 2012). Wall et al. (2015) and Walker et al. (2004) discuss four levels of uncertainties in decision making, ranging from natural variability to lack of knowledge. The highest order or Level-4 uncertainty, also called deep uncertainty in the literature, is considered to be the deepest level of recognized uncertainty – "we know only that we do not know"(Walker et al. 2004; Wall et al. 2015)(Walker et al. 2003). Extreme events falling under deep uncertainty are also called "black swans". Climate change and the extreme events it triggers are reasonably characterized under the deep uncertainty level (Camp et al. 2013; Rahman et al. 2008; Wall et al. 2015)

Dynamic Adaptive Planning (DAP) originates from the ideas of adaptive policies of Dewey (DEWEY 2012) in the 1900s (Marchau et al. 2010). A general framework, presented in **Figure 3-2**, was first developed by Walker et al.(Walker et al. 2001). The framework served as a basis for further modification and application in different domains such as airport planning(*34*), automated taxies(*17*), intelligent speed adaptation(*35*), and magnetically levitated rail transport

(Marchau et al. 2010). DAP also has gained importance in dealing with deep uncertainties related to climate change. The Netherlands and New Zealand have experimented with DAP (Lawrence 2015) in flood risk management and have since advocated for and supported its implementation in flood management in Florida, the U.S. and Bangladesh (Haasnoot et al. 2017).

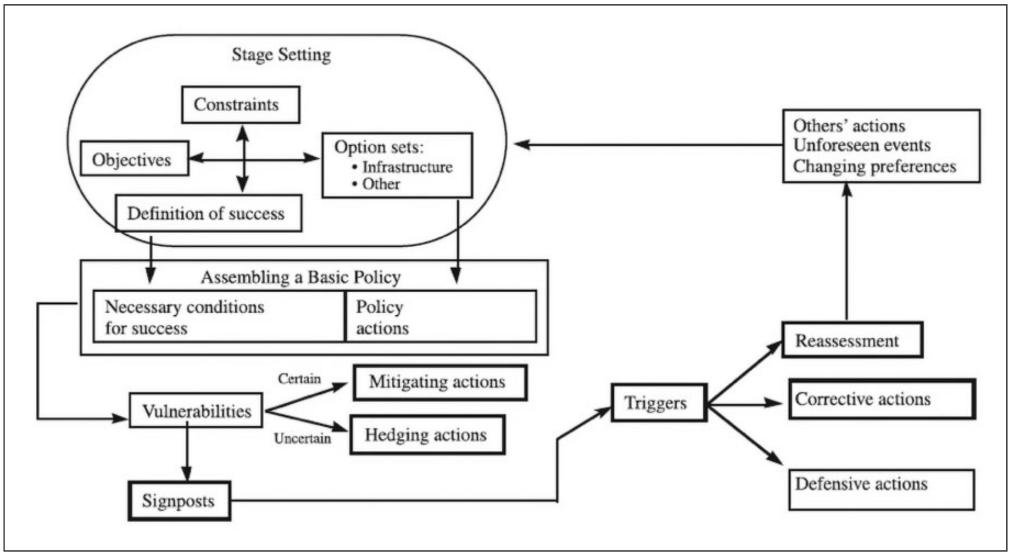

Figure 3-2:Dynamic adaptive planning process (adapted from Walker).

DAP can be explained as a process of developing a plan which starts off with a basic plan using the most probable/suitable scenario but plans further for the unanticipated future by developing a series of actions and associated trigger points to guard against vulnerabilities hindering the goals of the system from being achieved. Figure 3-3 presents this process. With DAP in place, if in the future a trigger is reached for any particular vulnerability, pre-planned adaptive actions can be taken. This process does not depend entirely on the 'predicted future' by current models; rather, it leverages new information as it becomes available. As factors involving deep uncertainty cannot be predicted accurately by current models that use historical data, DAP's reduced dependence on the 'predicted future' makes it more suitable for dealing with deep uncertainty. Wall et al. (Wall et al. 2015) developed a five-step DAP process, **(Figure 3-3),** used in the case study later in this paper, extending the framework of Walker (2001) (Walker et al. 2001), and applying it to transportation planning. DAP as a concept has been considered very useful for dealing with uncertainty, but its application to transportation systems for resilience to extreme events is limited. Other than in the Netherlands ("Dynamic Adaptive Policy Pathways" n.d.), the approach has not been applied at a formal institutional level in other countries but is only recently being applied in pilots (Haasnoot et al. 2017). The literature review suggests that this lack of application stems from multiple reasons, including the lack of a satisfactory business case for the economic benefits of DAP applications. This is primarily because the majority of financial analysis tools used to support decision makers are benefit-cost based, and do not incorporate the cost or benefits related to uncertainties and their potential solutions, even though they may address future uncertainty generally by discounting the future using some discount rate. With the basic benefit-cost method, a DAP-based project will have higher costs as it involves contingency plans beforehand, and the benefits will not be adequately accounted for due to the uncertainty associated with them. Wall et al. argue that "resistance to making up-front investments can be expected from managing agencies when risks are perceived to be low and long-term benefits are unclear"(Wall et al. 2015). Mainstreaming the DAP process with the current decision-making process, identifying synergies with ongoing efforts, and presenting methods that can quantify the benefits of project flexibility could help bridge the existing gaps in institutional decision making on infrastructure under uncertainty.

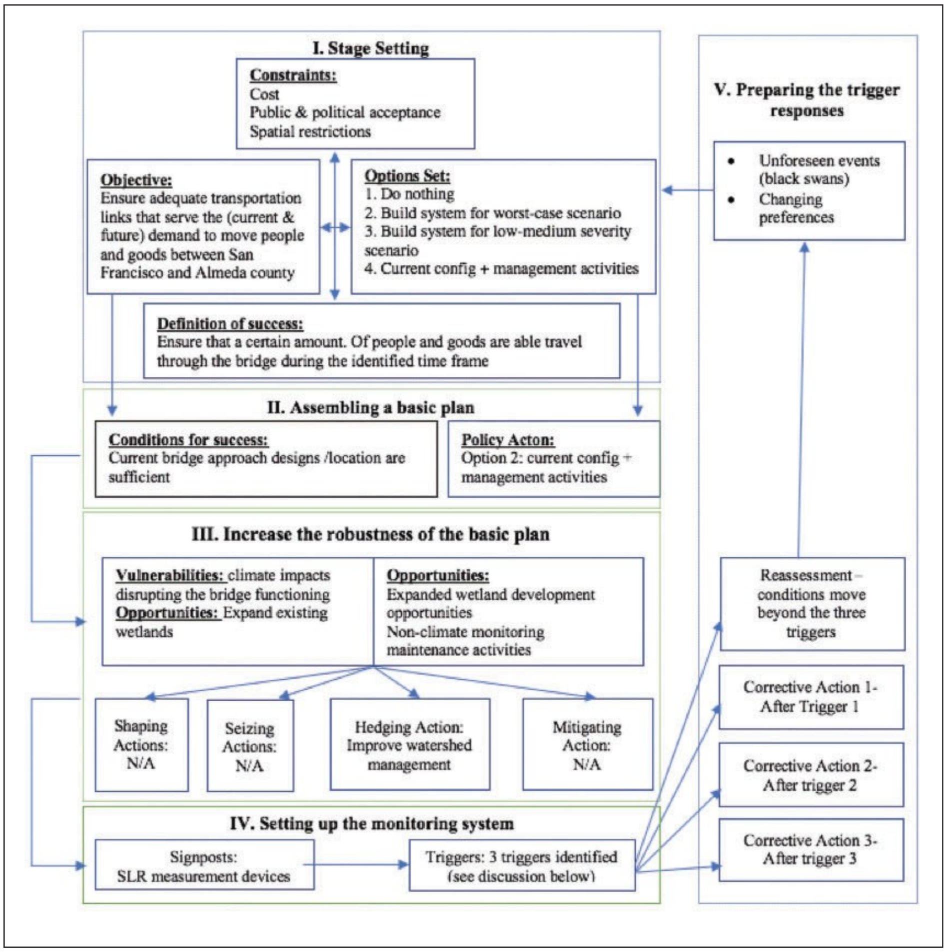

Figure 3-3: Dynamic adaptive plan for the San Francisco–Oakland Bridge segment (adapted from Walls et al.).

3.5 Investment Analysis under Uncertainty

Conventionally, the economic front of project prioritization and selection in the US transportation industry has been governed by Discounted Cash Flow (DCF), Net Present Worth (NPV), and Benefit/Cost Assessments (BCA) ("Benefit-Cost Analysis | Organizing and Planning for Operations - FHWA Office of Operations" n.d.; Walls III and Smith 1999). These methods have been widely applied in the transportation industry because of their simplicity, consistent decision criteria (positive NPV, or B/C ratio >1), and ease of explanation to multiple audiences (Mun 2006). On the down side, these methods are primarily static in nature and do not account for deep uncertainty in the future (Nivedya et al. 2018; Pizzutilo and Venezia 2016; Yzer et al. 2014). They support decisions based on an all-or-nothing approach, and do not account for the possibility that management has the flexibility of changing the course of investment over time with better understanding of current uncertainties. These methods thus underestimate an asset that provides less value today, but might be useful in the future, and overestimate the value of assets providing high value today but which may turn obsolete with a changing environment. Some of these drawbacks can be overcome by using Real Options theory.

"Real Options is a concept of evaluating flexibility in an investment decision and is founded in the analysis of financial decision making…Essentially Real Options allows a decision maker to make changes to an investment when new information arises in the future. Opportunities such as delaying the investment, abandoning, switching, expanding, contracting and having multiple options interacting together are potential choices for decision makers"(Woodward et al. 2011). Two types of real options are identified: real options 'in' projects, and real options 'on' projects. Real options 'on' projects resemble financial options and the option in itself is considered a *black box*, and the real options include options to defer, abandon, or switch to another project.(Martins et al. 2015) On the other hand, real options 'in' projects build flexibility inside the design of system by providing suitable conditions to allow future changes in the projects (Buurman and Babovic 2016; Martins et al. 2015; Woodward et al. 2011). Real options analysis (ROA) assigns value to the flexibility provided by adaptive projects by recognizing the possible downside of making a wrong decision due to uncertainty of a future scenario, and the benefits of additional information availability in near future to make a better decision (Buurman and Babovic 2016).

There are a variety of ways to conduct a real option analysis. Most common in the literature include the Black-Scholes Options Pricing Model (BSOPM), Risk-Adjusted Decision Trees (RADT), Monte-Carlo Simulation (MCS), and Hybrid Real Options. A detailed discussion on these different methods is given by Martins and others in a review of real options in infrastructure (Martins et al. 2015).

ROA has been used in various fields that involve future uncertainties (Martins et al. 2015). Initially applied in oil and gas industries, it has recently attracted the attention of researchers in fields of water management and climate change (Buurman and Babovic 2016; Woodward et al.

2011). In the transportation industry, ROA has been applied in airport planning in face of uncertain future demands (NEUFVILLE 1991), parking infrastructure (Zhao and Tseng 2003), highway toll systems (Blank et al. n.d.), and recently in resilience against extreme disasters (Buurman and Babovic 2016; Chan et al. 2016; Nivedya et al. 2018; Woodward et al. 2011).

The literature on applications of ROA in transportation infrastructure is limited, especially in presenting ROA in a larger, policy-based context. There is a specific divide on this front between the private and public industries, where private industries seem to adopt ROA to a much larger extent while it has been largely underused in the public sector(Pizzutilo and Venezia 2016). This lack of use of the concept can be attributed to multiple factors such as the complex nature of models, lack of guidelines for proper application (Garvin and Ford 2012; Gijsen 2016), institutional barriers in using methods different than the established NPV & BCA methods (required by law for federally-funded projects in the U.S.), and the lack of a framework to use ROA in long term decision making.

In the next section, we present a simplified application of options theory and dynamic adaptive planning for resilience using an example of a bridge approach susceptible to sea level rise and coastal flooding.

3.6 Case Study: San Francisco–Oakland Bridge

3.6.1 Background

The study area is selected from Adapting to Rising Tides (ART) - a vulnerability study conducted by Caltrans as a part of one of the resiliency pilot programs sponsored by the Federal Highway Administration (FHWA) in 2010 ("Adapting to Rising Tides | Plans + Projects | Our Work | Metropolitan Transportation Commission" n.d.). The study included vulnerability and risk assessment. The former including exposure and sensitivity to SLR, and adaptive capacity of the asset, while the latter included likelihood, consequence, and overall risk rating. From multiple assets assessed in the study, two were selected to present an example of adaptation planning, one of them being a section of San Francisco-Oakland Bridge. Based on the vulnerability assessment, the study suggested adaptation measures based on mid-century and end-century predictions of SLR models, and divided the measures into asset specific, regional, and non-structural adaptation. The final selection included end-of-century and midcentury asset specific adaptation measures.

Walls et al. (2015) (Wall et al. 2015) used this example from the ART study to present an alternate decision process, incorporating DAP. The paper by Walls et al. (2015) looked at multiple uncertainties: future travel demand, climate impacts, funding scenarios, alternative modes availability, and political changes. In this case study, we study the climate change uncertainty of the plan to identify the economic impacts of DAP versus static midcentury and end-of-century plans. **Figure 3-3** shows the DAP adopted from Walls et al. and modified for the case study in this paper.

Only the Hedging (H) action was identified for climate impacts, and three Corrective Actions (CR) were identified based on three different trigger points. The Hedging action involved supporting wetland growth. The triggers and respective corrective actions are identified by monitoring the frequency of roadway disruptions, and are presented below:

- Trigger 1: if disruption frequency exceeds low threshold (SLR>1.4 ft), retrofit/waterproof toll plaza electrical systems, toll booths, and related buildings to increase resilience to inundation
- Trigger 2: if disruption frequency exceeds mid threshold (SLR>2.7 ft), Construct berm to protect roadway and toll plaza from mid-century flooding projection
- Trigger 3: if disruption frequency exceeds high threshold(SLR>4 ft), Construct levee (or expand berm, if CR-2 is taken) to elevate the approach roadway surface above end-of-century projections
- Trigger 4: if disruption frequency exceeds critical threshold (SLR>8.5), reassess the plan.

To compare this DAP with static plans, we selected two worst-case scenario plans, and one low-middle case scenario plan. The three plans come from the ART report and were developed based on expert opinion in the report. The different pathways for resilience planning for the San Francisco Oakland Bridge section considered in the analysis are:

(4) End-century prediction plan 1: Construct a floodwall on the bridge approach to prevent wave overtopping and road flooding.

(5) End century prediction-based plan 2: Raise roadway surface and toll plaza above the end-century flood inundation estimate.

(6) Mid-century prediction-based plan: Create berm along the freeway perimeter based on mid-century inundation levels.

(7) Dynamic Adaptive Plan: Develop monitoring strategies, identify trigger points for different levels of disruptions based on SLR information, and follow the respective corrective actions when the trigger points are reached in time.

The three pathways other than the DAP are not extensive but cover the common pathways preferred by decision makers. For extensive possibilities of the options, once can review the ART report. The next section presents the economic analysis methodology used in this paper to assess the net worth of each of the four pathways.

3.6.2 Analysis Methodology

The economic analysis uses Net Present Value (NPV) evaluation of the four alternatives considering a life span of 80 years (2020-2010) and uses sea level rise variability based on climate change for incorporating uncertainty.

Table 3-1 presents the key data inputs and their sources. The unit cost estimates of constructing a floodwall (Option 1) and raising a roadway (Option 2) were obtained from Bouwer et al. (Bouwer et al. 2017) as part of assessment of flood mitigation strategies in Miami, Florida. The estimates for the DAP actions were obtained from multiple resources, including unit cost of berm construction from one of the State of California's contract documents (Caltrans 2014); the unit cost of retrofitting the toll plaza from journal article on review of costs of flood mitigation strategies by Aerts (2018) (Aerts 2018), and the unit cost of levee construction from FEMA (Federal Emergency Management Agency) guidance on flood management (FEMA 1986). The costs were converted to 2019 dollars using the Construction Cost Index. The benefits were monetized as the avoided damage cost from bridge failure, which included capital improvement costs, and the truck travel time delay cost, data being obtained from the assessment report (Kline et al. 2011).

The climate impacts uncertainty was quantified using the probability estimates of different sea-level rise scenarios under the three Representative Concentration Pathways (RCP) identified as the different plausible scenarios for future climate change. The information is obtained from the 2017 Climate Science Special Report by USGCRP (USGCRP 2017). **Table 3-2** presents the probability estimates of the different SLR scenarios, and the associated estimates of sea level rise. The table highlights the different trigger points identified in the DAP.

Table 3-1: Input Data Sources

DATA INPUT	VALUE	SOURCE
Damage cost (capital cost of rebuilding, delay cost)	6.06 billion	(Kline et al. 2011) ,(FHWA 2011)
Floodwall construction cost (Alternative 1)	31.7 million	(Bouwer et al. 2017)
Cost of raising roadway (Alternative 2)	26.4 million	(Bouwer et al. 2017)
Berm construction cost (Alternative 3 and DAP)	0.25 million	(Caltrans 2014)
Levee construction cost (DAP)	1.75 million	(FEMA 1986)
Cost of retrofit (DAP)	0.05 million	(Aerts 2018)
Climate change data (SLR projections and scenario probabilities)	See Table 3-2	(USGCRP 2017)
Discount rate	7%	(Lawrence et al. 2018)

Note: DAP = dynamic adaptive planning; SLR= sea level rise.

Table 3-2: Sea-Level Rise Scenarios

	Probability estimates of SLR scenarios			The Interagency GMSL rise scenarios in feet relative to 2000 (for every 10 years)								
Scenario	RCP2.6	RCP4.5	RCP8.5	2020	2030	2040	2050	2060	2070	2080	2090	2100
None	6.0%	2.0%	0.0%	na	na	na	na	na	na	na	na	na
Low	45.0%	25.0%	4.0%	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
Intermediate-low	47.0%	70.0%	79.0%	0.3	0.4	0.6	0.8	0.9	1.1	1.3	1.4*	1.6*
Intermediate	1.6%	2.5%	15.7%	0.3	0.5	0.8	1.1	1.4*	1.8*	2.2*	2.7*	3.3**
Intermediate-high	0.3%	0.4%	1.0%	0.3	0.6	1	1.4	1.94*	2.6*	3.2**	4.01***	4.9***
High	0.1%	0.1%	0.2%	0.4	0.7	1.25	1.8*	2.5*	3.3**	4.3***	5.7***	6.6***
Extreme	0.05%	0.1%	0.1%	0.4	0.8	1.45*	2.1*	3.04**	4.1***	5.3***	6.7***	8.2***

Note: SLR = sea level rise; GMSL = global mean sea level; RCP = representative concentration pathway; na = not applicable.
*Trigger 1.
**Trigger 2.
***Trigger 3.

To conduct the NPV analysis of the four alternatives, the following assumptions were made:

- The end-century alternatives will be able to keep the bridge functioning under any of the predicted SLR scenarios until year 2100.
- The mid-century alternative - (Creating a berm) will not be able to protect the bridge for a SLR scenario once trigger 2 is reached.
- If the alternative can keep the bridge functioning compared to no-alternative scenario, the avoided damage cost is counted as benefits incurred at every time period when the SLR is higher than the trigger.
- If the alternatives fail, the bridge fails, and the complete cost of capital improvement and travel delay will be incurred. Also, if none of these measures are taken, the bridge will fail after any of the three trigger points. This is assumed on the basis that under both

mid-century and end-century scenario, the vulnerability assessment suggests significant inundation and provides only one capital improvement cost value.

- The cost of each corrective action in DAP occurs in the year the trigger point is reached.
- The initial cost of the DAP is not included in the analysis, as the main costs incurred would be associated with the stakeholder-based and expert opinion-based planning of the DAP process, and the monitoring systems required for trigger points identification - already put in place by State of California's Ocean Protection Council. Hence, it is safe to assume that the initial costs associated with DAP will be negligible compared with the other three alternatives.

The investment costs for the static plans are incurred in the year 2021. The investment for static alternatives does not depend on the distribution of scenarios, and hence the investment portion of cash flow will remain the same for all six scenarios for each static alternative. For the DAP, the investment portion of the cash flow will be adjusted for the risks for each scenario branch. The risk-adjusted decision tree approach for the DAP allows for a different investment approach for each SLR scenario, making the approach adaptive in nature, responding to occurrence of trigger points. The decision tree for DAP alternative is presented in **Figure 3-4**, where the pathway for each scenario is presented as a branch of the tree.

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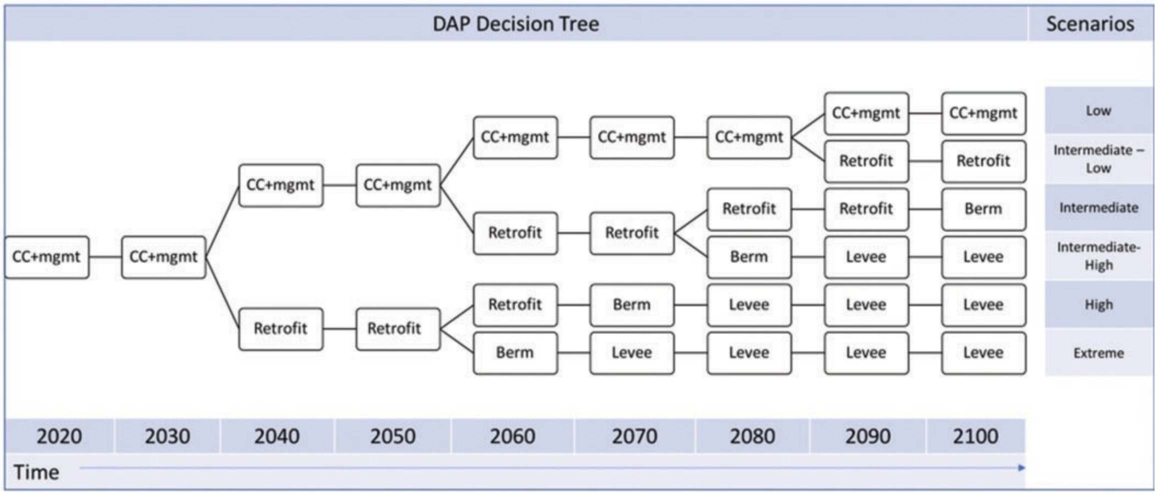

Figure 3-4: Decision tree for dynamic adaptive plan (DAP)

The costs and benefits are discounted to current dollars and the net present worth of all the four alternatives is calculated for six different scenarios (low to extreme). A discount rate of 7% was used for NPV analysis, based on a FHWA guidance document on Highway Safety BCA(Lawrence et al. 2018). The expected NPV is calculated for each alternative using the probabilities associated with the respective SLR scenarios. This is done in all the three RCP scenarios. Finally, considering the three RCMs to be equally likely, overall expected NPV for all climate change scenarios is calculated.

3.6.3 Results

Figure 3-5 presents the standardized expected NPV for the four alternatives for each RCP scenario and the overall expected NPV considering each RCP as equally likely. The NPV data is standardized with respect to the mean and standard deviation for each scenario. This helps in visualizing the results and avoiding the scale differences in the different scenarios. The actual expected NPV results (averaged over all RCPs) for each alternative, and the expected saving of DAP compared to the other alternative are presented in Table 3-3.

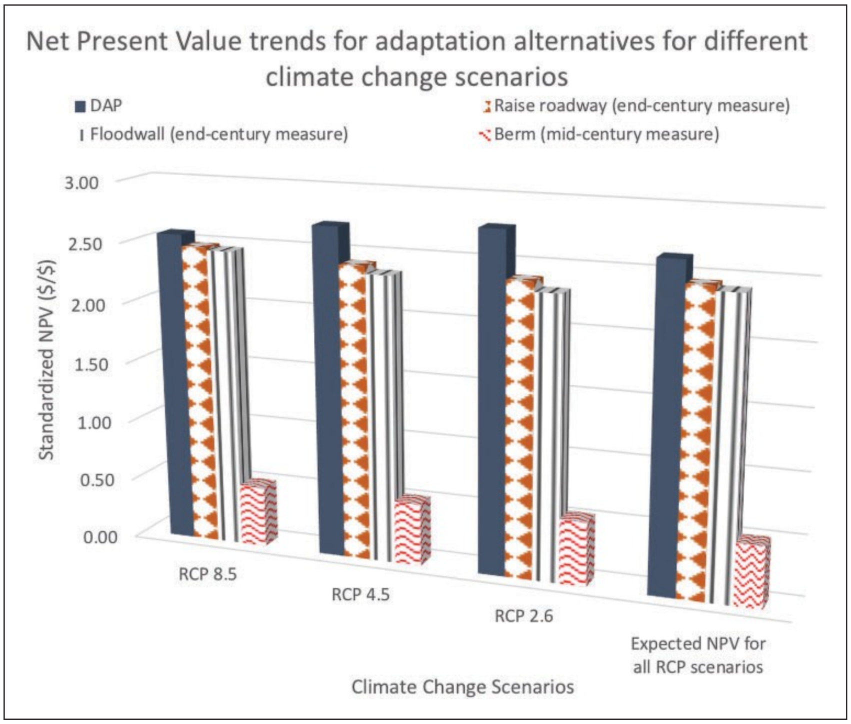

Figure 3-5: Standardized expected net present values trends for adaptation alternatives for different climate change scenarios.

Note: DAP = dynamic adaptive plan; NPV = net present value; RCP = representative concentration pathways.

Table 3-3: Expected NPV Results (Averaged over All RCPs) for Each Alternative, and the Expected Saving of DAP Relative to the Other Alternatives

Alternative	Expected NPV	DAP savings (NPV_{DAP}-NPV_{Alt})
Flood wall (end-century measure)	$ 31.517 Billion	$29.5 Million
Raise roadway (end-century measure)	$ 31.521 Billion	$24.6 Million
Berm (mid-century measure)	$ 31.258 Billion	$288.36 Million
DAP	$ 31.547 Billion	-

3.6.4 Inference

The results indicate the dynamic adaptive plan has a higher value compared with the other static plans. The end century plans have high values overall but will have a high financial impact on the budgeting for the given year. This makes these plans have a lower chance of application, primarily because of financial constraints of the agencies. Also, we have not considered black-swan events, which might go beyond the predicted worst condition, and then the pre-designed end-century plans might fail. These plans can only be applied in a setting with high levels of funding, affluent states or regions, and hence are not realistic plans for all socioeconomic settings. The mid-century plan has a low value due to the longer span of this analysis compared with the mid-century timeline. Nevertheless, it (i.e., the mid-century alternative) is a very plausible plan and may be selected by policy because of political and financial constraints. The Dynamic Adaptive plan has a significantly higher value than the mid-century plan because of the avoidance of damage costs. It also has higher returns than the end-century plans because of the savings from deferring the investment on the time scale and in sub-sections as and when needed.

3.6.5 Limitations

The paper reviews a selected section of the transportation system, and aspects of interdependencies of connecting routes from the bridge section are not accounted for in this paper. Further research examining the problem from a systems level will add value to this analysis. It could include similar analyses on the key roadway network of the city, of which this bridge section was a small part. Complex systems involving multiple infrastructure systems such as utilities, freight, and roadways could be evaluated together to understand the inter-dependencies and the overall complex interactions. Costs for the DAP approach are obtained from sources from Florida as it was the closest DAP plan being developed in the US with published resources so far. The values might differ from California costs, but the estimates can be used to demonstrate the application of DAP in this research. The RCP scenarios (2.6, 4.5 & 8.5) are used in the analysis because of the availability of published data on probability and SLR projections for the three RCPs. With the changing climate, including RCP 10.0 will add value to the analysis. Similarly, with the current scenarios, RCP 2.6 is certainly less likely, but this can be reflected in the analysis only when data on the estimated probabilities of the RCP scenarios is published. The paper reviews DAP as an approach compared to the static planning approaches used in transportation decision making. Other approaches for planning under deep uncertainty, e.g., Robust Decision Making (RDM), InfoGap Decision Theory, Decision Scaling, and Many Objective Decision Making, have been studied elsewhere with DAP to understand parallels, merits, and limitations (See for example- (Ben-Haim 2005 p.; Hall et al. 2012; Kwakkel et al. 2016; Matrosov et al. 2013a; b; Regev et al. 2006; Roach et al. 2016)). These should also be studied in the context of transportation.

3.7 Future Applications and Research, and Concluding Remarks

Traditionally, State Departments of Transportation (DOT) and Metropolitan Planning Organization (MPO) plans have largely been static even though there has been movement toward the development of scenario plans, more common at the MPO level. Long range plans, asset management plans, and TSMO (transportation system management and operations) plans, for example, have all largely been developed as static plans that are renewed periodically, as have emergency response plans under the purview of federal and state emergency management agencies. In 2012, the U.S. national surface transportation re-authorization: Moving Ahead for Progress in the 21st Century (MAP 21) established the importance of and required risk-based asset management. In 2015, the FAST (Fixing America's Surface Transportation) Act recommended addressing system resilience, without providing any explicit guidance on how to develop system resilience. Dynamic adaptive planning (DAP) is a promising approach for the systematic development of system resilience.

Exploring the most appropriate uses of DAP to upgrade formal agency plans would entail understanding which portions of an agency's asset portfolio and business operations are subject to deep uncertainty, and have the most significant vulnerabilities or opportunities, for example a subset of a state's bridges in a coastal flood plain subject to sea level rise and storm surge, or portions of the existing transportation network being considered for various levels of automation. The development of dynamic adaptive plans for these subareas within the overall system, should augment the overall value of the system, including the costs of such development efforts, and in some cases significantly so.

Ongoing movement of people and assets to urban and coastal regions has occurred in parallel with growing climate threats to coastal regions. While there is ongoing displacement of entire communities as a result of sea level rise (Stapleton et al. 2017), a large percent of the population has also not thought frequently nor deeply enough about the implications of the most severe climate scenarios for livelihoods, buildings, infrastructure, economies, cultures and other assets in regions of high vulnerability. DAP offers the transportation community tools for systematic exploration of proactive policies and plans ahead of penultimate trigger points, making a business case for systematically proactive or reactive changes to augment system resiliency, and identifying trigger points when it makes economic sense to make certain critical decisions for system resilience.

While the flexibility provided by DAP is valuable, and this value can be characterized, flexibility alone in ensuring adaptation goals are met may not be sufficient for system sustainability in the long run. While DAP has largely been applied for adaptation, the transportation community could also become strategic about thinking through and identifying network-level adaptations that will result in mitigation in substantial ways for system users and surrounding communities, for example multimodal solutions that will simultaneously enhance mobility for emergency response during perturbations while reducing the overall transportation system energy and carbon footprints.

Finally, DAP could also be used to undergird opportunity-driven thinking and action in areas where there are institutional and cultural roadblocks to alternate development pathways, owing to path dependency. For example, in areas where there is deep-seated and cultural opposition to public transit, DAP could be used to offer authentically multimodal plans and demonstrate when such plans would become economically viable, while highlighting their resilience and natural environment benefits and how much more viable they might be than the status quo plan or other static plans under consideration.

Future work exploring the combination of financial theory and methods with DAP toward the development of more robust decision-making frameworks to handle deep uncertainty will secure the means for advancing adaptive resilience in transportation planning, as will updating federal surface transportation legislation to underscore the importance of using appropriate methods for investment decision making under deep uncertainty to secure transportation system resilience.

3.7.1 Data Accessibility Statement

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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3.7.3 Authors Contributions

The authors confirm contribution to the paper as follows: study conception and design: Singh, Amekudzi-Kennedy, Ashuri; case study methodology and analysis: Singh, Ashuri, Amekudzi-

Kennedy; future applications and research: Singh, Amekudzi-Kennedy, Ashuri. All authors reviewed and approved the final version of the manuscript.

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CHAPTER 4. ADAPTIVE RESILIENCE CAPABILITY MATURITY MODEL

P. Singh, A. Amekudzi-Kennedy, T.A. Wall, and M. Chester. Capability Maturity Model for Improving Adaptive Resilience of Transportation Agencies under Climate Change Uncertainty. (Under Review)

4.1 Abstract

Transportation resilience has largely focused on increasing system's strength to withstand disasters and/or speeding up the recovery process after disasters. With increasing frequency and intensity of extreme events due to the changing climate, and with deep uncertainties associated with the climate, the toolsets in wide use among transportation agencies are rendered inadequate to meet the emerging resilience needs. This paper focuses on the 'adaptation' aspect of resilience, presenting a Capability Maturity Model, developed to improve a transportation agency's adaptive resilience under future uncertainty. With a literature review of resilience across multiple disciplines, semi-structured interviews of practitioners and academic experts, and thematic data analysis using NVIVO, this paper presents an innovative approach to assess the current maturity of adaptive resilience in a system, and identify strategies on advancing resilience maturity. The resulting Adaptive Resilience-Capability Maturity Model (AR-CMM) can serve as a self-assessment tool and guide for improving transportation agencies' adaptive resilience.

4.2 Introduction

The concept of resilience is comparatively new to the fields of critical infrastructure and built systems, but has a much longer history among other fields of scientific study, and hence has over 70 definitions in literature (Fisher 2015). The commonly agreed upon definition is the ability of a system to prepare and plan for, absorb, recover from, and more successfully adapt to changing conditions (Martin-Breen and Anderies 2011). Holling categorized resilience into two areas- engineering resilience focuses on a system's ability to come back to its original state after a disruption, while ecological resilience allows a system to change its equilibrium stage to something different (and potentially better) as a response to change in the environment, as long as the system functionality remains intact (Holling 1996). This multi-equilibrium approach uses the adaptive characteristic of the resilience definition. The adaptive capacity of a system allows it to change its form in response to changing environment, to maintain system functionality. This concept of *adaptive resilience* can be viewed as the basis of evolution of species, changing of human behavior with changing environment, and adapting of business strategies to the changes introduced by technology and several other factors.

In built systems however, especially in the transportation field in the U.S., resilience has been primarily viewed as a property of a system that allows it to 'bounce back better' (Ayyub 2015). This aligns more with the 'engineering resilience' characterization of Holling. The aspect of 'fail-safe' assets hinges on the assumption of being able to anticipate the level of threat, and then prepare the asset to be safe from failure. Ahern discusses how the fail-safe approach may not be the best approach for infrastructure systems in the current timeframe (Kim et al. 2019) . In the past decade we have seen an increasing number of unexpected events, reducing our confidence in our predictive abilities to anticipate the next disaster (Adam B. Smith 2019). Climate change and massive human intervention in the general environmental cycle of earth has made the historical data on climate insufficient in predicting the future (Chester et al. 2020). This current situation demands infrastructure systems to adopt a more flexible and agile approach, over a fail-safe, resistance-based approach. In this paper we characterize this as adaptive resilience, which is defined as the characteristics of a system that enable it to change in response to changing environment, and hence enable it to better prepare and plan for, absorb, and recover from a disruption.

While the emerging literature has identified the importance of adaptive resilience in infrastructure systems, the U.S. transportation industry lacks a formalized understanding of the concept as it pertains to this sector. This paper attempts to address the issue, with the objective to identify the capabilities of a transportation system (including but not limited to aspects of physical assets, organizations, and institutions) that can improve its adaptive resilience to extreme events, both climate and non-climate-related.

4.3 Methodology

The paper uses a constructivist grounded theory (CGT) approach to identify the capabilities of transportation systems that support adaptive resilience, and to develop a maturity model to reflect different levels of adaptive resilience maturity in a transportation agency. Figure 4-1 presents the research framework used in the study. CGT is a qualitative research methodology used to explore a space where there is no existing adequate theory. CGT uses an inductive approach to generate a new theory from the data gathered through participant interviews or focus groups. In this study, the approach uses expert interviews as a key data collection method along with an iterative literature review process to develop a comprehensive portfolio of capabilities that adequately characterizes the adaptive resilience of a transportation agency. Generally used in Social Science, this approach is useful for this research problem as there is no existing and commonly agreed upon theory of adaptive resilience in the transportation field. While such theories exist in other disciplines, the difference in the structure of the systems pertaining to each discipline makes it difficult for the theories to translate accurately and appropriately across disciplines. This leads to a need to develop a better suited adaptive resilience theory for transportation systems, and the generation of one requires inputs from experts who have had direct experience with building resilience to adverse events in their organizations or infrastructure systems, along with acquiring prior knowledge from a broader resilience theory.

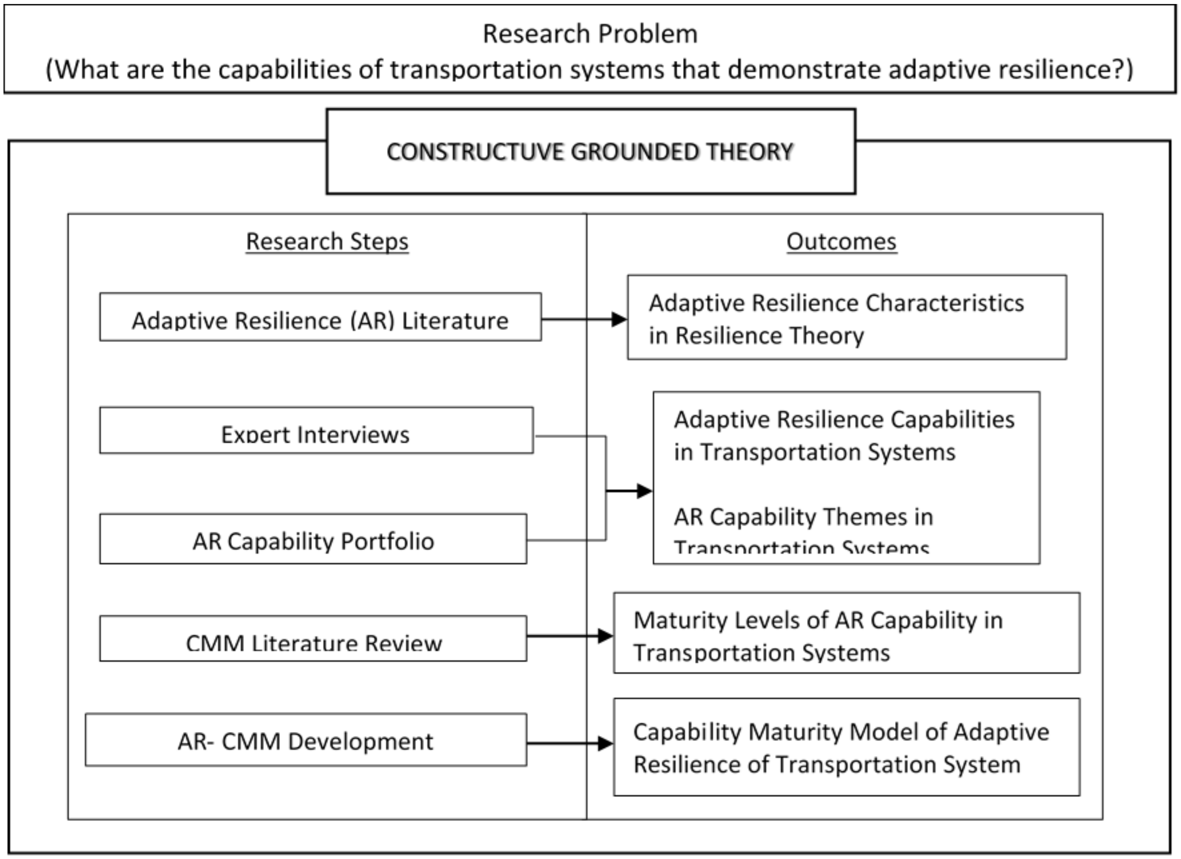

Figure 4-1: Research Framework

A thorough literature review of resilience, and the adaptive aspect of resilience was conducted across different fields. Through this an initial set of characteristics of adaptive resilience was generated that was then used to develop an interview guide. Expert interviews were conducted by inductive theoretical sampling, where participants were selected based on their expertise in the subject area. The selection of participants occurred along with data collection, where we started with a small list of participants, and then based on their inputs, we used snow-ball sampling to expand the participant list. The process of sampling continued with more data collection until data saturation was reached: interviews appeared to converge, and no significant new information was collected with subsequent interviews. The criteria of participant selection were their expertise in the field of resilience, adaptation, disaster management, and transportation. We conducted 20 expert interviews, in 5 sets of sampling with approximately 4 participants in each sampling round. Seventy percent of the participants were working professionals, who have had experience managing transportation systems under extreme events, and 30 percent of the participants were in academia, researching on the same subjects. The interview format was semi-structured, to facilitate the development of a theory around adaptive resilience in transportation systems based on the experience of the experts. An interview guide was developed using the initial set of adaptive resilience characteristics from the literature review. The interview data was then coded using NVIVO to identify patters and themes. Open coding was used on the data collected to identify codes that represent capabilities of transportation system reflecting adaptive resilience.

Simultaneously, a literature review of capability maturity models in transportation systems was conducted. This was used define transportation specific maturity levels for adaptive resilience. Codes generated from NVIVO analysis of the interview data were then axially coded along with the CMM literature review, to explore the relationships between the codes, and to identify themes in which the capabilities were then categorized. Finally, each capability in the identified themes was then defined over the different levels of capability maturity model to develop the Adaptive Resilience Capability Maturity Model (AR-CMM) for a transportation agency.

The subsequent sections of the paper discuss the results of the process. We first present a review of adaptive resilience, synthesized from various fields, and discussed in the context of transportation systems. The next section discusses the results of the NVIVO analysis of the expert interviews and literature review, where a portfolio of adaptive resilience capabilities of was developed for transportation systems. These capabilities are further distributed into three themes, and the five levels of maturity are discussed. Further, maturity levels for capabilities in each theme are discussed. The paper ends with potential applications of the AR-CMM, outlining some of its limitations and future work.

4.4 Adaptive Resilience (AR) in Theory

The traditional definition of resilience, especially in the engineering domain, primarily focuses on the system being "strong, static, and resistant to change" (Tiernan et al. 2018). The resilience triangle approach (Figure 4-2), initially presented by Bruneau and others (Bruneau et al. 2003), quantifies resilience by representing a 'loss of functionality or discomfort'. With this approach, a smaller reduction in performance (absorption), and a faster recovery indicate a resilient system. The model has been extensively applied in infrastructure systems, especially in measuring the resilience of built systems and supply chains to natural disasters such as earthquakes (Bevilacqua et al. 2017; Bruneau et al. 2003; Yu et al. 2014).

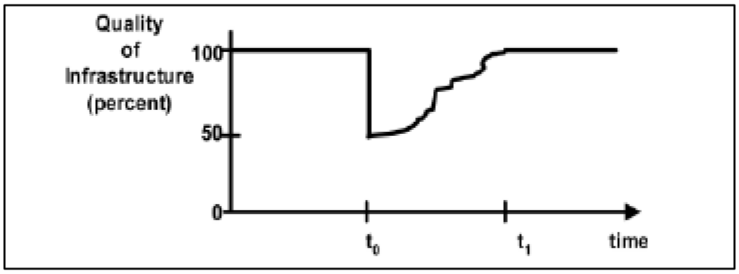

Figure 4-2: Resilience triangle- Measure of seismic resilience-conceptual definition (Bruneau et al. 2003)

This characterization of resilience is described as 'Engineering Resilience' by Holling (1996), who defines two faces of resilience: engineering resilience and ecological resilience. Engineering resilience is characterized by the ability of "bouncing back faster after expected stress, enduring greater stresses, and being disturbed less by a given amount of stress." (Martin-Breen and Anderies 2011). This form of resilience is measured in reference to a single-equilibrium point, quantifying a system’s resistance to disturbance and speed of return to that equilibrium, while the other face, ecological resilience, allows the system to move to a different equilibrium following the disturbance, as long the system sustains itself (Holling 1996). Engineering resilience relates more to the idea of developing infrastructures that can handle large stresses and are expected to return quickly to normal once the stresses are removed.

Holling further presents three characteristics of engineering resilience that need to be critically evaluated when assessing its application on complex systems, such as transportation. He indicates that engineering resilience is based on the following three assumptions:

1) There is only one equilibrium

2) The object returns to the same state after a disturbance it can handle

3) The type of disturbances are expected (Holling 1996; Martin-Breen and Anderies 2011)

Martin-Breen and Anderies (2011) also categorize resilience based on whether the subject of resilience is an isolated system or a system of systems (SOS) functioning together. Under this distinction, they equate the resilience of an isolated system to engineering resilience, the same as defined by Holling. System resilience as defined by Martin and Anderies extends the engineering resilience paradigm to consider interdependent and interactive components that make up a system of system (SOS). Under this expanded definition, system resilience here is defined as the property of a system maintaining its overall function in the event of a disturbance, even if the individual system components change their structure or functionalities (Martin-Breen and Anderies 2011; Pregenzer 2011).

In practice, the transportation sector currently characterizes risk identification, shock absorption, and quick recovery (back to normal) as the key elements of a resilient system (Bruneau et al. 2003; Wan et al. 2018). This follows the 'engineering resilience' and 'isolated system' approach to resilience applications.

But infrastructure system in general, and specially transportation systems, do not function in isolation; rather, they are highly interconnected with other systems to form a complex ecosystem of critical infrastructure on which the functioning of a community depends.

Hence, the use of engineering resilience has been challenged in recent years with changing paradigms of disruption in the system (e.g., climate change, rapid technological changes/advances). The resilience paradigm requiring a return to single equilibrium restricts a system from adapting to a new or different equilibrium state in response to the environment around it changing. Climate change also renders the characteristic regarding disturbances being expected less applicable, as the intensity, frequency, and duration of the extreme weather events have been changing significantly in the past few decades (Field et al. 2012; Ummenhofer and Meehl 2017). As evidence of this, the "reported losses from extreme weather events rose by 151% between these two 20-year periods (1978-1997 and 1997-2017)." (UNISDR 2018).

Adaptive capacity and shift from single-equilibrium focus to multi-equilibria have been emphasized in recent studies (Amoaning-Yankson 2017; Martin-Breen and Anderies 2011).

Amoaning-Yankson (2017) reasons this by stating that the concept of engineering infrastructure out of risk is not practical in the current era given the variable frequency and strength of natural hazards. Martin-Breen and Anderies (2011) conceptualize this approach as 'Embracing Change':

> "One slogan of resilience thinking is "Embracing Change." One part of this is accepting that change in response to adversity is itself normal. Fighting against it, as well, can actually cause a decrease in resilience. Try to keep everything the same, and the chance of future catastrophe can actually increase." (Martin-Breen and Anderies 2011)

While adaptive capacity as part of resilience has gathered the attention of researchers across the globe, its use in practice to date is not very advanced (Eisenberg 2018). Given the varied use of resilience across multiple domains, it currently serves as an umbrella word in practice covering risk-based planning, climate-change impact assessment, emergency planning, and green-urban development (Amoaning-Yankson 2017; Lizarralde et al. 2015).

A recent study done by the European Virtual Institute for Integrated Risk Management (EU-VRi) on analysis of existing resilience assessment approaches, indicators and data sources of smart critical infrastructures concluded that majority of resilience frameworks emphasize more understanding, anticipating and preparing for emerging risks compared to absorbing and recovery; and the focus on adaptive capacity or transformation is the least evident (Jovanović et al. 2018). Figure 4-3 reflects the results of the study, presenting the distribution of studied literature over the different dimensions of resilience.

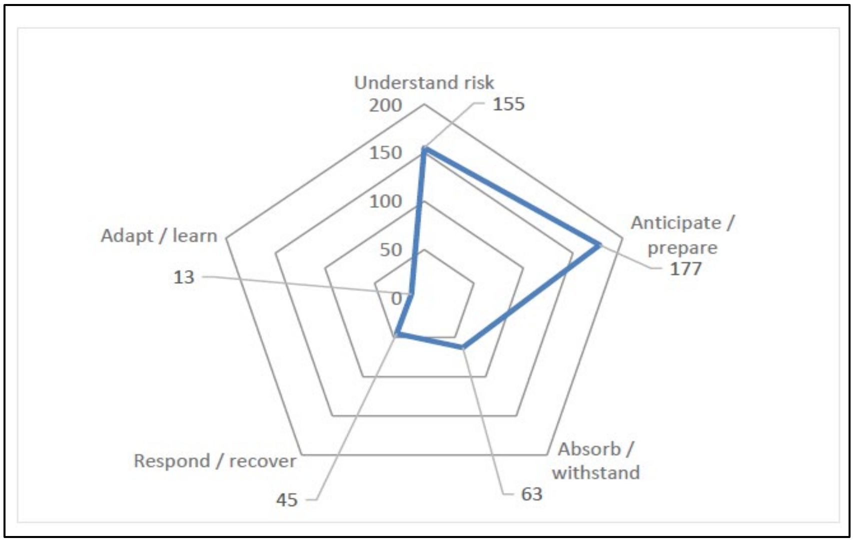

Figure 4-3: Number of candidate indicators in each phase and dimension of the SmartResilience matrix (45)

Understanding risk and anticipating the threats are generally the first logical steps to be taken towards making a system more resilient. Recent Federal Highway Administration (FHWA) resilience pilots also focus strongly on better vulnerability assessments of assets (Rodehorst et al. 2018). Several state agencies have developed vulnerability assessment frameworks that support them to identify critical assets that need attention. As discussed before, withstanding/absorption of shock is a common solution pathway considered in the field of infrastructure, which has led to the prevalence of engineering resilience in practice. These three phases of resilience (understanding risks, anticipating/preparing for risk, and absorbing risks) attempt to reduce the uncertainty associated with either the exposure (understanding risk) or with the consequence (withstand/absorb) to a certain extent.

A critical reason for the lack of adaptation elements in the transportation system is the lack of quantifiable performance metrics for adaptation. Adaptation is not easily quantified—yet public investment decision-making has historically favored objective and measurable processes to evaluate and fund projects. In the US transportation system, federal funding is generally distributed based on the overall asset valuation of the state/regional agency (FHWA 2016c), and the valuation framework currently being followed considers almost exclusively the condition-based value of the asset (Amekudzi-Kennedy et al. 2019). This undervalues the assets that have adaptive capacity and hence favors investment in non-adaptive assets to avoid the added costs. This is a major issue due to the increasing uncertainty associated with future climate scenarios and extreme events, thereby increasing the need for adaptation of infrastructure systems, while there is still a lack of objective parameters to evaluate them over other competing investment needs.

In this paper, we define adaptive resilience as the ability of a system to learn from past events and adapt to changes by building flexibility and agility in the system. This aspect of resilience, along with the engineering resilience aspects, together form a holistically resilient system.

With an adaptive approach to resilience, the absorption and recovery capacities of the system are also enhanced. With inclusion of a complex multiple state system approach, factors of sensitivity other than physical (i.e., social and functional) can also be incorporated in building absorption capacity. Adaptive resilience also supports building back 'better', over building back to 'normal', thereby acknowledging and enacting on the changes in the environment needing better responses. In a quantitative sense, the adaptive resilience approach modifies the resilience triangle of a system over time. With building back better and learning from past and current events, it enhances future recovery process- faster recovery, and recovery to a better state. It also reduces future consequences by improving the absorption capacity of the system by applying a multiple state complex system approach.

4.5 AR Capabilities of Transportation Systems

Categorizing resilience capabilities has been a major focus of researchers in all the fields where resilience is studied, primarily to develop metrics that can be used for quantification of system resilience. Categorizations of resilience capabilities reflect the interpretation of resilience in different fields. Earlier built system literature characterizes resilience of a system based on its properties to 'bounce back to normal'. Hence the capabilities primarily focus on 'engineering resilience'. Earlier works on resilience in infrastructure systems came from the field of seismic safety, and the four Rs framework (Robustness, Redundancy, Resourcefulness, and Rapidity) was recommended for characterizing resilience (Tierney and Bruneau 2007). This framework has been used to quantify resilience in the fields of internet infrastructure systems (Omer et al. 2009), homeland security (McGill and Ayyub 2009), and urban infrastructure systems (Attoh-Okine et al. 2009). Organizational resilience categorizes resilience capabilities into three categories (include capabilities here). (Francis and Bekera 2014) comprehensively review definitions and properties of resilience in different fields. Case studies in organizational resilience field have identified three different attributes and 13 indicators of resilience (Resilient Organizations 2021), as presented in figure 4-4. Recent literature in the infrastructure field has also attempted to expand the characteristics of resilient infrastructure systems by including institutional, organizational and financial components along with the physical components (Amoaning-Yankson 2017). Amoaning-Yankson (2017) presents different capabilities of a system emerging from the four components of infrastructure systems, enhancing persistence, adaptability and transformability of the system as presented in figure 4-5.

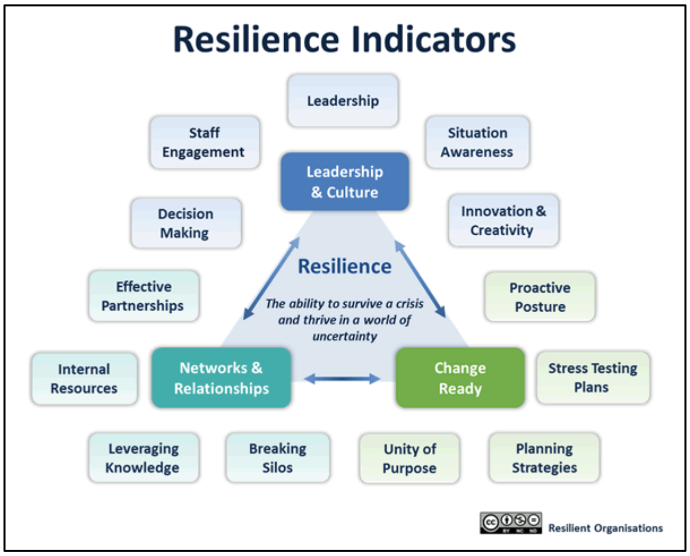

Figure 4-4:Organizational Resilience Indicators (Resilient Organizations 2021)

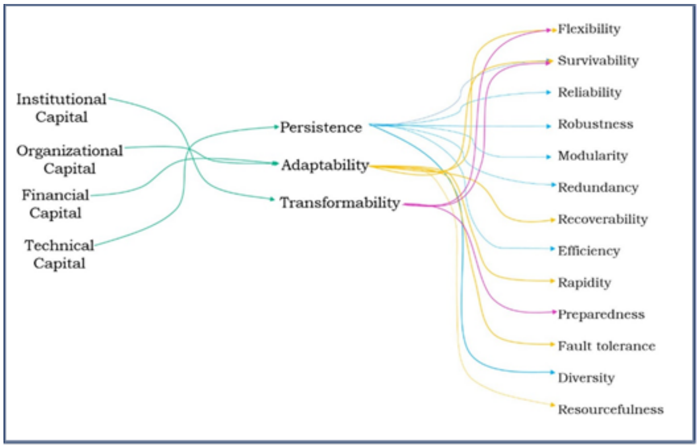

Figure 4-5: Infrastructure Resilience Indicators (Amoaning-Yankson 2017)

As discussed in the previous section, the literature on the adaptive and transformative capabilities of resilience in built infrastructure systems is in a developing stage. Chester and Allenby (2018) began to identify characteristics of infrastructure systems that create flexibility and agility in the systems, to enhance adaptive resilience (Chester and Allenby 2018). Gilrein and others (2019) further improved the work by identifying a defined set of characteristics based on a review of resilience and adaptation in different infrastructure fields, presented in Table 4-1 (Gilrein et al. 2019).

This set of characteristics is taken as the starting point in this research to further identify transportation specific adaptive resilience capabilities. The expert interviews conducted in this research used Table 4-1 as the information base to create the interview guide and generate conversations on similar potential capabilities of transportation systems that can enhance system flexibility and agility. Through nodal analysis of the expert interview data, 16 capabilities and their context-specific definitions were identified. These are presented in Table 4-2.

Table 4-1: Definitions for characteristics of agile and flexible infrastructure. (Adopted from Chester and Allenby (2019) and (Gilrein et al. 2019))

Competency	Definition
Modularity	The ability to readily add, remove, or modify individual technical or institutional components without significantly disrupting or affecting other components and in turn, the overall system.
Connectivity	The degree to which infrastructure components can readily interact with other components within the system and with the components of other systems.
Compatibility	The ability to integrate into a common or shared network of rules, material, energy, and information flows.
Hardware-to-Software/-Services	Substitution of physical components and mechanical processes for services or information-based mechanisms
Culture of Change	Management, design, and planning practices that embrace continuous and reflexive experimentation, innovative strategies, and 'learning by doing'.
Planned Obsolescence	Planning practices based on the view that conditions may change, and an awareness of potentially creating path dependencies that may complicate future adaptivity in light of potential changes regarding functions, demands, and Earth systems.
Roadmapping	Managing short-term demands and urgencies along with an intentional long-term perspective toward developing structures that cope with rapid evolution of systems and deep uncertainty.
Organic structure & Management	An organizational structure characterized by a more decentralized decision-making authority, fluid division of labor, and transparent communication practices.
Risk to Resilience	Awareness of non-stationarity in Earth Systems and a focus on building adaptive capacity, anticipation, experimentation, and learning, in lieu of a probabilistic and deterministic risk-based approach.
Transdisciplinary Education	Fostering education that acknowledges the diversity of actors, institutions, and ways of knowing involved in the design and management of infrastructure as a complex system.
Multi-functionality	A coupling of multiple purposes, processes, or functions within a system component that is either able to perform multiple functions simultaneously, or intentionally switch between multiple functions.

Table 4-2: Adaptive Resilience Capabilities of Transportation Systems as identified from the literature review and expert interviews.

Adaptive Resilience Capabilities	**Description**
Communication Connectivity	Connectivity of resilience plans with internal and external stakeholder objectives and goals, with the agency goals and objectives, and long & short-range plans
Diversity of Inputs	Diversity in disciplinary background of staff, input from a diverse set of external and internal stakeholders, outputs and outcomes measured on a diverse scale (i.e., different types of impacts)
Culture of Change	Continuous and reflective experimentation, innovation,' learning by doing' approach
Organic Management Structure	Decentralized decision making, fluid division of labor, transparent communication practices
Organic/diverse Finance Structure	Fluid flow of finances for resilience investments, diverse set of potential inputs, diverse set of measured benefits, multiple ways of measuring the costs & benefits
Vulnerability Assessment	Assessment of hazard exposure and vulnerability of system assets
Program Connectivity (within)	Connectivity between offices in terms of objectives and target setting, data sharing, projects impact assessment.
Roadmapping	Managing short term demands and urgencies along with an intentional look at long term planning under emerging uncertainties; *making intentional efforts to reduce path dependencies for future changes in plans*
Risk-based Resilience to Adaptive Resilience	Reduced dependence on deterministic risk-based plans and designs, and movement towards developing adaptive capacity, anticipation, experimentation, and learning approach.
Obsolescence Planning	Planning for potential obsolescence of current systems under uncertain future conditions
Multi-functionality	Coupling multiple purposes, processes, and functions within system components that can either perform multiple functions simultaneously, or switch between them as needed
Modularity/Redundancy	Ability to readily add, remove, or modify individual components without disrupting other components and hence the overall system
Technological advancement (updates)	Update on existing hardware and software systems of transportation assets
Hardware to software substitution	Substitution of physical components and mechanical processes for services or information-based mechanisms
Tech Connectivity	Connectivity of hardware and software systems across projects and offices, connectivity of different types of physical assets
Compatibility	Compatibility of connected hardware, software, and physical assets to integrate into a common or shared network of rules, material, energy, and information flows.

4.6 Thematic Distribution of AR Capabilities

The capabilities identified in the previous section, emerging from the adaptive resilience literature review and expert interviews, provide insights on what areas need to be improved to enhance system resilience. The capabilities by themselves though do not provide a direction on how to make these improvements. For such systematic stepwise improvements in a system, a capability maturity model (CMM) is developed. The CMM concept was originally developed by the US Department of Defense, to be used for continuous improvement in software development (Paulk 2002). The model has subsequently been used in a range of systems, including cybersecurity, construction management, project management, systems engineering, product development, and transportation systems (Bate et al. 1995; Crawford 2006; Gimenez et al. 2017; Lockamy and McCormack 2004; McCuen et al. 2012). Research under the SHRP 2 (Strategic Highway Research Program 2) by FHWA in 2011, along with the efforts of AASTHO, led to the development of a capability maturity model for Transportation System Management and Operations (TSMO) (FHWA 2016a). Expanding on these earlier efforts, six different Capability Maturity Frameworks were developed by FHWA to provide focused assessment and actions in the areas of traffic management, traffic incident management, planned special events, work zone management, road weather management, and traffic signal control (FHWA 2016b). The FHWA CMM frameworks promote a process-driven approach to improve maturity of agencies on the different focus areas. CMMs can be used to identify capabilities that are limiting the agency from developing successful projects for reasons unrelated to technology. It also helps identify the weakest links in the systems, which hold back agencies to become leaders in the particular area. Finally, CMM allows agencies to prioritize the right actions by identifying the readiness, current state and next steps (FHWA 2016a).

Resilience maturity models have also been developed in various fields. Hernantes and others (2019) developed a system level maturity model to operationalize resilience in cities in Spain. A European Union study on Smart Mature Resilience developed a maturity model to operationalize resilience in European cities (SMR 2016). Zamuda and others (2019) developed similar maturity framework for resilience capabilities of electric utility systems under extreme weather. In the US transportation space, research sponsored by NCHRP (NCHRP 20-117) on deploying transportation resilience practices in state DOTs is developing a resilience maturity model for state DOTs (WSP USA Inc. 2020).

In this paper we extend the resilience frameworks to identify maturity levels of capabilities that enhance adaptive resilience with an intentional focus on flexibility and agility as the key concepts of adaptive resilience. The identified capabilities enhance the overall resilience framework including readiness, resistance, recovery, and adaptation. We then integrate it with the general format of the existing transportation CMM frameworks to develop a maturity model that can be easily adopted by the transportation agencies.

Thematic analysis of the expert interview data along with a review of existing CMMs in the transportation field led to identification of themes in which the 16 capabilities can be categorized: under overarching strategic, programmatic, and tactical domains. This categorization is in alignment with the TPM-CMM, the TSMO CMM, and the HSIP-CMM, which makes for easy adoption in the existing transportation CMM realm. The Strategic theme focuses on capabilities related to institution and governance. It includes aspects as stakeholders, vision and goals, leadership, direction, accountability, funding, collaboration, integration of programmatic and tactical elements with planning, program staffing, and establishing procedures. The Programmatic theme centers around performance management processes, with focus on aspects such as objectives, performance measures, target setting, resource allocation, monitoring and reporting, and management and operations. Lastly, the Tactical theme is focused on tools and technology, data collection-sharing-& standardization, analysis tools, and physical performance.

Table 4-3 presents the capabilities categorized in the three identified themes.

Table 4-3: Thematic categorization of the Adaptive Resilience Capabilities of Transportation Systems

Strategic	***Programmatic***	***Tactical***
• Communication Connectivity	• Vulnerability Assessment	• Multi-functionality
• Diversity of Inputs	• Program Connectivity (within)	• Modularity/Redundancy

• Culture of Change • Organic Management Structure • Organic/diverse Finance Structure	• Roadmapping • Risk based Resilience to Adaptative Resilience • Obsolescence Planning	• Technological advancement (updates) • Hardware to software substitution • Tech Connectivity • Compatibility

4.7 Adaptive Resilience – Capability Maturity Model (AR-CMM)

To evaluate a transportation agency's adaptive resilience maturity, a capability maturity model was developed using the five levels of maturity and the sixteen capabilities of adaptive resilience identified for transportation systems.

For each capability in the three themes, 5 capability maturity levels were defined, ranging from Level 1 as Initial, to Level 5 as Advanced. The maturity levels form a continuous improvement spectrum for the capabilities, and hence provide the current standing and the logical next steps to move from one maturity level to the next. The ideal goal for any agency would be to at the highest maturity level for each capability, but in a practical setting, prioritization of the capabilities based on agency goals and current maturity might lead to a different objective maturity levels for different capabilities. The five maturity levels are discussed below:

- Level 1 (Initial): Either the particular capability has not yet been identified as something that can enhance resilience and needs improvement, and hence no action has been taken on improving the capability, or such a need has emerged in some assessments or reports as limitations, but no action has been taken yet. Most of the resilience or risk management practices, if existing, rarely account for uncertainty of future changes and apply a deterministic, single decision path, based on a single expected future scenario.

- Level 2 (Championed): Having identified the need of improvement of the particular capability, champion-based or ad-hoc efforts are taken for assessment and prioritization of projects supporting improvement of the capability. Base performance measures of the system are possibly tracked to assess the current levels of the capability. The risk and resilience management accounts for future uncertainty by considering sensitivity analysis in decision making. The decisions still follow a single determined path based on a selected scenario post sensitivity analysis.
- Level 3 (Defined): Assessment of outputs and outcomes of the efforts made to enhance the particular capability are conducted. Actions are documented, and shared understanding of the motives behind these efforts exist across the agency. Resilience and risk management plans use probabilistic scenario-based approach for decision making, to identify the decision path for the most likely scenario.
- Level 4 (Integrated): Performance measures to assess the improvement of the given capability are integrated into existing plans. The capability is integrated as a key element of decision making across offices and long-term plans. Quantitative measurements of performance of the capability based on its outputs and outcomes, and its impact on other capabilities across themes is formalized. Standardized feedback channels exist in

planning to use the performance measures in further enhancements. Risk and resilience plans identify multiple possible future pathways based on different possible scenarios. Deep uncertainty is acknowledged as a factor affecting decisions based on changing future conditions.

- Level 5 (Advanced): At this stage, all Level 4 actions are conducted, and the resilience approach focuses on transition to transformative resilience. A stable continuous improvement stage is established, which allows for feedback loops utilizing the performance measures to continuously improve system resilience. A change management system is in place, to account for continuous and rapid changes in the demands of the system and its environment, demanding possible changes in the capability functionalities and all related efforts.

Table 4-4 ((a) and (b)), 5((a) and (b)), and 6((a), (b), and (c)) present the developed AR-CMM with description of each maturity level for every capability identified in the strategic, programmatic, and tactical themes, respectively. Each table (4,5, and 6) is split into smaller table sections (a, b, and c) for easier readability.

Table 4-4(a): Adaptive Resilience Capability Maturity Model (AR-CMM)- Strategic Theme Capabilities (1-3)

Characteristics	***Level 1: Initial***	***Level 2: Championed***	***Level 3: Defined***	***Level 4: Integrated***	***Level 5: Advanced***
Communication Connectivity (CC)	No focus on the capability so far; or Certain assessments and/or reviews have identified the need for communication connectivity across plans, but no action has been taken	Champion-based efforts in connecting resilience and uncertainty planning to long & short-range plans; formal assessment of gaps in connectivity on an ad-hoc basis	Actions taken are formally documented; a shared understanding of the motives exist between internal and external stakeholders; outputs of communication connectivity are measured in terms of impact on the overall system	Adaptive resiliency is communicated across different plans of the agency; quantitative measurement of the factor's performance, standardized feedback channels into planning to improve the capacity	Level 4 accomplished, and performance of level 4 initiatives tracked and integrated into planning; change management in place for various modes of communication connectivity
Diversity of Input	No focus on the capability so far; or Identified the need for diverse set of stakeholders in DM although decision making is still done by a small homogenous group of decision makers	Champion-based efforts in incorporating some diverse stakeholders in a few decisions; assessment of impacts of AR initiatives on various sectors – economic, social, environmental etc.	Actions to diversify stakeholders' input are formally documented; shared understanding of need for diversity in generating DM inputs and outputs; outputs are measured in terms of impacts on the overall system	Diversity of stakeholders is integrated across development of plans; quantitative PMs of diversity of inputs and diversity of output fields; standardized feedback channels into planning to improve this AR factor capacity	Level 4 accomplished, and performance of level 4 initiatives tracked and integrated into planning; change management in place for inclusion of diversity at various decision points
Culture of Change	No focus on the capability so far; or Need identified for reflective experimentation, but no action taken; current processes do not account for changing future conditions	Champions or 1-2 offices attempting to conduct innovative experiments; assessment of performance characteristics that need experimental ideas and/or can be improved by innovation	Actions taken are formally documented; a shared understanding of the need for change as part of the culture; outputs of cultural change are measured in terms of impact on the overall system.	Culture of change is integrated across all plans and processes; quantitative PMs of inputs and outputs of innovation and experimentation are tracked and evaluated, and used in standardized feedback channels to improve DM	Level 4 accomplished, and performance of level 4 initiatives tracked and integrated into planning; change management encompasses the change management of all other AR factors.

Table 4-4(b): Adaptive Resilience Capability Maturity Model (AR-CMM)- Strategic Theme Capabilities (4-5)

Characteristics	***Level 1: Initial***	***Level 2: Championed***	***Level 3: Defined***	***Level 4: Integrated***	***Level 5: Advanced***
Organic Management Structure	No focus on the capability so far; or Existing hierarchical structure identified as presenting challenges- need identified for organic elements in management; no action taken to modify existing structure	Champion-based efforts in bringing fluidity in division of labor, and decentralization of DM; few assessments conducted on the impacts of hierarchical (non-organic) management on resilience	Actions taken to bring organic structure in management are formally documented; shared understanding of the need for organic management structure exists; outputs are measured in terms of its impact on the overall system	Integration of organic decision-making structure into agency goals, objectives, plans and processes; quantitative PMs of inputs and outputs of organic management structure are documented, tracked, and used in standardized feedback channels to improve DM	Level 4 accomplished, and performance of level 4 initiatives tracked and integrated into planning; change management in place to plan for potential needs of change in management structure as needed
Organic Finance Structure	No focus on the capability so far; or Need identified for fluid division and access to finances across programs for resilience development; no actions taken; existing financial allocation restricts improvement, experimentation, innovation, and cross-office developments for resilience	Champion-based efforts; external financial alternatives pursued to develop organic financial structure; formal assessment of impact of rigid financial structure conducted	Actions taken are documented; a shared understanding of the need for fluid financial structure; outputs of organic financial structure are measured in terms of its impact on the overall system	Actions to create flexibility in finance for resilience planning are integrated across the agency; Level 3 actions are formalized; quantitative assessment of inputs and outputs of organic financial structure is conducted; agency understands the impacts of flexibility on finances under uncertainty	Level 4 accomplished, and performance of level 4 initiatives tracked and integrated into planning; change management in place to plan for potential need for changes in financial structure and assessment methods; benefit assessment methods for DMDU developed and integrated in planning

Table 4-5(a): Adaptive Resilience Capability Maturity Model (AR-CMM)- Programmatic Theme Capabilities (1-3)

Characteristics	***Level 1: Initial***	***Level 2: Championed***	***Level 3: Defined***	***Level 4: Integrated***	***Level 5: Advanced***
Vulnerability Assessment (VA)	No focus on the capability so far; or Need for vulnerability assessment identified but not conducted an assessment yet	Champion-based efforts for VA; uncertainty accounted for in terms of sensitivity analysis of hazards and risk; historic data used as-is to project future conditions	Actions taken are documented; a shared understanding of the motives exist to conduct vulnerability assessments; outputs are measured in terms of VA's impact on the overall system; probabilistic scenario-based assessment of vulnerability to develop single decision path	Integration of VAs in plans and projects; documentation of methods and formalization of regular assessment; probabilistic scenario-based assessment to develop multiple decision pathways; assessment covering variety of impact categories	Level 4 accomplished, and performance of level 4 initiatives tracked and integrated into planning; change management in place for variations in vulnerability assessment methods
Program Connectivity (PC)	No focus on the capability so far; or Certain assessments and/or reviews have identified the need for program connectivity across offices, but no action has been taken	Champion-based efforts in connecting resilience programs across offices; formal assessment of gaps in connectivity on an ad-hoc basis	Actions taken are documented; a shared understanding of the need for PC across offices; qualitative assessment of the outcomes of PC; outputs are measured in terms of its impact on the overall system	Adaptive resiliency is communicated across different program development units; Integration of adaptive resilience concepts throughout program processes; quantitative PMs of PC tracked, documented, and used in standardized feedback channels into strategic planning to improve PC	Level 4 accomplished, and performance of level 4 initiatives tracked and integrated into planning; change management in place for various modes of program connectivity
Roadmapping	No focus on the capability so far; or Short-term programs and processes identified as potentially creating roadblocks for future change; no formal assessment or action taken	Champion-based efforts in a few programs to intentionally reduce path dependencies for future changes; formal assessment of negative impacts of rigid short-term projects on long term planning	Actions taken in Level 2 are documented; a shared understanding of the need for Roadmapping exists; qualitative assessments of outcomes of Roadmapping are conducted in terms of their impact on the overall system	Integration of Roadmapping across target setting, O&M, monitoring and reporting, and objectives setting; quantitative PMs of inputs and outputs of Roadmapping are tracked, documented, and used in standardized feedback channels to improve Roadmapping processes in DM	Level 4 accomplished, and performance of level 4 initiatives tracked and integrated in planning; All short-term programming processes incorporate formal consideration of reducing future path dependencies; change management in place to keep the programming process up to date with evolving future roadblocks

Table 4-5(b): Adaptive Resilience Capability Maturity Model (AR-CMM)- Programmatic Theme Capabilities (4-5)

Characteristics	***Level 1: Initial***	***Level 2: Championed***	***Level 3: Defined***	***Level 4: Integrated***	***Level 5: Advanced***
Risk-based resilience to Adaptive Resilience (RRtoAR)	No focus on the capability so far; or Challenges with deterministic approaches for assessment identified; no action taken yet; programming processes follow deterministic approaches	Champion-based efforts in incorporating future non-stationarity in programming processes; multiple future scenarios developed for some projects on an ad-hoc basis; programs focused on hardening efforts to reduce risk	Actions taken to incorporate future non-stationarity in programs are documented; a shared awareness of non-stationarity of the environment exists; qualitative assessment of the outcomes of applying RtoR approach; outcomes are assessed in terms of their impacts on the overall system	Integration of RtoR approach across all programs and projects, and alignment with the strategic AR factors; formalized focus on building adaptive capacity, anticipation, experimentation and learning in short-term and long-term programming processes; quantitative PMs to assess the RtoR approach incorporation in programs are tracked and evaluated, and used in standardized feedback channels to improve DM	Level 4 accomplished, and performance of Level 4 initiatives tracked and integrated in planning; All programs transitioned from probabilistic and deterministic risk-based approaches to a resilience-based approach with focus on building adaptive capacity, anticipation, experimentation, and learning; change management in place to update the resilience approach with changing environment and external factors
Obsolescence Planning (OP)	No focus on the capability so far; or Informally identified existing or soon to be obsolete systems and/or assets; no formal program to plan for the assets other than equivalent replacement	Champion-based efforts in a few programs to actively plan for soon to be obsolete assets/systems; formal assessment of the existing and near-term obsolete systems using deterministic future condition estimates	Actions taken in Level 2 are formally documented; a shared understanding of the need for OP exists; qualitative assessment of outcomes of OP; outcomes are assessed in terms of their impacts on the overall system	Integration of OP across all program elements and with overall planning goals and objectives; quantitative PMs of inputs and outputs of OP are tracked, documented, and used in standardized feedback channels to improve OP processes in DM	Level 4 accomplished, and performance of level 4 initiatives tracked and integrated in planning; Innovation and experimentation to plan for alternative usage of near obsolete systems; proactive identification of obsolescence formalized in the programming process; change management in place for continuous improvement in OP

Table 4-6(a): Adaptive Resilience Capability Maturity Model (AR-CMM)- Tactical Theme Capabilities (1-3)

Characteristics	***Level 1: Initial***	***Level 2: Championed***	***Level 3: Defined***	***Level 4: Integrated***	***Level 5: Advanced***
Multi-functionality	No focus on the capability so far; or Some discussion on the application and benefits of multifunctionality in making resilience investments; no action taken	Champion-based efforts in incorporating multi-functionality in project design; formal assessment of limitations of single-function tools and assets in advancing system resilience	Actions taken are formally documented; a shared understanding of the need for multi-functionality exists; qualitative assessment of the outcomes of multi-functionality in terms of their impacts on the overall system	Integration of multi-functionality as a key characteristic of tools and assets across programming and planning; quantitative PMs of inputs and outputs of multi-functionality tracked and evaluated, and used in standardized feedback channels to improve DM	Level 4 accomplished, and performance of level 4 initiatives tracked and integrated into planning; change management in place to continuously enhance multifunctionality of assets and tools
Modularity	No focus on the capability so far; or Informally identified the need for modularity in assets for quicker system recovery; existing assets do not demonstrate modularity	Champion-based efforts in making some tools & technical systems modular; ad-hoc investments in adding redundancy in physical assets to enhance resiliency; assessment of the limitations of non-modular systems on resilience	Actions taken are formally documented; a shared understanding of the need for modularity in the identified system exists; qualitative assessment of the outcomes of modularity in terms of their impact on the overall system	Integration of modularity as a key characteristic of tools and assets across programming and planning; quantitative PMs of inputs and outputs of modularity tracked and evaluated, and used in standardized feedback channels to improve DM	Level 4 accomplished, and performance of level 4 initiatives tracked and integrated into planning; change management in place to continuously improve impacts of modularity on system functionality
Technological advancement (updates) (TA)	No focus on the capability so far; or Informally identified the need for updating the technical systems, and challenges faced due to older technology in developing resilience initiatives; no action taken yet	Champion-based efforts in advancing selected technical systems; formal assessment of the current technical systems and their update needs; formal assessment of the need for updates in technical guidelines for physical asset design	Actions taken are formally documented; a shared understanding of the need of TA in the identified system exists; qualitative assessment of the outcomes of TA in terms of their impact on the overall system	Integration and standardization of the process of technological advancements within overall planning process; quantitative PMs of inputs and outputs of TA tracked and evaluated, and used in standardized feedback channels to improve DM	Level 4 accomplished, and performance of level 4 initiatives tracked and integrated into planning; change management in place to continuously enhance TA of assets and tools

Table 4-6(b): Adaptive Resilience Capability Maturity Model (AR-CMM)- Tactical Theme Capabilities (4-6)

Characteristics	*Level 1: Initial*	*Level 2: Championed*	*Level 3: Defined*	*Level 4: Integrated*	*Level 5: Advanced*
Hardware to software substitution (HSS)	No focus on the capability so far; or Informally identified the challenges of hardware systems and the need for software replacement to improve resilience in some business processes; no action taken; currently all systems are hardware based	Champion-based efforts in substitution of some hardware systems by software systems; formal assessment of all hardware systems to identify those that can be replaced/ supported/ advanced by complete/partial software replacements	Actions taken are formally documented; a shared understanding of the need for HSS in the identified system exists; qualitative assessment of the outcomes of HSS in terms of their impact on the overall system	Integration of HSS needs assessment, and the process of conducting HSS in the overall planning process; quantitative PMs of inputs and outputs of HSS tracked and evaluated, and used in standardized feedback channels to improve DM	Level 4 accomplished, and performance of level 4 initiatives tracked and integrated into planning; change management in place to give continuous feedback on the need for HSS and a formal process for the required HSS
Technical Connectivity (TC)	No focus on the capability so far; or Challenges and gaps informally identified in resilience planning due to disconnect between various technical systems; existing tools do not share or integrate information from other tools in the system; existing physical assets have limited connectivity and form a poorly shared network; no action has yet been taken to improve TC	Champion-based efforts to connect the information flow between tools and technology of different projects and programs; formal assessment of gaps in TC and opportunities where TC can improve system performance and system resilience	Actions taken are formally documented; a shared understanding of the need for TC exists; qualitative assessment of the outcomes of TC in terms of their impact on the overall system	Integration of TC with PC and CC; quantitative PMs of inputs and outputs of TC tracked and evaluated, and used in standardized feedback channels to improve DM	Level 4 accomplished, and performance of level 4 initiatives tracked and integrated into planning; change management in place to continuously improve TC of the system
Compatibility	No focus on the capability so far; or Informally identified the need for compatibility of tools, technology, and physical assets that are connected; no actions taken yet; current connected systems are rarely compatible and/or have challenges in functioning due to lack of compatibility	Champion-based efforts in building compatibility between connected tools, technology, and/or physical assets; formal assessment of the lack of compatibility between connected assets, and opportunities where compatibility can improve TC, and hence, system performance and system resilience	Actions taken are formally documented; a shared understanding of the need for compatibility of connected system exists; qualitative assessment of the outcomes of compatibility in terms of their impact on the overall system	Integration of compatibility as a key characteristic of connected tools and assets across planning and programming; quantitative PMs of inputs and outputs of compatibility tracked and evaluated, and used in standardized feedback channels to improve DM	Level 4 accomplished, and performance of level 4 initiatives tracked and integrated into planning; change management in place to continuously improve compatibility of the connected tools and assets of the system

4.8 Conclusion

With increasing uncertainty in future predictions, the need to focus on system adaptability is critical to making any system resilient to future threats. Flexibility and agility are relatively new concepts in the engineering resilience domain, hence limited guidance exists on how to assess and enhance the adaptive resilience of a system. This is an even bigger gap in the field of transportation. This paper aims to bridge that gap by extracting, through literature reviews and expert interviews, the key fundamental principles of a transportation system that can enhance its adaptive resilience. From these concepts, we have constructed a model to assess the maturity level of a transportation system's adaptive capacity.

The current standard practices on resilience in transportation include condition-based assessments and a focus on direct quantifiable benefits, leading to deterministic and rigid long-term plans. This needs to change given the increasing uncertainty and need for adaptive capacity in the systems. The AR-CMM will support agencies in identifying their adaptive resilience gaps and strengths. Low maturity can be used as a factor in prioritization of projects that focus on those capabilities. Further, higher maturity capabilities can be used to systematically support improvement in the prioritized spaces. The maturity model also provides logical guidance on continuous improvement along each capability, through guided next steps for moving to the next maturity level. The AR-CMM and identified adaptive resilience capabilities can be used further to develop measures for quantitative assessments of performance of initiatives and projects that improve transportation system priorities such as mobility, safety, system condition, environmental sustainability, while improving resilience adaptively.

4.9 Limitations and Future Research

Given that the research identifies the adaptive resilience capabilities through the literature and expert interviews, limitations of those research methods apply in this paper as well. The list of capabilities identified here are comprehensive based on the current existing research and practitioner knowledge but are by no means exhaustive. As the nature of flexible and agile systems evolves, new capabilities of the systems will emerge with changing environment, demand, and system characteristics. Therefore, there will be a persistent need to periodically re-assess and amend the list of adaptive resilience capabilities.

Another limitation of adaptive resilience in general, and therefore of this paper is the lack of focus on mitigation. Without mitigative efforts, continuous adaptation might not be the most resilient or sustainable solution in the long term. While this is understood, resilience transitions from engineering-based resilience to mitigative transformative resilience is a continuum, with adaptive resilience somewhere in the middle. To move to mitigative and transformative resilience, a system first needs to transition from a single-equilibrium engineering resilience approach to an adaptive resilience approach – this paper contributes to enabling this transition in the field of transportation. Future research needs to focus on similar theory development on mitigative resilience capabilities in the built systems.

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CHAPTER 5. MODIFIED RESILIENCE TRIANGLES APPROACH

P. Singh, A. Amekudzi-Kennedy, B. Ashuri, M. Chester, S. Labi, and T.A. Wall. Developing adaptive resilience in infrastructure systems: An approach to quantify long-term benefits. (Under Development)

5.1 Abstract

Increasingly frequent, intense, and consequential disasters, necessitate building greater resilience into infrastructure systems. In order to enable systems to re-organize, or adapt to changing future conditions, ensuring adaptive capacity in resilience planning is critical. This paper presents an approach to evaluate the long-term benefits of adaptive resilience investments in infrastructure systems under future uncertainty. The methodology builds on the existing work on resilience assessments and uses long timeframe assessment methods based on NPV and various approaches to quantify different levels of uncertainty along with multi-criteria assessment methods. The application of the proposed methodology is demonstrated using three case studies, where investments have focused on different aspects of adaptive resilience enhancement in various infrastructure systems. The results from all three case studies demonstrate the increasing benefits of adaptive resilience strategies over the extended time periods of ongoing learning and the evolving nature of the resilience strategies. The approach presented in the paper can be used by public and private agencies in multiple infrastructure sectors such as transportation, power,

water, and communication. A flexible approach to evaluate the long-term benefits of building adaptive capacity to enhance resilience in the system, this methodology can be a useful tool for practitioners and policymakers to present a business case for long-term adaptive resilience investments.

5.2 Background and Motivation

The intensity and frequency of disasters have been rising in recent decades, as has their consequences on social, ecological, and economic systems. Seemingly every year over the last decade, new records are being set for the number of billion-dollar events that occur annually (NOAA 2021), and there is growing recognition that resilient systems are critical to a sustainable future. Agencies focused on critical infrastructure systems such as transportation, water, power, and communication, have started investing in making their systems resilient to future disruptions - natural or human-made (Kafalenos 2018, AASHTO 2017, FHWA 2017).

The American Society of Civil Engineers (ASCE) defines critical infrastructure resilience as "the ability to plan, prepare for, mitigate, and adapt to changing conditions from hazards to enable rapid recovery of physical, social, economic, and ecological infrastructure" (ASCE 2013). However, the definitions of resilience vary widely across disciplines. Detailed literature reviews on resilience definitions, (Häring et al. 2017; Pendall et al. 2010; Righi et al. 2015) reflect that the current state of resilience practice in infrastructure systems is focused on a 'bounce back to normal' approach. This focus, based on the origins of the word from the Latin word 'resiliens', meaning 'to rebound', falls short in the current era where there is a need for the system to be built back better, to adapt, and to transform, based on changing nature and environment. Aspects of flexibility and agility are gaining traction in infrastructure resilience discussions (Chester and Allenby 2018; Gilrein et al. 2019), which can support long term system resilience under uncertainty of factors such as climate change, population growth, and urbanization (Bosello and Chen 2011; Chester et al. 2020).

While conceptual frameworks on building adaptive capacity as part of infrastructure resilience efforts have been emerging in the recent literature, methods to quantify the benefits of resilience efforts still focus on the bounce-back approach to resilience. This paper introduces an approach to assess the value of adaptive resilience investments by examining the long-term benefits of continuous adaptation of a system under future uncertainty. The approach builds on the resilience triangle approach, which has been applied widely in the infrastructure field to quantify resilience. The paper presents the changes made in the existing resilience triangle approach, introduces the methodology of the Modified Resilience Tringles (MRT) approach, and demonstrates its application using three case studies of adaptive resilience strategies implemented in different infrastructure systems across the US.

5.3 Resilience Assessment

The foundations of resilience assessment for infrastructure systems are in the Resilience Triangle (RT) approach. The resilience triangle approach, first presented by Bruneau et al. (2003), enables visualization of the impact of a disruption to a system. The y-axis presents the system's functionality, and the x-axis presents time (Figure 5-1). The drop in functionality as the disruption occurs, and the subsequent recovery phase over a period of time can be used to quantify the loss in functionality due to the disruption, which is the area of the triangle. This loss in functionality can be considered as resilience loss. The reduction in the resilience loss area can be a measure of benefits by a resilience investment.

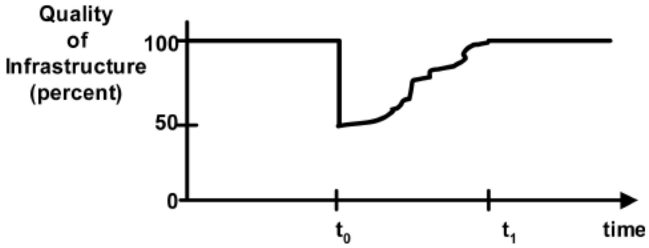

Figure 5-1: Resilience triangle (Bruneau et al.2003)

Considering the y-axis as the performance function, ranging from 0% to 100%, the resilience loss is calculated using the following formula:

$$RL = \int_{t_0}^{t_1} [100 - Q(t)]dt$$

Having identified that building back to the same level might not be the best approach in all situations, building back better has been introduced in the RT approach by multiple researchers. Yu et al. (2014) use the RT approach to compare the seismic resilience of Japan and Oregon and demonstrate Japan's enhanced resilience by building back better (Figure 5-2).

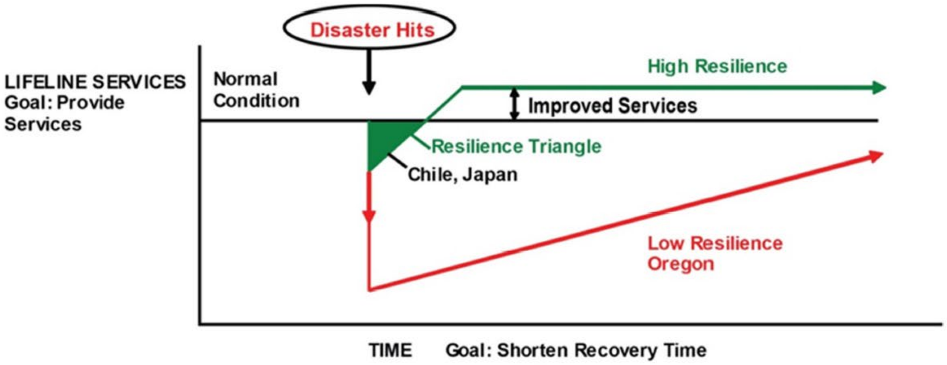

Figure 5-2: Seismic resilience triangle assessment comparing Oregon and Japan's resilience (Yu et al. 2014)

Future detailed applications of the RT approach in supply chains present the non-linear trends in the changes in the performance function as a result of a disruption and the long-term impacts of the disruption on the system (Figure 5-3).

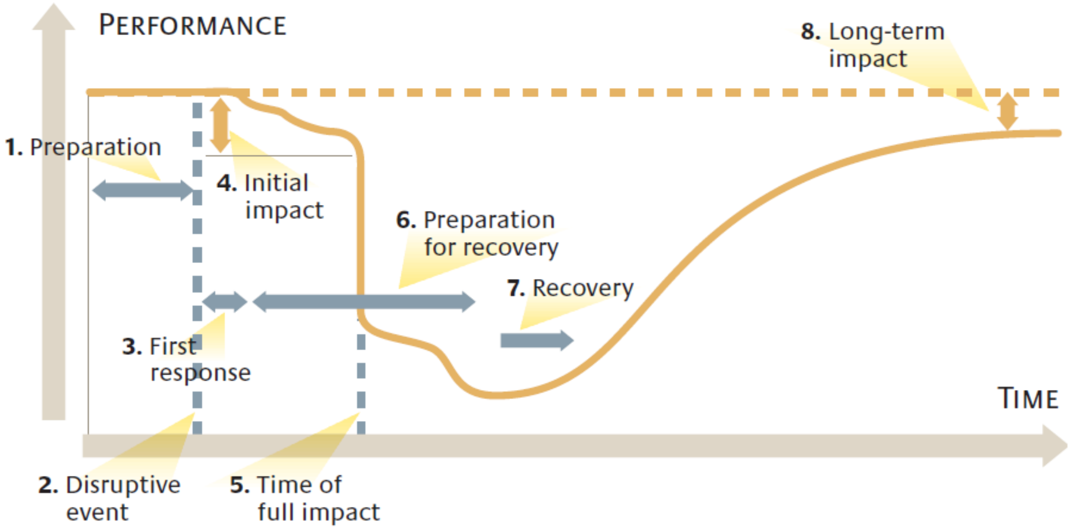

Figure 5-3: Resilience loss triangle for supply chain (Sheffi and Rice 2005)

Quantification efforts for resilience in the infrastructure discipline include research in freight and transit systems, with application of the RT approach in traffic recovery assessment (Tang and Heinimann 2018), public transit resilience evaluation (Mudigonda et al. 2019), and freight resilience measures (Adams et al. 2012). These efforts to quantify resilience losses can be instrumental in presenting a business case for resilience initiatives to decision makers by demonstrating, visually as a resilience triangle, how the application of a resilience initiative can reduce the impacts and consequences of a disruption.

While the existing resilience triangle approach presents a cross-sectional view of resilience loss at a given point of time for a specific event, understanding the longitudinal effects of resilience investments in the reduction of future resilience triangles is and will continue to be valuable. This is especially true given the growing need for adaptability and flexibility in systems in order to ensure improved future responses in the face of evolving uncertainties. Such an approach that examines the long-term effects of resilience strategies on the long-term resilience loss of a system does not exist in the literature.

5.4 Modified Resilience Triangles (MRT) Approach

This paper bridges the existing gap by developing a Modified Resilience Triangles (MRT) approach, which builds on existing resilience triangle approaches and adds modifications that can allow for the long-term benefits of building adaptive resilience to be assessed in systems facing uncertainty.

Three specific aspects of adaptive resilience are reflected in the MRT approach being introduced:

a) Long-term RT assessment: In order to use the RT approach to assess the benefits of resilience strategies, the benefits need to be assessed over the full life of the system, or at least over the life-cycle of the resilience strategy being evaluated, as opposed to the current applications of the RT approach which are generally applied at a single-event level (Tang and Heinimann 2018, Mudigonda et al. 2019, Adams et al. 2012). Long-term assessments will incentivize adaptive resilience investments that foster continuous and reflective learning, as the benefits of such efforts can be quantified.

b) Context-specific system assessment metric (Y-axis): Bruneau et al. note the need for the y-axis to be context-specific, but the resilience triangle has been most traditionally applied with either system performance or system condition as the y-axis. In a complex system, adaptive resilience investments can target any of the multiple possible performance parameters, and in such cases, the appropriate context-specific measure is needed to assess the benefits of such investment. For example, suppose a resilience strategy is focused on building redundancy in the power supply to a transit system. In that case, this enhancement of the system might not be directly reflected in building back better if the y-axis is transit network functionality- recovery can only go to 100%, although the system becomes more resilient after the intervention. In such a case, a more appropriate context-specific y-axis would be a composite score of transit network power functionality, such that adding redundancy increases the composite score, thereby counting the resilience benefit in the quantification process.

c) Building back better: While some recent resilience quantification literature does demonstrate building back better in the resilience triangle figure, an immediate upward increase might not always be evident. This is especially true in cases where the y-axis is performance using a percentage scale, which traditionally only goes up to 100%. This does not necessarily mean that such systems cannot be built back better, but rather that the 'better' will not directly relate to regular system performance. Instead, it implies that the system will be ‘better’ able to respond to future disruptions. In such cases, a system’s future RTs can be modeled as a function of time, where after each revision or update cycle of the resilience project, there is a possible reduction in the area of future resilience triangles. It is important to note that being able to assess such building back better efforts are dependent on doing a long-term assessment, and using a context specific metric (the first and second modifications presented in the section). The concept is further illustrated in figure 5-4.

Figure 5-4 presents the three different ways benefits from adaptive resilience strategies can be accounted for over a long-term time assessment period. Each red triangle demonstrates a simplified version of the resilience triangle during the occurrence of a disruptive event (denoted by a red star on the time axis). As previously discussed in the literature resilience assessment section, the resilience drop and recovery might follow a curve instead of a straight triangular path. The simplified version in Figure 5-4 is to demonstrate the different ways adaptations can change the curve.

Responses to the first event in each series occurs without any adaptive resilience strategy in place, and all the future RTs are assessed in comparison to the first RT. The first potential adaptive resilience strategy is to building back better (figure 5-4(a)), where the same magnitude of loss in functionality on subsequent events would keep the system at a better functional state than the previous, and hence there would be a reduced RT with each new disruption. This building back better occurs at every event, assuming the adaptive resilience strategies include a reflective element which leads to learning from each event and adapting accordingly. Such a representation of improvements in future RTs can be demonstrated if the assessment metric (Y-axis) allows for reflecting continuous improvements over time.

The second way adaptive resilience strategies can enhance long-term system resilience (Figure 5-4(b)) is by improving the planning and preparation for future absorption, response, and recovery for the system. For investments that do not directly affect system performance, such as workforce training and modular rebuilding process development, the benefits are only evident in the future resilience triangles. A smaller future resilience triangle can demonstrate benefits from such adaptations due to an increased slope of the recovery or a smaller loss in the relevant performance measure on the y-axis. A continuous increase in slope of recovery in future RTs indicates adaptive efforts to enhance future response and recovery efforts, and a continuous reduction in the drop of the y-axis in future RTs reflects adaptive efforts to enhance future absorption of the disruption by the system. The figure 5-4(b) indicates both these effects together, but an adaptive resilience strategy can focus on either one or both.

The third pathway an adaptive resilience strategy can take (Figure 5-4(c)) could be focused on mitigative measures, or measures that reduce the possibility of disruption in the system even with the occurrence of a potentially disruptive event. The common form of such adaptations is raising roadways and increasing the factors of safety in design manuals, such that the threshold for system disruption is increased for any given phenomenon. For example, increasing the bridge height from a 50-yr return period flood level to a 100-yr return period flood level will increase the threshold at which the bridge collapses, therefore reducing the occurrence of resilience triangles in the future. This approach can also be applied for strategies that focus on mitigation, thereby changing the probabilities of occurrence of future disruptions.

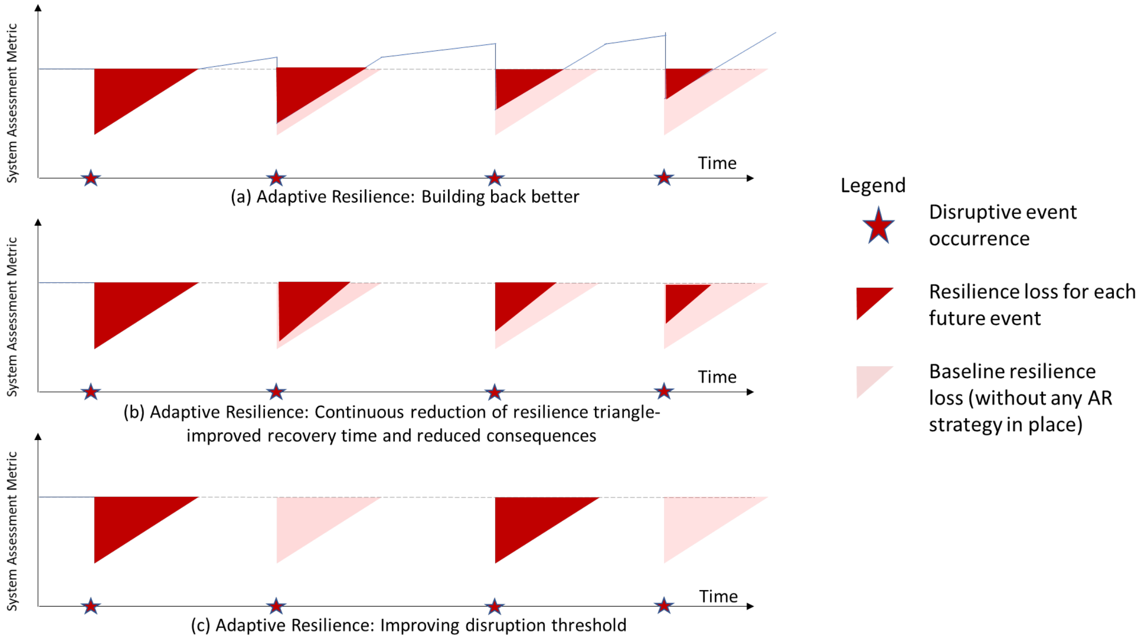

Figure 5-4: Resilience loss changes with different adaptive resilience strategy directions

A critical aspect of the MRT assessment approach is focused on handling future uncertainty. Climate change is a key factor affecting the occurrence of future RTs in the presented case studies, and must be considered when using the MRT approach to assess adaptive resilience investments against natural disasters in infrastructure systems. This, along with other factors of complex infrastructure systems such as urbanization trends, population increase, and economic changes, increase the uncertainty surrounding future resilience loss estimation. The MRT assessment approach uses scenarios for factors with an uncertainty where multiple plausible scenarios are identified; for example, using the different RCPs for plausible future scenarios. The assessment approach also uses probabilistic distributions for factors where such data is available, for example climate models that provide a probabilistic estimate of future precipitation. Lastly, it accounts for factors where a general trend exists, such as time value of money, and sensitivity analysis can be performed to see there are changes in the results with possible changes in such factors.

5.5 Assessment Methodology

The MRT assessment approach can be segmented into four sections. The first three sections focus on different aspects of input information needed to conduct the assessment, while the fourth segment focuses on the assessment outputs and how to interpret them. Table 5-1 presents the four sections with specific details on the different aspects of the assessment related to each section.

The first section focuses on the system characteristics. The MRT tool provides flexibility in its application where the infrastructure system is not only just the physical asset, but the overall socio-technical system involving the complex aspects of the users, organizations and institutions managing the assets, along with the physical infrastructure asset. Thus, a system under consideration could be as broad as a city managing disaster response using their public infrastructure, or as specific as a given bridge segment under consideration for resilience enhancements. The approach is thus scalable and therefore broadly applicable.

The second section focuses on the disruption characteristics. MRT assessment uses a specific disruption as the base to assess the impacts, or reduced impacts of such disruption on the system in light of the resilience strategies in place. The disruption characteristics required for the assessment are based on the level of uncertainty associated with the disruption. Scenarios need to be included if the disruption falls under a level of uncertainty where there could be multiple distinctive scenarios that will majorly alter the results, which is the case for the most part while dealing with natural disasters where climate change patterns fall under these uncertainty levels. In such case, assessment is performed for each plausible future scenario.

Having identified the scenarios, the assessment of resilience loss over the time period of the assessment is considered for each scenario. Within each scenario, probabilistic estimates of future occurrences of the disruption are used to simulate random events using generalized extreme value distribution or generalized Pietro distributions. A parameter associated with the disruption, which beyond a certain threshold could indicate the occurrence of a disruptive event, is modeled over the time period of the assessment. The last aspect of the disruption characteristics is the event threshold for the baseline case. The threshold might change with the application of different resilience strategies, but for comparison, a threshold as per current standards and assuming a do-nothing or build back to normal approach is identified under this section.

The third section inputs requirements of the adaptive resilience strategies. This is where the change in the resilience triangles due to implementing resilience strategies is accounted for. This includes identifying the type of impact the strategy could have on the future RTs, which can be identified from figure 5-4. Having identified the type of enhancements that the resilience strategy brings, the next step is to estimate the extent of reduction in the resilience loss in the future. If a strategy is focused on continuous improvement over the time period of the assessment, resilience loss as a function of time is to be identified. If a strategy affects the event occurrence threshold over the assessment time period, then event thresholds as a function of time are to be identified for each such strategy.

The final section of the assessment approach is the output or the results element, where the expected resilience loss for each year of the time period of the assessment is calculated, along with the net present value of the expected resilience loss under the baseline case and with each adaptive resilience strategy implemented. This is calculated for each future scenario, and an overall NPV of resilience loss is estimated based on information on the probabilities associated with the different scenarios. Table 5-1 summarizes the key sections of the Modified Resilience Triangles assessment.

Table 5-1: Modified Resilience Triangles Assessment – Key Segments

System characteristics	Disruption characteristics	Adaptive resilience strategies	Resilience assessment results
•System performance metric (y-axis), •Life-cycle (x-axis) •Baseline resilience triangle- historic record of past event and its consequences •Factors affecting the system over the life-cycle beyond the disruption (population increase, time value of money, expansions etc. – low uncertainty)	•Disruptions – e.g.,: hurricane category 3+, extreme rainfall, bridge closure, and power outage •Uncertainty related to the disruptions: •Future possible scenarios (high uncertainty) •Probability distributions (GEV or GPD) of disruption parameters (wind speed, max daily rainfall, max temperature etc.) for each scenario •Baseline event occurrence threshold	•Strategies affecting the future resilience triangle areas (better response and recovery), or resilience triangle occurrence (better absorption – improving system threshold limits), or both •Enhanced RTs with applications of the AR strategies •Improvements in RTs over time (continuous improvement within the AR strategies) •Strategy-specific event occurrence threshold	•Expected resilience loss for each year of the life-cycle of the assessment for each strategy and for the baseline case – for each scenario •Net Present Value of the expected resilience loss for each strategy under each scenario

The step-by-step process of MRT assessment is presented below:

(1) Establish the resilience strategies being compared. Let us consider there are n strategies, and one do-nothing strategy to be used as a baseline.

$$Resilience\ Strategy(i) = RS_i, where\ i = \{0,1,2, \ldots n\}$$

Baseline strategy occurs at i = 0.

(2) Establish the context-specific performance measure (PM) to be used to assess resilience loss in the event of a disruption.

(3) Establish the time period of the assessment.

$$Time(j) = T_j, where\ j = \{1,2,3, \ldots \ldots . LC\}$$

where LC = established time period of the assessment. j= jth year in the assessment time frame, where the time frame ranges from T_1 to T_{LC}.

(4) For each resilience strategy (RS_i), calculate the resilience loss in the system considering a disruption event occurrence at year T_1 (the first year in consideration of the assessment's time period), with the considered strategy in application on the system. Use the resilience triangle approach to calculate the performance metric loss (RL_i), using the following formula:

$$RL_i = \int_{t=1}^{m} (Q_N - Q_i(t))dt$$

Where $RL_i =$ Resilience loss in the event of a disruption with resilience strategy i. $Q_i(t)$ = Performance Metric Function, as a function of time t, where t is the time unit used to assess impacts of each event. Time value t varies from 1 to m, where m is the total time impacted by a single event on the system. The unit of t could range from hours to months – smaller than the unit of T. QN = Performance metric Function in the normal state (without any disruption).

(5) If any of the strategies impact the resilience triangle of future years, input the resilience loss as a function of time (T). Use the function to calculate the potential resilience loss with each strategy applied, for each year in the future ($RL_{i,T}$).

$$RL_i = f(RL_{i,}T)$$

(6) Identify if there is a factor of low uncertainty that affects the system but is not related to the disruption (population increase, time value of money, and system expansion over time). Use discount rate to account for this uncertainty and create a vector of the factor over time using the current factor value and identified discount rate (f(T)). If there is no such factor, use a unit value for f(T).

(7) Identify the level of uncertainty related to the future occurrence of a disruptive event. If the uncertainty is high, a scenarios-based assessment is needed. In this case, identify and create a list of possible scenarios.

$$Scenario\ (k) = Sc_k, \qquad k = \{1,2, \dots .q)$$

where q is the number of total plausible scenarios under assessment)

(8) Identify a parameter related to the disruption, which can be used to identify the occurrence of a disruptive event by using a threshold on the parameter. For example, if parameter = wind speed, for a wind speed greater than a pre-defined threshold, a hurricane of a given category will occur.

(9) For each future scenario, use generalized extreme value distribution to generate appropriately randomized values of disruption parameters over the time period of the assessment. The GEV parameters could be time (T) dependent. If the data is available, use time-variable GEV parameters to generate appropriate randomized parameter values for each year. If the data is not available, assume that the GEV parameters are stationary with respect to time. The assumption loses its validity as the time period of assessment increases. Create (r) such simulations, where r is dependent on the computing capacity of the platform where the assessment is being conducted. In applying the approach in this paper, r = 1000, i.e., we ran the simulation 1000 times for each scenario over time period of the assessment.

(10) Identify the threshold for the disruption event occurrence with each resilience strategy (Th_i). The thresholds could be a function of time if the strategy affects the threshold of event occurrence $(Th_i(T))$

(11) Use the thresholds identified in step 9 on the randomized disruption parameter estimates calculated in step 8, to estimate the occurrence of the disruptive event over the time period of the assessment, for r simulations. This will create a matrix with dimensions (LC X r), where for each simulation of a time frame of LC years, the event occurrence (OC) value will be 0 or 1, based on whether the corresponding parameter value is smaller or larger than the threshold.

(12) Calculate the expected value of resilience loss for each strategy under each scenario by the following formula:

$$ERL_{ik}(T) = \frac{1}{r} \times \sum_{Sm=1}^{r} OC_{i,Sm,k} \times RL_i(T) \times f(T)$$

Where $ERL_{ik}(T)$ is the expected value of the resilience loss under scenario k, with strategy i in place, for the year T.

$OC_{i,Sm,k}$ = {0,1}, based on the value of the disruption parameter generated by the GEV estimates of the kth scenario and threshold Th_i, for the Sm^{th} simulation. If the value of the parameter for the Sm^{th} simulation obtained in step 10 is greater than Thi, $OC_{i,Sm,k}$ is 1, or else it is 0.

(13) Calculate the Net Present Value of the expected resilience loss (for strategy i, under scenario k) across the time period of the assessment, using the following formula:

$$E(RL_{ik}) = NPV[ERL_{ik}(T)]|_{T=1}^{T=LC}$$

(14) If a probability distribution of future occurrence of the different scenarios under consideration is available, the overall expected resilience loss under each strategy can be calculated using the following formula:

$$E(RL_i) = \sum_{k=1}^{q} P_k \times E(RL_{ik})$$

Where, P_k is the probability of occurrence associated with each future scenario. If a distribution is not available, the overall expected resilience loss can be calculated by considering each future scenario equally likely – akin to applying a uniform distribution.

The $E(RL_i)$ for each strategy can be compared with the do-nothing case (baseline), and with the other strategies to determine which one causes the lowest resilience loss to the system, and is therefore the best alternative under the considered uncertainties..

5.6 MRT Approach Demonstration – Case Studies

The MRT approach presented in this paper is applied to three different case studies to demonstrate multiple application possibilities of the assessment methodology. Different resilience strategies that support adaptation in each of the three ways presented in figure 5-4 are evaluated with the three case studies. The case study subjects capture the different scales of infrastructure systems, with a case study each on a city scale, a transit network scale, and on the scale of a single physical asset (a bridge). The maturity of the adaptive resilience strategies for each of the case studies also varies. For the first case study, the strategy under assessment has already been applied, and adaptive learning from the first applications has been formally identified. A plan has been established for the second case study, but the resilience strategy has not yet been put to the test. In the last case study, the assessment approach is being used to assess multiple possible resilience strategies in order to identify the best approach to plan for in an exploratory setting. With these differences in maturity in the case studies, a good range of possible applications of the MRT assessment approach can be demonstrated.

The first case study focuses on the City of New Orleans and its response to hurricanes that require the city's evacuation, and the City Assisted Evacuation Plan (CAEP) is the resilience strategy under assessment. The second case study examines the New Jersey Transit Network, where the resilience strategy under assessment is the TransitGrid project, focused on strengthening the resilience of the power distribution of the transit network under future hurricane risks. The third case study focuses on the Tex-Wash Bridge in California, where bridge collapse due to flooding is studied as the disruptive event. The potential adaptive resilience strategies to be compared in this case study are derived from the literature expanding the CalAdapt project conducted by Caltrans, which provides recommendations on different flood management practices for roadway infrastructure such as bridges. In terms of maturity of the adaptive resilience strategies, CAEP in the first case study has been applied once during hurricane Gustav, and further improvements from the lessons learned from the first application have been put into formal documentation for future application. The TransitGrid project in the second case study emerged as a part of the resilience efforts in New Jersey post Sandy. The project has been funded, and the implementation is in progress as of 2021, but the application of the system during a hurricane is not yet tested. In the last case study, the maturity of the resilience strategies application is the most nascent, where multiple possible strategies are being assessed for a comparative analysis that can be used to select the best strategy to be planned and implemented in the future.

5.6.1 New Orleans Hurricane Evacuation – City Assisted Evacuation Plan

In August 2005, Hurricane Katrina, which was a category five hurricane at its peak, made landfall in Louisiana as a category three hurricane and had catastrophic impacts, including over 1000 fatalities in Louisiana alone. Safe evacuation was a challenge to the city officials. While Louisiana evacuated almost 1.5 million people before Katrina made landfall, almost 150,000 people did not or could not evacuate (Zimmermann 2015). Many of those who did not evacuate, did so due to lack of resources. The plans made during the event's unfolding to evacuate those without personal vehicles were cancelled due to roads being clogged by those self-evacuating. Lack of foresight in planning for the vulnerable populations caused many to die. In the City of New Orleans, almost 30% of the population does not own a car, and more than 25% of the population lives below the poverty line (Wade 2017). With the lessons learned from Katrina, the City of New Orleans developed an improved emergency management plan, which includes a formal evacuation plan - City Assisted Evacuation Plan (CAEP), for those who cannot evacuate by themselves (Kiefer et al. 2009).

The plan was applied during Hurricane Gustav in 2008, where approximately 18,000 people were evacuated using CAEP. While mostly considered successful, gaps were identified in its application, and further assessments and studies were conducted to improve the plan for a better future implementation (Kiefer et al. 2009; Schrilla 2019). The development, implementation, and reflective learning in the planning of CAEP is reflective of adaptive resilience being practiced by the city. The use of diverse stakeholders such as NGOs, federal and state government, private agencies, under the guidance of the Office of Homeland Security and Emergency Management, and formalized reflective learning demonstrated after the first application present some of the critical attributes of adaptive resilience from the city.

5.6.1.1 MRT Approach Assessment

This case study evaluates the resilience benefits of the implementation of CAEP in the City of New Orleans. The infrastructure system under consideration is the City of New Orleans, which comprises the users, public transit infrastructure, the shelter infrastructure, among the other elements of the city affected, or being utilized for a system-level response to disruptions. The disruption considered in the study is a hurricane category three and above - a disruption that would demand a mandatory evacuation by the city. A 50-year time period is considered for assessment (LC=50). The assessment will compare the following four cases of resilience strategies (RS_i):

(1) If CAEP did not exist (RS_0)

(2) If CAEP is applied during future evacuations just as it was applied during hurricane Gustav (no future improvements)(RS_1)

(3) If CAEP is applied during future evacuations with the improvements identified from Hurricane Gustav Lessons (assuming complete application of the lessons learned from Gustav) (RS_2) (Kiefer et al. 2009; Schrilla 2019)

(4) If CAEP is applied with continuous improvements identified and implemented every ten years (assuming reflective learning and improvements will continue on a formal basis) (RS_3 - RS_n)

The first case can be used to assess the relative benefits of cases 2-4. The 3rd and 4th cases are forward-looking cases, which can be used to estimate the future benefits of investing in improving the program. Such information could be helpful for decision makers for project prioritization.

The resilience triangle for each case is estimated using historical data and future assumptions based on literature review and expert input. Given that CAEP is developed to provide better evacuation response for those who cannot evacuate by themselves, the context-specific performance measure to assess the resilience benefits provided by the program needs to reflect the same. The context-specific assessment metric here is a multi-criteria metric to assess the availability of essential services – ESAI (Essential Services Availability Index). ESAI can be considered an equivalent metric of quality of life, but for disaster evacuees (Puskorius 2015).

ESAI for any fraction of the population would be a factor of the satisfaction level of that population with the essential services availability. During an evacuation process, people can be categorized to be in one of the four situations: 1) self-evacuate to friends/family/hotel, 2) use CAEP for evacuation, 3) do not evacuate. Based on previous information about shelters, the 2nd situation can be sub-categorized into two situations: 2(a) - CAEP with sufficient capacity, 2(b) - CAEP with reduced capacity. This categorization is based on the fact that for Hurricane Gustav, the CAEP shelters and transport facilities ran out of capacity mid-way during the evacuation effort (Brodie et al. 2006; Fetters 2018). This will change the availability of essential services to those using CAEP.

The value of ESAI for any given day during the event time frame could be calculated using the following formula.

$$Q(t) = ESAI_t = \sum_{j=1}^{m} (P_j \times S_j)_t$$

- where,
  - t = time (in days) Time ranging from t_0-t_1, where t_0 is the time (days) before the evacuation order is put in place, and t_1 is the time by which recovery of the event is complete
  - P_{ji} = percentage population in the j_{th} availability situations
  - S_j = satisfaction factor (weighting factor) of the essential services availability in the j_{th} scenario.

- m = maximum number of different types of possible essential service availability situations (here, m = 5: 1- all services met (normal state), 2- shelter at friends/family, 3- shelter with CAEP with full capacity, 4- shelter with CAEP with reduced capacity, 5-stuck in the hurricane with no services)

Jordan (2015) provides a hierarchy of needs of disaster survivors, which can be used as the essential services needed for the evacuees. The weights associated with each need are assumed to follow a centroid weight distribution, with the highest weight given to the lower order needs of food, water, and shelter and subsequently lower weights to the higher-order needs in the hierarchy. The weight distribution and the essential needs being used for assessment were validated via expert interviews of those involved in Hurricane Katrina and Hurricane Gustav's evacuation efforts. The interviews were also used to identify which of these essential needs were fulfilled in each of the four situations. The percentage of population in each situation was estimated based on Hurricane Katrina and Hurricane Gustav's data.

Calculation of the resilience loss in each case (RLi) uses the data from Hurricane Gustav and Katrina’s evacuation efforts to estimate the percentage of the target population in each situation for each case. As per Hurricane Gustav CAEP's use survey (Kiefer et al. 2009), about 40% of those who registered for CAEP used other means to evacuate, about 42% of those registered used CAEP, and about 18% did not evacuate. The target population is the population that cannot evacuate by themselves and would need CAEP or other support to evacuate. In the case of RS0, which is the case without CAEP, it is assumed that a total of 60% of the target population did not evacuate. This could be assumed as those who could have used CAEP and could not find any other way to evacuate (42%) will not be able to evacuate, along with those who choose not to leave (18%). In the case of RS1, the original data from CAEP's application is used. In the case of RS2, RS3, and RSn, it is assumed that the improvements are in the satisfaction factor of the essential services provided by CAEP, and efforts to spread awareness of the program to nudge the 18% people who would otherwise choose not to evacuate. RSn is estimated assuming the best case of application of CAEP, in which the shelters are at the same satisfaction level as evacuation to friends/family, and all of the 18% population is successfully nudged to use the program to evacuate. RSn is used to calculate the linear trend of improvements over time in the CAEP program until the best possible application is achieved, in order to explore the potential benefits of the fourth case of continuous improvement in the program.

Due to climate change, the future occurrence of hurricanes cannot be predicted with a reasonable level of confidence. Sea Level Rise has a direct correlation with the frequency and intensity of hurricanes (Marsooli et al. 2019, Wdowinski et al. 2016). Hence three future SLR scenarios are considered for assessment. The probability estimates of the three scenarios are based on Intergovernmental Panel on Climate Change(IPCC) estimates (Field et al. 2014). For each SLR scenario, a Generalized Extreme Value function for hurricane wind speed is used to generate 1000 simulations for maximum wind speed over the time period of assessment. The GEV parameters based on historical data are obtained from the existing literature, and change in parameters under different SLR scenarios is estimated from the change in return periods of events for each SLR as identified by IPCC and other literature (IPCC 2019; Keim et al. 2007). The wind speed threshold for hurricane category 3+ is obtained from the Saffir-Simpson Hurricane Wind Scale (NOAA n.d.).

Table 5-2 summarizes all the data inputs for the MRT assessment and Table 5-3 provides the GEV parameters for the different SLR scenarios.

Table 5-2: MRT Assessment Steps- Input

1	Resilience Strategy(i)	CAEP | (RS_0 …..RS_n)
2	Context-specific performance measure (Q)	Essential Services Availability Index (ESAI)
3	Time period of assessment	50 years
4	RL(i) calculation	[See the results section]
5	RL(i,T)	RL_4 as a function of time – linear improvement every 10 years from RL_1 to RL_n over the LC
6	f(T)	Population (future projections based on census data)
7	Scenarios (k)	K={1,2,3} : SLR – Low, SLR– low-intermediate, SLR–Intermediate-High (based on IPCC)
8	Disruption Parameter	Hurricane Wind Speed
9	GEV parameters	[See table 5-3]
10	Disruption threshold	96 knots (Hurricane category 3 wind speed)
11-14	Results Calculation	[See the results section]

Table 5-3: GEV parameters for the different SLR scenarios

	GEV parameters		
Scenario	Location (μ)	Scale (σ)	Shape (ξ)
BaseLine- Low SLR	64	36	-0.37
Low-Int SLR	66.47	36	-0.37
Int-High SLR	69.09	36	-0.37

5.6.1.2 Results

Figure 5-5 presents the resilience triangles for the four different cases of the resilience strategy application. The red area indicates the resilience loss during the time of the disruption event. The x-axis ranges from 1 to 113, based on Hurricane Katrina's duration of evacuation and recovery. It is evident the with better application of CAEP, the resilience triangle is reducing, indicating the benefits of the resilience strategy.

The point values of resilience loss (ESAI units) are used along with disruption uncertainty to estimate the resilience loss over the time period of the assessment. If an event occurs in a given year, for each case, the total area under the resilience triangle, multiplied by the total target population for that year is considered the resilience loss for that year. Expected resilience loss over the 1000 simulations is presented for the time period of the system for each scenario in figure 5-6(a-c). The y-axis is the resilience loss area for the given case for the year, multiplied by the overall target population (Population Resilience Loss). The figures show the resilience loss for the RS0- no CAEP case, RS1- Current CAEP application, and RS2-n- CAEP application with continuous improvement. The figure indicates that without CAEP, with increasing population, the resilience loss is increasing over time. While for the initial years in the life cycle, RL1 and RL2-n show similar results, with continuous improvements, the overall resilience loss of the RL2-n is decreasing over time. The expected value of the resilience loss over the assessment's time period is presented in figure 5-7, along with an overall expected resilience loss estimate based on probabilities associated with each SLR scenario. The figure indicates a lower resilience loss with CAEP in application compared to the case without it, and further reduction in resilience loss with continuous improvements in the system. While the results are intuitive, the assessment provides quantitative values to compare the benefits of implementing any given resilience strategy.

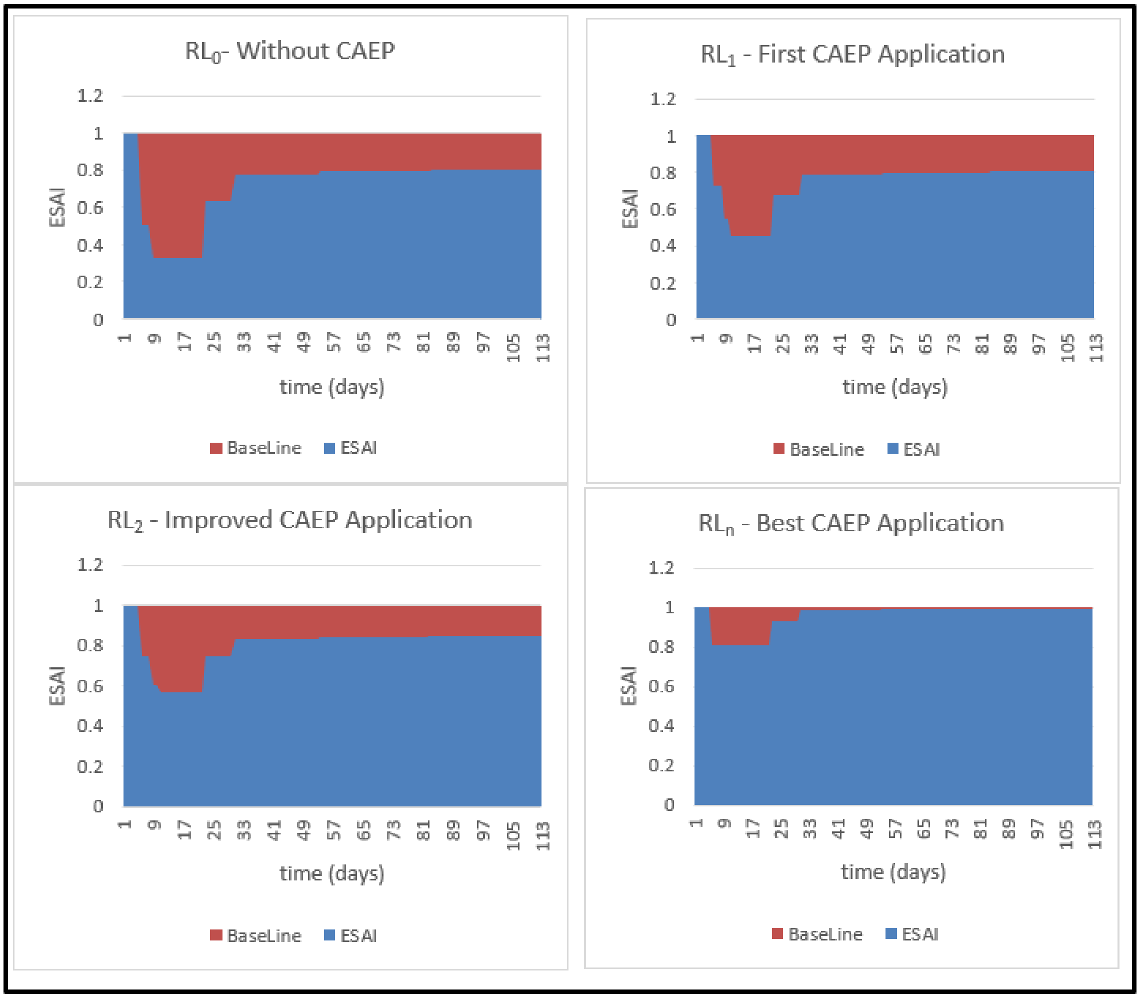

Figure 5-5: Resilience Triangle for different RL cases- CAEP

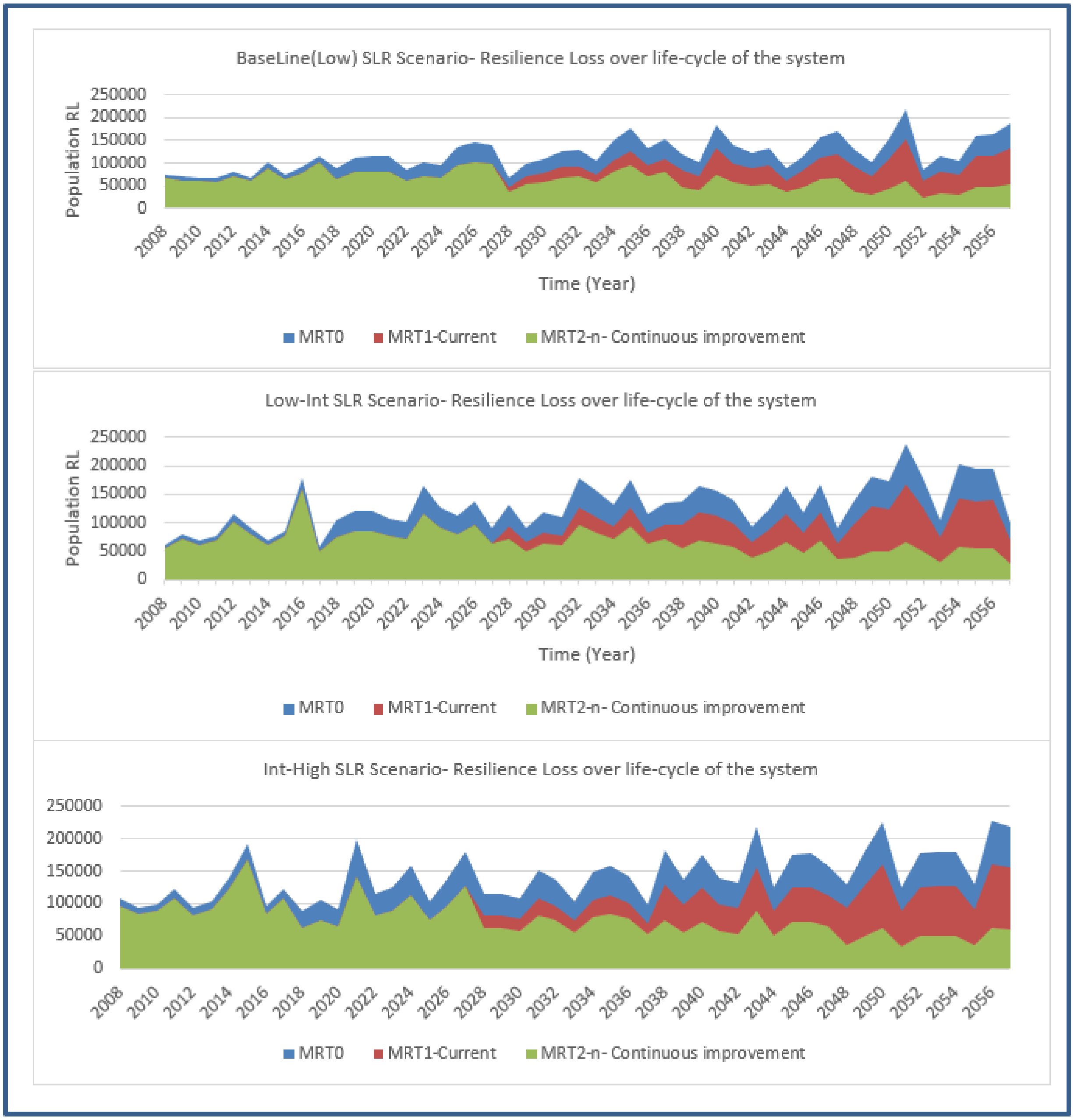

Figure 5-6: Expected Resilience loss for each year in the life-cycle of the system for each SLR scenario – CAEP

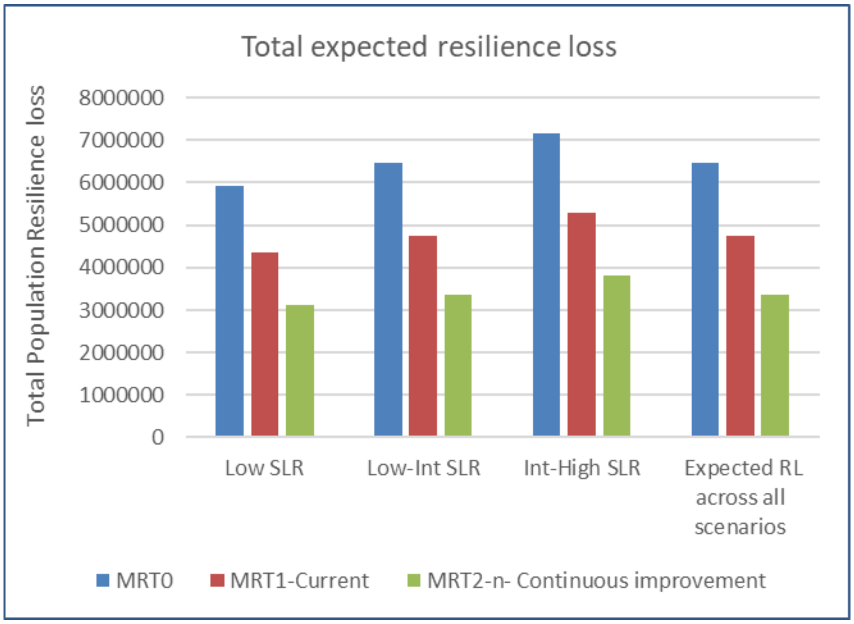

Figure 5-7: Total expected resilience loss over the life-cycle of the assessment for each SLR scenario, and the Expected RL across all scenarios

5.6.2 NJ Transit Power Outage – NJ Transitgrid

Hurricane Sandy in 2012 exposed the vulnerabilities of the transit systems in New York and New Jersey. The centralized power system breakdown during Sandy significantly disrupted the NJ Transit functioning (Comes and Van de Walle 2014). NJ Transitgrid project is developed to build resilience against this identified vulnerability of the NJ Transit System. Transitgrid is one of the many projects being developed as part of the Resilience Program by NJ Transit, which came into action after Hurricane Sandy ("NJ TRANSITGRID" n.d.). Under the Transitgrid project, NJ Transit plans to construct an electrical microgrid system capable of supplying power to some key parts of the network during future storms, which could cause the centralized power system to fail. Transitgrid project promotes adaptive resilience by building in modularity and redundancy in the system, as it provides multiple sources of power to the network, thereby increasing its chances of sustaining network functionality when one of the power sources fails. The project is funded by a grant awarded by Federal Transit Administration (FTA) through its emergency relief program in response to Superstorm Sandy ("NJ TRANSITGRID" n.d.). The project has not yet been implemented and tested with any disruption. Hence the estimates of its functionality in case of disruption are assessed by applying the project on hurricane Sandy's timeline and assuming that the system will function as planned. The assessment could be improved in the future as the project is put to real test by a disruption, and the model can be calibrated based on observed data.

5.6.2.1 MRT Approach Assessment

This section evaluates the benefits of implementing Transitgrid in improving the resilience of the NJ Transit network. The infrastructure system under consideration is the NJ Transit network of rail lines. The disruption considered in the study is a hurricane category 3 (Sandy made landfall as a category three hurricane in NJ). A 50-year time period is considered for assessment (LC=50). The assessment compares three cases of resilience strategies (RS_i):

1. If Transitgrid is not put in place (RS_0)
2. If Transitgrid is applied during future disruptions as per the current plans (RS_1)

3. If Transitgrid is applied during future disruptions with an increase in its network coverage after ten years (potential project expansion) (RS_2)

As the project has not yet been implemented, unlike CAEP, where the first implementation and lessons have already been established, the improvements for Transitgrid are only projected one step ahead – with an assessment of the impacts of a possible expansion at year 10.

The context-specific performance metric here is a score of transit network functionality, which is a score accounting for the power redundancy of the system. The following formula can represent the Transit Functionality Score:

$$TFS = \sum_{i=0}^{i=n} i \times P(RM_i)$$

- n= maximum number of power sources available to a given mile of transit (in this case, i={0,1,2} – max two sources of power)
- $P(RM_i)$= Percentage of rail miles with i number of power sources
- Without TransitGrid, all of the rail miles are served with only one power source in normal conditions (centralized power system), i.e., i={0,1}
- With TransitGrid (as of current plans), a small selected percentage of rail miles have access to two power sources during regular times, and when the centralized power is cut off, the percentage of rail miles has one source of power (TransitGrid)

- Enhancements on TransitGrid plans could expand on the coverage of the program for a higher percentage of rail miles

Table 5-4 presents the key inputs on the MRT assessment steps.

Table 5-4: MRT Assessment Steps: Data inputs for Transitgrid

1	Resilience Strategy(i)	TransitGrid | (RS_0, RS_1, RS_2)
2	Context-specific performance measure (Q)	Transit Functionality Score (TFI)
3	Time period of assessment	50 years
4	RL(i) calculation	[see the results section]
5	RL(i,T)	RL_2 as a function of time – first potential improvement at year 10, constant thereafter
6	f(T)	Rail miles (expansion of rail miles over time- NJ Transit data)
7	Scenarios (k)	K={1,2,3} : SLR – Low, SLR– low-intermediate, SLR– Intermediate-High (based on IPCC)
8	Disruption Parameter	Hurricane Wind Speed
9	GEV parameters	[see table 5-5]
10	Disruption threshold	96 knots (Hurricane category 3 wind speed)
11-13	Results Calculation	[see the results section]

Table 5-5: GEV parameters for NJ hurricane wind speeds

	GEV parameters		
Scenario	Location (μ)	Scale (σ)	Shape (ξ)
BaseLine- Low SLR	77.2	10.6	-0.0544
Low-Int SLR	79.49	10.6	-0.0544
Int-High SLR	83.25	10.6	-0.0544

5.6.2.2 Results

Figure 5-8 presents the resilience triangles for the three cases of the resilience strategy application. The red area indicates the resilience loss during the time of the event. The x-axis ranges from 1 to 73, based on Superstorm Sandy's transit network disruption and recovery duration. It is evident the with better application of Transitgrid, the resilience triangle is reducing, indicating the benefits of the resilience strategy. The RL1 and RL2 triangles also indicate an immediate improvement in the level of TFI, indicating building back better. A value higher than one corresponds to the fraction of the network with more than one power source in normal conditions.

The point values of resilience loss are used along with disruption uncertainty to estimate the resilience loss over the time period of the assessment. If an event occurs in a given year, for each case, the total area of the resilience triangle is considered the resilience loss for that year.

Expected resilience loss over the 1000 simulations is presented for the time period of the assessment for each scenario in figure 5-9. The y-axis is the resilience loss value, multiplied by the total rail miles of the network for the given year for the given case (miles of network with reduced functionality score). The figures show the resilience loss for the RS0- no Transitgrid case, RS1- Current planned Transitgrid application, and RS2- Potential expansion of Transitgrid by 10% at year 10. The expected value of the resilience loss over the assessment's time period is presented in figure 5-10, along with an overall expected resilience loss estimate based on probabilities associated with each SLR scenario. The figure indicates a lower resilience loss with Transitgrid in application compared to the case without it, and further reduction in resilience loss with improvement in the project. These results are consistent with the CAEP case study, only differing in the lack of a continuous improvement case, with respect to which the CAEP case study is currently at a higher maturity level.

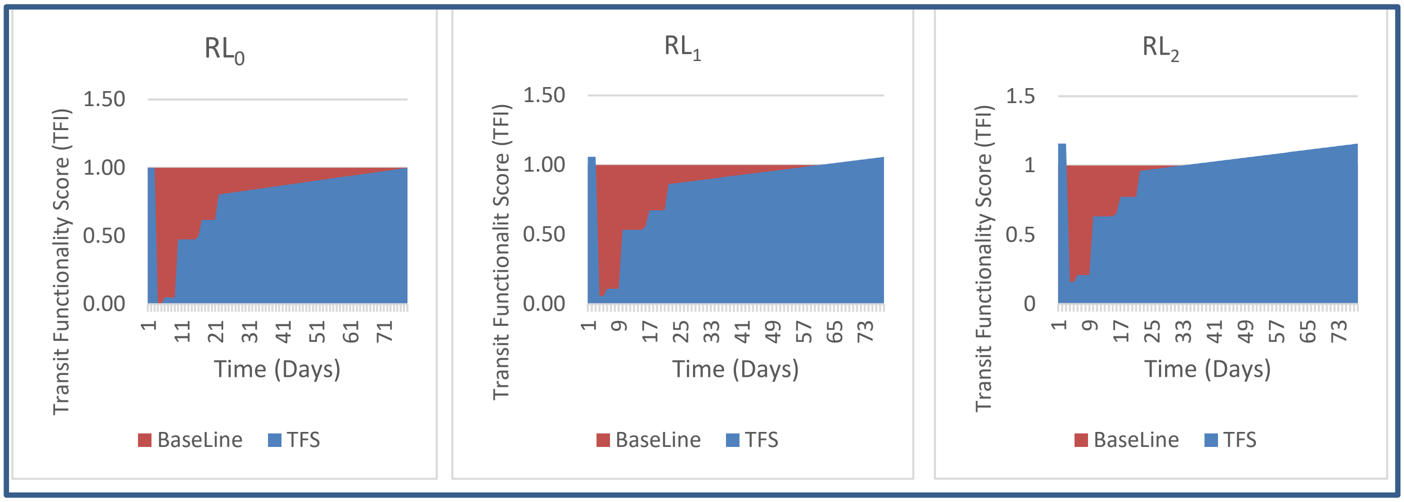

Figure 5-8: Resilience loss for different cases of Transitgrid application

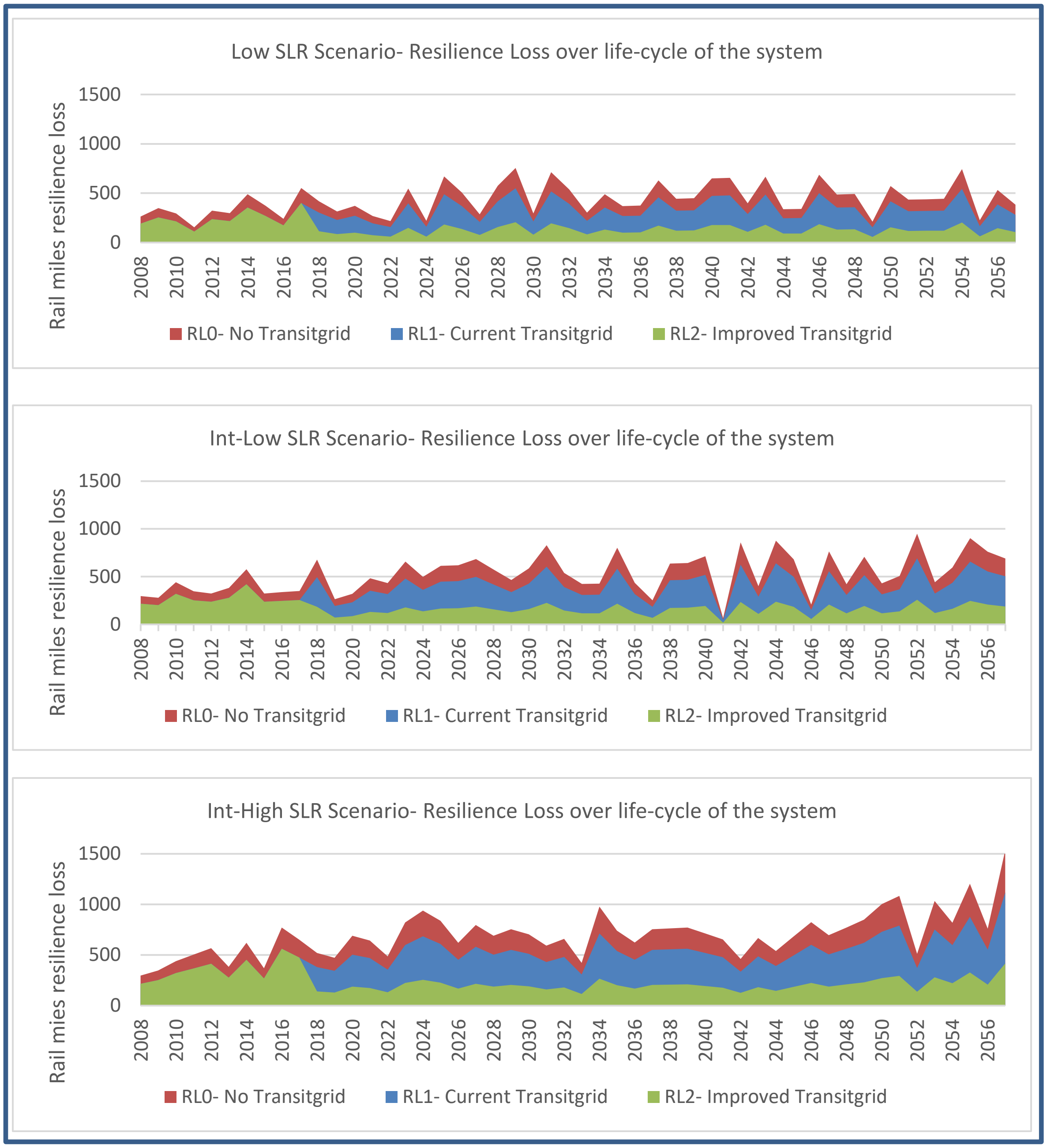

Figure 5-9: Expected Resilience loss for each year in the life-cycle of the system for each SLR scenario -Transitgrid

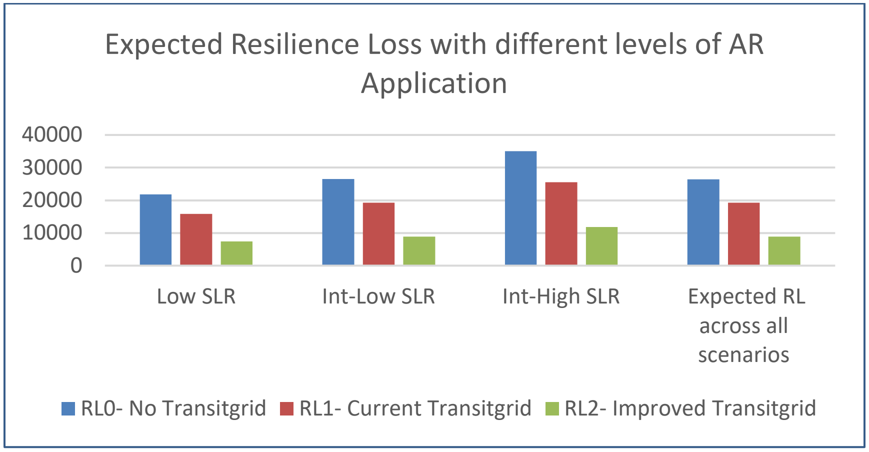

Figure 5-8: Total expected resilience loss over the timeframe of the assessment for each SLR scenario, and the Expected RL across all scenarios - Transitgrid

5.6.3 Tex-Wash Bridge Closure, California –DAP

On July 19th, 2015, extreme precipitation of over 6 inches in a day caused flash flooding in Riverside County in California, which caused the Tex-Wash Bridge to collapse. The bridge was rebuilt back to previous design standards with almost an $8 million rebuild cost (Tabbakhha et al. 2016). With uncertainty in future precipitation projections and increasing frequency and intensity of extreme events, building back to the previous design standards might not be the optimal decision in the long term. In this case study, we compare different possible resilience strategies that can enhance the bridge's resilience against such events in the future. While currently no such plan exists for this specific bridge, the data of the disruption impact can be used for a demonstrative example for bridge flood management, or any asset-specific resilience effort for transportation agencies.

This assessment compares static plans of transportation flood management with a Dynamic Adaptive Plan for the same. With increasing uncertainty associated with climate change, dynamic adaptive plans are more aligned with the adaptive resilience approach, allowing for flexibility in future actions, and preventing roadblocks while reducing significant upfront investments. Under the 2010-2011 FHWA Climate Change Vulnerability Assessment Pilot program, the metropolitan planning organization (MPO) of San Fransisco conducted a study – Adapting to Rising Tides (ART) (Kline et al. 2011). The study assessed the impacts of SLR and coastal flooding, and provided recommendations on possible actions based on mid-century and end-century predictions of future disruptions. Wall et al. (2015) built on the study and demonstrated a Dynamic Adaptive Plan (DAP) building on the actions identified in the ART study. Singh et al. (2020) conducted a quantitative assessment of the DAP approach vs. the two static approaches to capture the value of flexibility in transportation resilience planning. In this paper, we use the approaches presented by Wall et al. (2015) and Singh et al. (2020) to generate static mid and end-century plans, and a dynamic adaptive plan for the bridge under consideration, and compare their resilience benefits over the time period of the assessment. Using a DAP approach reflects the agency's capabilities in roadmapping, and the successful implementation of DAP is only possible with an organic finance structure in the system to allow for planning for flexibility in investment in the future. These capabilities reflect adaptive resilience maturity of an agency.

5.6.3.1 MRT Approach Assessment

This section compares the benefits of implementing different resilience strategies in improving the resilience of a bridge. The infrastructure system under consideration is the Tex-Wash Bridge. The disruption considered in the study is a bridge collapse event which could occur at different extreme precipitation levels based on the flood protection level of the bridge. A 90-year time period is considered for assessment (LC=90) based on future projection data availability. The assessment compares the following four cases of resilience strategies (RS_i):

(1) The bridge is built back to previous standards (current state) (RS_0)

(2) Improvements are made based on current mid-century projections from a selected projection model (RS_1)

(3) Improvements are made based on current end-century projections from a selected projection model (RS_2)

(4) Dynamic improvements are made over the time period of the assessment based on emerging data over time (DAP) (RS_3)

The context-specific performance metric here is the economic benefit provided by the bridge (EBB), which is lost when the bridge is closed:

$$EBB(\$) = C_{pv} \times AADT + \ C_T \times AADTT$$

- $\mathrm{C_{pv}}$= Detour cost of passenger vehicles
- $\mathrm{C_T}$ = Detour cost of trucks

Any of the four adaptation options do not reduce the EBB loss of the bridge collapses, but reduce the occurrence of the collapse event by improving the threshold– RT stays the same for any future disruption, but the frequency of disruption is to be reduced (Figure 5-4(c))

Disruption uncertainty is modeled based on projected future precipitation data developed by Cal-Adapt (Cal-Adapt 2021), whose database of downscaled climate change projections was developed by the Geospatial Innovation Facility at the University of California. The future projections are based on different projection models. Two of these models are considered here for assessment as the two possible scenarios with level 3 uncertainty (lack of confidence in which model will unfold in the future). These models, modelling potential future scenarios, emerged from California's Fourth Climate Change Assessment, 2018 (CA.gov 2018). The two models considered for this assessment cover the two opposite future scenarios, with a cool/wet future presented by the CNRM-CM5 model and the warm/dry future presented by the HadGEM2-ES model (Pierce et al. 2018). To calculate the total resilience across both scenarios, each scenario is considered equally likely. The future projected data is used to calculate the GEV parameters and is also used to calculate the change in GEV parameters over time. This provides a better reflection of climate change over time in accounting for future uncertainty in the assessment. Table 5-6 presents the key inputs on the MRT assessment steps.

Table 5-6:MRT Assessment inputs: Tex-Wash Bridge

1	Resilience Strategy(i)	Bridge Flood Management | (RS_0, RS_1, RS_2, RS_3, RS_4)
2	Context-specific performance measure (Q)	Economic benefit of the bridge ($)
3	Time period of assessment	90 years
4	RL(i) calculation	[See the results section] All RL(i) have the same value

5	RL(i,T)	-
6	f(T)	Time value of money – discount rate of 5%
7	Scenarios (k)	K={1,2} : Two future projection models – CNRM-C5 (Cooler/Wetter), and HadGEM2-ES(Warm/Drier)
8	Disruption Parameter	Max daily precipitation
9	GEV parameters	Calculated using projection models
10	Disruption threshold	Variable with each strategy [see table 7]
11-13	Results Calculation	[See the results section]

The disruption threshold varies based on the resilience strategy implemented:

(1) RS0: Build back to previous standards- the threshold would be the same value at which the bridge collapsed – 6 inches of rainfall in a day

(2) RS1: Mid-century static plan - the threshold would be the mid-century estimate of 100-yr return level precipitation estimated by each model at the start of the assessment timeline.

(3) RS2: End-century static plan - the mid-century estimate of 100-yr return level precipitation estimated by each model at the start of the assessment timeline.

(4) RS3: Dynamic adaptive plan – the threshold is based on triggers identified from the near-term future projection of a 100-yr return level. Every year, the 100-yr return level is

calculated 20 years in the future, and if the value goes beyond the identified trigger, a corresponding adaptation action is applied, thereby increasing the threshold by a set amount.

Table 5-7 presents the details of the variable thresholds used in the DAP process. Table 5-8 presents the thresholds for the three static plans for each scenario.

Table 5-7: DAP triggers and improved thresholds

Trigger	Action	Improved threshold
Trigger 0: 100-yr return level projected 20 years from time (T) is less than 6 inches	No action	6 inches
Trigger 1: 100-yr return level projected 20 years from time (T) is between 6-8 inches	Deck rehab (raising/strengthening)	8 inches
Trigger 2: 100-yr return level projected 20 years from time (T) is between 8-10 inches	Deck replacement	10 inches
Trigger 3: 100-yr return level projected 20 years from time (T) is between 10-12 inches	Deck replacement+ superstructure & substructure rehab	12 inches
Trigger 4: 100-yr return level projected 20 years from time (T) is greater than 12 inches	bridge replacement	14 inches

Table 5-8: Thresholds for static resilience strategies

Resilience Strategy	CNRM-CM5 Model	HadGEM2-ES Model
RS0 (Build back same)	6 inches	6 inches
RS1(mid-century plan)	8.23 inches	7.09 inches
RS2(end-century plan)	10.25 inches	8.37 inches

5.6.3.2 Results

Figure 5-11 presents the resilience triangle for the case of bridge collapse based on the 2015 event details. The red area indicates the resilience loss during the time of the event, calculated in terms of economic loss of passenger and freight traffic due to detours. The x-axis is a timeline of the event, from July 2015, when the bridge closed, to Sep 2015, when the bridge came back to full functionality. As the resilience strategies under assessment do not change future resilience triangles, but change their frequency of occurrence, only one resilience triangle is needed for the assessment.

Expected resilience loss over the 1000 simulations is presented for the time period of the assessment for each scenario in figure 5-12. The y-axis is the resilience loss value for the given year for the given resilience strategy. The figures indicate reduced resilience loss with each of the resilience strategies compared to the strategy of building back to the same level. It can also be observed that the end-century static plan has smaller resilience loss compared to the mid-century plan, which makes sense as with the increasing frequency of the disruptions as presented by the models, the threshold for the static mid-century plan will not be sufficient over the assessment’s time period. Comparing the end-century static plan with the DAP, the results indicate that the DAP has higher resilience loss for earlier years in the time period than the end-century static plan, which can be understood as DAP gradually increases the system’s threshold to disruption, but the end-century plan starts with a higher threshold. This allows the end-century plan to reduce the potential resilience loss under rare extreme events beyond the estimated DAP thresholds. However, as we move forward in the time period, the resilience loss of the static end-century plan is increasing as the return level is continuously increasing over the time period of the assessment due to climate change. However, the static plan's threshold is based on previous static information, while the DAP continues to improve its thresholds using the updated information. The expected value of the resilience loss over the system's life cycle is presented in figure 5-13, along with an overall expected resilience loss estimate based on equal probabilities associated with each climate model scenario. The figure also indicates the smallest resilience loss over the assessment’s time period under the DAP resilience strategy. Using this information, along with the fact that upfront capital investment for the 2nd best strategy (the end-century static plan) will be much higher than that of DAP, it makes more of a business case to use a flexible, evolving strategy that has overall higher benefits, and smaller upfront investment cost.

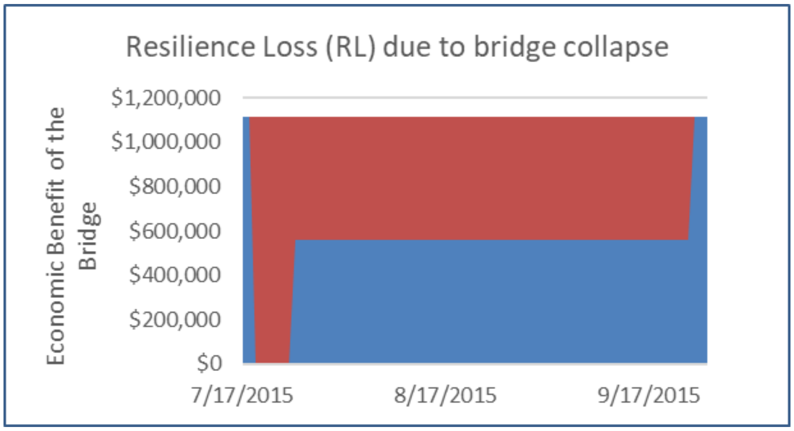

Figure 5-11: Resilience loss triangle for bridge closure \ Tex-Wash Bridge

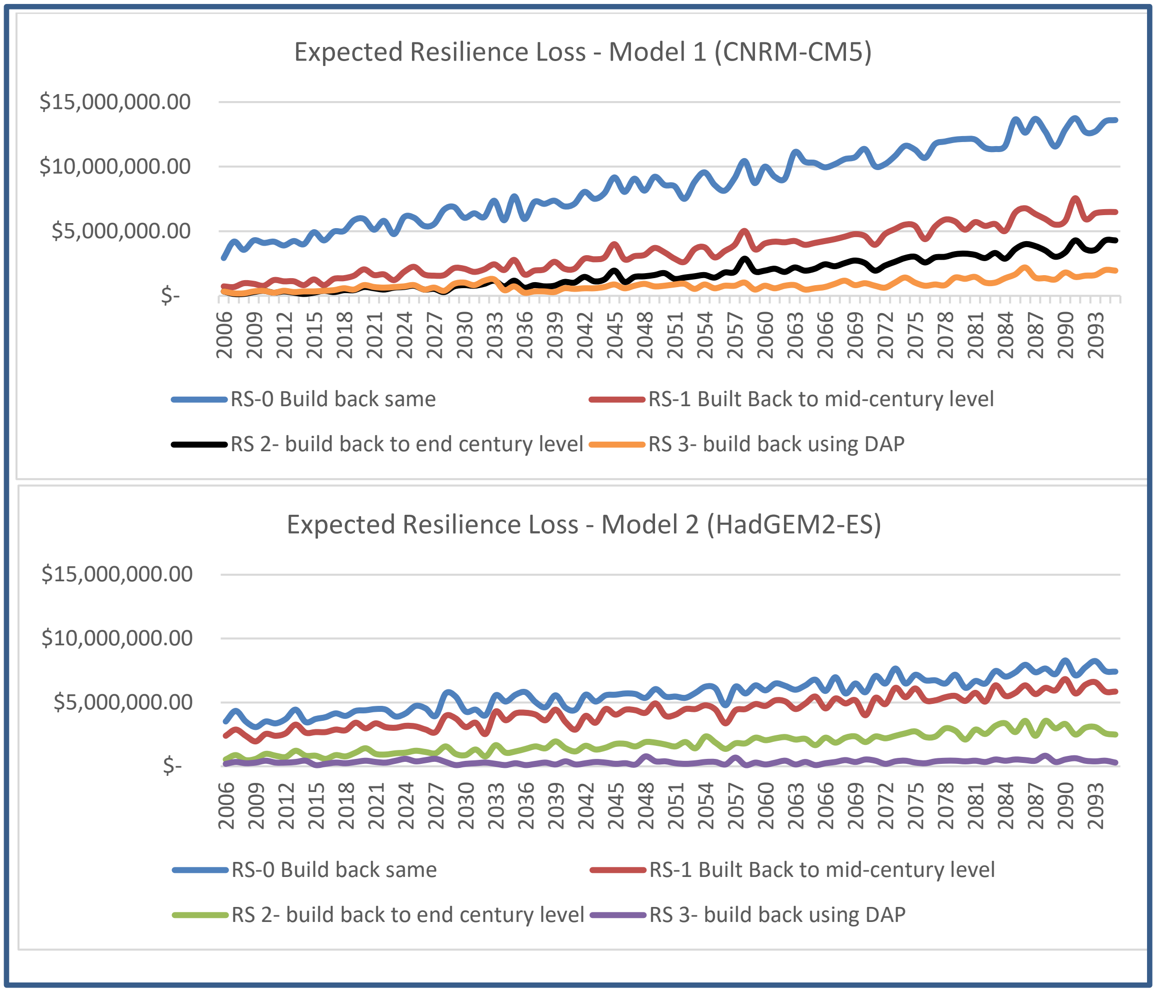

Figure 5-12: Expected Resilience loss for each year in the assessment timeframe for each SLR scenario -Tex Wash Bridge

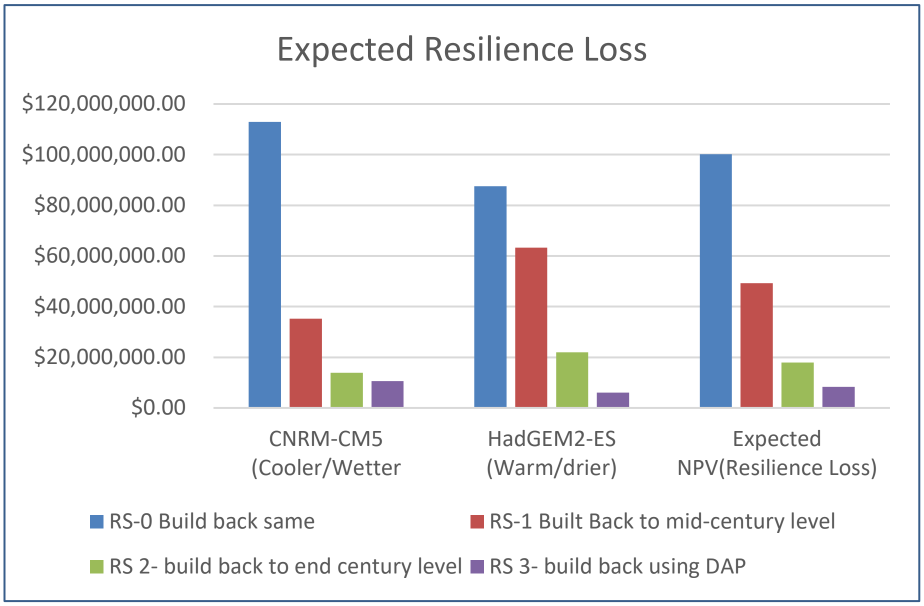

Figure 5-13: Total expected resilience loss over the life-cycle of the assessment for each SLR scenario, and the Expected RL across all scenarios – Tex Wash Bridge

5.6.4 Overall Results

Results across all the three case studies indicate significant benefits (or reduced resilience loss) of adaptive resilience strategies as compared to the baseline (do-nothing or build back without adaptation). Further, continuous improvements in the adaptive strategies reflect increasing benefits over time, which makes a case for investing in plans and procedures established for reflective learning through one or more lifecycles of the system. Table 5-9 presents the relative reduction in the expected resilience loss for each case study across all considered scenarios. It indicates that a one-time implementation of AR strategy resulted in an approximately 27% reduction in loss for both the CAEP and TransitGrid case studies with an even higher resilience loss reduction (48% and 66% respectively) under the case where the AR strategies were improved over time. For the Tex-Wash Bridge case study, the AR strategy of DAP presents a 92% expected reduction in loss compared to build-back to the same level scenario.

These results demonstrate significantly long-term benefits of adaptive resilience strategies, continuous reflective learning, and flexible long-term planning, thereby presenting a strong business case for investment in such adaptive resilience strategies.

Table 5-9: Percentage reduction in expected resilience loss with different AR strategies across all considered scenarios

CAEP		TransitGrid		Tex-Wash Bridge DAP	
-	-	-	-	RL1- Built Back to mid-century level	**51%**
RL1-Current CAEP	**27%**	RL1-Current TransitGrid	**27%**	RL2- build back to end century level	**82%**
RL2- Continuously Improved CAEP	**48%**	RL2- Improved TransitGrid	**66%**	RL3- build back using DAP	**92%**

5.6.5 Conclusion

Quantification of long-term benefits of adaptive resilience strategies is critical in making a stronger business case for long-term planning that incorporates flexibility and agility as key attributes to augment adaptive resilience. Such quantifications can also support project prioritization for practitioners by providing an objective measure of the performance of the projects, as demonstrated by the third case study. Efforts in long-term planning for system resilience with an intentional efforts towards adaptive resilience is key for a holistic resilient system under future uncertainty. Hence an approach that quantifies the long-term benefits of such adaptive resilience strategies is beneficial for decision makers to use for effective project prioritizations. This paper presents an approach for agencies to assess their investments in building resilient infrastructure systems, over a range of scales of infrastructure and type of resilience strategies. The three case studies demonstrate the range of possible applications of the MRT approach, with results indicating a general trend towards higher benefits with more flexible and adaptive strategies in the long term. The approach presented in the paper can be used by public and private agencies in multiple infrastructure sectors such as transportation, power, water, and communication. A flexible approach to evaluate the long-term benefits of building adaptability as a part of enhancing resilience in the system can serve as a helpful tool for practitioners and policymakers to present a business case for long-term adaptive resilience investments.

5.6.5.1 Limitations and Future Work

Some of the limitations in applying the MRT approach in the case studies came from the availability of data. While for the third case study, quality downscaled future projection data was available, from which we were able to estimate the time-variability of future disruption estimates, lack of similar data for the first two case studies limited our assessment to a smaller timeframe, within which the GEV parameters did not change over time. The confidence in the results of the approach will increase with improved data inputs of future projections. In the first case study, where the resilience strategy is focused on the social infrastructure of the city, quantification of satisfaction of disaster evacuees in the shelters is based on expert input. As the event under consideration occurred over a decade ago, the input from experts might not be very accurate. Better documentation of future applications of CAEP and immediate surveys of evacuees will help validate the inputs used in the case study. Another limitation of the demonstrated application of the approach is in quantifying time value of non-monetary assessment metrics. While for the third case study where the metric was monetary, a discount rate could be used to reflect the time value of the metric, for the other two case studies, it was assumed that the value of the non-monetary metrics does not increase (or decrease) over time. Future work to assemble better records of such non-monetary metrics could help in estimating their discount factors.

Further work on incorporating the MRT approach in the formal asset valuation and asset management plans of infrastructure agencies will support its application in practice. The MRT approach can also be used in combination with other approaches such as real options analysis to value investments under uncertainty in order to increase the flexibility in the dynamic plans instead of associating fixed time frames with improvements as depicted in this paper. Further, incorporating the MRT approach in benefit-cost assessment approaches at infrastructure agencies could enhance the BCA analysis and support better project prioritization efforts.

5.7 References

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CHAPTER 6. **DISCUSSION AND CONCLUSION**

With a growing recognition of the need for resilient infrastructure systems, there is a need to develop a holistic understanding of resilience theory as it pertains to specific infrastructure systems. The existing resilience literature on infrastructure systems inclines heavily towards risk-based planning, which certainly is essential, but not sufficient in the current era due to deep uncertainty associated with the future of infrastructure systems owing to uncertainties associated with factors such as climate change, technical advancements, and social changes such as urbanization and population growth. These uncertainties necessitate the need for resilience approaches to be broadened in their spectrum to not only be able to anticipate future disruptions, but also be able to persist under unanticipated events. The adaptive resilience approach presented in this dissertation aims to facilitate this transition from risk-based resilience to adaptive resilience in infrastructure system, with a particular focus on transportation systems. The research first presents an application of an existing adaptive resilience approach to transportation systems and assesses its benefits over time (Chapter 3), thereby validating the hypothesis that there are long term benefits from adaptive resilience approaches. Having established the benefits of adaptive resilience planning over risk-based planning under uncertainty, the next question was to understand how adaptive resilience can be incorporated in transportation systems. To answer this question, in Chapter 4, the research focuses on development of the theory of adaptive resilience in transportation systems, by identifying the key fundamental capabilities of the transportation system that foster adaptive resilience in the system and developing a capability maturity model for adaptive resilience. The CMM can be used to understand the current standing of any transportation agency with respect to their AR capabilities maturity levels, and identify those capabilities at low levels of maturity. The next step is to answer the question: why should an agency invest in enhancing the maturity of these AR capabilities? To provide a tool that can be used to develop a business case to proactively invest in adaptive resilience, Chapter 5 presents an assessment methodology that quantifies the long-term benefits of adaptive resilience initiatives in any infrastructure system.

6.1 Contributions

6.1.1 Contributions to Theory

The dissertation contributes to the growing field of resilience in infrastructure systems by first identifying the gaps and opportunities in applications of resilience through an extensive literature review. Some of the identified gaps are then filled through theory development in Chapters 4 and 5. The developed methodologies are also being used in the development of tools that can be used by researchers and practitioners alike, bridging the gap between research and practice in the field of resilience. The beta-versions of the developed tools are presented in the Appendix.

With increasing uncertainty in future predictions, the need to focus on system adaptability is critical to making any system resilient to future threats. Flexibility and agility are relatively new concepts in the engineering resilience domain, hence limited guidance exists on how to assess and enhance the adaptive resilience of a system. There is an even bigger gap in the field of transportation. Chapter 4 focuses on bridging that gap by extracting, through literature reviews and expert interviews, the key fundamental principles of a transportation system that can enhance its adaptive resilience. Further, Chapter 5 extends the theory of resilience assessment by enhancing existing assessment approaches to include the long-term impacts of incorporating adaptive resilience in infrastructure systems.

6.1.2 Contributions to Practice

The research also has direct contributions to the practice of transportation systems and general infrastructure systems. The current standard practices on resilience in transportation include condition-based assessments and a focus on direct quantifiable benefits, leading to deterministic and rigid long-term plans. This needs to change given the growing uncertainty surrounding climate, cybersecurity and other hazards and need for adaptive capacity in the systems. The AR-CMM will support agencies to identify their adaptive resilience gaps and strengths. Low maturity can be used as a factor in prioritization of projects that focus on those capabilities. Further, higher maturity capabilities can be used to systematically support improvement in the prioritized low-maturity spaces. The maturity model also provides logical guidance on continuous improvement along each of the capabilities, through guided next steps for moving to next-level maturity.

Quantification of long-term benefits of adaptive resilience strategies is critical in making a stronger business case for long-term planning that incorporates flexibility and agility as key attributes to augment adaptive resilience. Such quantifications can also support project prioritization for practitioners by providing an objective measure of the performance of the projects. Chapter 5 presents an approach for agencies to assess their investments when creating adaptive resilient infrastructure systems, over a range of scales of infrastructure and type of resilience strategies. The three case studies demonstrate a range of possible applications of the MRT approach, with results indicating a general trend towards higher benefits with more flexible and adaptive strategies in the long term under uncertain future conditions. The approach presented in the chapter can be used by public and private agencies in multiple infrastructure sectors such as transportation, power, water, and communication. A flexible approach to evaluate the long-term benefits of building adaptability as a part of enhancing resilience in the system can serve as a helpful tool for practitioners and policymakers to present a business case for long-term adaptive resilience investments.

6.2 Limitations and Future Work

Chapters 3, 4, and 5 discuss the respective limitations and future work in detail. Here, a summary is presented along with some overall limitations and future work directions of the dissertation.

As the research ventured into a space with limited existing literature (specifically the area of adaptive resilience in transportation systems), qualitative approaches were used to develop the theories. The qualitative research involving human subjects has the potential for bias and given the nature of the research, bias reducing strategies such as randomized sampling were not possible. Hence, the portfolio of adaptive resilience capabilities identified in Chapter 4, although comprehensive based on current knowledge, is not exhaustive. The list of capabilities will also evolve with changes in demand and system functionality with future transportation systems transformations from factors including but not limited to connected and autonomous vehicles, electrification, shared mobility, and telecommuting. Thus, a continuous revision of the AR capabilities is needed with added expert inputs and considerations of the latest transportation system trends.

The quantitative aspects of the research rely on availability of data related to previous disasters and future climate change predictions. As the historical data on disasters and their impacts are observational, generating a controlled environment is challenging, thereby increasing the potential of bias. Further, uncertainties associated with climate projection data also affect the confidence in point projections of expected returns estimated in Chapters 3 and 5. Confidence in the results obtained using the methodologies presented in this research can be increased with improved data collection for future disasters, and better future projection models for climate change.

Further work on incorporating the MRT approach in the formal asset valuation and asset management plans of infrastructure agencies will also support its application in practice. The MRT approach can also be used in combination with other approaches such as real options analysis to value investments under uncertainty, in order to increase the flexibility in dynamic plans instead of associating fixed time frames with improvements as depicted in this dissertation. Further, incorporating the MRT approach in benefit-cost assessment approaches at infrastructure agencies could enhance BCA analysis and support better project prioritization efforts.

An overall limitation of this research is that majority of the work is focused on US infrastructure systems. While the literature review is conducted on a global scale, with inputs incorporated from best practices of countries outside the US, the tools have been applied only in the context of US infrastructure systems. The fundamental concepts developed in the research are certainly applicable to infrastructure systems across different counties, but further calibration of the methods based on results from a broader range of applications will support its broader generalizability.

Another limitation of adaptive resilience in general, and therefore of this dissertation is the lack of focus on mitigation. Without mitigative efforts, continuous adaptation might not be the most resilient or sustainable pathway in the long term. While this is understood, resilience transitions from engineering-based resilience to mitigative transformative resilience is a continuum, with adaptive resilience somewhere in the middle. To move to mitigative and transformative resilience, a system first needs to transition from a single-equilibrium engineering resilience approach to a multiple-equilibria adaptive resilience approach – this dissertation contributes to enabling this transition in the field of transportation. Future research should focus on similar theory development on mitigative resilience capabilities in built systems.

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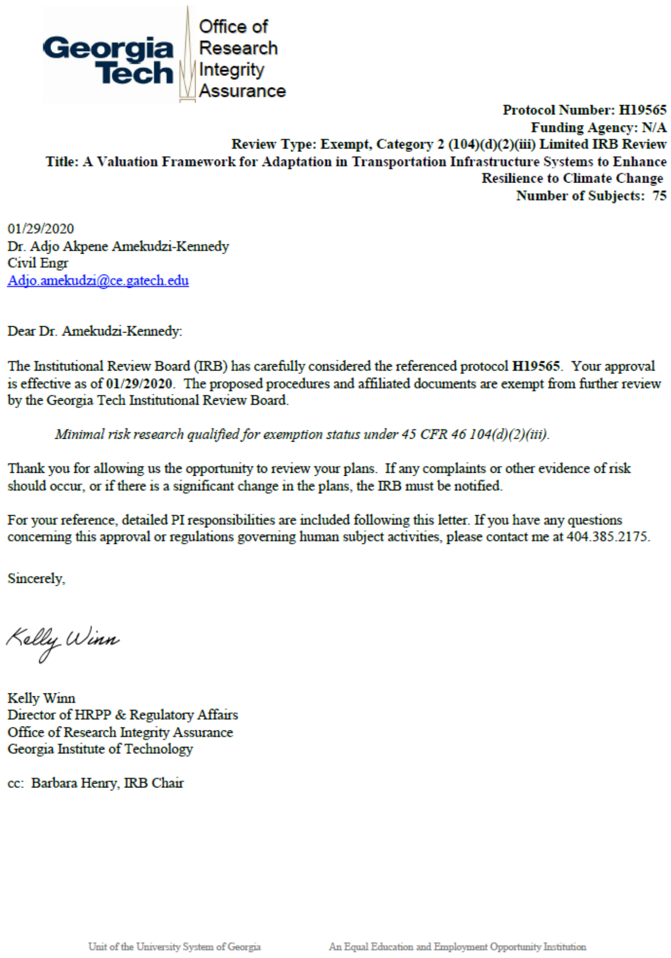
APPENDIX

6.3 Appendix A: Expert Interviews: IRB Approval



Georgia Tech
Office of Research Integrity Assurance

Protocol Number: H19565
Funding Agency: N/A
Review Type: Exempt, Category 2 (104)(d)(2)(iii) Limited IRB Review
Title: A Valuation Framework for Adaptation in Transportation Infrastructure Systems to Enhance Resilience to Climate Change
Number of Subjects: 75

01/29/2020
Dr. Adjo Akpene Amekudzi-Kennedy
Civil Engr
Adjo.amekudzi@ce.gatech.edu

Dear Dr. Amekudzi-Kennedy:

The Institutional Review Board (IRB) has carefully considered the referenced protocol **H19565**. Your approval is effective as of **01/29/2020**. The proposed procedures and affiliated documents are exempt from further review by the Georgia Tech Institutional Review Board.

Minimal risk research qualified for exemption status under 45 CFR 46 104(d)(2)(iii).

Thank you for allowing us the opportunity to review your plans. If any complaints or other evidence of risk should occur, or if there is a significant change in the plans, the IRB must be notified.

For your reference, detailed PI responsibilities are included following this letter. If you have any questions concerning this approval or regulations governing human subject activities, please contact me at 404.385.2175.

Sincerely,

Kelly Winn

Kelly Winn
Director of HRPP & Regulatory Affairs
Office of Research Integrity Assurance
Georgia Institute of Technology

cc: Barbara Henry, IRB Chair

Unit of the University System of Georgia An Equal Education and Employment Opportunity Institution

Semi-structured interview guide:

Interview Guide

Development of a portfolio of adaptive capacity indicators

Semi-structured Expert Interviews

Code:

<u>Underlined:</u> Outline of the interview

<u>Bold & underlined</u>: Potential Questions

Italics bold: Interviewer instructions

Italics: Guidance text for the interviewer

Basic information:

To be collected before interview

- Name
- Area of Expertise: ITS/AM/Design &Construction/Planning/…
- Transportation sector: Roadways/Railways/Buses/Subway systems/Airways/Waterways
- Type of employment: Federal/State/Consulting/NGO

Introduction:

- ***Resilience****: The ability to prepare and plan for, absorb, recover from, or more successfully adapt to actual or potential adverse events (National Research Council 2012).*
    - *"Function is maintained, but system structure may not be"(Martin-Breen and Anderies 2011)*
- ***Adaptation in resilience & its relevance today (uncertainty in future)***
    - *Adaptation: adjustment in the face of change*
    - *Adaptive Capacity: Adaptive capacity (or adaptability) is characterized as a property of complex adaptive systems defined as "the ability of a (human) system to adjust to climate change (including climate variability and extremes), to moderate potential damages, to take advantage of opportunities, or to cope with the consequences"(Climate-ADAPT n.d.). Essentially, the adaptive capacity of a system allows it to implement sustainable adaptations.*
    - *Increasing uncertainty of future conditions- present a need for adaptation now much more than before for infrastructure systems to maintain resiliency*
    - *Lack of substantial literature in the infrastructure systems field*
- ***Adaptation examples in other systems***
    - *Fields such as biology, food production, & psychology have experienced uncertain and faster change in environment than civil systems, and hence have looked into resiliency and adaptation in a higher detail.*

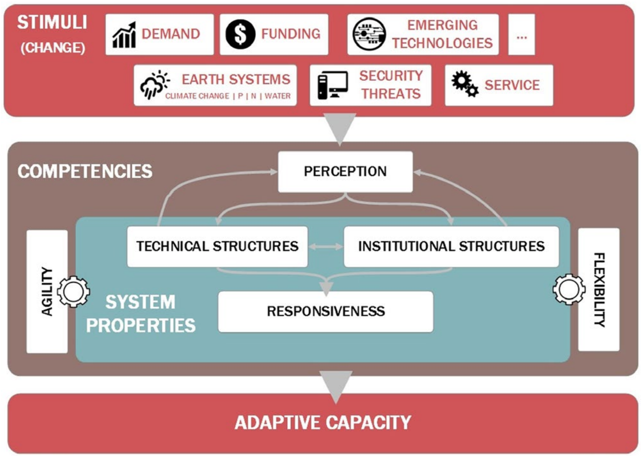
    - *Example of adaptive capacity:*
        - *In food production:*
            - *Natural systems: drought-tolerant crops*
            - *Human systems: capacity to switch to alternative land use within the agri-food systems*
        - *In ecological systems:*
            - *Structural: Fur on a bear, bill on a bird*
            - *Behavioral: bird calls, migrations*
- ***Purpose of the research***
    - *To identify indicators of adaptive capacity in transportation systems*
- ***Verbal consent- recording & right to withdraw***

Basic questions:

- **Their opinion on need for adaptation in the system of their expertise**
- **What does adaptation involve in transportation system**

[Introduction of flexibility & agility from literature]

"We distinguish between flexibility and agility based on changing demands and non-stationarity. With rapid changes in technology and ultimately the services that our systems provide, infrastructure will need to be flexible to changing demands. Infrastructure will also need to be agile in that its physical structure and the rules, policies, norms, and actors who manage and operate it, will need to be able to maintain function in a non-stationary future." (Chester and Allenby 2018)



[Example characteristics identified in literature for adaptive capacity]

- *Technical structure:*
    - *Software for hardware substitution*
    - *Connectivity, compatibility, & modularity*
- *Perception & responsiveness:*
    - *Road mapping & design for obsolescence*
    - *Trans-disciplinary education*
- *Institutional Structure:*
    - *Organic*
    - *Culture of change*

- **What do you think about these characteristics, their relevance, and how they are reflected in your system**
    - ***[identify the key aspects indicated by the participant, further questions will be focused on those aspects]***

[Introduction of AC (adaptive capacity) in relation to the real options theory, type of options (with examples]

Adaptation is most useful under uncertain conditions: thus making the benefit assessment equally uncertain using traditional benefit cost estimation methods. Instead, we here introduce adaptive capacity as providing options to the system. Where 'options' is used in the context of real option theory.

Real Option is a concept of evaluating flexibility in an investment decision and is founded on the analysis of financial decision making…Essentially Real Options allows a decision-maker to make changes to an investment when new information arises in the future. Opportunities such as delaying the investment, abandoning, switching, expanding, contracting and having multiple options interacting together are potential choices for decision-makers"(Woodward et al. 2011)*. Two types of real options are identified: real options 'in' projects, and real options 'on' projects. Real options 'on' projects resemble financial options and the option in itself is considered a black box and the real options include options to defer, abandon, or switch to another project.*(Martins et al. 2015) *On the other hand, real options 'in' projects build flexibility inside the design of the system by providing suitable conditions to allow future changes in the projects* (Buurman and Babovic 2016; Martins et al. 2015; Woodward et al. 2011).

Examples:

Options relating to project size: expansion or contraction

Options relating to project life & timing: initiation or deferment options, option to abandon, sequencing options

Options relating to project operations; Output mix options; input mix options; operating scale options

In-depth questions:

- **How can (fill in the specific characteristic) be identified in (your system)? Or What indicates (your system) having ((fill in the specific characteristic))**
- **What type of option does having (the specific ACI) provide to the system?**
- **Can you think of a way to quantify/measure/identify the specific indicator in (your system)?**
- ***(Repeat the above questions for all the AC characteristics relevant to the participant)***

[Introduction to our efforts in quantification: Damage categories]

- **What type of damage category will be affected by (your system) having (identified ACI)**
- **In your opinion, if the system has the best possible level of (identified ACI), by how much extent will the damage be reduced (range of percentages)**

Ending of the interview:

- **Do you think the range of AC characteristics, options, and damage categories captures everything for their system?**
    - **If not, then can you suggest what other AC characteristics/option types/damage categories should be included**
- **What are the key challenges the transportation industry faces in implementing adaptive investments for resilience?**
    - **Do you have any recommendations on what can be done to overcome these challenges?**
- **If you were doing the interviews, would they have done anything different or additional?**

After the interview:

- ***How the data will be used:*** *The ACIs will be consolidated into distinct categories, and scales will be developed to quantify them in terms of potential reduction in damage*
- *Case Studies will be used to identify the economic benefits of AC in a system using real option modelling*
- *Recommendations will be developed for systematically incorporating AC in transportation systems*
- ***[Acknowledgment of their contribution]***
- ***[Expression of anonymity (if requested)]***
- ***[Expression of confidentiality of their personal information]***
- ***[If they seem interested, ask if they would like to validate the final findings]***

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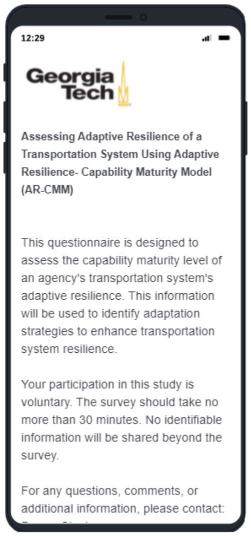
6.4 Appendix B: AR-CMM Survey Tool – Beta version (2021)

Assessing Adaptive Resilience of a Transportation System Using Adaptive Resilience-Capability Maturity Model (AR-CMM)

This questionnaire is designed to assess the capability maturity level of an agency's transportation system's adaptive resilience. This information will be used to identify adaptation strategies to enhance transportation system resilience.

Your participation in this study is voluntary. The survey should take no more than 30 minutes. No identifiable information will be shared beyond the survey.

For any questions, comments, or additional information, please contact:
Prerna Singh
prerna.singh@gatech.edu
(470)351-1694



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Assessing Adaptive Resilience of a Transportation System Using Adaptive Resilience- Capability Maturity Model (AR-CMM)

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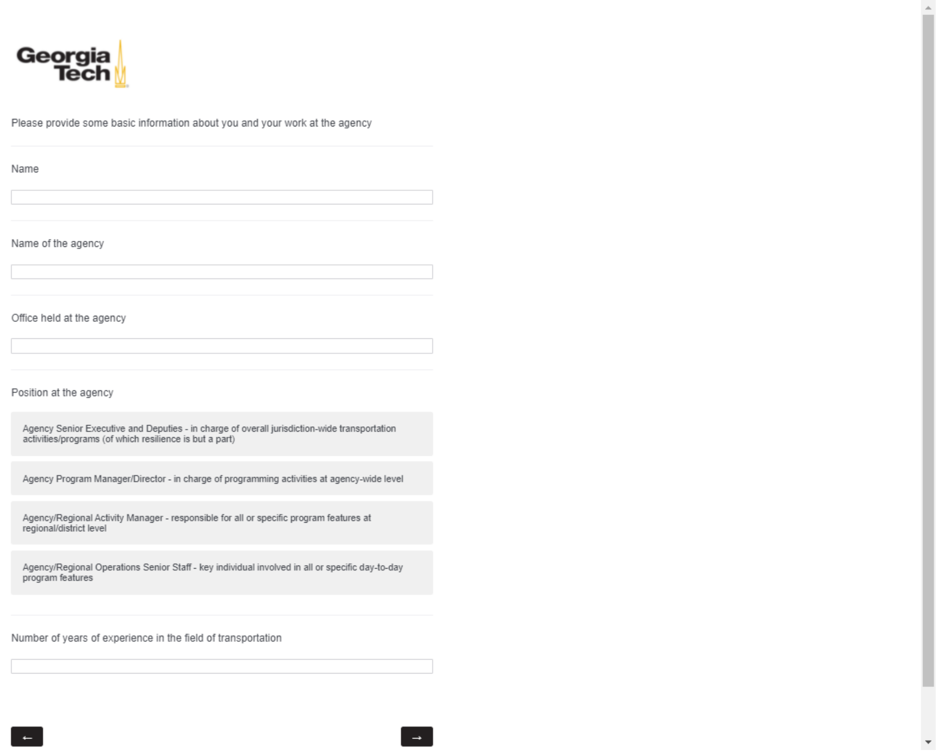


Please provide some basic information about you and your work at the agency

Name

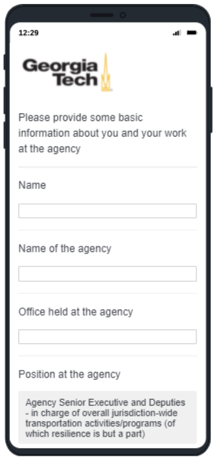
Name of the agency

Office held at the agency

Position at the agency

- Agency Senior Executive and Deputies - in charge of overall jurisdiction-wide transportation activities/programs (of which resilience is but a part)
- Agency Program Manager/Director - in charge of programming activities at agency-wide level
- Agency/Regional Activity Manager - responsible for all or specific program features at regional/district level
- Agency/Regional Operations Senior Staff - key individual involved in all or specific day-to-day program features

Number of years of experience in the field of transportation



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Please provide some basic information about you and your work at the agency

Name

Name of the agency

Office held at the agency

Position at the agency

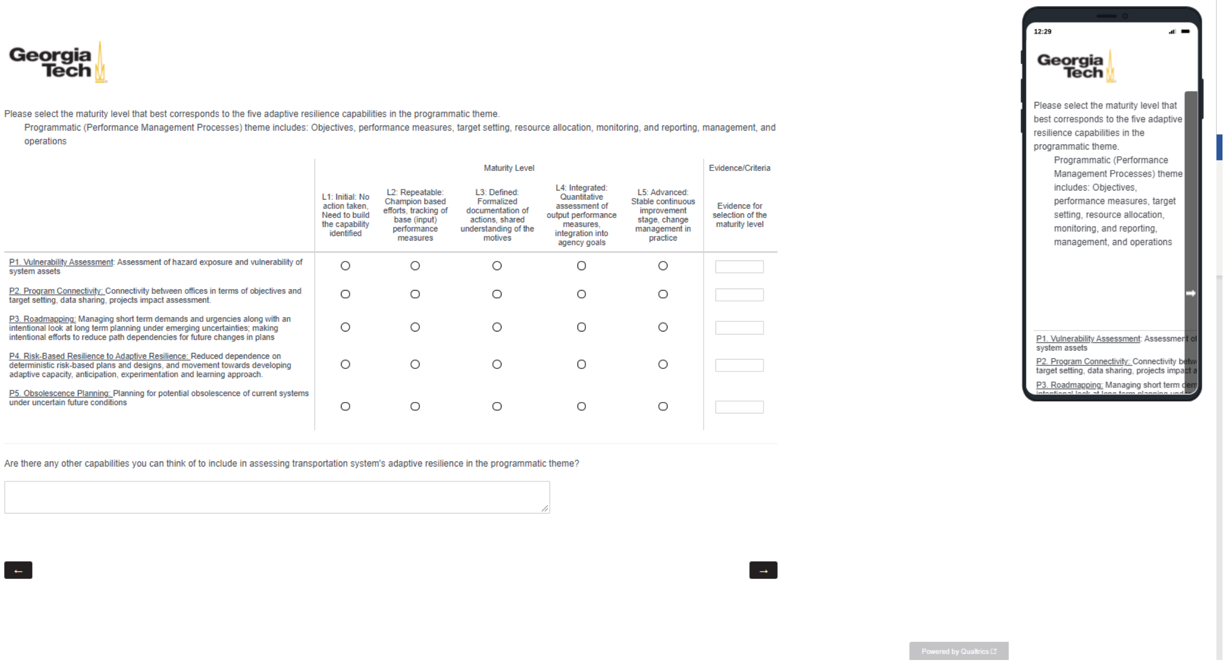
Agency Senior Executive and Deputies - in charge of overall jurisdiction-wide transportation activities/programs (of which resilience is but a part)

Please select the maturity level that best corresponds to the six adaptive resilience capabilities in the tactical theme.

Tactical (Tools and Technology) theme includes: Tools, data collection, sharing, and standardization, analysis tools, physical performance

	Maturity Level					Evidence/Criteria
	L1: Initial: No action taken, Need to build the capability identified	L2: Repeatable: Champion based efforts, tracking of base (input) performance measures	L3: Defined: Formalized documentation of actions, shared understanding of the motives	L4: Integrated: Quantitative assessment of output performance measures, integration into agency goals	L5: Advanced: Stable continuous improvement stage, change management in practice	Evidence for selection of the maturity level
T1. Multi-functionality: Coupling multiple purposes, processes, and functions within system components that can either perform multiple functions simultaneously or switch between them as needed	○	○	○	○	○	
T2. Modularity: Ability to readily add, remove, or modify individual components without disrupting other components and hence the overall system	○	○	○	○	○	
T3. Technological advancement: Update on existing hardware and software systems of transportation assets	○	○	○	○	○	
T4. Hardware to software substitution: Substitution of physical components and mechanical processes for services or information-based mechanisms	○	○	○	○	○	
T5. Tech connectivity: Connectivity of hardware and software systems across projects and offices, connectivity of different types of physical assets	○	○	○	○	○	
T6. Compatibility: Compatibility of connected hardware, software, and physical assets to integrate into a common or shared network of rules, material, energy, and information flows	○	○	○	○	○	

Are there any other capabilities you can think of to include in assessing transportation system's adaptive resilience in the tactical theme?

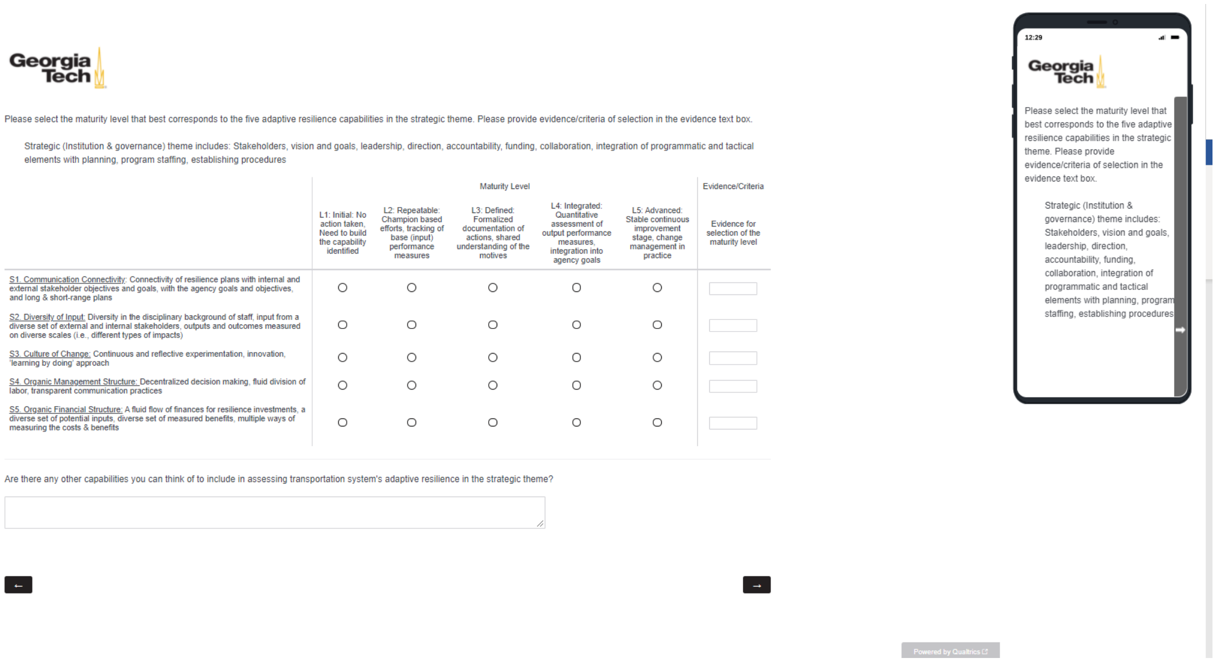


Please select the maturity level that best corresponds to the five adaptive resilience capabilities in the programmatic theme.

Programmatic (Performance Management Processes) theme includes: Objectives, performance measures, target setting, resource allocation, monitoring, and reporting, management, and operations

	Maturity Level					Evidence/Criteria
	L1: Initial: No action taken, Need to build the capability identified	L2: Repeatable: Champion based efforts, tracking of base (input) performance measures	L3: Defined: Formalized documentation of actions, shared understanding of the motives	L4: Integrated: Quantitative assessment of output performance measures, integration into agency goals	L5: Advanced: Stable continuous improvement stage, change management in practice	Evidence for selection of the maturity level
P1. Vulnerability Assessment: Assessment of hazard exposure and vulnerability of system assets	○	○	○	○	○	
P2. Program Connectivity: Connectivity between offices in terms of objectives and target setting, data sharing, projects impact assessment.	○	○	○	○	○	
P3. Roadmapping: Managing short term demands and urgencies along with an intentional look at long term planning under emerging uncertainties; making intentional efforts to reduce path dependencies for future changes in plans	○	○	○	○	○	
P4. Risk-Based Resilience to Adaptive Resilience: Reduced dependence on deterministic risk-based plans and designs, and movement towards developing adaptive capacity, anticipation, experimentation and learning approach.	○	○	○	○	○	
P5. Obsolescence Planning: Planning for potential obsolescence of current systems under uncertain future conditions	○	○	○	○	○	

Are there any other capabilities you can think of to include in assessing transportation system's adaptive resilience in the programmatic theme?



Please select the maturity level that best corresponds to the five adaptive resilience capabilities in the strategic theme. Please provide evidence/criteria of selection in the evidence text box.

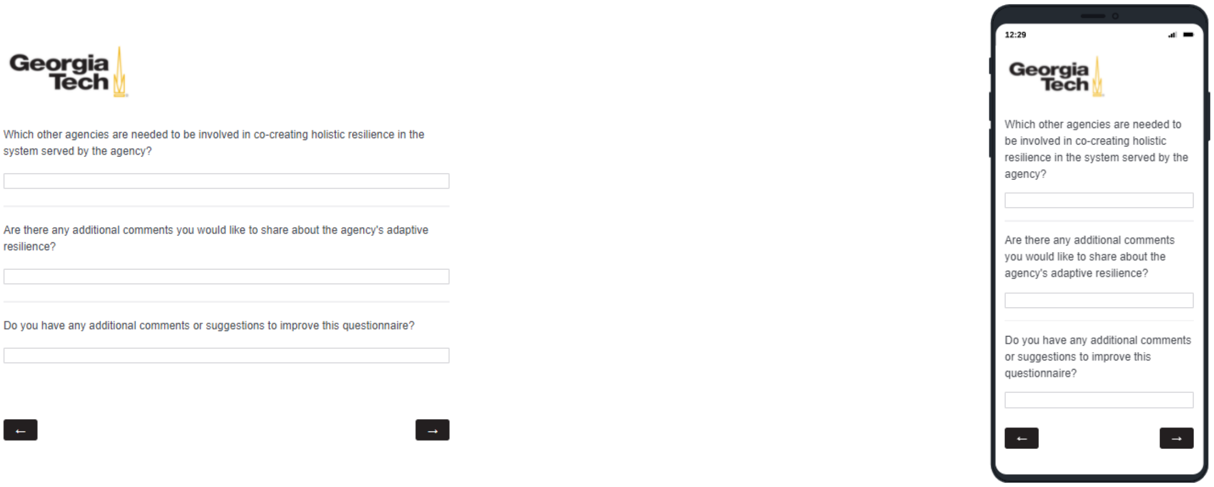
Strategic (Institution & governance) theme includes: Stakeholders, vision and goals, leadership, direction, accountability, funding, collaboration, integration of programmatic and tactical elements with planning, program staffing, establishing procedures

	Maturity Level					Evidence/Criteria
	L1: Initial: No action taken, Need to build the capability identified	L2: Repeatable: Champion based efforts, tracking of base (input) performance measures	L3: Defined: Formalized documentation of actions, shared understanding of the motives	L4: Integrated: Quantitative assessment of output performance measures, integration into agency goals	L5: Advanced: Stable continuous improvement stage, change management in practice	Evidence for selection of the maturity level
S1. Communication Connectivity: Connectivity of resilience plans with internal and external stakeholder objectives and goals, with the agency goals and objectives, and long & short-range plans	○	○	○	○	○	
S2. Diversity of Input: Diversity in the disciplinary background of staff, input from a diverse set of external and internal stakeholders, outputs and outcomes measured on diverse scales (i.e., different types of impacts)	○	○	○	○	○	
S3. Culture of Change: Continuous and reflective experimentation, innovation, 'learning by doing' approach	○	○	○	○	○	
S4. Organic Management Structure: Decentralized decision making, fluid division of labor, transparent communication practices	○	○	○	○	○	
S5. Organic Financial Structure: A fluid flow of finances for resilience investments, a diverse set of potential inputs, diverse set of measured benefits, multiple ways of measuring the costs & benefits	○	○	○	○	○	

Are there any other capabilities you can think of to include in assessing transportation system's adaptive resilience in the strategic theme?

Please select the maturity level that best corresponds to the five adaptive resilience capabilities in the strategic theme. Please provide evidence/criteria of selection in the evidence text box.

Strategic (Institution & governance) theme includes: Stakeholders, vision and goals, leadership, direction, accountability, funding, collaboration, integration of programmatic and tactical elements with planning, program staffing, establishing procedures



Which other agencies are needed to be involved in co-creating holistic resilience in the system served by the agency?

Are there any additional comments you would like to share about the agency's adaptive resilience?

Do you have any additional comments or suggestions to improve this questionnaire?

Which other agencies are needed to be involved in co-creating holistic resilience in the system served by the agency?

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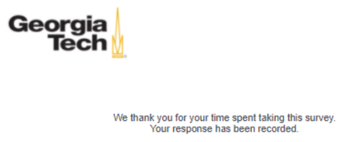
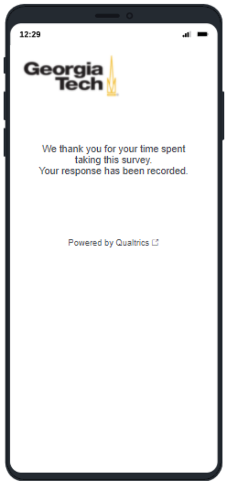


We thank you for your time spent taking this survey.
Your response has been recorded.



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