CAIT-UTC-NC 45

# COLLABORATIVE PROPOSAL: The Connection between State of Good Repair and Resilience: Measures for Pavements and Bridges

FINAL REPORT
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Submitted by:


Sue McNeil
Professor

Earl (Rusty)Lee
Assistant Professor

Yuanchi (Daniel) Li
Research Assistant

Rachel Chiquoine
Civil Engineer
Volpe Transportation Systems Center
(formerly Research Assistant)

Department of Civil and Environmental Engineering
301 Dupont Hall
University of Delaware
Newark DE 19716

Kevin Heaslip
Associate Professor
Virginia Tech

Gordana Herning
Massachusetts Institute of Technology (formerly Rutgers)

External Project Manager
Silvana Croope, University of Alabama (formerly DelDOT)

In cooperation with

Rutgers, The State University of New Jersey

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# Disclaimer Statement



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16. Abstract

Resilience has received a lot of attention in the past two decades as events, such as hurricanes and flooding, have captured the attention of transportation agencies and legislation requires the development of risk-based transportation asset management plans (TAMPs). This project explores strategies for operationalizing the concept of resilience through a literature review, case studies and meta-analysis of selected state risk-based transportation asset management plans. The case studies indicate that resilience is difficult to measure and interpret. However, the TAMPs integrate the concepts of resilience as needed enterprise risk management and vulnerability assessment tools support the integration of resilience into the plans.

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## EXECUTIVE SUMMARY

Resilience has received a lot of attention in the past two decades as events, such as hurricanes and flooding, have captured the attention of transportation agencies, and legislation requires the development of risk-based transportation asset management plans (TAMPs). This project explores strategies for operationalizing the concept of resilience through a literature review, case studies and meta-analysis of selected state risk-based transportation asset management plans.

Resilience is widely used by both academics and practitioners to capture the capacity of physical infrastructure to withstand and provide service after significant events such as extreme weather, operational failures, and manmade or technological impacts. In the United States, interest in resilience is increasing with growing awareness of the potential impacts of climate change, events such as Superstorm Sandy in the mid-Atlantic region, and increasing emphasis on performance-based management in transportation infrastructure legislation, such as the Moving Ahead for Progress in the 21$^{st}$ Century Act (MAP-21) and the Fix America's Surface Transportation (FAST) Act.

The American Society of State Highway and Transportation Officials' (AASHTO) definition of resilience - the ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events - captures the concept. However, operationalizing these concepts, integrating them into risk management and asset management plans, and measuring progress towards achieving resilience is challenging. In this report we provide a synthesis of the resilience literature relevant to pavement management, bridge management and asset management. Then, to demonstrate the applicability of the concepts, we present case studies.

The first case study focuses on Prime Hook Road in Delaware, which was subject to flooding. We use two examples of resilience measures and apply these to the pavement at the project level. The first example applies the concepts of robustness, redundancy, resourcefulness and rapidity. The second example uses the functionality over time as a measure of resiliency. The results illustrate the application of resilience measures to a pavement segment at two different temporal scales – specific flooding events and progressive degradation. The results provide insight into the impacts of different strategies for ensuring the functioning of the pavements prior to, during and immediately following an event including the limitations of project level analysis.

The second case study uses data from North Carolina on road closures and damage to I-95 due to Hurricane Matthew in October 2016. This case study shows how to measure resilience of the road network in terms of mobility and accessibility, and how the measures vary over time. This retrospective network-level case study also shows how to connect resilience measures with costs and underscores the importance of rapid repair and the high costs of network disruption.

Three other case studies explore the resilience of damaged pavements due to flooding in Robeson County, North Carolina, the changes to network resilience due to closure of the I-495 bridge in Delaware and the measures required to minimize the loss of resilience, and the operational impacts of a major blizzard.

The case studies indicate that resilience is difficult to measure and interpret. However, the concept of resilience, particularly as it relates to state of good repair (SOCR) can be connected to decision making through the risk-based transportation asset management plans (TAMPs). The TAMPs integrate the concepts of resilience as needed through enterprise risk management and vulnerability assessment tools. Each State is required to develop and maintain a risk-based asset management plan for the National Highway System (NHS) to improve or preserve the condition of the assets and the performance of the system.

The concepts, legislative requirements and tools that link asset management, risk and resilience are reviewed. We also review the transportation asset management plans developed by twenty-eight state departments of transportation in 2018 to understand how the states used resilience and document the approaches to risk management.  Opportunities to better integrate resilience into the risk-based asset management plans are then identified. Examples, drawn from the case studies, are presented that demonstrate the role of resilience related technical performance measures that reflect decisions related to flooding in the various stages of the disaster cycle (preparedness, response, recovery and mitigation).

Our conclusion is that resilience is a useful concept for exploring gaps in decision-making related to extreme events. However, risk-management provides tools and these concepts can be integrated in to the risk-based TAMPs.  An outline for a short guide is presented. The purpose of such a guide is to provide a clear concise summary of the concepts and direct the reader to the existing tools and related resources for risk management.

# INTRODUCTION

## Description of the Problem

The Fixing America's Surface Transportation (FAST) Act, our most recent surface transportation bill was passed into law in December 2015 (114th Congress, 2015). The FAST Act explicitly includes resiliency as a performance measure (Sect 1105, 1116, 1201, 1202, 1428, 3003, 8001). Although resilience has been widely used by both academics and practitioners to capture the capacity of physical infrastructure to return to providing service after significant events including weather events, operational failures, and man-made or technological impacts, there is little experience with regard to how to operationalize measures of resilience to either support decision making, or track progress.

A recent review of published literature on the performance measures for transportation infrastructure following a disaster identified many different approaches to measuring resilience at different scales and over different time periods (see for example (Faturechi & Miller-Hooks, 2014), (Heaslip, Louisell, & Collura, 2009), (Reinhorn, Bruneau, & Reinhorn, 2007), (Bocchini & Frangopol, 2012)). Furthermore, the CAIT "Resiliency of Transportation Infrastructure Workshop" identified the need to "develop robust, performance-based resilience metrics for transportation infrastructure." (Herning, Maher, & McNeil, 2016)

This report explores the connection between resilience measures and state of good repair (SOGR), and the application of resilience related performance measures in asset management.

## Overview

The research project focused on case studies and then a review of the connections between resilience and asset management as a way of connecting resilience to SOGR. The report includes material from several conference papers:

1) McNeil, S., Y. Liu, and A.S. Ramirez-Villamizar (2019). "Infrastructure Resilience: From Concept to Performance to Decisions," 7th International Conference "Bituminous Mixtures and Pavements, Thessaloniki, Greece, June 11-14.
2) McNeil, Sue. (2017), "Asset Management, Sustainability and Resilience: Connecting the Concepts to Maintenance and Inspection Decisions for Infrastructure Systems," 2017 MAIREINFRA, Seoul, South Korea, July 19-21.

3) Liu, Yuanchi, Sue McNeil and Rusty Lee. (2017). "Operationalizing the Concept of Resilience: A Case Study of Flooding in North Carolina," 2017 MAIREINFRA, Seoul, South Korea, July 19-21.
4) Liu, Yuanchi, Sue McNeil and Gordana Herning. (2017). "Integrating Resilience Concepts with Pavement Management: A Case Study in Delaware," World Conference on Pavement and Asset Management (WCPAM2017), Italy, June 12-16.
5) McNeil, Sue and Yuanchi Liu. (2019). "Using Resilience in Risk-Based Asset Management Plans" Paper submitted to the 2020 Transportation Research Board Annual Meeting.

## Background

Connecting an emerging concept and potential performance measure, in this case resilience, to a well-defined and widely used strategic goal - State of Good Repair - is critical to achieving these strategic goals and ensuring that the needs of agencies are being met. This research also supports the FAST Act and MAP-21 performance management requirements and the requirement to develop a risk-based asset management. Furthermore, the goal of the Federal Highway Administration (FHWA), as stated in their strategic plan (March 2015), is to provide safe, reliable, effective and sustainable mobility for all highway users. Research on connecting resilience to SOGR also supports this initiative. The Transportation Systems Sector-Specific Plan ( (Department of Homeland Security and United States Department of Transportation, 2015)), developed by Department of Homeland Security in cooperation wit US Department of Transportation and the State, Local, Tribal and Territorial Government Coordinating Council (SLTTGCC) working groups, is specifically aimed at securing and strengthening the resilience of critical infrastructure.

## Goals and Objectives

The goal of this research is to demonstrate the relationships among the concepts of resilience, other performance measures particularly related to state of good repair, and decisions related to improvement of pavements and bridges. The focus is on how to operationalize pavement and bridge network resilience measures (both at the project and network level) for state DOTs and MPOs given the requirements of the FAST Act to "improve the resiliency and reliability of the transportation system." Building on concepts and tools presented in the literature, selected resilience measures will use commonly available state of good repair data for pavements and bridges in Delaware and New Jersey to demonstrate their application.

The objectives are:

1) Synthesize the literature focused on measures of resilience.
2) Identify measures of resilience that can use state of good repair and are applicable to pavements.
3) Identify criteria and attributes for selecting measures appropriate for pavement and bridge management.
4) Identify data and tools, such as risk analysis, that can be used to support these measures.
5) Develop three to five short case studies demonstrating the application of these measures.
6) Develop an outline of a step by step guide for selection and implementation of resilience measures for pavement and bridge management for use by state DOTS.

The end product is a critical evaluation of potential pavement and bridge resilience measures connected to state of good repair, and a demonstration of how these measures can be used for pavement and bridge decision making. The outline of the step by step guide will serve as a starting point for future work.

Other research questions identified include:

- How do state, regional and local governments operationalize the concept of resilience?
- What measures do they use, how do they interpret the measures, and how do they use the measures of resilience?
- What does resilience mean for life cycle cost?
- Is resilience just another level of service, or performance measure?
- How does resilience recognize the number of users affected by a disruption?
- Is resilience an appropriate metric for an objective function or is resilience part of multi-attribute decision making?
- How does resilience relate to sustainability?
- Is resilience the complement of risk/ vulnerability?

## Context

Maintaining a state of good repair (SOGR) is particularly challenging when changes occur. Vulnerable environments; hazards such as storms and the resulting damage to infrastructure, properties and businesses; community and stakeholder input; and the range of condition of the transportation assets all influence the demand for services and the decisions that are made in the context of asset management. While forecasting demand is a clearly identified step in asset management it has not been given a lot of attention beyond the use of simple growth rates. As asset management is a data drive decision process, this project will focus on the data to support that process. At the same time this data is also likely to be useful in support of all of the USDOT Strategic Goals.

The last two highway bills, Moving Ahead for Progress in the 21st Century Act (MAP-21) (112th Congress, 2012) and the Fix America's Surface Transportation (FAST) Act (114th Congress, 2015) resulted in requirements for each state to develop risk based asset management plans (FHWA, 2017) that implicitly connect resilience and SOGR.

## Report Outline

This report is organized into twelve chapters and two appendices. This chapter presented an introduction to the problem, research approach and the concept of resilience. The following chapter describes the research approach in more detail followed by a brief literature review. The next chapter explores measures of resilience including tools to support modeling and measurement. The next five chapters are case studies. These are followed by a chapter on the relationship between resilience, state of good repair (SOGR), and asset management. Analysis and findings are then summarized following by a conclusions chapter. The first appendix includes definitions of resilience. The second appendix summarizes a short survey of our advisory committee members.

## RESEARCH APPROACH

*Resilience: "The ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events" Disaster Resilience: A National Imperative*

While there are many definitions of resilience (see Appendix A for addition definitions) and almost as many measures of resilience, operationalizing the concept to be useful in decision making is particularly challenging. These challenges include:

- The diverse hazards that impact transportation infrastructure including climate change, particularly sea level rise, extreme weather events (wind, storm surge, flooding, erosion and deposition), land subsidence, seismic events, and tornadoes, as well as exposure to biological and technological hazards, and terrorist activities.
- The changes that occur over time as well as from location to location.
- The different perspectives including the owner, the operating agency, and the user (both passenger and freight)
- The interdependencies with other infrastructure systems such as electricity, communications, water and wastewater, as well as network connectivity.

To address these challenges, we connect the concepts of resilience and performance measures related to decision making related to pavements and bridges. The research builds on work in three areas:

- The growing body of literature to connect the concepts of resilience and performance measures related to state of good repair to meet the needs of state DOTs.
- Recent work on integrating risk into the decision-making process and asset management provides access to appropriate tools.
- Familiarity with the widely available data on State of Good Repair related data for pavements and bridges will provide a base from which to test the applicability of the concepts including their effectiveness in capturing the concept of resilience and changes over time, and the relevance to the needs of state agencies.

The research approach begins with a critical review of the literature on resilience measures in the context of its relevance to pavement related decisions and the use of State of Good Repair related measures to connect to resilience performance measures. Related measures such as robustness, and vulnerability will also be considered as alternatives. The critical review requires an understanding of the appropriate criteria and attributes that can be used to benchmark different measures and tools both in the literature and practice.

This will be followed by a critical assessment of the tools available and the tools needed to assess resilience as a measure to support state of good repair. Drawing on these reviews and assessment, the project will then propose measures of resilience and assess these measures for states to understand:

1) Does existing data related to State of Good Repair adequately support the concept of resilience?
2) Do the measures of resilience support risk based pavement/ asset management?

This will be accomplished through meetings with relevant stakeholders. As needed the measures may be revised and reassessed.

Case studies applying the resilience measures are presented. Many candidate case studies were considered including:

- I-10 Bridge, Escambia Bay, FL after Hurricane Ivan, September 2004
- Twin Spans Bridge (I-10) after Hurricane Katrina, August 2005
- Freight railroad bridge reconstruction after Hurricane Katrina
- Flood in Lyons, CO, September 2013
- Superstorm Sandy damage – Oakwood Beach, New York and Sea Bright, New Jersey
- Flooding on Prime Hook Road in Sussex County, Delaware
- Closure and damage to I-95 in North Carolina due to Hurricane Matthew.
- Flooding in Robeson County, North Carolina from Hurricane Matthew
- I-495 closure from summer 2014
- Blizzard

Based on access to data and information, three case studies related to flooding are developed in detail:

- Prime Hook Road in Sussex County, Delaware: a pavement in Delaware subject to frequent flooding compared with the local network that in general is subject to degradation over time;
- I-95 in North Carolina due to flooding and damage: the closure of the interstate highway resulted in significant disruption;

- Degradation of roads in Robeson County, North Carolina due to flooding: an exploration of the changes in functionality due to flooding and repair.

A fourth case study look at the role of the resilience measures in the closure of the I-495 bridge in Delaware, and a brief fifth case study on blizzards are also presented. These case studies demonstrate the role of resilience in relatively sudden closures and operational problems.

The results illustrate the application of resilience at different spatial and temporal scales - a segment subject to specific flooding events, a network with progressive degradation, and a sudden onset event on a critical link. For example, the concepts of robustness, redundancy, resourcefulness and rapidity (Bruneau & Reinhorn, 2007) may be more applicable at the project level, where functionality over time (Bocchini & Frangopol, 2012) may be appropriate at the network level. The case study results provide insights into the impacts of different strategies for ensuring the functioning of the pavements prior to, during and immediately following an event.

The research then explores the role of risk and resilience in asset management reviewing how a sample of state asset management use risk and resilience. This analysis focuses on the tools to support risk and resilience. Drawing on this analysis and the case studies, an outline for a guide for selecting resilience measures for use by state DOTS is presented. The results are documented in this report.

## RELEVANT LITERATURE

Holling (1973) used resilience to measure how an ecological system can withstand and absorb change during a disturbance. Over decades, the concept of resilience has evolved to capture the impact of a hazard on the physical infrastructure system in terms of its resistance and ability to recover quickly to the initial state. The growing body of literature on resilience, for example, (Bruneau, et al., 2003) (Oswald, McNeil , Ames, & Gayley, 2013) (Faturechi & Miller-Hooks, 2014), provide a foundation from which to explore concepts of resilience, and related performance measures. Over one hundred papers presenting concepts and measures related to resilience have been identified. The literature covers simple measures, such as VMT (Croope & McNeil, 2011) to conceptually interesting but difficult to implement measures such as Bruneau et al's (2003) measures of robustness, rapidity and redundancy; and other measures requiring the use of fuzzy inference (Heaslip, Louisell, & Collura, 2009) and graph theory to quantify resilience (Berche, von Ferber, Holovatch, & Holovatch, 2009).

Using these concepts, Bruneau et al. (2003) defined resilience as “the ability of social units to mitigate hazards, contain the effects of disasters when they occur, and carry out recovery activities in ways that minimize social disruption and mitigate the effects of future earthquakes.” Although the paper focuses on seismic events, the concept is also applicable to other hazards (Bruneau & Reinhorn, 2007).

Bruneau et al. (2003) also characterize resilience using four properties: robustness, rapidity, resourcefulness and redundancy. Robustness is the functionality of infrastructure to withstand and continue to function as a hazard event occurs. Rapidity is the ability of infrastructure to recover and return to the level of functionality that existed before the hazard event occurred. Resourcefulness refers to the effort put into the infrastructure to shorten the time of recovery. Robustness, rapidity, and resourcefulness can be associated with mitigation, preparedness and recovery, three of the four phases of the disaster cycle. Redundancy is the capability of alternative infrastructure to serves as a substitute to meet the original demand following the hazard event. Redundancy is an attribute of the network and can be enhanced as a mitigation activity.

Emphasizing resistance and recovery, the National Infrastructure Advisory Council (National Infrastructure Advisory Council, 2009) defines infrastructure that is able to anticipate, absorb, adapt, and recover rapidly when hazards occur as resilient. Resilience focuses on the impact of pre-hazard damage prevention (reducing the probability of failure), abrupt changes that occur following a disaster (the consequences of damage), like a major flood, and the subsequent restoration (time to recover). (Hosseini, Barker, & Ramirez-Marquez, 2016) classify resilience assessment approaches into two major categories: qualitative and quantitative. Quantitative assessment methods include general measures (deterministic and probabilistic) and structural based models (optimization, simulation and fuzzy logic). Similarly, Faturechi and Miller-Hooks (2014) categorize methods for assessing performance in disasters as analytical, simulation, and optimization models. Their review of performance measures for transportation infrastructure in disasters finds no resilience measures applicable to recovery but does identify travel time and accessibility as measures of performance during recovery (Faturechi & Miller-Hooks, 2014).

Resilience measures applicable to the recovery of transportation systems fall into three categories: 1) suites of measures that usually represent indicators of the extent to which services are impacted (Freckleton, Heaslip, Louisell, & Collura, 2012) (Murray-Tuite, 2006); 2) measures of the loss of functionality or the performance of the systems (Bocchini & Frangopol, 2012) (Cimellaro, Reinhorn, & Bruneau, 2010); and 3) recovery ratios representing the ratio of service prior to the event to the service after the event, or its reciprocal (Ye & Ukkusuri, 2015). (Henry & Ramirez-Marquez, 2012) recognize that there are no consistent quantitative approaches to measuring resilience, and that the available data, models and assumptions restrict the application of the existing quantitative approaches to specific fields. In addition, the suites of measures are often not supported by the available data, the measures based on functionality are difficult to interpret as they integrate over time and space (Liu, McNeil, & Herning, 2017), recovery ratios do not capture network redundancy, and the application of all methods to realistic networks can be computationally intensive.

In this research, we use measures of loss of functionality or performance as measures of resilience applied to case studies. The specific measures vary for each case study and are defined in the relevant case study using the following attributes or dimensions:

- Spatial scale of the infrastructure being studied: project, corridor or network
- Infrastructure type: pavement or bridge
- Spatial scale of the resilience measures: facility or network
- Function of the resilience measure: maintenance or operations
- Phase in the disaster cycle:
    - Mitigation: Preventing future emergencies or minimizing effects

    - Preparedness: Plans/preparation in advance of emergency to get ready
    - Response: Actions in the midst or immediately following emergency to save lives and prevent further damage
    - Recovery: Actions to return community to pre-disaster state or better
- How the measure is used: assessment or evaluation, prediction, decision-making
- Temporal scale of the resilience measures: duration of the event, life cycle of the infrastructure
- Characteristics of the weather event or hazard
    - Speed of onset: rapid, gradual or slow
    - Intensity: significant disruption, modest disruption, some disruption
    - Duration: hours, days, weeks
    - Nature of the hazard: flooding (storm surge, riverine), hurricanes (flooding, wind), fire, earthquake, blizzards, tornadoes, landslides/mudslides, sinkholes, volcanoes, tsunamis

The attributes of the case studies, as described above are summarized in Table 1. Each column represents a case study and each row the attributes.

**Table 1. Case Study Attributes**

| Attribute | Prime Hook | I-95 – North Carolina | Robeson County | I-495 Bridge | Blizzard |
|---|---|---|---|---|---|
| Infrastructure Spatial Scale | Project | Corridor | Network | Project | Network |
| Infrastructure Type | Pavement | Pavement and Bridge | Pavement | Bridge | Pavement and Bridge |
| Resilience Spatial Scale | Facility | Network | Facility | Network | Network |
| Function of the Resilience Measure | Operations and Maintenance | Operations | Maintenance | Operations | Operations |
| Phase in the Disaster Cycle | Mitigation and Recovery | Recovery | Mitigation, Preparedness and Recovery | Recovery | Preparedness and Recovery |
| Use of the Measure | Assessment and Decisions | Assessment | Prediction | Assessment | Assessment |
| Temporal Scale | Life cycle | Event | Life cycle | Event | Event |
| Event Speed of onset | Rapid | Rapid | Rapid | Rapid | Gradual |
| Event Intensity | Modest | Significant | Modest | | |
| Event Duration | Days | Days | Days and weeks | Weeks | Hours |
| Event Nature | Flooding | Flooding | Flooding | Damage due to loading | Blizzard |

# RESILIENCE MEASURES

## Practitioner Survey

A survey was developed to determine how practitioners define resilience, use resilience measures, and what concepts would apply to future measures. The survey was sent out to the seven members of our ad hoc advisory committee. Three responded, although all participated in the follow up phone call. The questions are documented and the results are summarized in Appendix B.
In summary:

- Definitions and concepts consistent with common practice
- Currently not widely used
- Specific measures and uses need better definitions
- Slight preference for system level and long to medium term timeframes for use

Based on the responses, it was agreed that additional surveys would not be very fruitful.

## Measures in the Literature

### *Resilience Triangle or Loss of Resilience*

Bruneau and Reinhorn (2007) use the resilience triangle, first introduced by Bruneau et al. (2003), to quantify the loss of resilience. The measure computes the cumulative loss of performance or functionality over time. Resilience loss is defined by Eqn 1.

$$R_L = \int_{t_0}^{t_1} \big(100 - Q(t)\big)dt \qquad (1)$$

Where $R_L$ is the loss of the resilience,
Q(t) is the functionality at time t,
$t_0$ is the time at which the event occurs, and
$t_1$ is the time at which recovery is complete.

### *Average Residual Functionality*

Bocchini and Frangopol (2012) measure the average residual functionality between the occurrence of the hazard and the completion of restoration, using a resilience metric defined by Eqn 2.

$$R = \frac{\int_{t_0}^{t_1} Q(t)dt}{t_1 - t_0} \qquad (2)$$

Where R is the average resilience between when the event occurs ($t_0$) and the time at which recovery is complete ($t_1$).

***Degradation of System Performance***

Resilience measures based on the degradation and restoration of system performance build on the concepts presented by Bruneau et al. (2003), capturing recovery by measuring the loss of functionality during recovery are shown in Table 2.

**Table 2. Degradation of System Performance Resilience Measures**

| Measure | Change in Travel Time | Change in Vehicle Kilometers Traveled (VKT) |
|---|---|---|
| Calculation | $R = \sum_{t=1}^{T}\sum_{i=1}^{n}(TT_{it}q_{it} - TT_{i0}q_{i0})$ | $R = \sum_{t=1}^{T}\sum_{i=1}^{n}(L_i q_{it} - L_i q_{i0})$ |

***Recovery Ratio***

Ye and Ukkusuri (2015) equate maximizing the recovery ratio to maximizing resilience. Using the notation defined above, the recovery ratio is defined as:

$$R = \sum_{t=1}^{T}\sum_{i=1}^{n}\frac{TT_{i0}q_{i0}}{TT_{it}q_{it}}$$

## Measures of Functionality

Measures of functionality found in the literature include:

- Project or facility level
    - Flow (measured in vehicles per hour)
    - Capacity
    - Condition measures such as PCI/OPC or visual ratings
    - Number of lanes closed
    - Speed

- Network level
    - Number or percentage of bridges open
    - Number or percentage of pavement sections damaged
    - Delay
    - Additional travel time
    - Additional travel distance
    - Additional costs

Most of the measures can be modeled, observed or recorded.

## Tools to Support Resilience Modeling and Measurement

### *Frameworks*

A variety of frameworks have been developed to support the modeling and measuring resilience (Rose, 2009). The frameworks briefly discussed here provide insights into how resilience can be used to enhance SOGR of pavements and bridges:

- The framework presented by Bruneau et al. (2003) was developed to assess and enhance resilience to earthquakes. The framework captures the influences on resilience using the resilience properties of robustness, resourcefulness, rapidity and redundancy.
- The disaster resilience of place (DROP) model (Cutter, et al., 2008) is a place-based framework for assessing disaster resilience at the community level.
- The PEOPLES resilience framework captures seven dimensions (Renschler, Fraizer, Arendt, Cimellaro, & Reihardt, 2010): Population and Demographics, Environmental/Ecosystem Services. Organized Governmental Services, Physical Infrastructure, Lifestyle and Community Competence, Economic Development and Social-Cultural Capital. These dimensions provide a performance management framework.
- The NIST (2015) community resilience planning guide for buildings and infrastructure is focused on communities (NIST, 2015). A six-step plan process is used to develop customized plans with performance targets.

- The Rockefeller 100 resilience cities program (Rockefeller Foundation and ARUP, 2014) address health and well being of individuals, infrastructure and the environment, economy and society, and leadership and strategy. Indicators are used with qualities that relate to a resilient city to develop a common understanding, identify gaps and determine appropriate investments.
- The Sendai Framework for Disaster Risk Reduction (SFDRR) **Invalid source specified.** is aimed at reducing risk and increasing resilience at national and regional levels. Priorities are to: 1) understand risk, 2) strengthen disaster risk governance, 3) invest in resilience, and enhance preparedness.
- The Composite of Post-Event Well-being (COPEWELL) framework is a system dynamics model focusing on the functioning and well-being of communities (Links, et al., 2018). The models focus on community well-being through existing indicators.
- AASHTO's framework includes a step by step guide and comprehensive lists of resources to management risks and address security (AASHTO, 2015). The framework uses resilience to connect infrastructure protection to emergency management.

Table 3 summarizes the attributes of the frameworks in terms of the stage of the life cycle (each row), the relevant timeframe for the stage (the second column) and one column for each framework.

**Table 3. Frameworks for Resilience**

| Life Cycle Stage | Timeframe | Influences… (Bruneau 2003) | DROP Model (Cutter | PEOPLES Model | NIST | Rockefeller 100 Resilient Cities | Sendai Framework | COPEWELL | AASHTO |
|---|---|---|---|---|---|---|---|---|---|
| Mitigation | Long term | Robustness Redundancy | | Performance - based management framework | Proactive resilience | Categories; indicators; qualities<br><br>Assessment<br><br>Progress | Investment and prevention | Factors: natural and engineered systems and countermeasu res | Infrastructure protection and Resilience |
| Prepared-ness | Short to medium term | Robustness Rapidity Resourcefulness | Initiation of the model | | Assessment | | Assessment | Resources, socioeconomi c factors | |
| Event/ Response | Immediate | Robustness | Coping responses/ Absorptive capacity | | Assessment | | Enhanced preparedness | Event, resources, community activities | Emergency Response |
| Recovery | Short to long term | Rapidity Resourcefulness | Degree of recovery | | Target times | | "Build Back Better" | Community well-being | (Not included in report) |

## Modeling Changes in Functionality

Most of the resilience measures use functionality. The transportation and infrastructure literature provides many models to support the prediction of functionality and changes in functionality. Important tools include network models, deterioration models, traffic assignment, capacity analysis, and thresholds for performance.

## CASE STUDY 1: PRIME HOOK ROAD DELAWARE

### Context

Prime Hook Road is a local two-lane road that is the only public access to the Prime Hook community of 200 homes on Delaware Bay in Kent County, Delaware (USA). The road is an embankment 1.6 km long, crossing several thousand acres of tidal salt marsh (as shown in Figure 1) at an elevation between 0 and 1 meter with an average slope of 0.46% as shown in Figure 2. The road is owned and maintained by the Delaware Department of Transportation (DelDOT).


**Figure 1. Prime Hook Road © 2016 Google**

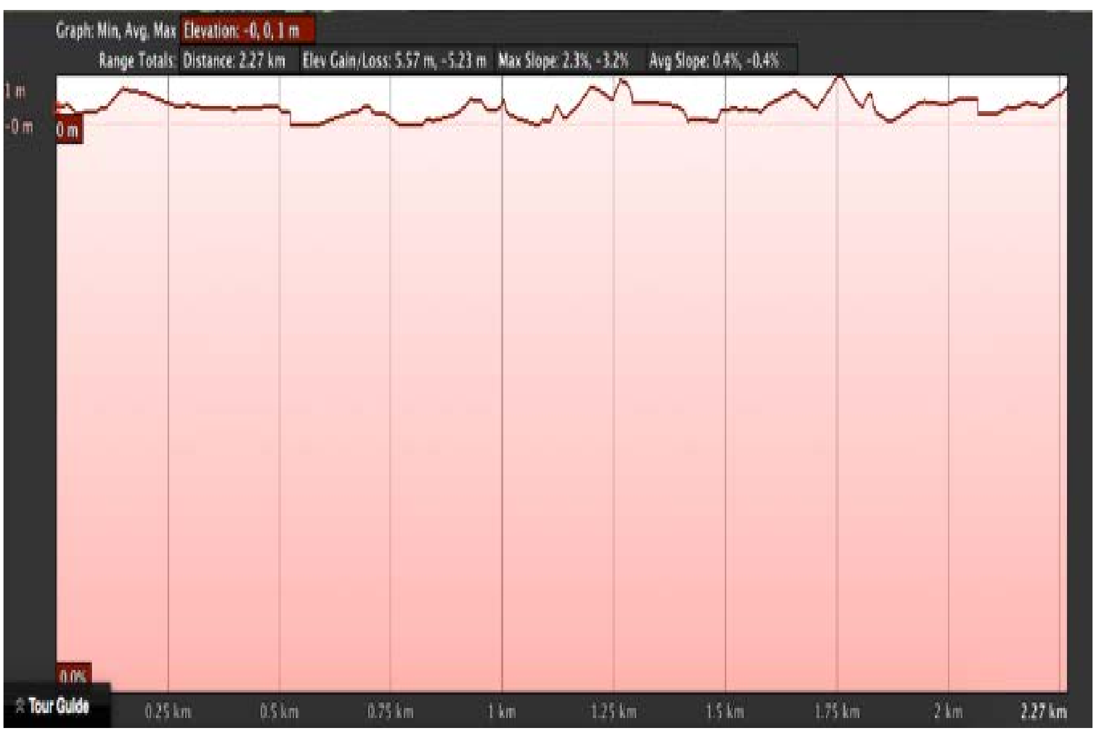



**Figure 2. Elevation of Prime Hook Road. © 2016 Google**

This segment of the road has major flooding problems as water from the bay begins to cover the roadway when storm surges or tides are higher than the mean high tide. In the period 2010-2012, the road was rebuilt twice and was closed for more than 17 days due to flooding. Data on the duration of each event and the nature and the cost of repairs can be found in Archibald (2013).

The road provides the only public access to the community of Prime Hook (approximately 200 households), so when it floods, DelDOT provides a detour for the community members across private property. In 2013, three alternatives were considered as possible long-term solutions: build a bridge, elevate the road, or continue to repair the road after each flood (Archibald 2013). Two strategies have been implemented, reconstruction of the beachfront sand dunes to protect the marsh from seawater flooding, and construction of a 60 feet long bridge to carry Prime Hook Road over a new drainage canal. (Delawareonline 2016)

## Determination of functionality

To develop resilience measures, we need to infer a model of functionality, Q(t). Our model is based on pavement performance (distress data), and capacity. DelDOT uses an objective rating system to capture distress extent and severity and then compute an Overall Pavement Condition (OPC) as a representation of pavement condition (Attoh-Okine & Adarkwa, 2013). OPC uses fatigue cracking, environmental cracking, surface defects, and patching data to measure distress on a scale of 0-100, where 100 is assigned to a perfect pavement. The data for the case study was collected by DelDOT for the road section of interest. Table 4 shows the actual records of OPC for 2005, 2007, 2008, 2011, and 2013. Archibald (2013) provides details of when the road was closed as shown in Table 5. The road was closed in 2010 for construction, 2011 due to Hurricane Irene and 2013 due to Hurricane Sandy.

**Table 4. Actual records of OPC**

| Year | OPC index |
|---|---|
| 2005 | 61 |
| 2007 | 58.3 |
| 2008 | 49.4 |
| 2011 | 62.2 |
| 2013 | 83.8 |

**Table 5. Events Causing Closure of Prime Hook Road**

| Event | Start of Closure | End of Closure |
|---|---|---|
| Reconstruction | March 31, 2010 | April 1, 2010 |
| Hurricane Irene and Rebuilding | August 28, 2011 | September 1, 2011 |
| Hurricane Sandy and Rebuilding | October 28, 2012 | November 5, 2012 |

Using the data in Table 4 and Table 5, and our knowledge of pavement deterioration, we define a model of OPC as a function of time for the period 2005 to 2014 using six time periods representing different flooding or repair events:

(1): Jan 1 2005 < t < Mar 31 2010;

(2): Apr 1 2010 < t < Aug 27 2011;

(3): Aug 28 2011 < t < Sep 1 2011;

(4): Sep 2 2011 < t < Oct 27 2012;

(5): Oct 28 2012 < t < Nov 5 2012; and

(6): Nov 6 2012 < t < Nov 6 2013.

To compare the impact of different strategies on pavement resilience, we define three scenarios.

I: Observed conditions: this is the original situation (that is, the road is repaired after flooding);

II: Bridge constructed in 2005, slowing the deterioration of the pavement;

III: Bridge constructed in 2005, pavement continues to deteriorate as in Scenario I.

## Scenario I

We inferred the models based on a power function and observed data points, shown in Eqns (3) – (5) to capture deterioration, road closures and the different repair actions after two major flooding events in 2010 and 2012, as shown in Figure 3. The figure shows that the OPC declines from 2005 until 2010 when the road is rebuilt following Hurricane Irene, the again declines until 2013 when the road is rebuilt due to damage from Hurricane Sandy.   The numbers in parentheses refer to the six time periods. $Age_{(1)}$ starts from 21 years, which was the age of the pavement when data was first collected in 2005.  For other cases $Age_{(t)}$ is the age of pavement (in years) since the last reconstruction period, t. We model the OPC over time as follows:

$$OPC = -1126.2 + 109.38 * Age_{(1)} – 2.52\ Age_{(1)}^2 , \quad (3)$$

$$21 < Age_{(1)} < 26$$

$$OPC = 59.46 + 3.54 * Age_{(i)} – 2.52\ Age_{(i)}^2 , \quad (4)$$

where i= 2, 3, 4, 5)

$$0 < Age_{(2)} < 1.30;$$

$$1.30 < Age_{(3)} < 1.31;$$

$$1.31 < Age_{(4)} < 2.45;$$

$$2.45 < Age_{(5)} < 2.47$$

$$OPC = 83.8 + 0.25 * Age_{(6)} – 1.25\ Age_{(6)}^2, \quad (5)$$

$$0 < Age_{(6)} < 1$$

We define capacity, C(t), as the capacity of the road section over time, and assign values 1 and 0 to an accessible and closed road, respectively. As shown in Figure 4, the capacity is 1 from 2005 to 2011 when the road is closed (capacity is 0) for 5 days after Hurricane Irene, and then the capacity is again 1 until 2012 when the road is closed (capacity is 0) for 8 days after Hurricane Sandy. We focus on the two hurricanes that caused severe damage and road closure longer than 1 day, i.e., C = 0 in period 3 and period 5 and C = 1 otherwise. Then, we set Q(t) equal to the product of OPC and capacity C(t), that is:

$$Q(t) = OPC(t) * C(t).$$

When the section is closed due to the flooding, Q(t) is equal to zero, otherwise Q(t)= OPC(t).

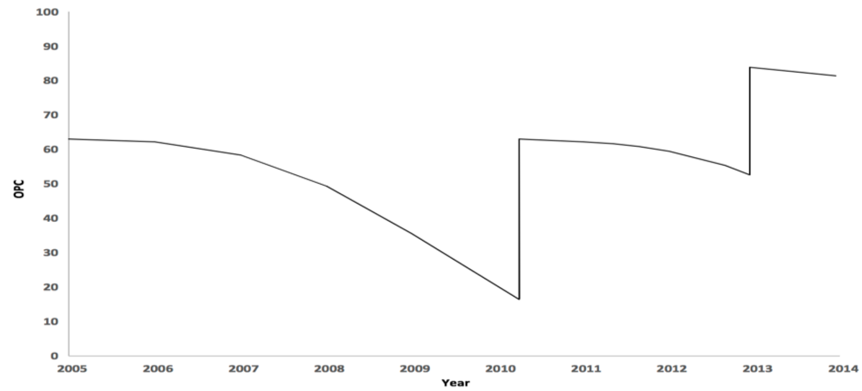



Figure 3. Pavement deterioration of Prime Hook Road

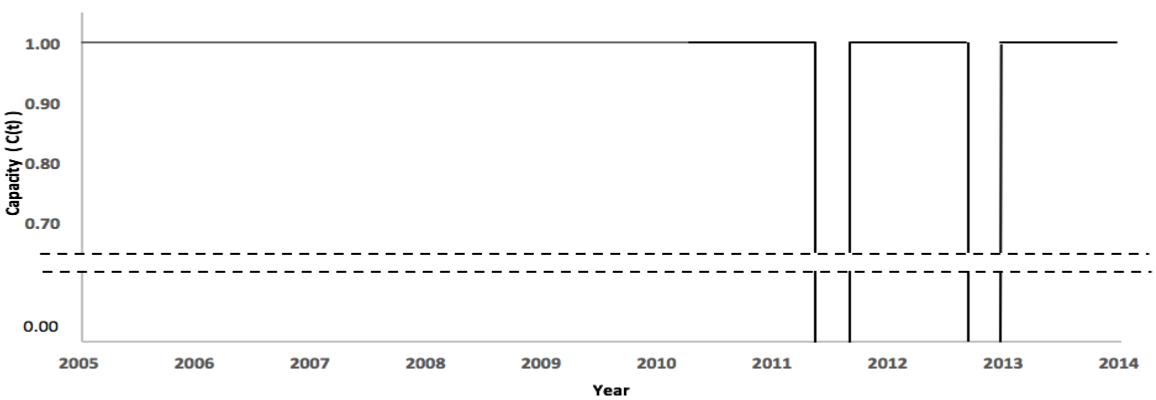



**Figure 4. Capacity (C(t)) of Prime Hook Road**

## Scenario II and Scenario III

We assume the bridge built in 2005 is a 60-foot concrete-girder crossing. The bridge permits the flow of water and the road is not inundated or damaged resulting in no road closure and less deterioration. In Scenario II, the deterioration model is modified as shown in Eqn (6).

$OPC = 70 – 1.1* Age_{II} – 0.1\ Age_{II}^2,\ 0< Age_{II}< 9$(6)

Where $Age_{II}$ is the age of the pavement (in years) for Scenario II since the last reconstruction (assumed to be the bridge construction).

This power equation is fitted to be similar to Scenario I between 2010 and 2013. Scenario III involved modifying Scenario II assuming that the pavement section deteriorates at the same rate as Scenario I in 2005 – 2010 and 2010 – 2013 with a pavement reconstruction in 2010. Therefore, it has the same deterioration model as Eqn (3) and (4). The only difference from Scenario I is that there is no road closure due to flooding because of the bridge crossing. That is, the pavement still deteriorates and has to be reconstructed in 2010.

The functionality as modeled for Scenarios I to III is presented in Figure 5. The figure shows that in Scenario I the functionality declines over time, improves when the road is reconstructed and drops to zero when the road is closed due to flooding or damage. Scenario II follows Scenario I except the road does not close due to flooding and damage. Scenario III shows gradual deterioration over

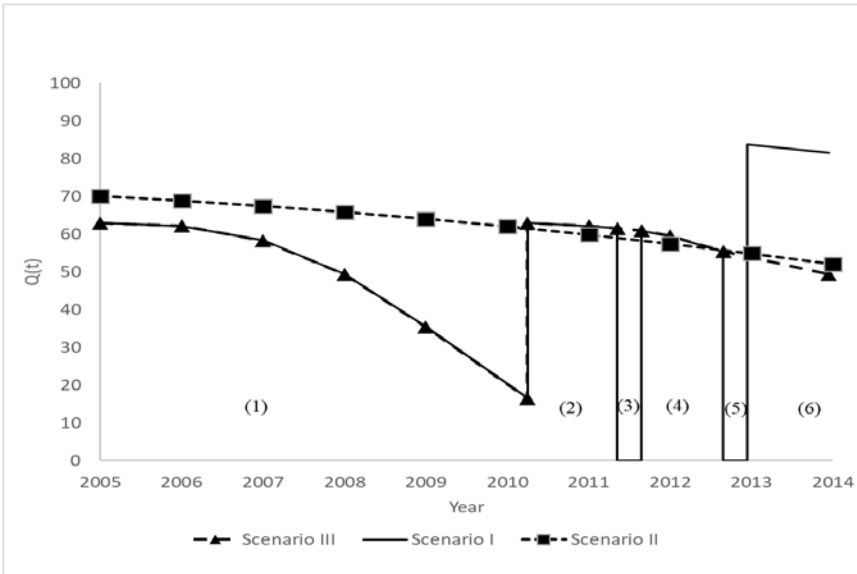



**Figure 5. Change in Functionality for Three Scenarios**

the entire planning horizon. The purpose of presenting Scenario II and Scenario III is to compare the changes in resilience.

## Measuring Resilience for Prime Hook Road

These measures of functionality are used to quantify resilience loss and resilience using the measures defined by Bruneau and Reinhorn (2007) and Bocchini and Frangopol (2012) respectively. Liu et al. (2017a) used the product of the Overall Pavement Condition (OPC), a unit-less measure on a scale of 0-100, and the capacity of the road as a measure of functionality for three scenarios shown in Figure 5. Resilience measures were calculated for different time periods, indicated by the numbers (1)-(6), in Figure 5 using the measures posed by Bruneau and Reinhorn (2007) and Bocchini and Frangopol (2012), which are shown in Figure 6. The figure shows Bruneau and Reinhorn's measure of resilience loss as the area between the functionality curve and "normal" functionality and Bocchini and Frangopol's measure as the area beneath the functionality curve. The time periods (measured from 2005) are described as follows:

1. Degradation of the pavement (0-5 years)
2. Rehabilitation followed by degradation (5-6.3 years)
3. Road closure and repair due to damage (6.30-6.31 years)
4. Repair and degradation of the pavement (6.31-7.45 years)
5. Road closure and repair due to damage (7.45-7.47 years)
6. Reconstruction followed by degradation (7.47-8.57 years)

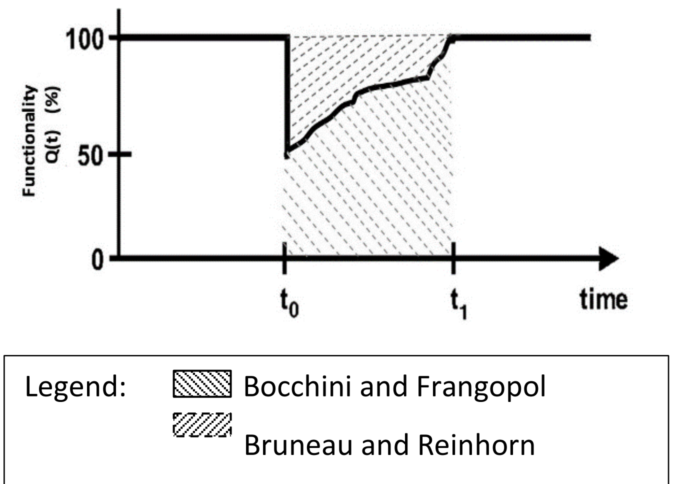



**Figure 6. Theoretical Measures of Resilience**

Using Equations (1) and (2), the resilience of the pavement is calculated as shown in Table 6. We break the calculation into the six different time periods represented in Eqns (3) to (5). Each row represents one of these time periods and the columns are the resiience measures for each method and each scenario.

**Table 6. Resilience Measures**

| **Time Period** | **Method** | **Bruneau & Reinhorn (2007) (OPC * years)** | | | **Bocchini & Frangopol (2012) (OPC)** | | |
|---|---|---|---|---|---|---|---|
| | Scenario | I | II | III | I | II | III |
| Overall | 2005 – 2013 | 361.08 | 313.83 | 392.48 | 56.17 | 63.1 | 52.29 |
| (1) | 2005 Jan. 1– 2010 Mar. 31 | 253.87 | 167.92 | 253.87 | 49.22 | 66.42 | 49.22 |
| (2) | 2010 Apr. 1– 2011 Aug. 26 | 49.44 | 51.25 | 49.44 | 61.97 | 60.58 | 61.97 |
| (3) | 2011 Aug. 27 – Sep. 1 | 1.4 | 0.41 | 0.38 | 0 | 59.09 | 61.51 |
| (4) | 2011 Sep. 2 – 2012 Oct. 27 | 37.41 | 48.24 | 37.41 | 58.43 | 57.69 | 58.43 |
| (5) | 2012 Oct. 28 – Nov. 5 | 2.47 | 0.88 | 0.9 | 0 | 56.23 | 54.82 |
| (6) | 2012 Nov. 6 – 2013 Nov 6 | 16.49 | 45.13 | 50.48 | 83.51 | 54.87 | 49.52 |

## Discussion

The analysis results shown in Table 6 quantify the concepts presented by Bruneau and Reinhorn, and by Bocchini and Frangopol, and underscore the differences. Four points warrant further discussion. First, the overall results of the analysis demonstrate that the method of Bruneau and Reinhorn accumulates resilience loss through the period of analysis. It helps decision makers to understand degradation over time and set thresholds

These measures represent the cumulative loss of functionality over time and the average functionality per unit time, respectively. The measures for each time period using each method are shown in Figure 7 and Figure 8, respectively. Figure 7 (Bruneau and Reinhorn's measure) shows resilience loss. As the resilience loss is cumulative over the period being considered the short periods of time when the road is actually closed show only minimal resilience loss and that the loss due degradation is much more significant.  Figure 8 (Bocchini and Frangopol's measure) shows the functionality per unit time. The figure clearly shows the impact of road closure on functionality.

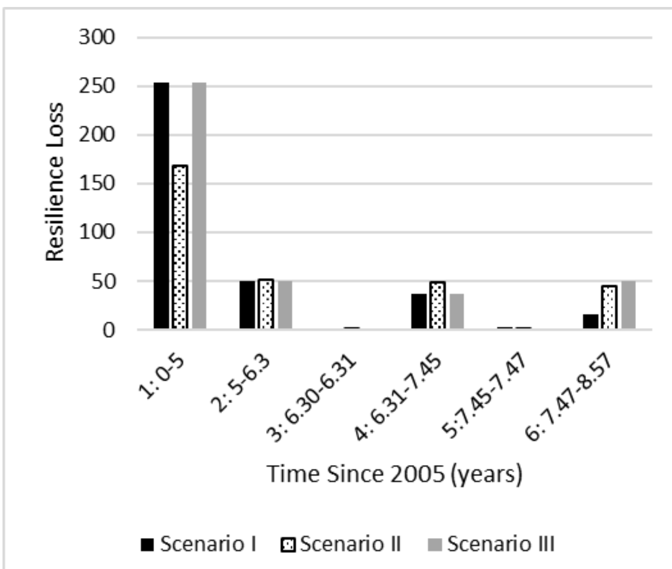



**Figure 7. Bruneau and Reinhorn Resilience Measures**

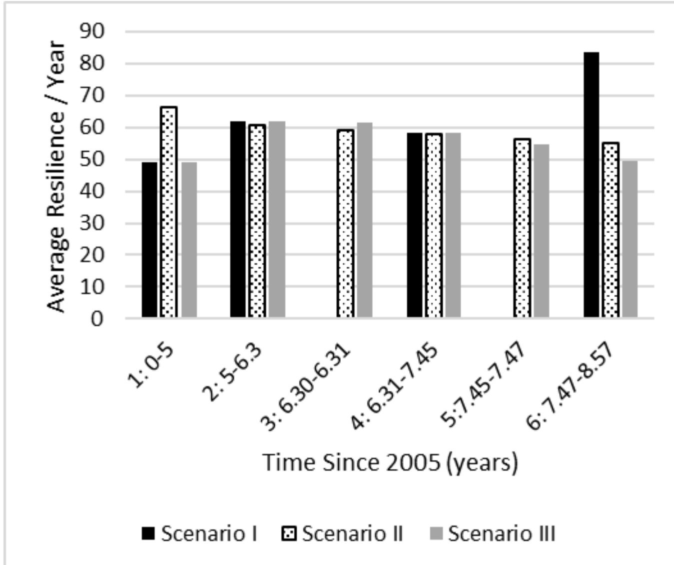



**Figure 8. Bocchini and Frangopol Resilience Measure**

## Interpreting Resilience Measures

These measures are difficult to interpret and connect to decisions. The Bruneau and Reinhorn measure is unit-less, where the Bocchini and Frangopol measure is a unit-less number per year. If the Bruneau and Reinhorn measure is divided by the time frame (in years), then the two measures (Bruneau and Reinhorn and Bocchini and Frangopol) sum to 100. For example, in Scenario I, time period (1), the resilience using the Bruneau and Reinhorn method is 253.87 years over a five-year period, or 50.77. This complements the resilience loss measured by Bocchini and Frangopol as 49.22. The two measures sum to 99.99, approximately 100, due to rounding errors.

These measures are most useful when comparing the measures between different scenarios during any single time frame. Tracking resilience over time requires careful consideration of the units as the Bruneau and Reinhorn (2003) measure captures the resilience loss over the specified time period, where the Bocchini and Frangopol (2012) measure captures the average resilience per year. However, investment decisions influence more than a single time frame. For example, the role the bridge plays in improving resilience is barely captured using the Bruneau and Reinhorn measures as the time periods in which the bridge reduces the resilience loss are so short. Computing the resilience measures over the entire period 2005-2014 gives a clearer picture as shown in Table 7 with each row representing a scenario and the columns representing the two methods. If the pavement deterioration is impeded once the bridge is constructed, Scenario II is clearly the better option. However, if the road continues to deteriorate then the bridge (Scenario III) is not necessarily the best option as Scenario I enhances the functionality in the last two years and the resilience improvement is not as clear for Scenario III. Nevertheless, the ranking of the scenarios is the same using either resilience measure.

**Table 7: Overall Resilience Measures 2005-2014**

| Method | Bruneau and Reinhorn (Resilience Loss) | Bocchini and Frangopol (Average Resilience/ Year) |
|---|---|---|
| Scenario I | 361.08 | 56.17 |
| Scenario II | 313.83 | 63.1 |
| Scenario III | 392.48 | 52.29 |

***What does resilience mean for life cycle cost?***

The resilience measures do not directly account for cost. A resilient facility, such as Prime Hook Road with a bridge added to reduce flooding, can also be an expensive facility. Comparison between alternatives must be made based on life cycle cost.

Using data provided by DelDOT and published data, we compared the incremental costs of operating Prime Hook Road for Scenario I and Scenario II over the life cycle using the following assumptions (based on the data and common practices):

- Road is closed 5 times every three years for an average of 3.4 days each time.
- Road is repaired each time it is closed ($12,334) and rebuilt every three years ($130,000)
- Each closure incurs an additional cost of $3,200 per day to maintain community access over private property. The costs include security and payments to the property owner.
- Incremental travel time during closures is $2000 per day based on 10 minutes per trip at $30/hour for two trips per day per household (assuming the road serves 200 households).
- The bridge costs $1.25m and has a life of 50 years.
- All other costs (routine maintenance and operations) are assumed to be equal.
- The discount rate is 5%.

Using this data, the equivalent annual cost for Scenario I is $77,500 compared to the equivalent annual costs for Scenario II of $79,400. While scenario I represents the least life cycle cost, this does not account for disruption and inconvenience. This data suggests that the bridge is a feasible alternative. The costs for Scenario III were not computed as they exceed those for Scenario II as the road was assumed to continue to deteriorate after the bridge was built and a reconstruction was required.

***Is resilience just another level of service, or performance measure?***

Performance is the degree to which a facility serves its users and fulfills the purpose for which it was built or acquired (Uddin, Hudson, W. R., & Haas, 2013). Resilience and resilience loss as measured here are functions of two commonly used performance measures – condition and capacity. Resilience is another performance measure as it captures the degree to which the pavement provides a functional riding service. The real challenge comes in learning to interpret the measure.

***How does resilience recognize the number of users affected by a disruption?***

In this case the resilience members do not account for the number of users affected. With only 200 homes at Prime Hook, the resilience measures are the same as if there were 2000 homes. This is one of the significant limitations of using functionality to capture resilience.

***Is resilience an appropriate metric for an objective function or is resilience part of multi-attribute decision making?***

The objective is to either maximize resilience or minimize the resilience loss. Integrating resilience into a multi-criteria decision-making strategy is presented in  (Dojutrek, Labi, & Dietz, 2016). This methodology also facilitates accounting for other performance measures such as safety, and service while recognizing budget constraints using well understood methods.

***How does resilience relate to sustainability?***

The UN World Commission's "Our Common Future" (Brundtland Commission, 1987) provides the most widely accepted definition of sustainability: "meeting the needs of the present without compromising the ability of future generations to meet their own needs". Many of the concepts associated with sustainability are rooted in principles of conservation and the modern environmental movement. From the Clean Air Act Amendments (1990), to the Clinton administration's President's Council on Sustainable Development to the Department of Energy's Better Buildings Initiative (National Research Counci, 2011), policies and programs are fragmented across many agencies and organizations. Over the past three decades the focus has shifted from environmental sustainability to the triple bottom line: economic, environmental and social sustainability (National Research Council,

2009) . Many of these principles such as smart growth and new urbanism share some common elements with resilience However, resilience is more event focused (McNeil, 2017).

***Is resilience the complement of vulnerability?***

Vulnerability is described as a concept capturing the consequences but not the probability of a disaster event (Faturechi & Miller-Hooks, 2014). Consistent with this description, (Dehghani, Flintsch, & McNeil, 2017) “define the vulnerability of a network based on the expected network performance that results from all conceivable disruption scenarios for a network at a particular state.” In contrast, Francis and Bekera (2014) connect the two concepts, vulnerability and resilience, in a framework for resilience analysis, emphasizing vulnerability assessment to identify the hazards, threats or shocks and their probability of occurrence (Francis & Bekera, 2014). Alternatively, resilience is related to connectivity, and vulnerability is related to accessibility, but both related to robustness, reliability and friability (Reggiani, Nijkamp, & Lanzi, 2015).

In our retrospective evaluation of resilience, the events have been defined. However, measuring resilience to support decisions will require vulnerability assessments.

## CASE STUDY 2: I-95 NORTH CAROLINA

### Overview of the Case Study Area and Event

Interstate 95 (I-95) runs from Maine to Florida along the eastern seaboard of the United States. This significant route is heavily traveled, carrying heavy volumes of passenger and truck traffic. The 292-km (95-mile) long, four-lane wide section of I-95 in North Carolina diagonally crosses the eastern part of the state from the northern border with Virginia to the southern border with South Carolina. In 2015, average annual daily traffic (AADT) along I-95 in North Carolina was between 32,000 and 40,000 vehicles per day. The route is owned and maintained by North Carolina Department of Transportation (NCDOT). In early October 2016, rainfall from Hurricane Matthew caused the closure of I-95 in North Carolina. In addition to flooding, a major washout and bridge damage disrupted travel requiring significant detours. Flooding and damage also closed many alternate routes. In this case study we focus on I-95 and the alternate routes recommended by NCDOT.

The chronology of events between October 7, 2016 and October 18, 2016 is shown in Table 8. This chronology was assembled from news reports and NCDOT news releases. The data is not intended to be comprehensive or complete but to provide a realistic scenario. Detours suggested by NCDOT (NCDOT., 2016) were used to develop a representative network. These detours and study area are shown on the map in Figure 9.  To understand the impact of I-95 closures we model the diversion from I95 to the routes shown on the map in Figure 9 as a network model represented in Figure 10 where links are individual road segments and nodes are the junction of links. We use a deterministic routing and ignore congestion and closures on local roads. In the nework representation shown in Figure 10, Node 1 represents the junction of I-95 and US-64 (Exit 138) and node 4 represents the junction of I-95 and I-74 (Exit 13). For southbound traffic we use two intermediate nodes: node 2 (Exit 119) and node 3 (Exit 81). For northbound traffic we only model the network between node 4 (exit 13) and node 3 (Exit 81). Figure 10 also shows the length of each link with the free flow travel times in parentheses.

**Table 8. Chronology of Events**

| Date | Event | Assumptions made for analysis |
|---|---|---|
| October 7, 2016 | Normal operations. | Pre-event conditions. |
| October 8, 2016 | I-95 impassible at mile marker (MM) 44, MM 116, MM 119, and between Exit 25 and Exit 33. | Trips are reduced by 10 and 20%; SB: All through traffic follows NCDOT suggested detours; some local traffic follows detours; most local traffic uses alternative routes; NB: Most traffic uses NCDOT suggested detours. |
| October 10, 2016 | I-95 impassible between Exit 13 and Exit 31. | |
| October 12, 2016 | I-95 southbound (SB) closed between Exit 13 and Exit 56. | |
| October 12, 2016 | I-95 northbound (NB) closed between Exit 13 and Exit 22. | |
| October 15, 2016 | I-95 open except for restrictions SB at MM 78. | Users use one lane section rather than alternate routes. |
| October 18, 2016 | All lanes open. | Same as pre-event conditions. |

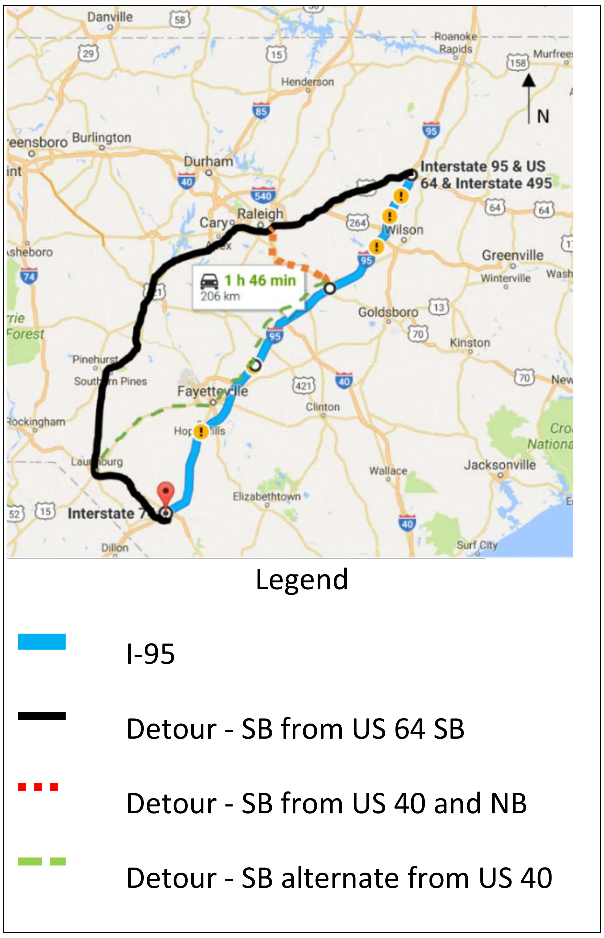



**Figure 9. Network Map (©2017 Google)**

***Data, Assumptions and Calculations***

To compute the resilience, numerous assumptions regarding the redistribution of traffic need to be made. The data and assumptions needed to compute steps 2 and 3 of the case study methodology are summarized in Table 9. Data in the table include traffic, number of lanes, link classification, K-factor, origin-destination matrix, traveler behavior, impact of congestion, peaking characteristics, value of time, and vehicle operating cost. While the event occurred in 2016, the annual average daily traffic (AADT) data is for 2015. Also noteworthy is the fact that the calculations indicated that no significant congestion occurred, but the media reports significant local congestion, illustrating the limitations of the modeling approach. The changes to travel times and traffic volumes were determined using two different models. Initially changes were tracked using a spreadsheet (Liu, McNeil, & Lee, 2017). An updated network model was thend developed (Ren, 2019).

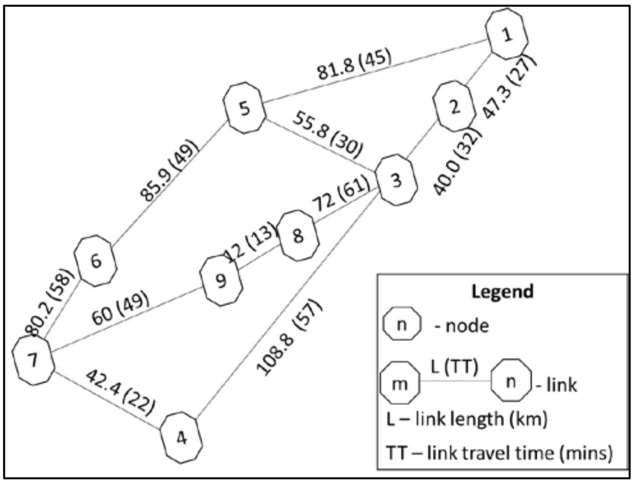



**Figure 10. Network Representation of Links and Nodes**

***Results and Discussion***

Given the extent of the disruption (many local roads were damaged and flooded in addition to I-95) and duration (12 days) of the flooding and damage, long detours were required. Using the recommended detour, the 208 km trip from Exit 138 to Exit 13 of about two hours increased to 290.4 km and took nearly three hours. Furthermore, the heavy volumes on I-95 meant that a lot of traffic was impacted.

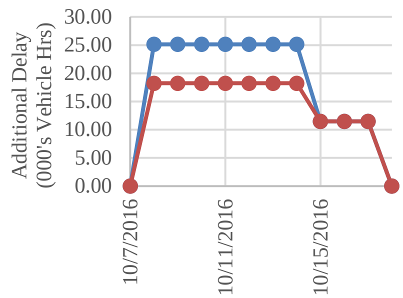
The performance measures and reciprocals of the recovery ratios for each day, resilience measures and costs are shown in Figure 11 for a 10% and 20% reduction in travel. All three measures show similar patterns; the loss of resilience is greatest during the closures nad reduces during partial closure. The measures are also sensitive to the percentage of trips not made. However, VKT is not sensitive to the closure of a single lane. The performance measures are intuitive and show that the disruption to the network is very significant both in terms of delay and VKT. As shown in Figure 11, these values can easily be monetarized showing an impact of approximately $8.5 million if 10% if the trips are not made. This does not account for the monetary loss when a trip is not made.

**Table 9. Data, Sources and Assumptions Used for Analysis**

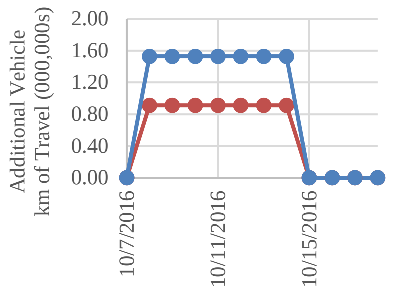
<table>
<tr><th>Data</th><th>Assumptions</th><th>Source</th></tr>
<tr><td>Traffic - AADT</td><td>AADT selected at location on route. Variations along link are ignored.</td><td>(NCDOT, 2015)</td></tr>
<tr><td>Number of lanes</td><td>All links are 4 lanes except for US-401</td><td rowspan="3">(Cambridge Systematics, 2013)</td></tr>
<tr><td>Link classification</td><td>Freeway or arterial</td></tr>
<tr><td>K-factor= 0.1</td><td>Proportion of AADT in peak hour</td></tr>
<tr><td>Origin Destination Matrix for AADT on I-95 (Vehicles/ day)</td><td><table>
<tr><td></td><td>Origins</td><td>1</td><td>2</td><td>3</td></tr>
<tr><td rowspan="4">Destin-<br>ations</td><td>1</td><td></td><td></td><td></td></tr>
<tr><td>2</td><td>8500</td><td></td><td></td></tr>
<tr><td>3</td><td>8500</td><td>3250</td><td></td></tr>
<tr><td>4</td><td>17000</td><td>3250</td><td>19750</td></tr>
</table>
Where the origins and destinations represents the nodes shown in Figure 10.</td><td>Inferred from vehicle counts</td></tr>
<tr><td>Behavior when roads are closed</td><td>10% and 20% do not travel; All through traffic (assumed to be 50%) uses detour; 50% of local traffic uses detour; Remainder of traffic uses local road with similar travel time to direct route.</td><td>Expert judgement</td></tr>
<tr><td>Impact of congestion</td><td>Bureau of Public Roads function: $t=t_0(1+\alpha(q/C)^{\beta})$,<br>where t = travel time, $t_0$= initial travel time, $\alpha$, $\beta$ = parameters, q = volume, C= capacity<br>Freeways: $\alpha$ = 0.83, $\beta$ = 5.50, C=2000 veh/hr/ln; Arterials: $\alpha$ = 1.00, $\beta$ = 5.40, C=1600 veh/hr/ln</td><td>(Cambridge Systematics, 2013)</td></tr>
<tr><td>Peaking characteristics</td><td>Four peak hours per day: two morning, two evening</td><td></td></tr>
<tr><td>Value of time</td><td>$20/hour</td><td>(Cambridge Systematics, 2013)</td></tr>
<tr><td>Vehicle operating cost</td><td>$0.3125/ km ($0.50/mile), approximated by US government reimbursement rate</td><td></td></tr>
</table>

The reciprocal of the recovery ratio is actually in units of link days and an undamaged network for the twelve days would have a value of 204 compared with the computed value of 285. This resilience calculation treats all links equally. For example, with some segments of I-95 closed, other segments are only accessible to local traffic and while travel times remained the same, traffic volumes decreased substantially and the reciprocal of the recovery ratio was very low. Using and interpreting this measure is difficult as it does not capture network redundancy and connectivity.

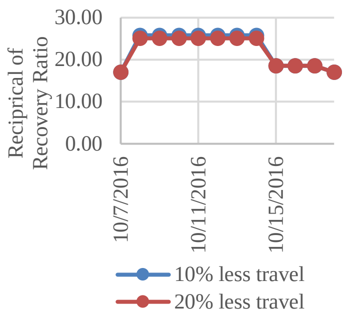
The analysis can be repeated for alternative scenarios and alternative assumptions. For example, the results show the value (in terms of vehicle delay) of reopening I-95 on October 15 even though the one-lane section created somewhat of a bottleneck. The analysis demonstrated: 1) Network impacts are important. The performance of I-95 improved as trips not taken experience no delay, but the network as a whole degraded. While the volume of diverted traffic did not cause a significant increase in congestion on the detour routes, it is important to consider this; 2) Performance measures used to compute resilience are the most easily interpreted. In this case, these measures can also be monetarized; 3) Resilience based on recovery ratios is not very intuitive and difficult to connect to decisions. This measure also treats also links equally.




| Reduction in travel | 10% | 20% |
|---|---|---|
| Resilience (000s veh hr) | 210.4 | 162.2 |
| Cost ($M) | 4.21 | 3.24 |




| Reduction in travel | 10% | 20% |
|---|---|---|
| Resilience (000,000s VKT) | 10.7 | 6.4 |
| Cost ($M) | 3.35 | 2.00 |




| Reduction in travel | 10% | 20% |
|---|---|---|
| Resilience (link days) | 270 | 265 |

**Figure 11. Resilience Measures**

## CASE STUDY 3: ROBESON COUNTY NORTH CAROLINA

### *Context*

In early October 2016, Hurricane Matthew made landfall in North Carolina. Unprecedented rainfall in North Carolina closed 635 roads including a section of I-40 West in Johnston County that was closed for 7 days, and sections of I-95 North and South in Robeson and Cumberland Counties that were closed for 10 days (Robeson County, 2017).

Using a database of the 65 road closures in Robeson County and condition data provided by North Carolina Department of Transportation (NCDOT), this research analyzes the condition of 18 road pavement sections on 8 different roads that were damaged by the flooding and then repaired. The flooded sections of road were geocoded and could then be linked to the annual surveys of pavement condition. These surveys provided an assessment of roughness (using the International Roughness Index (IRI)) and rutting between 2012 and 2017. In all cases the 2016 data had been collected prior to the flooding.

To illustrate the types of data available, we look at three flooded segments on NC-72. NC-72 is 33 miles long running from Orrum in the south east of the county to Red Springs in the north east of the county through Lumberton, the county seat. The damaged locations are identified by the linear referencing system by milepost on NC-72. All three segments were flooded, damaged and then repaired. Table 10 tabulates the closure duration, AADT, damage, and repair costs.

**Table 10. NC-72 Closures and Damage**

| Location (based on milepost) | 8.5 | 15.21 | 28.7 |
|---|---|---|---|
| Initial Closure Date | 10/12/16 | 10/10/16 | 11/22/16 |
| Duration of Closure (days) | 56 | 22 | 70 |
| AADT | 7200 | 16000 | 2600 |
| Damage | Washout | Washout | Hole in road |
| Repair Cost | $66,400 | $53,400 | $240,800 |

North Carolina conducts pavement assessments annually. IRI and rutting data are available for all routes. Figure 12 shows the IRI NC-72 between 2011 and 2017 for three locations that were flooded. The first segment, beginning at milepost 8.5 has moderate AADT and was in relatively good condition before the flood and after the flood even though the road was closed for 56 days due to a washout. The second segment, beginning at milepost 15.21, has a high AADT. The road was closed for 22 days due to a washout. The road was replaced and the roughness declined significantly. The third segment, beginning at milepost 8.6 has low AADT and was in relatively poor condition prior to the flooding. Similarly, Figure 13 shows the rutting data. Consistent with Figure 12, the first and third segments are in the best condition. The heavily traveled second segment was repaired and showed an improvement.

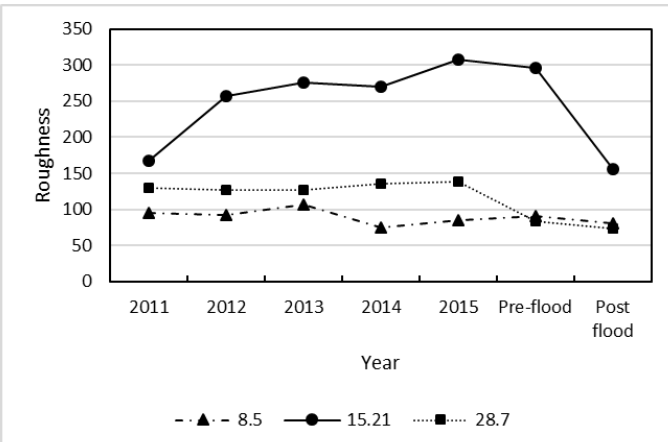



**Figure 12. NC-72 Roughness (IRI) 2011 - 2017**

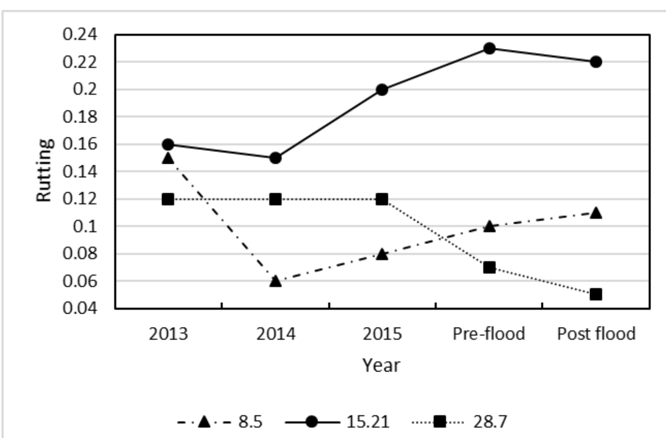



**Figure 13. NC-72 Rutting 2013-2017**

This research reviewed the available data for 18 segments of roads in Robeson County. The NC roads that were flooded after Hurricane Matthew and included in this study are:

- NC-72 (3 locations)
- NC-130 (3 locations)
- NC-904 (4 locations)
- US-74 (2 locations)
- NC-211 (1 location)
- NC-41 (2 locations)
- NC-71 (1 location)
- I-95 (2 locations)

All locations were damaged by flooding and then repaired.

## Measuring Resilience

In this case study we look at resilience measures in three ways. First as a snapshot of condition on a segment, second as functionality changes over time and third at the network level.

Looking at resilience at a point in time we use the original characteristics of resilience, robustness and rapidity, posed by Bruneau et al (2003). At the project or facility level, we measure robustness as the functionality when the event occurs and rapidity as the time it takes to reopen the road. For all 18 segments the robustness of the segment at the time of closure is zero. Rapidity, the duration of the closure varies from 3 days to 136 days. For NC-72, Table 10 indicates that the most resilient section, as measured by rapidity, is also the most heavily traveled. What we cannot tell from the data is whether this pavement section was designed to be more resilient, or NCDOT was resourceful when repairing the segment and recognized the importance of minimizing the resilience loss.

Using the second perspective, looking at resilience over time, we can use measures of resilience and resilience loss like those used in the Prime Hook case study. However, these measures provide little insight. Furthermore, for all segments, except I-95, roughness was reduced (due to the repair) or essentially remained constant. Attempts to analyze the rutting provided less consistent results.

Finally, the third perspective would consider the network impacts. While not directly computed for these segments, Liu et al (2017b) considered the additional travel time and vehicle kilometers of travel involved in the closure of I-95 in North Carolina as measures of resilience. The incremental cost and kilometers of travel due to detours is very significant and underscores the significance of the disruption. This is exacerbated as the many local roads that could serve as detours were also flooded.

## Interpreting Resilience Measures

It is important to note that the less rough, the less rutting and the faster a segment is repaired the more resilient the segment. The fact that all of these performance measures are minimized is often counter intuitive and adds to the challenge of interpreting measures of resilience.

Repairing these 18 segments in Robeson County cost NCDOT almost $8m, a significant investment. However, resources committed to events such as Hurricane Matthew go far beyond the monetary investment incurred in making repairs. North Carolina Department of Transportation stated (NCDOT, 2016):

> *NCDOT has demonstrated time and again that it has the skills and readiness to respond to emergency events with minimal impact on the ability to deliver its core mission. This operational resiliency was demonstrated most recently through the response to Hurricane Matthew in October 2016, which was a historic event in terms of rainfall and number of flooded river basins. At the height of the storm there were over 600 road closures, with 90% of the eastern division staff engaged in the response efforts (approximately 2,800 employees). Emergency crews worked around the clock to reopen the I-95 corridor by the start of the following week – just a few days later. Contributions from FHWA and FEMA are instrumental in NCDOT providing such a response which allows the State to rebound rapidly from emergency events.*

To truly capture resilience, we must think about the actions to mitigate damage, the resources required to prepare for the event, the resources required to respond to the event including closing roads and bridges, and then the repair strategy.

***Mitigation to improve robustness***

Protecting pavements from flood waters will certainly enhance resilience but flood protection is expensive and must be well placed (recognizing the hydrological conditions) and account for the nature and the frequency of the hazard. Similarly, pavements can be designed to withstand frequent inundation, particularly if the water is not moving.

***Preparedness to support both response and recovery***

Actions associated with preparedness include pre-positioning equipment and crews, the development of mutual aid agreements, contracts to support rapid response and repair, training of personnel, and installation of sensors and detectors. These actions include data and information to support communication, processes, personnel and materials.

***Recovery strategies to take advantage of resources and redundancy, and support rapidity***

Elegant algorithms to allocate resources to segments of the network to optimize recovery (for example, see (Henry & Ramirez-Marquez, 2012), (Zhang & Miller-Hooks, 2014)) resilience or rapidity are unlikely to be implemented. Recovery strategies must take advantage of redundancy in the network to post detours and allocate resources understanding what is at stake in terms of the more common performance measures, such as accessibility and mobility. Little seems to be gained by relabeling these measures as resilience measures. However, the concept of resilience is important.

***Post event deterioration***

While most of the immediate repairs are due to wash outs, removal of surface layers due to high flood water velocity, scour, and bridge damage, for pavements the lack of resilience may also manifest itself over time. Saturated subgrade, subbase and base layers behave differently. Detours impose additional traffic and loads far in excess of design loads. The result of the flooding is faster deterioration of pavements.

Our data on roughness and rutting did not capture these changes as this data is simply a single snap shot less than one year after the flooding. However, a large body of literature (see for example, (Gaspard, Martinez, Zhang, & Wu, 2007); (Zhang, Wu, Martinez, & Gaspard, 2008); (Sultana M. , Chai, Martin, & Chowdhury, 2015); (Sultana M. , Chai, Chowdhury, Martin, & Anissimov, 2018)) is devoted to modeling post flooding deterioration of pavements and this deterioration can be linked to resilience. The methods presented in these papers require extremely detailed data on pavement deflection, subgrade resilient moduli, design loads, structural numbers and how these parameters change over time with flooding. While we can infer approximate values for many of the parameters, this analysis underscored the need for a simple method to forecast deterioration after flooding.

## CASE STUDY 4: CLOSURE OF I-495 BRIDGE, DELAWARE

### Background

Delaware Bridge BR 1-813 spans the Christina River in Wilmington, DE. It was constructed in the 1970's and is made up of 38 spans with a total length of 4,390 ft. On Monday, June 2, 2014, Bridge 1-813 on Interstate 495 over the Christina River was ordered to be closed to due tilting support columns as shown in Figure 14. The cause of the tilting was determined to be the presence of a 50,000 ton pile of dirt on the bridge right of way. The pile had settled 4 feet into the soil, exerting a lateral force which acted on the piles and pile caps. Several of the pile caps exhibited large cracks.

Eight pier columns were affected. Four of the eight were repaired in place and reinforced. The other four required replacement. Temporary steel columns were erected; the existing columns dismantled and new concrete columns constructed. The foundation repairs are illustrated in Figure 15 and involved the addition of drilled shaft foundations and at grade beams. Temporary supports were used to ensure stability during the construction.

Interstate 495 was closed between exit 2 (Terminal Avenue) and exit 3 ($12^{th}$ St). Approximately 90,000 vehicles per day were affected by the closure. The southbound lanes were returned to service on July 31, 2014, followed by the northbound on August 24, 2014.

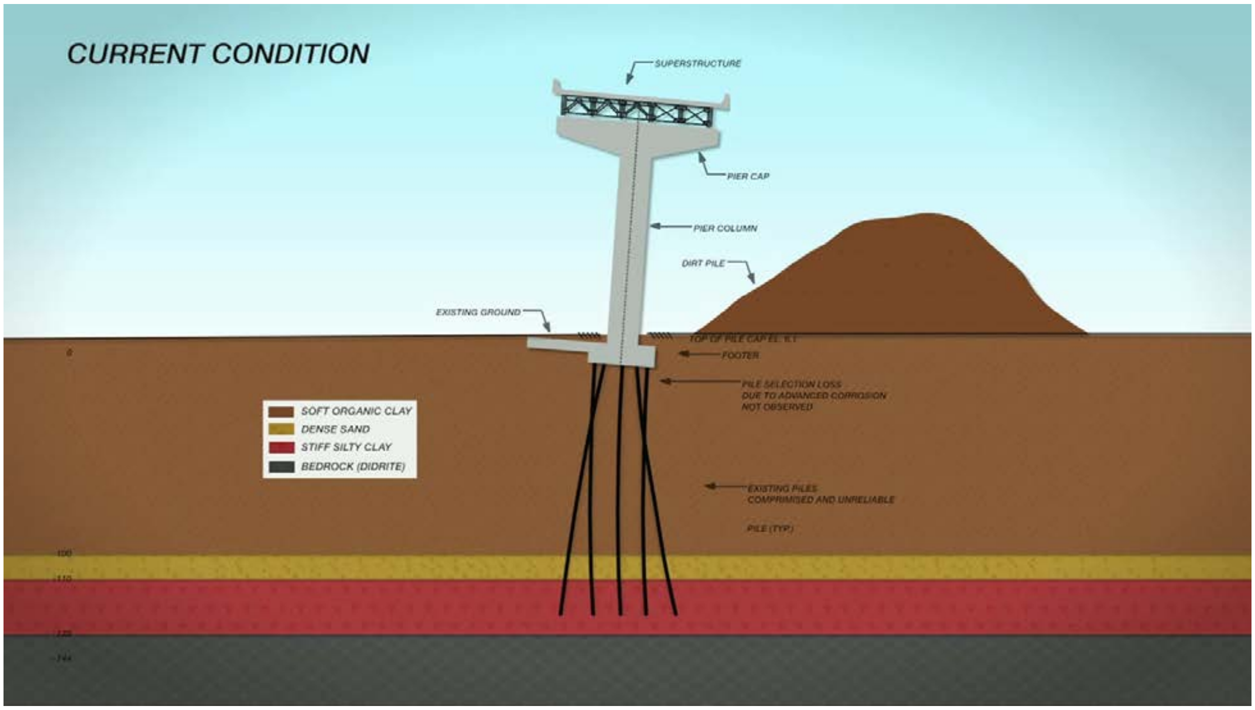



**Figure 14. Bridge 1-813 Damage**

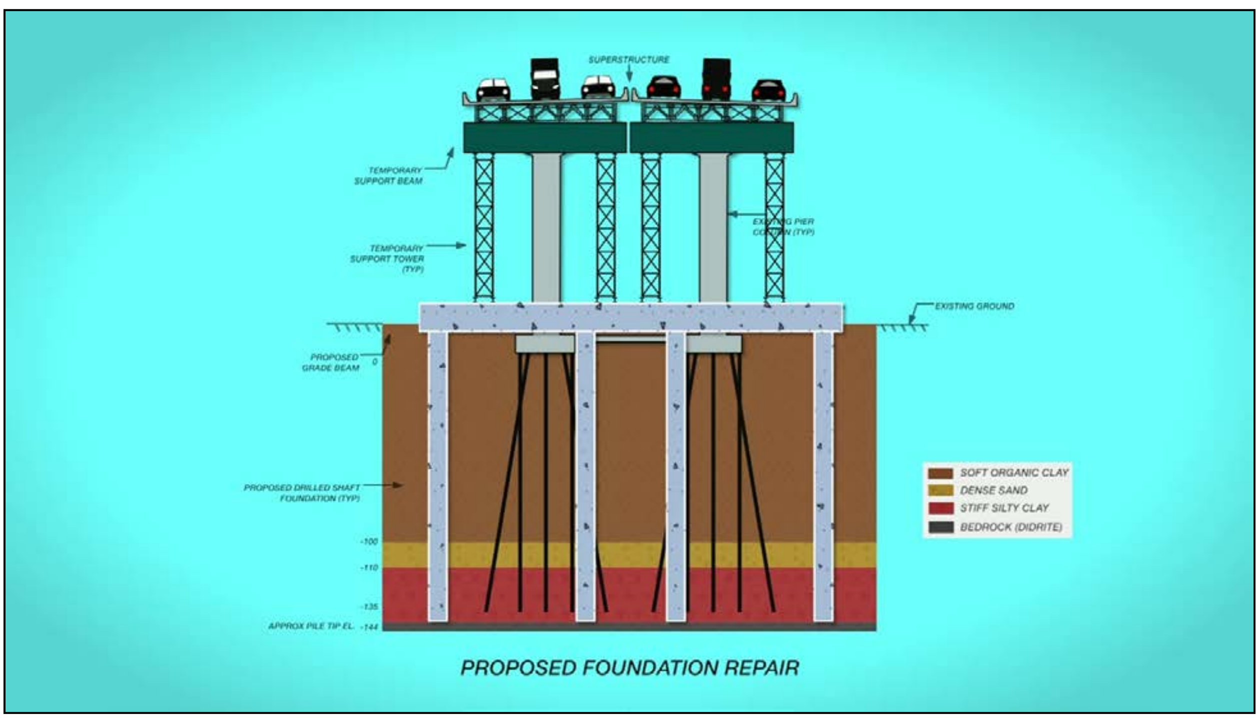



**Figure 15. Foundation Repair**

## Case Study Objective

The purpose of this case study is to demonstrate the roles played by redundancies in the transportation system.  agencies in responding to infrastructure closures and travelers adapting to the disruptions.

## Closure Process

Delaware Department of Transportation Bridge Division inspected the bridge the morning of the closure in response to calls received. The bridge condition was reported to the Secretary of Transportation via the Chief Engineer who consulted with the Governor and then ordered the bridge closed. This decision was made to close the bridge after the evening commute, since there was not an imminent hazard to drivers, but the cause of the tilting supports needed to be investigated. This gave the Traffic and Safety Divisions about 5 to 6 hours to plan how to close the bridge.

The work started in the Office of the Chief Traffic Engineer and Safety Program Officers. A basic plan was developed and then the Traffic Management Center was notified. North Division personnel were already responding to the area. It was determined that DelDOT had sufficient (though limited) resources to get the bridge closed, but would require support from contractors to establish a proper, long term closure. The Traffic division started moving available equipment (drums, barricades, signs, cones, etc.) to the scene while a detailed closure plan was developed. The DelDOT sign shop began making signs needed for the closure and detours as soon as requirements were identified.

The TMC began working with the Public Relations Section to get the word out. Local media outlets were notified about the closure and the expected traffic impacts. The obvious diversion was Interstate 95 through Wilmington. There would be limited access to 495 north and south of the closure area and there would be no through traffic. The TMC also notified the Interstate 95 Corridor Coalition; the Delaware River and Bay Authority; the New Jersey and Pennsylvania Departments of Transportation; Maryland State Highway Administration and the City of Wilmington of the intended closure and potential impacts to their highway networks. The City of Wilmington also had the additional burden of re-routed truck traffic to and from the

Port of Wilmington that would no longer be able to easily access I-495, but would instead be using local streets as part of the detour route.

The Interstate was closed at Exit 2 on the Northbound side and Exit 3 on the Southbound. This was accomplished using a “rolling closure”. A sufficient number of DelDOT and Delaware State Police vehicles with arrow boards and flashing lights were staged on the road shoulder; merged into traffic; occupied each lane and the shoulders and then slowly formed a road block at the exit ramp. Traffic was directed down the ramps by Delaware State Police and by City of Wilmington Police through the detours. Message boards along Interstate 95 and at the I-95 – I 495 split notified drivers that 495 was closed to through traffic and that they should take alternate routes.

During the day of June 2, the TMC was developing alternate signal timing plans for intersections along and near the detour routes that would see increased traffic. They were also working on where portable monitoring devices would be needed. It was determined very early that a new signal would be required at the bottom of the Terminal Ave ramp. This was a stop controlled intersection before the closure. Police were used at this location until the signal was installed to control queuing. A signal design was developed and approved and this new signal was in place on June 6, 2014. New striping was also completed and on-street parking was removed along Terminal Avenue during the detours.

During the first few days of the closure, DelDOT barricades, portable message boards, cones and barrels were replaced by equipment from Enterprise Flasher. Drums replaced cones along the lane closures. DelDOT’s equipment was needed to support all the normal maintenance and the upcoming Firefly event in Dover. The number of DelDOT motorist assistance patrol vehicles was increased and service hours increased from just peak hours to 24 / 7 eventually. These patrols were also valuable in reporting traffic conditions and assisting at incidents.

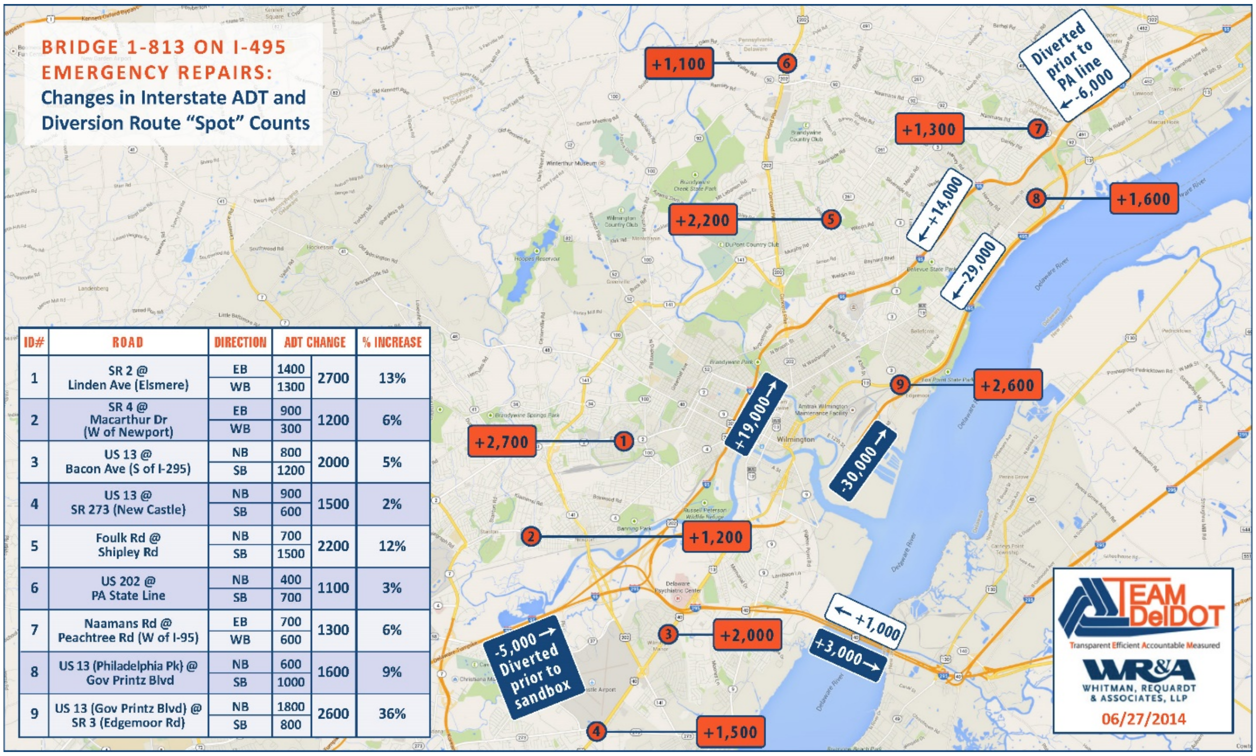
At the merge of I 495 and I 95 Southbound, there were two lanes for each set of traffic. However, with no traffic coming from I-495, a plan was developed to re-stripe the area to provide 3 lanes for I-95. New signing and striping were needed as well as re-paving a rumble strip area. This new area was ready for traffic on June 16th and helped relieve congestion along I 95.

As the scope of work was better understood to repair the bridge, a decision was made to prioritize the southbound side repairs due to the impacts on the City of Wilmington. The repairs to the southbound section was completed on July 31st (about a month ahead of schedule). Northbound lanes reopened on August 23rd (also, well ahead of schedule). The signal at the Terminal Ave off ramp was removed.

## Disruptions due to the Bridge Closure

All DelDOT sections were relying on the extensive sensor network that was in place. The closure diverted between 55,000 and 70,0000 vehicles per day off I 495. About 35,000 chose to use Interstate 95 and the rest chose other alternatives. The website for Firefly (a large, multi-day concert event in Dover) was updated to remind drivers about the closure and best routes to take. Information was also available at the Service Plaza on Interstate 95.

Figure 16 is a map showing the changes in ADT on major routes impacted by the bridge closure. For example I-95 southbound say an addition 14,000 vehicles per day and I-95 northbound 19,000 vehicles per day. Other roads impacted include SR2, SR4, US 13, Foulk Road, US 2002, Naamans Road and US 13.




| ID# | ROAD | DIRECTION | ADT CHANGE | | % INCREASE |
|---|---|---|---|---|---|
| 1 | SR 2 @ Linden Ave (Elsmere) | EB | 1400 | 2700 | 13% |
| | | WB | 1300 | | |
| 2 | SR 4 @ Macarthur Dr (W of Newport) | EB | 900 | 1200 | 6% |
| | | WB | 300 | | |
| 3 | US 13 @ Bacon Ave (S of I-295) | NB | 800 | 2000 | 5% |
| | | SB | 1200 | | |
| 4 | US 13 @ SR 273 (New Castle) | NB | 900 | 1500 | 2% |
| | | SB | 600 | | |
| 5 | Foulk Rd @ Shipley Rd | NB | 700 | 2200 | 12% |
| | | SB | 1500 | | |
| 6 | US 202 @ PA State Line | NB | 400 | 1100 | 3% |
| | | SB | 700 | | |
| 7 | Naamans Rd @ Peachtree Rd (W of I-95) | EB | 700 | 1300 | 6% |
| | | WB | 600 | | |
| 8 | US 13 (Philadelphia Pk) @ Gov Printz Blvd | NB | 600 | 1600 | 9% |
| | | SB | 1000 | | |
| 9 | US 13 (Gov Printz Blvd) @ SR 3 (Edgemoor Rd) | NB | 1800 | 2600 | 36% |
| | | SB | 800 | | |

**Figure 16. Changes in ADT (Source: DelDOT, 2014)**

Data from sensors on Interstate 95 showed the speed patterns for the daily commute as shown in Figure 17. The green line shows a typical day prior to the closure, the red and blue after the closure. The first morning following the closure, the congested period started an hour earlier and lasted an hour longer. These patterns were sustained for the first month of the closure.

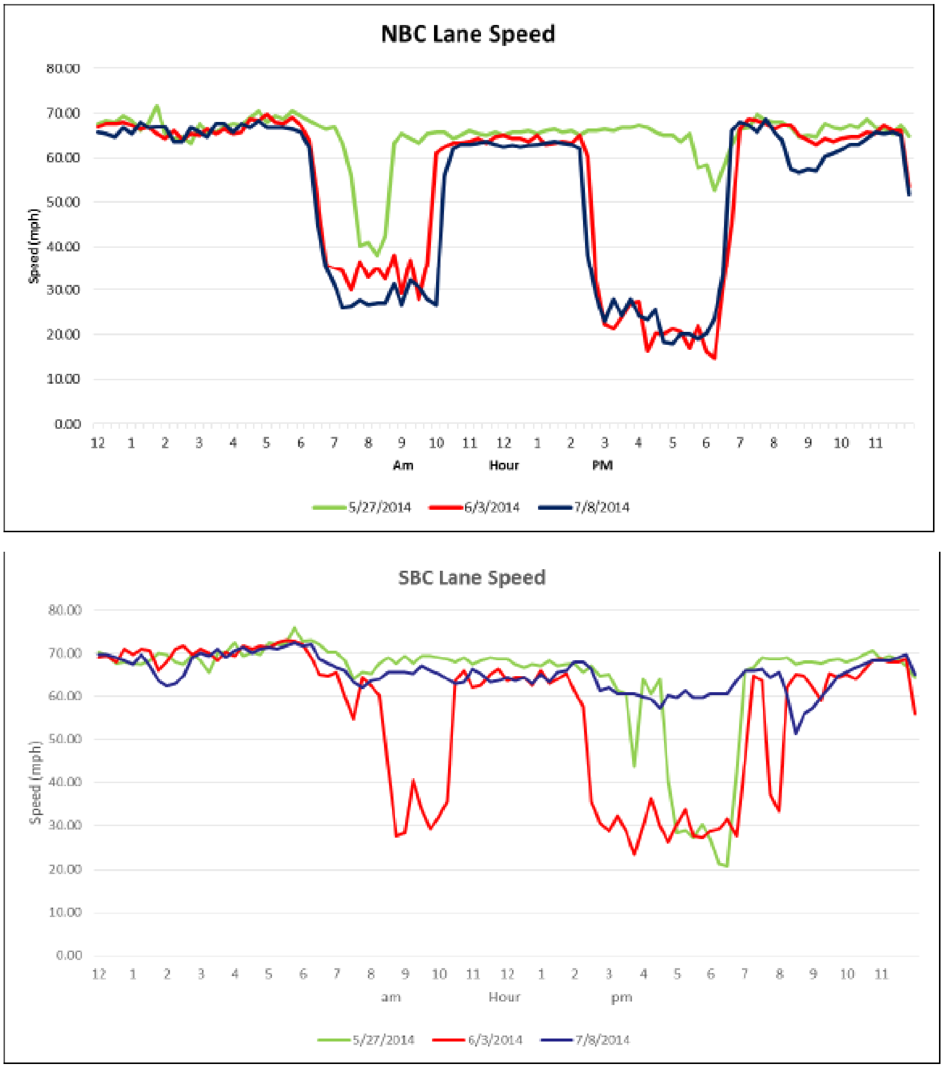



**Figure 17. Speed Data on I-95 by Time of Day for Three Selected Days**

Before the closure, about 95,000 cars used Interstate 95 and 495 to cross the Christina River. Following the closure, about 25,000 fewer cars were using the interstate. Drivers had immediately sought out alternate routes and continued to use those routes throughout the closure. These changes are shown in Figure 18.

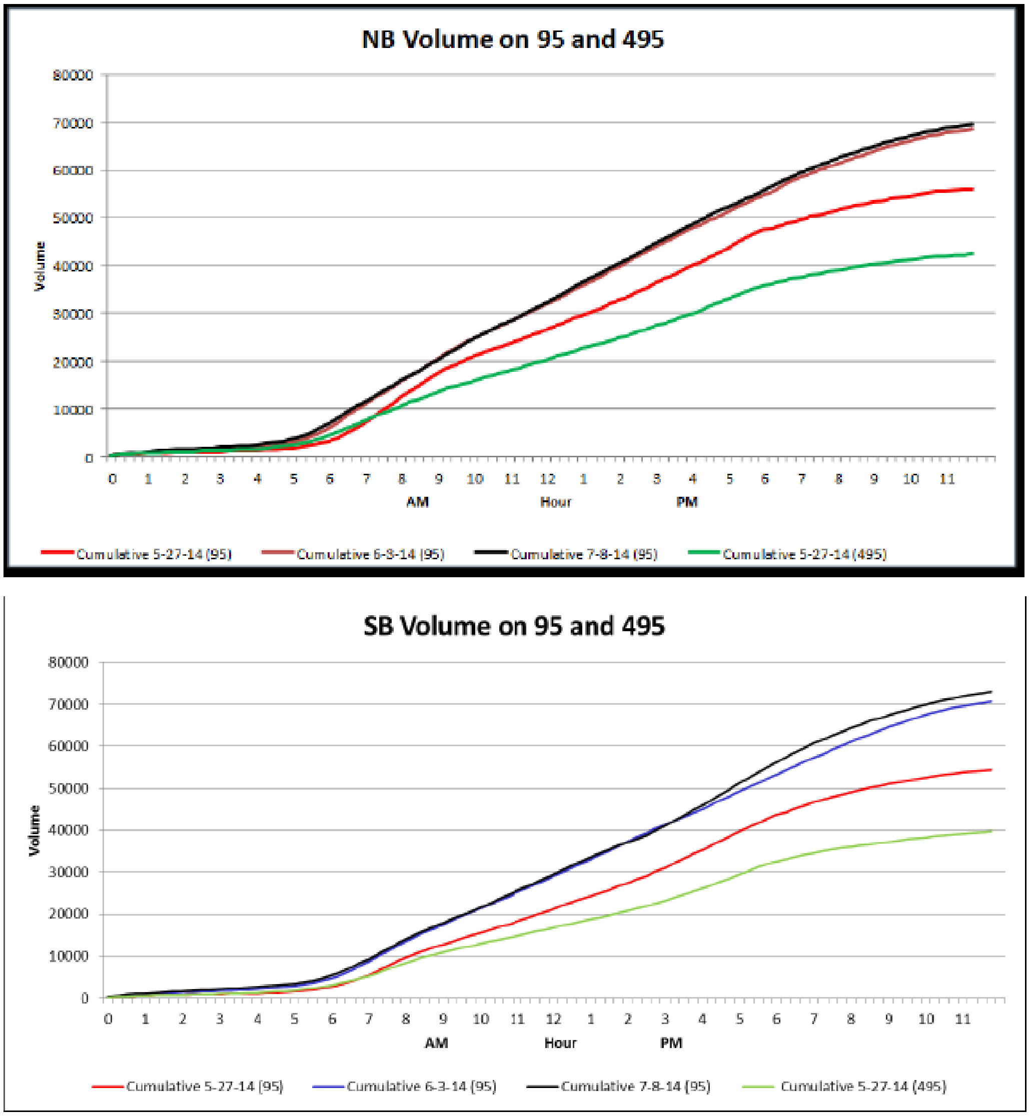



**Figure 18. Cumulative Travel Volumes on I-95 and I-495 by Time of Day**

## Discussion

This work provides insight into how agency operations can enhance resilience and how traveler behavior accommodates the disruptions following a major infrastructure closure. DelDOT was able to respond to the incident and put in place detours that took advantage of redundancies in the system. Uses modified their behavior, demonstrating individual resilience. The pattern that was present on the first day following the closure for departure time persisted throughout the first month. Users did adjust the routes they took with about 25% changing routes to avoid congestion. The morning congested period increased from 1 hour to 3 hours and the afternoon from about 90 minutes to around 4 hours. The start of that congested period showed a dramatic response by the public on even the first day of the closure. Drivers rapidly decide on alternative routes following major infrastructure closures. Decisions regarding times to travel were also quickly made and those decisions persisted throughout the closure.

Incidents such as this closure due to the physical condition of the infrastructure are due to external factors but could become more common as infrastructure funding lags the deterioration of our roads and bridges. In addition to attending to infrastructure renewal, it is critical to enhance emergency response capacities to reduce the effects of network disruptions (Zhao & Mao, 2009).

The case study also demonstrates the role network redundancy plays in system resilience. Existing routes were generally able to accommodate the traffic.

## CASE STUDY 5: SNOW STORM

The case study is not based on a specific event but a discussion with Delaware Department of Transportation to help us understand how operations deals with a major event such as a snow or a blizzard.  Specifically, we were interested in understanding actions taken to enhance preparedness and response and to see if we could see connections between resilience attributes such as resourcefulness and rapidity.

The response to a major snow event for the Delaware Department of Transportation now what starts in the 48-72 hours before the storm arrives. The response strategy was formed years earlier and is manifested in the large equipment purchases (snow plows, salt and brine equipment, etc.). With those purchases also goes the training of operators. When possible (but by budget limits), snow plow drivers attend simulator training, which can provide a realistic experience for operators and remind them of the issues with visibility and handling and anything else they may have forgotten since the last major snow event. All DelDOT operators are certified on equipment (equipment operator 1,2,3,4) and each certification allows them to operate larger equipment. All equipment is maintained and calibrated so it is ready when the snow arrives.

When a major snow event is predicted, managers begin the planning. Based on the storm's characteristics, a decision will be made whether or not to apply brine to the roads. Brine is generally applied during the night when traffic is lowest. Brine is used when the storm does not start with a significant amount of rain which would remove the salt coating from the roads. Brining can start 48 hours before the storm. Also, depending on the specifics of the storm, DelDOT may start salting roads within a few hours of the start of a storm.

When a storm prediction is received, an evaluation must be made regarding all maintenance and construction operations that are in progress. Construction or repairs may be halted. Contractors and DelDOT maintenance must ensure that adequate lane widths and turning radii are available for plows. During most months, steel plates are used as temporary closures for pavement openings. However, these plates can be struck and moved by plows and may be restricted in their use based on time of year. This will be specified in the contract for that specific job. Snow removal around a work zone where equipment or materials are stored is generally the responsibility of the contractor. DelDOT has looked at using independent contractors in addition to DelDOT maintenance personnel for snow removal, but has found that contractors in this area lack the equipment for large scale snow removal. Subdivisions may contract snow removal to local governments or contractors, which may be reimbursed by DelDOT.

Technology has also become part of the arsenal against snow. Snow accumulation and snow plow tracking are available on the DelDOT app and DelDOT maps (http://www.deldot.gov/map/). The Roadway Weather System provides information from stations around the state on pavement and air temperature, wind speed, visibility, etc. which can be used by managers at the Traffic Management Center (TMC) and drivers via the DelDOT app to monitor conditions. When conditions worsen to a certain point, the state implements a three-level system of driving warnings and restrictions. These levels are implemented by the Governor based on the recommendations of the Director of the TMC, the Director of Operations and Maintenance and the Secretary of Transportation.

As snow season approaches, the public receives reminders through Public Service Announcements about proper driving etiquette in the vicinity of snow plows and in case of driving restrictions. At the end of each snow season, the Department collects lessons learned. Plow drivers are reminded about blind spots when moving and especially backing large equipment and the hazard of striking overhead structures when a dump truck body is raised. Lessons learned are collected at the end of each season for incorporation into future training. Additional information can be found at http://deldot.gov/home/faq_snow/

In summary, the state aims to enhance resilience through mitigation (anti-icing), preparedness (purchasing and maintaining equipment and supplies, training personnel), and responding as quickly as possible.

## RESILIENCE, STATE OF GOOD REPAIR AND ASSET MANAGEMENT

### What are the Issues?

Evidence of increasing interest in resilience appears in legislation, technical papers and reports. This interest is motivated by an increasing awareness of the impacts of extreme weather events, climate change and other natural hazards. Weather events are perceived as more frequent and severe, they impact local, regional and statewide transportation services, and the disruption often lasts for months and sometimes years. Furthermore, the cost of repair and replacement imposes burdens on transportation agencies. For example, Hurricanes Mathew (October, 2016) and Harvey (August, 2017) caused significant inland floods in Robeson County, North Carolina and Houston, Texas, respectively. Such events occur in a complex policy and funding environment and the consequences are exacerbated by network interactions and interdependencies with other types of infrastructure.

Moving Ahead for Progress in the 21st Century Act (MAP-21) (112th Congress, 2012), the surface transportation legislation from 2012, required performance-based management and the development of risk-based asset management plans. The subsequent 2015 legislation Fix America's Surface Transport (FAST) Act (114th Congress, 2015) reinforced this by explicitly mentioning resilience. The final rule "Asset Management Plans and Periodic Evaluations of Facilities Repeatedly Requiring Repair and Reconstruction Due to Emergency Events" requiring each State to develop and maintain a risk-based asset management plan for the National Highway System (NHS) to improve or preserve the condition of the assets and the performance of the system became effective October 2017 (FHWA, 2016). Mechanisms for accounting for risk in the transportation asset management plans (TAMP) vary with the nature of the risks in terms of both the exposure and the consequences.

Resilient transportation networks, capable of maintaining the designed capacity and mobility through the hazard event and able to recover the loss of functionality rapidly after the disasters, play a critical and holistic role in modern society and has been recognized by FHWA and state agencies, and academic research. Although the need for resilient transportation networks is recognized, an integrated, consistent, well-understood method to assess or quantify the resilience of transportation networks is still lacking.   For example, individual measures of resilience, robustness, rapidity, resourcefulness, and redundancy, different resilience perspectives, provide inconsistent and difficult to interpret performance measures.

This paper reviews the concepts of resilience in the context of the performance of the transportation network and the role of resilience in a risk-based asset management plan. This includes a review of the resources and tools to support risk-based asset management. Then, drawing on a review of twenty-eight published transportation asset management plans from state Departments of Transportation, the paper summarizes the approaches taken to risk management. The paper then reviews cases where the plans explicitly addressed resilience and identifies opportunities to better integrate resilience into the risk-based asset management plans. Examples, based on past flooding events, are presented that demonstrate the role of resilience related technical performance measures and their connection to the disaster cycle (preparedness, response, recovery and mitigation). Limitations and challenges are also presented.

## Resilience, Asset Management and Risk Management Concepts

Several AASHTO, FHWA and NCHRP reports focus on the concepts of resilience, asset management, performance management and risk management that are relevant to this study. While there is also a large volume of academic literature, the focus of this work is on the concepts relevant to state departments of transportation as the objective of this work is to connect the concepts of resilience to the decision-making tools used by agencies to improve system resilience.

### *Defining Resilience*

Early references to resilience come from sociology (Dynes, 1970) and ecology (Holling, 1973).  Over almost fifty years, the term has been used in many different fields and there are many definitions.  Resilience, defined by the Presidential Policy Directive-21 (PPD-21) (The White House, Office of the Press Secretary, 2013), is "the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions.” The AASHO definition of resilience “the ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events” and FHWA’s definition in Order 5520 “the ability to anticipate, prepare for and adapt to changing conditions and withstand, respond to and recover rapidly from disruptions” both capture recovery and change, important elements of resilience (Fletcher & Ekern, 2017).

Interest in resilience has increased as failures of aging infrastructure, the need for repair and improvement, and the increasing frequency and severity of extreme weather events disrupt the transportation system. This increasing interest in resilience is evident in the recent and current transportation legislation in the United States.

***Defining Asset Management***

Asset management is a strategic and systematic process of operating, maintaining, and improving physical assets, with a focus on engineering and economic analysis based upon quality information, to identify a structured sequence of maintenance, preservation, repair, rehabilitation, and replacement actions that will achieve and sustain a desired state of good repair over the lifecycle of the assets at minimum practicable cost. (23 U.S.C. 101(a)(2), MAP-21 § 1103) (112th Congress, 2012)

The fundamental elements of asset management are shown in the generic asset management process in Figure 19. The process begins by setting goals and policies, then develops an asset inventory, proceeds to condition assessment and performance modeling then alternative evaluation and program optimization, which includes information about budgets. The results are assembled into short and long-range plans and the program is implemented. Feedback is provided throughout the process but performance monitoring integrates the steps into a process involving continuous improvement. Asset management guidance can be found in the AASHTO Asset Management Guides (AASHTO, 2002) (AASHTO, 2012). For a more international focus, the international infrastructure management manual provides step by step instructions and case studies that go beyond transportation (Ingenium and Institute of Public Works Engineering of Australia, 2011).

The core principles of asset management (Cambridge Systematics, Inc, PB Consult, Inc. and Texas Transportation Institute , 2006) are policy driven; performance-based; analysis of options and tradeoffs; decisions based on quality information; and monitoring to provide accountability and feedback.

### *Performance Management*

"Performance management is a regular ongoing process of selecting measures, setting targets, and using measures in decision making." (Cambridge Systematics, Inc. and High Street Consulting Group, 2010) Like asset management the key issue is to identify goals and set targets and then use measures to accomplish those targets. The process has been directly connected to asset management through guidance on identifying performance measures and setting targets (Cambridge Systematics, Inc, PB Consult, Inc. and Texas Transportation Institute , 2006).

### *Risk Management*

The international standard ISO 31000 (International Organization for Standardization (ISO), 2009) defines risk as "the effects of uncertainty on objectives." An international scan describes risk management as one of the three pillars of strategic management, with the other two pillars being asset management and performance management (Curtis, et al., 2012). Building on these foundations a guide for state departments of transportation provides detailed information about risk management in the context of asset management and performance management (Proctor, Varma, & Roorda, 2016). The guide defines risk management as "the cultures, processes, and structures that are directed to the effective management of potential opportunities and threats."

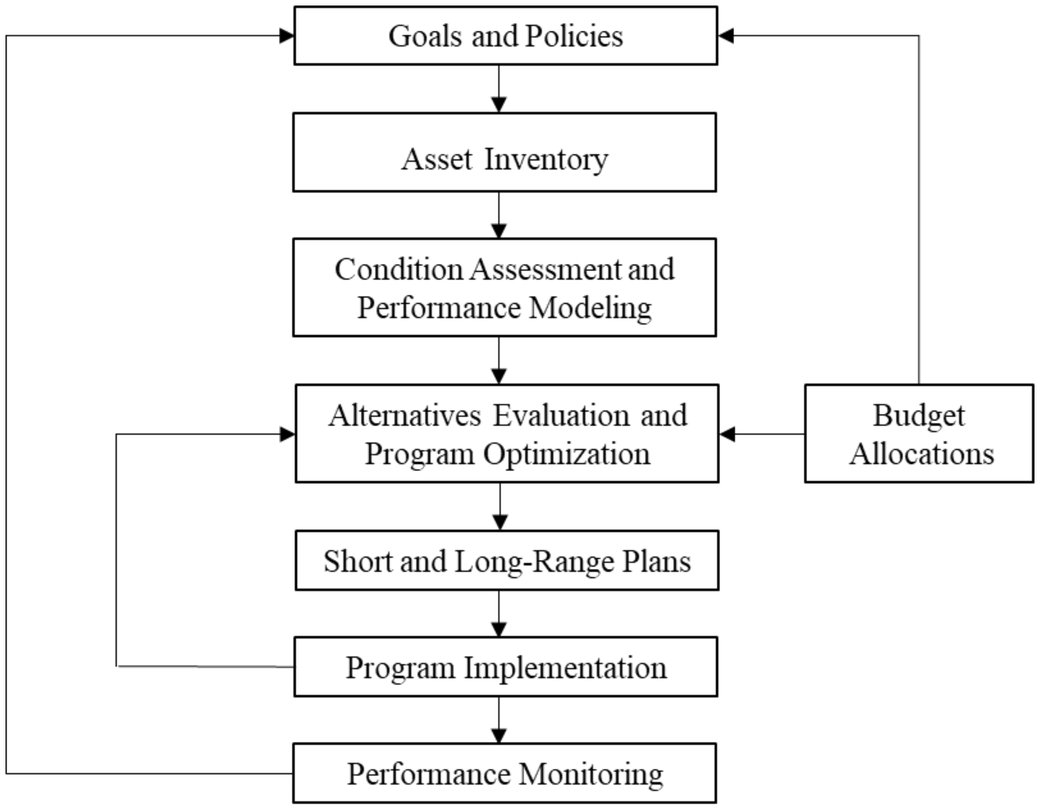



**Figure 19. Asset Management Process (based on AASHTO, 2002)**

***Connecting Resilience and Asset Management***

Fundamentally, the elements of asset management and the core principles connect asset management to performance management and risk management. By extension the connection to resilience is implicit. Beginning with a literature review on risk based transportation asset management, FHWA sponsored a series of reports defining and discussing the connections to risk-based asset management (Proctor & Varma, 2012) (FHWA, 2012) (FHWA, 2012) (FHWA, 2012) (FHWA, 2013) (FHWA, 2013). Fletcher and Ekern (2017) describe asset management as a facet of resilience. More importantly the role of resilience in asset management has been legislated. Moving Ahead for Progress in the 21st Century (MAP-21) (112th Congress, 2012) and then the 2015 Fix America's Surface Transportation (FAST) Act (114th Congress, 2015) require risk assessment, and performance measures, including resilience applied at the project, corridor, network or community level. MAP-21 also requires each state to develop a risk-based, performance-based asset management plan for the National

Highway System (NHS) to improve or preserve the condition of assets and performance of the system. These risk-based asset management plan must include:

- Pavement and bridge inventory and conditions on the NHS
- Objectives, measures, and targets
- Performance gap identification
- Lifecycle planning
- Risk management analysis
- Financial plan
- Investment strategies

FHWA provides detailed guidance on the development of the risk management section of the transportation asset management plan (FHWA, 2017). This guidance draws on two primary resources: 1) The Guide for Managing Enterprise-wide Risk (Proctor, Varma, & Roorda, 2016); and 2) FHWA's Vulnerability Assessment and Adaptation Framework (Filosa, Plovnick, Stahl, Miller, & Pickrell, 2017). These resources and related tools that are described in the following section.

The section of the TAMP on risk management should include (FHWA, 2016):

- *Set the context for risk management.*
- *Define key programmatic risks associated with implementation of the TAMP (e.g., cost escalations, budget cuts and environmental delays.)*
- *Define system risks that could adversely affect the NHS (e.g., asset failure and external events such as floods, earthquakes, and hurricanes.)*
- *Provide a map showing the NHS assets most at risk.*
- *Include a risk register that provides the following for each programmatic risk – likelihood of occurrence, consequences of occurrence, and mitigation activities.*

In addition, Title 23 Code of Federal Regulations (23 CFR) Part 667 "requires agencies to identify facilities that have required repair and reconstruction two or more times since Jan. 1, 1997, during formally declared emergency events."

The FHWA guidance document connects specific rules to specific methods and tools, suggests who should be involved in the process and an action plan, and identifies potential resources.

## Tools for Risk Management

### *Enterprise Risk Management*

The area of enterprise risk management (ERM) has been the subject of considerable research by the NCHRP, AASHTO and TRB. However, the ERM guide (Proctor, Varma, & Roorda, 2016) serves as a formal and systematic guide to designing, building, and operating an enterprise risk management program (ERM) to manage risk across the enterprise, programs, projects and activities connecting strategic management, performance management and asset management and builds on the ISO standard.

The guide provides step by step instructions following the ISO process. This process is very similar to the process presented in the AASHTO Asset Management Implementation Guide (AASHTO, 2012). Both are shown in Figure 20. The steps include: 1) Establish context; 2) Identify vulnerabilities; 3) Analyze risks; 4) Assess risks; 5) Plan for mitigation; 6) Mitigate risks. Again monitoring and review occurs throughout the process.

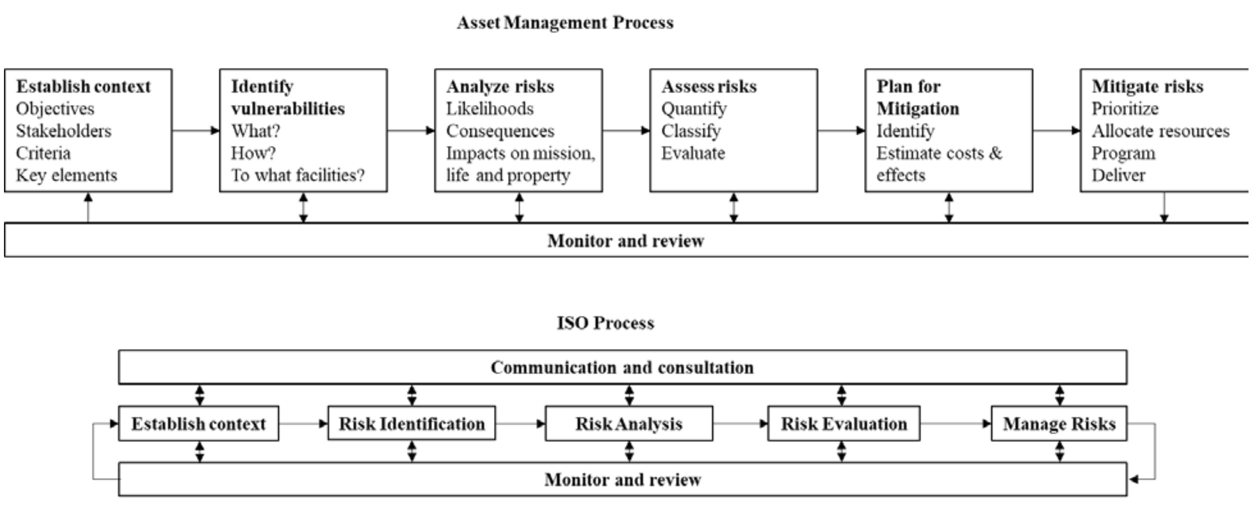



**Figure 20. The ISO and Asset Management Implementation Guide Process**
(Modified from (International Organization for Standardization (ISO), 2009) and (AASHTO, 2012))

Key steps for implementation are:

1. Adopt a risk management policy which includes assigning responsibility for risks and setting a risk appetite;

2. Provide the tools for managing risks including personnel, training, manuals, data management tools (such as risk tables and registers), and reporting mechanisms;

3. Integrate risks into key agency processes by setting priorities, populating the data, identifying communications and monitoring functions, and provide for updating.

Some of tools identified in the ERM Guide are briefly described in Table 11, as this chapter explores which tools are used in actual TAMP plans in the following section. The step in the risk management process and the tools considered include context setting and exercises; risk identification and workshops; risk analysis and understanding cause and effects, likelihood of risk, consequences, risk, determine cause, risk score and risk map; evaluating risks and risk appetite, and risk prioritization; managing risks and the five T's, and the three R's; communication monitoring and feedback and risk registers, scorecards, and risk indicators as metrics.

***FHWA's Vulnerability Assessment an Adaptation Framework***

An important element of the TAMP is to identify and manage high-priority asset risks. Such risks are unique to each agency and the analysis will vary with the sophistication and perhaps the experience of the agency. The vulnerability assessment framework supports a more sophisticated analysis involving modeling of the physical environment, the transportation assets, and the interaction between the natural and built environment. (Filosa, Plovnick, Stahl, Miller, & Pickrell, 2017) The vulnerability assessment framework provides the tools to do this. The process is similar to the risk management process in Figure 20 but the focus is on decision making. Building on already identified risks, the focus is on risk quantification and connecting the risk analysis to risk management. This framework is shown in Figure 21. The process begins by selecting objectives and defining the scope. Data is then compiled, and asset vulnerability is assessed and adaptation options identified. These options are then incorporated into the decision-making. Again, monitoring and review are built into the process.

**Table 11. Tools for Risk Management Identified in the ERM Guide**

| Step | Tool | Description |
|---|---|---|
| Context Setting | Exercise | Form teams, assign risks, clarify objectives and environment, set context. |
| Risk Identification | Workshop | Workshops are designed to engage experts in identifying risks using techniques such as brainstorming, interviews, Delphi, checklists, scenario analysis, cause and effect, and categorization. |
| Risk Analysis | Understanding cause and effects | Usually based on expert judgement |
| | Likelihood of the risk. | May be qualitative or quantitative; Set levels; Build likelihood table |
| | Consequences | Also, may be qualitative or quantitative;<br>Set levels;<br>Build consequence table |
| | Risk | Risk is the product of likelihood and consequences;<br>Assemble risk matrix |
| | Determine cause | Managing the cause, conduct analysis workshops and work groups, bow-tie analysis, structured what-if technique, root cause analysis, Monte Carlo simulation |
| | Risk score | Established a numerical score that maybe a normalized quantitative risk value. |
| | Risk map | Color code risk matrix |
| Evaluating Risks | Risk appetite | Sets threshold or tolerance for risk. May be value-based, program-based, cost-based, risk score-based or asset based. |
| | Risk prioritization | May be policy based, cost based or based on secondary benefits or impacts. |
| Managing Risks | Five T's (5 T's) | Tolerate, treat, transfer, terminate, take advantage of. |
| | Three R's | For catastrophic and disaster events: robustness (capacity to cope with stress), redundancy (alternative strategies) and resiliency (absorb, recover, adapt). |
| Communication, Monitoring and Feedback | Risk registers | Summarize the outcomes from the preceding steps |
| | Scorecards | Keeps track of activities |
| | Risk indicators as metrics | Integrates risk management with the process |

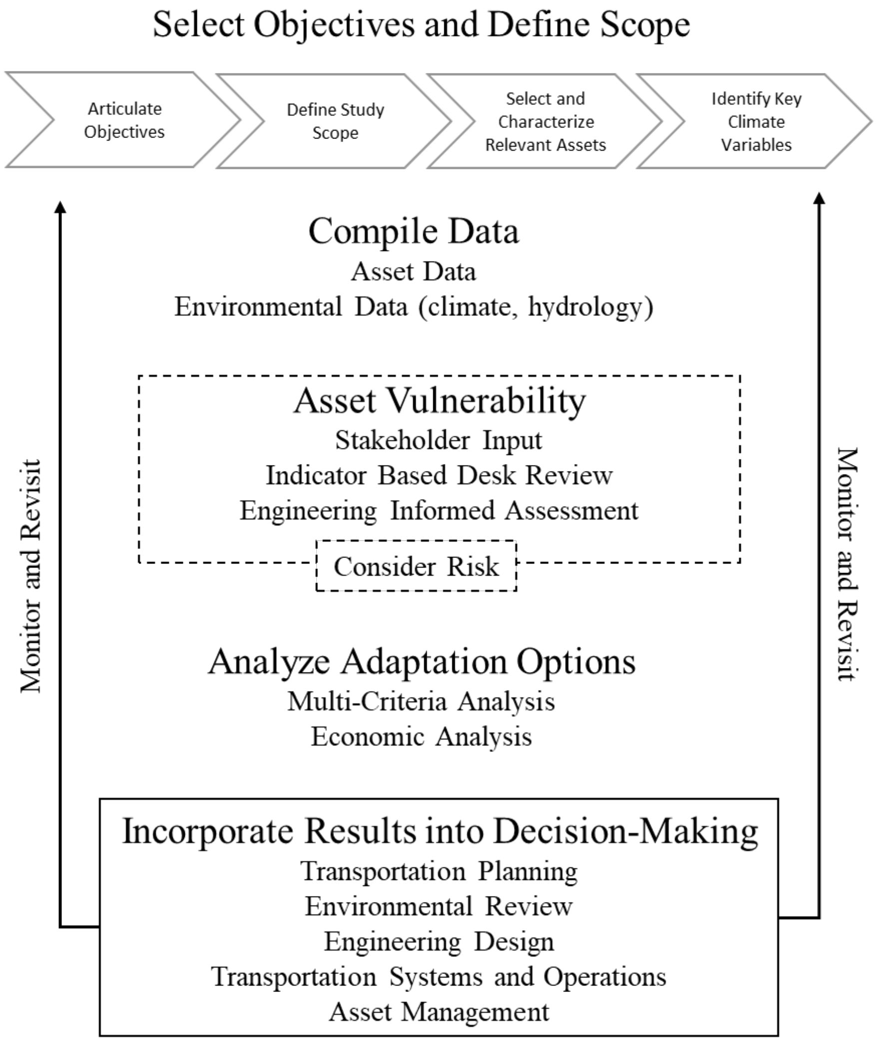



**Figure 21. FHWA's Vulnerability Assessment and Adaptation Framework**
(Modified from (Filosa, Plovnick, Stahl, Miller, & Pickrell, 2017))

## A Meta-Analysis of the Risk Management Sections of State Transportation Asset Management Plans

To understand how states are or are not integrating resilience into their TAMPs, twenty-six 2018 plans that are publicly available were reviewed. The majority of plans were obtained from the FHWA website that serves as a repository for TAMPs (http://www.tamptemplate.org/existing-tamp/?fwp_sections=11-risk).

This meta-analysis of the risk management sections of the TAMPs is based on a content analysis of the plans. While some states included assets other than roads and bridges, the scope in terms of the assets included was not considered. Also, some states present their risk management plan, where others talk about work to be completed or how they plan to develop the risk management section of the plan. The content analysis focused on the external threats relevant to resilience, the relevant actions, the tools used, the reports according to CFR 23 Part 667 and the references to resilience. The results are summarized in Table 12, Table 13 and Table 14.

Table 12 and Table 13 indicate:

- Most states focused on hazards relevant to their location.
- Most common tools are:
    - Assessment of the likelihood of an events and consequences (24 states, 92.3%)
    - Risk registers (19 states, 73.1%)
    - Risk matrix (18 states, 69.2%)
    - Workshops (18 states. 69.2%)
- The analysis of repeated damage to assets due to events involving a disasters declaration (CFR 23 Part 667) has not been completed by fifteen states (57.7%). For the eleven states that have completed the analysis, five states indicated that there were no assets in this category, and the remaining six states (California, Connecticut, Delaware, Montana, Oklahoma and Wyoming) reported recurrent damage to roads, bridges and embankments due to flooding and landslides.
- There is little focus on response and recovery strategies, although one element of the 5 T's, tolerate, is an important element of resilience.

To gain more insight into how resilience is treated, references to resilience, resiliency and resilient infrastructure, networks, systems, corridors, assets and facilities were identified in each plan. Six states (Delaware, Georgia, Illinois, Kansas, New Mexico, and North Dakota) of the 26 plans reviewed did not mention resilience. Of the remaining twenty states the references to resilience (or a derivative) are summarized in Table 14. Specifically, resilience is connected to the following themes:

- Resilience and vulnerability pilots: six (23.1%) states (California, Connecticut, Kentucky, Utah and Washington)

- Resilience as a goal or objective: nine states (34.6%) (Arkansas, Florida, Michigan, Minnesota, Montana, Nebraska, Rhode Island, South Carolina, Washington)
- Actions to improve resilience: six states (23.1%) (Minnesota, Oklahoma, Rhode Island, South Carolina, Utah, Vermont)
- Resilience tools: three states (11.5%) (Minnesota, Rhode Island, Vermont)
- Resilience as a performance metric: two states (7.7%) (Washington, Vermont)
- Resilience and risk management: eight states (30.8%) (Arkansas, Minnesota, Nebraska, North Carolina, Oklahoma, Tennessee, Washington, Wyoming)
- Resilience and asset management: three states (11/5%) (California, Nebraska, Vermont)
- Resilience and repeated damage: two states (7.7%) (Connecticut, Vermont)

While connections between asset management, risk management and resilience exist, there are many opportunities to enhance these connections. The following section reviews these opportunities.

**Table 12. External Events and Actions Covered in the Risk Management Section of Selected State TAMPs**

| Entity | External Events | Actions | Source |
|---|---|---|---|
| Arkansas | Earthquakes | Mitigation; Monitoring | (Arkansas Department of Transportation, 2018) |
| California | Floods, fires, earthquakes, geohazards, climate change | Risk programs, risk assessment, prioritization, mitigation | (Caltrans, 2018) |
| Connecticut | Extreme weather or climate | Program, project and enterprise levels | (Connecticut Department of Transportation, 2018) |
| Delaware | Hurricanes, storms, tornadoes, rain, flood | Risk assessment, mitigation | (Delaware Department of Transportation, 2019) |
| Florida | Flooding, tornadoes, wildfires, vehicle impacts, hazmat spills, retaining wall failure, landslides, scour, sinkholes | Mitigation | (Florida Department of Transportation, 2018) |
| Georgia | Earthquakes, floods, hurricanes, and tornados | Coordination with other agencies, mitigation | (Georgia Department of Transportation, 2018) |
| Illinois | Weather events | Mitigation: 5 T's; Response | (Illinois Department of Transportation, 2018) |
| Kansas | Extreme natural events | Emergency response plans; Continuity of Operations Plans (COOP); Coordination; Reprioritization; Mitigation | (Kansas Department of Transportation, 2018) |
| Kentucky | Earthquakes, floods, landslides, and sinkholes | Mitigation: 5 T's | (Kentucky Transportation Cabinet, 2018) |
| Michigan | Extreme weather and climate events | Mitigation | (Michigan Department of Transportation, 2018) |
| Minnesota | Floods, storms, earth movement, climate change | Avoiding risks, prioritizing risk prone assets for replacement, mitigating asset risks, working with partners and stakeholders | (Minnesota Department of Transportation, 2018) |
| Missouri | Earthquakes, blizzards, flooding, tornadoes | Activating EOC, creating and Incident Response Plan and using NIMS; Strategic assets added to the STIP | (Missouri Department of Transportation, 2018) |
| Montana | Extreme weather, natural disaster, scour | Emergency response protocol, set aside for repair, seismic retrofit, business continuity plan | (Montana Department of Transportation, 2018) |

| | | | |
|---|---|---|---|
| Nebraska | Fire, tornados, snow and floods | Engaging operation centers, prioritization, connection to asset management. | (Nebraska Department of Transportation, 2018) |
| New Mexico | Flooding, fires, slope failure | Institutional – training, communication, commitment; Mitigation: 5 T's | (New Mexico Department of Transportation, 2018) |
| North Carolina | In progress | In progress | (North Carolina Department of Transportation, 2018) |
| North Dakota | Not specified | Not specified | (North Dakota Department of Transportation, 2018) |
| Oklahoma | Extreme weather, seismic events | Mitigation: inspection, replacement or retrofit; Operation and emergency response<br>Incorporate resiliency into design standards | (Oklahoma Department of Transportation, 2018) |
| Pennsylvania | Extreme weather (flood risk) | Enterprise risk, mitigation strategies | (Pennsylvania Department of Transportation, 2018) |
| Rhode Island | Coastal hazards (sea level rise and storm surge), heat, drought, inland flooding | Environmental Resiliency Tool to help implement smart resilient policies and asset management strategies | (North Carolina Department of Transportation, 2018) |
| South Carolina | Natural disaster | Integrated into Strategic Plan; South Carolina Act 114 of 2007 used concepts including mitigating potential risks. | (South Carolina Department of Transportation, 2018) |
| Tennessee | In progress | In progress | (Tennessee Department of Transportation, 2018) |
| Utah | Extreme weather | Risk mitigation investments | (Utah Department of Transportation, 2018) |
| Vermont | Extreme weather and climate change | Resilience, monitoring climate change | (Vermont Agency of Transportation, 2018) |
| Washington | Seismic, scour, extreme events, climate change | Passive acceptance, active acceptance, transfer, mitigation/reduction, avoidance | (Washington State Department of Transportation, 2018) |
| Wyoming | Earthquakes, avalanches and rock falls; Winds, blizzards, flooding. | Mitigation through design and 5 T's | (Wyoming Department of Transportation, 2018) |

**Table 13. Tools Used for Risk Management in TAMPs in Selected States**

| Entity | ERM Process | Risk Identification Workshop | Risk Likelihood | Consequences | Risk Score | Risk Matrix/ Map | Risk Appetite | Risk Prioritization | 5 T's | Risk Registers | Vulnerability Analysis | CFR 23 Part 667: Assets with repeated damage |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Arkansas | | x | x | x | | x | | | | x | | no assets |
| California | | x | x | x | x | x | | x | | x | x | bridges; landslides |
| Connecticut | | x | x | x | | x | | x | | x | x | bridge |
| Delaware | | x | x | x | x | | | | | x | | roads; bridges |
| Florida | | x | x | x | x | x | | x | | x | x | NA |
| Georgia | | | x | x | | x | | | | x | | NA |
| Illinois | | x | x | x | x | x | | | x | x | | ND |
| Kansas | | x | x | x | x | x | x | x | | x | | NA |
| Kentucky | | x | x | x | x | x | | | x | x | x | NA |
| Michigan | | x | x | x | x | x | | | | x | x | NA |
| Minnesota | | x | | | | | | | | | | no assets |
| Missouri | x | | | | | | | | | | | NA |
| Montana | | | x | x | x | x | | | | x | | roads |
| Nebraska | | x | x | x | x | | | x | | x | | no assets |
| New Mexico | | x | x | x | | x | | | x | x | | NA |
| North Carolina | | x | x | x | | | | | | x | | NA |
| North Dakota | | | x | x | | | | | | x | | NA |
| Oklahoma | | x | x | x | | x | | x | | x | | roads, bridges, slopes |
| Pennsylvania | | | x | x | | x | | x | | | x | no assets |
| Rhode Island | | | x | x | | | | | | | x | NA |
| South Carolina | | x | x | x | | x | | x | | | | NA |
| Tennessee | | x | x | x | | | | x | | | x | NA |
| Utah | | | x | x | x | x | | x | | | x | no assets |
| Vermont | | | x | x | | x | | x | | x | x | NA |
| Washington | | x | x | x | | x | | x | x | x | x | NA |
| Wyoming | | x | x | x | x | x | | x | x | x | | bridges, road |

**Table 14. References to Resilience in TAMPs**

| Entity | Resilience |
|---|---|
| Arkansas | Safety and security goal: "Improve the resiliency of the transportation system to meet travel needs in response to extreme weather events."; Risk management: "Processes to incorporate resiliency into design standards." |
| California | Consequence of climate change; Climate change resilience pilots; Connected to information and decisions; Connected to coordination |
| Connecticut | Resilience discussed in the context of assets subject to repeated damage; Climate change and extreme weather vulnerability pilot |
| Florida | Objective: Reduce the vulnerability and increase the resilience of critical infrastructure to the impacts of extreme weather and events. |
| Kentucky | Extreme weather and other resilience pilot |
| Michigan | Bridge SOGR aimed at improving resiliency of the network. |
| Minnesota | System stewardship: Increase the resiliency of the transportation system and adapt to changing needs; Small programs: Ensure system resiliency to respond to unforeseen issues; "…acknowledging and understanding risk can help a transportation agency…. improve agency and infrastructure resiliency"; "Mitigating asset risks based on measurable characteristics that affect their resilience and exposure."; Scores facility level resilience (0-100) for bridges that then contributes to network resilience. |
| Montana | Mobility and Economic Vitality, and Freight Plan: Improve safety, security and resiliency of the transportation system. |
| Nebraska | Risk Management section includes subsection on resiliency.; Approach includes "improve infrastructure resiliency"; Argues that good asset management supports resiliency. Also connects to redundancy and operational efficiency. |
| North Carolina | Recognizes system resilience in the definition of project/asset risk. |
| Oklahoma | Incorporate resilience into design standards; Asset management processes addresses resilience by anticipating and mitigating external risks |
| Pennsylvania | "Phase 1 PennDOT Extreme Weather Vulnerability Study" Spring 2017 includes strategies to improve transportation system resiliency. |
| Rhode Island | Developing and Environmental Resiliency Tool; Committed to integrating sustainable, resilience designs; Collaborating with other agencies on Resiliency Council; and developing a statewide resiliency strategy; Previous studies have assisted environmental resilience efforts (statewide planning study and the development of STORMTOOLS) |
| South Carolina | "For South Carolina citizens and its economy to be competitive now and in the future, the State must maintain a functional and resilient transportation system."; Developing a resiliency plan for the state to protect key assets from disasters or emergency events. |
| Tennessee | Recognizes system resilience in the definition of project/asset risk. |
| Utah | "The I-15 Corridor Risk and Resilience (R&R) Pilot Project"; Approach consistent with FHWA's recommendations for evaluating Resilience & Durability to Extreme Weather events; Experience ensuring investment decisions increase system resilience. |
| Vermont | Transportation Flood Resilience Planning Tool; Develop transportation resilience plans for vulnerable assets and, where useful, watersheds; Incorporate resilience |

| | |
|---|---|
| | into the project selection and prioritization process; Enhance how asset management incorporates resilience planning into key program areas; Resilience and repeatedly damaged facilities |
| Washington | System-wide asset management objective: "Reduce the vulnerability and increase the resilience of critical infrastructure to the impacts of extreme weather and events."; Bridge objectives, performance measures and targets: "Design and preserve resilient structures"; Defines resiliency and vulnerability as a risk group; Skagit Basin pilot report (2015) – Creating a Resilient Transportation Network in Skagit County: Using Flood Studies to Inform Transportation Asset Management |
| Wyoming | Includes section on resilience citing PPD-21 and the need to apply principles of resilience. "Pavements do not currently have resiliency measures for natural or man-made events due to the rapid methods of temporary repair that are currently available. Resilience in bridges is covered by the risk analysis performance during the design process, including seismic ability and scour potential." |

## Enhancing the Integration of Asset Management and Resilience

To date resilience has primarily been used as a concept to explore the extent and duration of failure, or as a high-level goal or objective. While there has been some effort to explore resilience as a performance measure, and consequences of decisions, such measures are not widely used or well understood. Furthermore, most risk analysis is qualitative and only loosely linked to decisions. There are opportunities to integrate resilience into a risk-based approach to asset management through the risk analysis section of asset management plans. Computing the risk and then comparing that risk with the cost of potential actions provides a framework and trade-offs for considering alternatives for both pre-event mitigation and post-event recovery. Resilience captures the consequences of damage and failure, and then recovery. For example, the tradeoff between investing in more resilient design versus using resources to rebuild infrastructure after an event.

The elements of the asset management process (Figure 19) also support resilience: Goals and policies may include "improve the resiliency of the transportation systems"; Data is a critical component; Asset inventory includes network redundancy and condition assessment performance monitoring can be used to assess robustness or loss of resilience; and Alternative evaluation or program optimization include rigorous vulnerability and risk analysis serving as an input to risk management. These connections are reinforced when considering the attributes of asset management, these also support the analysis of resilience:

- Policy driven: goals and objectives set expectations and define overall priorities.
- Data driven: this data can be used to support the measurement of resilience.
- Performance based: supports the connection with stakeholders, accountability, and communication.
- Analysis of options and tradeoffs: supported by an array of tools that allow for analysis across a region or network, corridor or project.
- Connections with stakeholders: provides an opportunity to consider the perspectives of both users (for examples, consideration of disruption and inconvenience in terms of travel time, VMT, disruption duration) and owners (for example, consideration of damage, repair, recovery in terms of condition/location, capacity, accessibility)

However, an effective strategy has to be grounded in the principles of performance management, particularly the selection of appropriate performance measures, and the principles of risk management, particularly the rigorous quantification of vulnerabilities and consequences. In turn performance management and risk management require data and tools. Fundamentally, resilience may be more useful as a concept and organizing principle rather than measures and tools.

To illustrate these connections, examples the relationship between resilience and asset management decisions for highway infrastructure subject to flooding are considered. Decisions related to flooded highway infrastructure occur at all stages in the disaster life cycle as summarized in Table 15. The table shows the life cycle stage, timeframe, actions and goals. Mitigation activities reduce both the failure likelihood and the consequence of flooding; preparedness reduces the extent of flooding and the duration of flooding; an effective response helps to maintain continuity of operations; and recovery focuses on the restoration of the service.

Resilience measures related to performance or functionality and connected to the goals include travel time or cost, connectivity, and capacity. These measures can be used to quantify the network performance and identify the critical links. However, applying those performance measures in evaluating the flood resilience of the network may not reflect the actual recovery needs after the floods recede and roads reopen. The physical damage to inundated roads, embankment erosion, and damaged drainage structures can make links of the network impassible, but the long-term effects of inundation may also result in accelerated deterioration or loss of service life.

**Table 15. Actions and Goals Related to Flooding**

| Life Cycle Stage | Timeframe | Actions | Goals |
|---|---|---|---|
| Mitigation | Long term (months to years) | Raising and elevating; Building seawall/levy; Alternative designs; Inspection & identification of vulnerabilities | Reduce property damage<br>Reduce loss of network connectivity |
| Preparedness | Short to medium term (hours to days) | Sandbagging and similar actions; Prepositioning equipment; Training; Early warning systems, detectors, and sensors | Prepare infrastructure and personnel for response to event |
| Response | Immediate (hours to days) | Detours; Road closures; Debris removal; Temporary repairs; Adaptation of infrastructure to minimize disruption | Reduce loss of life, injury, and damage to property<br>Increase safety<br>Restoration |
| Recovery | Short to long term (days to months) | Repair and replacement; Redesign; Adaptation of infrastructure to minimize disruption | Restoration<br>Reduce loss of life, injury, and damage to property |

Three specific examples are used to explore these connections. The first two examples, the flooding of Prime Hook Road in Delaware and Interstate 95 in North Carolina are post event analysis of a project and corridor respectively. The third example, flooding in the region around Chur, Switzerland is a scenario analysis of a regional network to explore recovery strategies after an event.

Prime Hook Road in Delaware is a local road that was subject to repeated flooding. Quantification of resilience based on pavement functionality using two different measures found in the literature provided little insight into how to the address the problem (Liu, McNeil, & Herning, Integrating Resilience Concepts with Pavement Management: Two Case Studies, 2017). The resilience measures do not capture the service delivered. Prime Hook Road serves about two hundred households. While the disruption caused by flooding is of significance to any individual household, the overall consequences in terms of disruption and delay is relatively minor. A life cycle cost analysis clearly indicated that several alternatives were economically desirable (McNeil, Liu, & Ramirez-Villamizar, Infrastructure Resiience: From Concept to Performance to Decisions, 2019). This example illustrates the limitations of resilience and the importance of connection performance measures to life cycle cost.

Interstate 95 (I-95) in North Carolina was closed due to flooding and related damage from Hurricane Matthew for eleven days in 2016 and then for eight days in 2018 due to Hurricane Florence. I-95 the major north-south corridor on the East Coast of the United States serves between 30,000 and 60,000 vehicles per day in North Carolina (Ren, 2019). By measuring resilience in terms of the cost of disruption, Ren (2019) demonstrated that North Carolina Department of Transportation's strategy to expedite the repair of I-95 was economically justifiable. However, the long-term impacts of the flooding on local roads in terms of accelerated deterioration due to saturated subgrades and additional traffic due to detours is challenging to model. This example illustrates the role of resilience concepts of resourcefulness and rapidity in supporting emergency preparedness and recovery.

The road network in Chur, Switzerland is modeled by Hackl et al. (2018). Assuming a flood event damaging twenty-nine roads and bridges, a near optimal recovery strategy was developed using simulated annealing. Developing such as strategy is computationally intensive and could delay the repair strategy. Using a measure of resilience, the network robustness index, which captures changes in travel costs including disruptions, a strategy that performs almost as well as the near optimal strategy was developed (Liu Y. , McNeil, Hackl, & Adey, 2019). This example illustrates the role of resilience in recovery decisions.

## Integrating the Concepts

This chapter reviewed the concepts and tools for developing risk-based asset management plans, transportation system or facility resilience, and the connections amoung these concepts and tools. A review of twenty-six TAMPs from state DOTS suggests that resilience is not commonly integrated into the plans, although most plans mention resilience or resiliency. Furthermore, a wide variety of tools are used to support risk management.

While the analysis is limited by the content of the TAMPs, which is largely prescribed by the Code of Federal Regulations, the analysis does provide examples of the connections among the concepts and the role resilience can play in asset management. The plans also demonstrate that there are many ways in which resilience can be integrated with asset management, both qualitatively and quantitatively. However, the application of rigorous risk management tools is more likely to provide support for asset related decisions such as repair, maintenance and improvement. The decisions can be supported by measures of resilience.

Through the case studies it can be seen that the most applicable measures really depend on how the measure is going to be used. In the Prime Hook Road example, resilience measures related to functionality derived from pavement condition do not take into account costs or users so are simply an indicator not an attribute for decision making. In the North Carolina example, measuring changes in resilience in terms of user costs provides support for directing resources to recovery. In the Chur example, the network robustness index is a good indicator for prioritizing link repair. Such observations are key in the context of asset management related to relatively rare events that can have extreme consequences.

From the point of view of performance management, these resilience measures could provide input to a dashboard that reflects the current resilience of the segment or network and would reflect a wide range of events ranging from recurring congestion to system disruption. The idea of using resilience measures as constraints or performance thresholds is gaining some ground. ASCE is discussing a standard that might require a pavement to be available and accessible, say, 97% of the time with, say, a 99% probability. Such performance based design standards will require engineers to understand risk, vulnerability and resilience.

A more realistic strategy is to practice good risk management. Risk management is now an integral part of asset management, and agencies are more attune to the need for enterprise wide risk management. Risk registers, risk matrices and heat maps all are useful tools for improving the resilience of transportation assets.

Looking at the concept of resilience does help to identify gaps in our decision making. Specifically, supporting decisions related to each phase in the disaster cycle, the concept of resilience can be used to tailor decisions to to the risks identified in the risk management plan and contingent on the available resources. Examples of such decisions include strengthening infrastructure by enhancing design codes to reflect higher frequency or severity natural hazards (robustness); adapting infrastructure to climate change (robustness and redundancy); and leveraging limited resources by preparing efficient recovery plans for infrequent events with severe consequences (rapidity and resourcefulness).

## ANALYSIS AND FINDINGS

The five case studies and the chapter on resilience and asset management provide examples of the application of concepts and measures of resilience to operations and maintaining the state of good repair of pavements and bridges at a variety of spatial and temporal scales. The first two case studies, Prime Hook Road and the I-95 closure in North Carolina, show the calculation of resilience measures at the project level (Prime Hook Rd) and network level (I-95 closure in North Carolina). This chapter reviews the interpretation of these measures and concepts, how they can be used for decision making and suggests an outline for a guide for state DOTs on how to use resilience.

### What do resilience measures do and not do?

At the project level we have shown how the resilience changes if mitigation strategies are implemented. This calculation is very sensitive to the time frame selected as the reconstruction of the road near the end of the analysis period enhances the resilience of the do nothing alternative. The actual closure of the road has little impact on resilience.

Furthermore, the resilience measures based on condition do not consider cost. The $1.45m cost to construct the bridge on Prime Hook Road (Delawareonline, 2016) is very significant compared to the typical cost to provide alternative access during flooding events (estimated as $1000 per day) and for repair the road after the event (estimated to be between $20,000 and $125,000 per event (Delawareonline, 2016). The disruption costs also need to be considered in a life cycle cost analysis. The calculation of resilience in this case does not recognize that only 200 households are impacted. Most importantly, the calculation needs to include a risk analysis to determine how likely another event is. Archibald (Archibald, 2013) used both information gap theory and qualitative risk assessment to explore alternatives without any calculation of resilience and concluded that the qualitative risk assessment was intuitive, easy to communicate and gave results consistent with the more complex information gap models. The case study demonstrates that a life cycle cost analysis shows the total costs to be very similar.

Given the recent interest in performance management, resilience may be a useful measure to add to the suite of measures used for project prioritization. For example, DelDOT's Capital Transportation Program prioritizes projects based on improvement to safety, system operating effectiveness, multimodal mobility, economic development, social issues, environment and system preservation.  Each area is scored and then weights were determined using the analytical hierarchy process (AHP) (Delaware Department of Transportation, 2017). However, stakeholders will need to learn to interpret the measures.

At the network level we have shown how the resilience changes as the network recovers. We also demonstrated that the plots of resilience over time show similar patterns using each of three different measures. We also identified concerns with the recovery ratio when roads are closed and used the reciprocal of the recovery ratio. However this measure was not very sensitive to the number of users disrupted.

This case study underscored the challenges involved in coming up with mitigation/ adaptation projects that can impact the network. The level of flooding in Robeson County, North Carolina was unprecedented and hardening bridges and local roads to prevent damage throughout and provide flood-free alternative routes throughout the network is not a realistic solution. The strategy used by North Carolina Department of Transportation to repair high volume roads such as I-95 as fast as possible is likely the best solution.

In the case of two of the measures of network resilience – additional vehicle hours of travel and additional vehicle kilometers of travel – the resilience measures can easily be converted to cost. Our estimates range from \$5m to \$8m and can easily be compared to estimated costs for repair. For example, the emergency repair of I-95 in Robeson county cost approximately \$770,000.

From the point of view of performance management, these measures could provide input to a dashboard that reflects the current resilience of the network and would reflect a wide range of events ranging from recurring congestion to system disruption.

The idea of using resilience measures as constraints or performance thresholds is gaining some ground. The American Society of Civil Engineers is discussing a standard that might require a bridge to be available and accessible 97% of the time. Such performance based design standards will require engineers to understand risk, vulnerability and resilience.

## Does resilience provide new information?

The case studies and review of risk-based asset management plans suggests that resilience is another way to package existing information. The advantage of this repackaging is that it connects the concepts to events and what needs to be done in terms at different stages of the disaster cycle. In particular, resilience puts appropriate emphasis on recovery and opportunities to accelerate recovery and adapt to reduce disruption.

## What do state DOTs need?

There are many resources available to state DOTs to assist them in conceptualizing, measuring and modeling resilience to enhance the SOGR of pavements and bridges. There resources include guidance documents (Fletcher & Ekern, 2017) (AASHTO, 2015), and tools to integrate resilience, risk and vulnerability into asset management plans ( (FHWA, 2017) (Proctor, Varma, & Roorda, 2016) (Filosa, Plovnick, Stahl, Miller, & Pickrell, 2017). Based on our review of the literature, case studies and review of risk-based asset management plans, state DOTs need guidance to help them find these resources, characterize the problem, and then identify criteria to select which concepts, frameworks, measures or tools to use, and assess the validity of the approach. An outline for such a short guidance document is as follows:

**GUIDANCE FOR SELECTING AND USING RESILIENCE**

1. Introduction
   - 1.1. What is resilience – Short definition provided to set the stage. (1/2 page)
   - 1.2. Why use resilience – Examples of how resilience can be used. (1-2 pages)
   - 1.3. Connecting resilience to existing practices – Examples of resilience in practice. (1-2 pages with references to other examples and case studies)
2. Defining and characterizing problems related to resilience – Builds on the attributes presented in Table 1. (1-2 pages)
3. Resilience concepts – Short explanation of related terminology. (1-2 pages)

4. Resilience frameworks – Builds on the material in presented in this report and includes summary tables (2-3 pages)
5. Resilience measures - Builds on the material in presented in this report and includes summary tables (2-3 pages)
6. Resilience tools - Builds on the material in presented in this report and includes summary tables (2-3 pages)
7. Criteria to connect the right resources to the problem – Connects the problem attributes to features of the concepts, frameworks, measures and tools using checklists and tables (3-4 pages)
8. Assessing the validity of the approach – Includes questions to asks to validate the process (1-2 pages)

State Departments of Transportation should be able to use resilience to meet their needs. For example, Delaware Department of Transportation developed a "Strategic Implementation Plan for Climate Change, Sustainability & Resilience for Transportation" ( (Delaware Department of Transportation, 2017)) that addresses their needs without defining measures of resilience.

## CONCLUSIONS

This research developed case studies to better understand how resilience is used in practice. While most of the case studies focused on a retroactive analysis and flooding, the case studies demonstrated the challenges involved in measuring resilience and then using those measures. To compute resilience measures based on funcitionality at both the project and network level, significant amounts of data are required and models of the change in funcitionality over time. Once resilience is computed then the result has to be interpreted. Simulation allows us to understand the changes in resilience under different scenarios but most engineers and decision makers will not have any intuition that helps them to under whether a change in resilience is significant or not. In general, it is only once the change in resilience is reduced to dollars or time or number of users that we can say this change is important. Ultimately more experience is needed to operationalize the concept of resilience.

At the network the calculation of resilience as a performance measure based on functionality is computationally intensive requiring network models, link performance funcitons, origin destination matrices and network assignment models. The analysis used in this research is relatively crude based on deterministic network assignment to re-route traffic due to flooding and damage. This is one example of many opportunities to improve this type of analysis. Others include accounting for heavy vehicles, reviewing the impacts on pavement degradation of re-routing traffic, better modeling of bottlenecks, recognition of the impacts on the local network, and interactions between other events. Our analysis also used many assumptions that warrant further exploration.

The review of risk-based asset management identified many opportunities to include risk, vulnerability and resilience in analyses to support the SOGR of pavements and bridges. There is where state DOTs have an opportunity to integrate resilience into existing processes and influence SOGR.

## Bibliography


112th Congress. (2012). Moving Ahead for Progress in the 21st Century Act. Retrieved July 15, 2019, from https://www.govinfo.gov/content/pkg/PLAW-114publ94/pdf/PLAW-114publ94.pdf

114th Congress. (2015). Fixing America's Surface Transportation Act. Retrieved July 14, 2019, from https://www.govinfo.gov/content/pkg/PLAW-114publ94/pdf/PLAW-114publ94.pdf

AASHTO. (2002). *AASHTO Transportation Asset Management Guide.* AASHTO.

AASHTO. (2012). *AASHTO Transportation Asset Management Guide—A Focus on Implementation.* AASHTO.

AASHTO. (2015). *Fundamental Capabilities of Effective All-Hazards Infrastrucrture Protection, Resilience and Emergency Management for State Departments of Transportation.*

Archibald, E. (2013). *Infrastructrue Resilience at the Project Level.* Newark, DE: Department of Civil and Environmental Engineering, University of Delaware.

Arkansas Department of Transportation. (2018). *Risk-Based Transportation Asset Management Plan.* Retrieved July 13, 2019, from http://www.tamptemplate.org/wp-content/uploads/tamps/037_arkansasdot.pdf

Attoh-Okine, N., & Adarkwa, O. (2013). *Pavement Condition Surveys - Overview of Current Practices.* Delaware Center for Transportation. University of Delaware,.

Berche, B., von Ferber, C., Holovatch, T., & Holovatch, Y. (2009). Resilience of public transport networks against attacks. *European Physical Journal B, 7*(1), 125-137.

Bocchini, P., & Frangopol, D. (2012). Optimal Resilience- and Cost-Based Postdisaster Intervention Prioritization for Bridges along a Highway Segment. *Journal of Bridge Engineering, 17*(1), 117-129.

Brundtland Commission. (1987). *Our common future: Report of the World Commission on Environment and Development.* United Nations.

Bruneau, M., & Reinhorn, A. (2007). Exploring the concept of seismic resilience for acute care facilities. *Earthquake Spectra, 23*(1), 41-62.

Bruneau, M., Chang, S. E., Lee, G. C., O'Rourke, T. D., Reinhorn, A. M., Shinozuka, M., . . . Winterfeldt, D. (2003). A framework to quantitatively assess and enhance the seismic resilience of communities. *Earthquake Spectra, 19*(4), 733-752.

Caltrans. (2018). *California Transportation Asset Management Plan.* Retrieved July 13, 2019, from http://www.tamptemplate.org/wp-content/uploads/tamps/033_california.pdf

Cambridge Systematics. (2013). *North Carolina I-95 Economic Assessment Study, Task 4: Travel Demand Modeling.*

Cambridge Systematics, Inc, PB Consult, Inc. and Texas Transportation Institute . (2006). *Performance Measures and Targets for Transportation Asset Management.* Retrieved July 14, 2019, from https://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_551.pdf

Cambridge Systematics, Inc. and High Street Consulting Group. (2010). *Transportation Performance Management: Insight from Practitioners.* National Cooperative Highway Research Program. Retrieved July 14, 2019, from https://www.nap.edu/download/14384

Cimellaro, G. P., Reinhorn, A. M., & Bruneau, M. (2010). Framework for analytical quantification of disaster resilience. *Engineering Structures, 32*(1), 3639-3649.

Connecticut Department of Transportation. (2018). *Highway Transportation Asset Management Plan.* Retrieved July 13, 2019, from http://www.tamptemplate.org/wp-content/uploads/tamps/052_connecticutdot.pdf

Croope, S., & McNeil, S. (2011). Improving Resilience of Critical Infrastructure Systems Post-Disaster for Recovery and Mitigation. *Transportation Research Record, No 2234*, 3-13.

Curtis, J. A., Dailey, J. S., D'Angelo, D., DeWitt, S. D., Graf, M. J., Henkel, T. A., . . . Rocco, R. E. (2012). *Transportation Risk Management: International Practices for Program Development and Project Delivery.* Federal Highway Administration. Retrieved July 14, 2019, from https://international.fhwa.dot.gov/scan/12029/12029_report.pdf

Cutter, S., Barnes, L., Berry, M., Burton, C., Evens, E., Tate, E., & Webb, J. (2008). A Place-Based Model for Understanding Community Resilience to Natu-ral Disasters. *Global Environmental Change, 18*, 598-606.

Dehghani, M., Flintsch, G., & McNeil, S. (2017). Parametric analysis of roadway infrastructure vulnerability to disruptions. *Journal of infrastructure systems,, 23*(4), 04017017.

Delaware Department of Transportation. (2017). DelDOT Project Prioritization Criteria. Retrieved August 23, 2019, from https://deldot.gov/Publications/reports/CTP/pdfs/DelDOT_project_prioritization_criteria.pdf

Delaware Department of Transportation. (2017). *Strategic Implementation Plan for Climate Change, Sustainability & Resilience for Transportation.* Retrieved September 28, 2019, from https://deldot.gov/Publications/reports/SIP/pdfs/SIP_FINAL_2017-07-28.pdf

Delaware Department of Transportation. (2019). *Transportation Asset Management Plan.* Retrieved July 13, 2019, from https://deldot.gov/Publications/tamp/pdfs/DelDOT-Transportation-Asset-Management-Plan-2019.pdf

Delawareonline. (2016, March 22). $1.45 million Prime Hook bridge marks effort to fight floods. *New Journal*.

Department of Homeland Security and United States Department of Transportation. (2015). *Transportation Systems Sector-Specific Plan.* Retrieved September 28, 2019, from https://www.dhs.gov/sites/default/files/publications/nipp-ssp-transportation-systems-2015-508.pdf

Dojutrek, M. S., Labi, S. J., & Dietz, E. (2016). A multi-criteria methodology for measuring the resilience of transportation assets. *International Journal of Disaster Resilience in the Built Environment,, 7*(3), 290-301.

Dynes, R. (1970). Chapter 3: The Disaster Event and Community Stress. In *Organized Behavior in Disaster Analysis and Conceptualization.* The Disaster Research Center, Ohio State University.

Faturechi, R., & Miller-Hooks, E. (2014). Measuring the performance of transportation infrastructure systems in disasters: A comprehensive review. *ASCE Journal of Infrastructure Systems, 21*(1), 1-15.

FHWA. (2012). *Risk-Based Transportation Asset Management Report 1: Evaluating Threats, Capitalizing on Opportunities.* Retrieved July 14, 2019, from https://www.fhwa.dot.gov/asset/pubs/hif12035.pdf

FHWA. (2012). *Risk-Based Transportation Asset Management Report 2: Examining Risk-Based Approached to Transportation Asset Management.* Retrieved July 14, 2019, from https://www.fhwa.dot.gov/asset/pubs/hif12050.pdf

FHWA. (2012). *Risk-Based Transportation Asset Management Report 3: Achieving Policy Objectives by Managing Risks.* Retrieved July 14, 2019, from https://www.fhwa.dot.gov/asset/pubs/hif12054.pdf

FHWA. (2013). *Risk Based Transportation Asset Management Report 5: Managing External Threats through Risk-Based Asset Management.*

FHWA. (2013). *Risk-Based Transportation Asset Management Report 4: Managing Risks to Critical Assets.* Retrieved July 14, 2019, from https://www.fhwa.dot.gov/asset/pubs/hif13017.pdf

FHWA. (2016, October 24). Asset Management Plans and Periodic Evaluations of Facilities Repeatedly Requiring Repair and Reconstruction Due to Emergency Events. *Federal Register, 81*(205). Retrieved July 15, 2019, from https://www.federalregister.gov/documents/2016/10/24/2016-25117/asset-management-plans-and-periodic-evaluations-of-facilities-repeatedly-requiring-repair-and

FHWA. (2017). *Incorporating Risk Management into Transportation Asset Management Plans.* Retrieved July 14, 2019, from https://www.fhwa.dot.gov/asset/pubs/incorporating_rm.pdf

Filosa, G., Plovnick, A., Stahl, L., Miller, R., & Pickrell, D. (2017). *Vulnerability Assessment and Adaptation Framework, Third Edition.* Federal Highway Administration. Retrieved July 14, 2019, from https://www.fhwa.dot.gov/environment/sustainability/resilience/adaptation_framework/climate_adaptation.pdf

Fletcher, D., & Ekern, D. (2017). *Understanding Transportation Resilience: A 2016-2018 Roadmap.* AASHTO. Retrieved July 15, 2019, from https://environment.transportation.org/pdf/infrastructure_resilience/understandingtransresil_jan2017.pdf

Florida Department of Transportation. (2018). *Initial Transportation Asset Management Plan.* Retrieved July 13, 2019, from http://www.tamptemplate.org/wp-content/uploads/tamps/028_floridadot.pdf

Francis, R., & Bekera, B. (2014). A metric and frameworks for resilience analysis of engineered and infrastructure systems. *Reliability Engineering & System Safety, 121*, 90-103.

Freckleton, D., Heaslip, K., Louisell, W., & Collura, J. (2012). Evaluation of Resiliency of Transportation Networks After Disasters. *Journal of the Transportation Research Board, 2284*, 109-116.

Gaspard, K., Martinez, M., Zhang, Z., & Wu, Z. (2007). *Impact of Hurricane Katrina on roadways in the New Orleans area.* Technical Assistance Rep. No. 07-2TA.

Georgia Department of Transportation. (2018). *Transportation Asset Management Plan: Fiscal Years 2018-2027.* Retrieved July 13, 2019, from http://www.tamptemplate.org/wp-content/uploads/tamps/047_georgiadot.pdf

Heaslip, K., Louisell, W., & Collura, J. (2009). A methodology to evaluate transportation resiliency for regional networks. *Transportation Research Board 88th Annual Meeting (No. 09-3194).*

Henry, D., & Ramirez-Marquez, J. E. (2012). Generic metrics and quantitative approaches for system resilience as a function of time. *Reliability Engineering and System Safety, 99*, 114-122.

Herning, G., Maher, A., & McNeil, S. (2016). *Collaborative Proposal on Resilience: Definitions, Measurement, Tools and Research Opportunities.* Rutgers University.

Holling, C. (1973). Resilience and stability in ecological systems. *Annual Review of Ecological Systems, 4*(1), 1-23.

Hosseini, S., Barker, K., & Ramirez-Marquez, J. (2016). A review of definitions and measures of system resilience. *Reliability Engineering and System Safety, 145*, 47–61.

Illinois Department of Transportation. (2018). *Transportation Asset Management Plan.* Retrieved July 13, 2019, from http://www.tamptemplate.org/wp-content/uploads/tamps/041_illinoisdot.pdf

Ingenium and Institute of Public Works Engineering of Australia. (2011). *International infrastructure management manual, version 4.0.* Association of Local Government NZ Inc (INGENIUM and the Institue of Public Works Engineering of Australia (IPWEA).

International Organization for Standardization (ISO). (2009). *ISO 31000 Risk Management—Principles and.* Geneva, Switzerland: International Organization for Standardization.

Kansas Department of Transportation. (2018). *Transportation Asset Management Plan.* Retrieved July 13, 2019, from http://www.tamptemplate.org/wp-content/uploads/tamps/042_kansasdot.pdf

Kentucky Transportation Cabinet. (2018). *Transportation Asset Management Plan.* Retrieved July 13, 2019, from http://www.tamptemplate.org/wp-content/uploads/tamps/048_kentuckytc.pdf

Links, J. M., Schwartz, B. S., Lin, S., Kanarek, N., Mitrani-Reiser, J., Kirk Sell, T., . . . Kendra, J. (2018). COPEWELL: A Conceptual Framework and System Dynamics Model for Predicting Community Functioning and Resilience After DIsasters. *Disaster Medicine and Public Health Preparedness, 12*(1), 127-137.

Liu, Y., McNeil, S., & Herning, G. (2017). Integrating Resilience Concepts with Pavement Management: Two Case Studies. *World Conference on Pavement and Asset Management.* Milan, Italy.

Liu, Y., McNeil, S., & Lee, E. (2017). Operationalizing the Concept of Resilience: A Case Study of Flooding in North Carolina. *MAIREINFRA.* Seoul, South Korea.

Liu, Y., McNeil, S., Hackl, J., & Adey, B. (2019). *Prioritizing transportation network recovery using a resilience measure.* Working Paper.

McNeil, S. (2017). Asset Management, Sustainability and Resilience: Connecting the Concepts to Maintenance and Inspection Decisions for Infrastructure Systems. *2017 MAIREINFRA.* Seoul, Korea.

McNeil, S., Liu, Y., & Ramirez-Villamizar, A. (2019). Infrastructure Resiience: From Concept to Performance to Decisions. *7th International Confrence on Bituminois Mixtures and Pavements.* Thessalonki, Greece.

Michigan Department of Transportation. (2018). *Initial Transportation Asset Management Plan.* Retrieved July 13, 2019, from http://www.tamptemplate.org/wp-content/uploads/tamps/046_michigandot.pdf

Minnesota Department of Transportation. (2018). *Draft Transportation Asset Management Plan.* Retrieved July 13, 2019, from http://www.tamptemplate.org/wp-content/uploads/tamps/045_minnesotadot.pdf

Missouri Department of Transportation. (2018). *MoDOT's National Highway System Transportation Asset Management Plan.* Retrieved July 13, 2019, from http://www.tamptemplate.org/wp-content/uploads/tamps/040_missouridot.pdf

Montana Department of Transportation. (2018). *Transportation Asset Management Plan.* Retrieved July 13, 2019, from http://www.tamptemplate.org/wp-content/uploads/tamps/030_montanadt.pdf

Murray-Tuite, P. M. (2006). A comparison of transportation network resilience under simulated system optimum and user equilibrium conditions. *Winter Simulation Conference*, (pp. 1398-1405).

National Infrastructure Advisory Council. (2009). *Critical Infrastructure Resilience Final Report And Recommendations.*

National Research Counci. (2011). *Sustainability and the US EPA.* Washington D.C.: National Academies Press.

National Research Council. (2009). *Sustainable Critical Infrastructure Systems: A Framework for Meeting 21st Century Imperatives, Report of a Workshop.* Washington D.C.: National Academies Press.

National Research Council of the National Academies. (2012). *Disaster Resilience: A National Imperative.* Washington, D.C. : National Academies Press.

NCDOT. (2015). *NCDOT AADT Traffic Volume Reports .*

NCDOT. (2016). *Maintenance Operations and Performance Analysis Report (MOPAR).* Retrieved August 23, 2019, from https://connect.ncdot.gov/resources/Asset-Management/MSADocuments/2016%20Maintenance%20Operations%20and%20Performance%20Analysis%20R

NCDOT. (2016). *Sec. Tennyson Visits Areas Flooded by Matthew.* Press Release (October).

Nebraska Department of Transportation. (2018). *Transportation Asset Management Plan.* Retrieved July 13, 2019, from http://www.tamptemplate.org/wp-content/uploads/tamps/043_nebraskadot.pdf

New Mexico Department of Transportation. (2018). *Delivering Asset Performance.* Retrieved July 13, 2019, from http://www.tamptemplate.org/wp-content/uploads/tamps/034_nmdot.pdf

NIST. (2015). *Community resilience planning guide for buildings and infrastructure systems.* NIST Special Publication 1190, NIST (National Institute of Standards and Technology). Retrieved from http://dx.doi.org/10.6028/NIST.SP.1190v1

North Carolina Department of Transportation. (2018). *Transportation Asset Management Plan: 2018 Interim Report.* Retrieved July 13, 2019, from http://www.tamptemplate.org/wp-content/uploads/tamps/056_northcarolinadot.pdf

North Dakota Department of Transportation. (2018). *Transportation Asset Management Plan.* Retrieved July 13, 2019, from http://www.tamptemplate.org/wp-content/uploads/tamps/038_northdakotadot.pdf

Oklahoma Department of Transportation. (2018). *Transportation Asset Management Plan 2018-2027.* Retrieved July 13, 2019, from http://www.tamptemplate.org/wp-content/uploads/tamps/035_oklahomadot.pdf

Oswald, M., McNeil , S., Ames, D., & Gayley, R. (2013). Identifying Resiliency Performance Measures for Mega-Regional Planning: Case Study of BosWash Transportation Corridor. *Transportation Research Record, No. 2397*, 153-160.

Pennsylvania Department of Transportation. (2018). *Transportation Asset Management Plan 2018.* Retrieved July 13, 2019, from http://www.tamptemplate.org/wp-content/uploads/tamps/049_penndot.pdf

Proctor, G. D., & Varma, S. (2012). *Risk-Based Transportation Asset Management Literature Review.* Federal Highway Administration. Retrieved July 14, 2019, from https://www.fhwa.dot.gov/asset/pubs/hif12036.pdf

Proctor, G., Varma, S., & Roorda, J. (2016). *Managing Risk across Enterprise: A Guide for State Departments of Transportaiton.* National Cooperative Highway Research Program. Retrieved July 14, 2019, from http://onlinepubs.trb.org/onlinepubs/nchrp/docs/NCHRP08-93_FullGuide.pdf

Reggiani, A., Nijkamp, P., & Lanzi, D. (2015). Transport Resilience and Vulnerability: The Role of Connectivity. *Transportation Research Part A: Policy and Practice, 81*, 4-15. Retrieved from https://doi.org/10.1016/j.tra.2014.12.012

Reinhorn, A., Bruneau, M., & Reinhorn, A. (2007). Exploring the concept of seismic resilience for acute care facilities. *Earthquake Spectra, 23*(1), 41-62.

Ren, T. (2019). *Operationalizing the Concept of Resilience: Case study of Flooding in North Carolina.* Newark, DE: Department of Civil and Environmental Engineering, University of Delaware.

Renschler, C., Fraizer, A. E., Arendt, L., Cimellaro, C., & Reihardt. (2010). *A Framework for Defining and Measuring Resili-ence at the Community Scale: The PEOPLES Resilience Framework.* U.S. Department of Commerce National.

Robeson County. (2017). *Hurricane Matthew Resilient Redevelopment Plan.* Retrieved August 23, 2019, from https://files.nc.gov/rebuildnc/documents/matthew/rebuildnc_robeson_plan_combined.pdf

Rockefeller Foundation and ARUP. (2014). *City Resilience Framework.* Retrieved from https://www.rockefellerfoundation.org/report/city-resilience-framework/

Rose, A. (2009). *Economic Resilience to Disasters.* CARRI Research Report 8, Published Articles & Papers, Paper 75, Community and Regional Resilience Institute. Retrieved from http://research.create.usc.edu/published_papers/75

South Carolina Department of Transportation. (2018). *Initial Transportation Asset Management Plan.* Retrieved July 13, 2019, from http://www.tamptemplate.org/wp-content/uploads/tamps/051_scarolinadot.pdf

Sultana, M., Chai, G. W., Martin, T. C., & Chowdhury, S. H. (2015). A study on the flood affected flexible pavements in Australia. *9th International Conference on Road and Airfield Pavement Technology*, (pp. 9-13).

Sultana, M., Chai, G., Chowdhury, S., Martin, T., & Anissimov, Y. (2018). Rutting and Roughness of Flood-Affected Pavements: Literature Review and Deterioration Models. *Journal of Infrastructure Systems, 24*(2), 04018006.

Tennessee Department of Transportation. (2018). *Transportation Asset Management Plan.* Retrieved July 13, 2019, from http://www.tamptemplate.org/wp-content/uploads/tamps/044_tennesseedot.pdf

The White House, Office of the Press Secretary. (2013). Presidential Policy Directive -- Critical Infrastructure Security and Resilience. Retrieved July 14, 2019, from https://obamawhitehouse.archives.gov/the-press-office/2013/02/12/presidential-policy-directive-critical-infrastructure-security-and-resil

Uddin, W., Hudson, W. R., W. R., & Haas, R. C. (2013). *Public infrastructure asset management.* McGraw Hill Professional.

United Nations. (2016). *United Nations. (2016). "The Infrastructure – Inequality – Resilience Nexus," Chapter 2 in the Global Sustainability Development Report.* New York: United Nations, De-partment of Economic and Social Affairs.

Utah Department of Transportation. (2018). *Utah Transportation Asset Management Plan.* Retrieved July 13, 2019, from http://www.tamptemplate.org/wp-content/uploads/tamps/053_utahdot.pdf

Vermont Agency of Transportation. (2018). *Transportation Asset Management Plan: Right Investment, Right Asset, Right Time.* Retrieved July 13, 2019, from http://www.tamptemplate.org/wp-content/uploads/tamps/055_vtrans.pdf

Washington State Department of Transportation. (2018). *Transportation Asset Management Plan.* Retrieved July 13, 2019, from http://www.tamptemplate.org/wp-content/uploads/tamps/054_washingtonstatedot.pdf

Wyoming Department of Transportation. (2018). *Transportation Asset Management Plan.* Retrieved July 13, 2019, from http://www.tamptemplate.org/wp-content/uploads/tamps/039_wyomingdot.pdf

Ye, Q., & Ukkusuri, S. V. (2015). Resilience as an Objective in the Optimal Reconstruction Sequence for Transportation Networks Resilience as an Objective in the Optimal Reconstruction Sequence. *Journal of Transportation Safety & Security*, 9962.

Zhang, X., & Miller-Hooks, E. (2014). Scheduling short-term recovery activities to maximize transportation network resilience. *Journal of Computing in Civil Engineering, 29*(6), 04014087.

Zhang, Z., Wu, Z., Martinez, M., & Gaspard, K. (2008). Pavement structures damage caused by Hurricane Katrina flooding. *Journal of geotechnical and geoenvironmental engineering, 134*(5), 633-643.

Zhao, H. T., & Mao, H. Y. (2009). Highway emergency response system based on GIS-T. *Information and Computing Science, ICIC'09, Second International Conference. 1*, pp. 208-211. IEEE.

# Appendix A. Definitions of Resilience

## General

"The ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events" (National Research Council of the National Academies, 2012)

The National Preparedness Goal within PPD-8 (2011) envisions "a secure and resilient nation with the capabilities required across the whole community to prevent, protect against, mitigate, respond to and recover from the threats and hazards that pose the greatest risk."

PPD-21 (The White House, Office of the Press Secretary, 2013) on Critical Infrastructure Security and Resilience designates 16 critical infrastructure sectors, and defines resilience as the *"ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions. It includes the ability to withstand and recover from deliberate attacks, accidents, or naturally occurring threats or incidents."*

"Resilient infrastructure assets, systems, and networks must also be robust, agile, and adaptable. Mitigation, response, and recovery activities contribute to strengthening critical infrastructure resilience." 2013 National Infrastructure Protection Plan: Partnering for Critical Infrastructure Security and Resilience

Department of Homeland Security defines resilience variously as, "The ability to resist, absorb, recover from, or successfully adapt to adversity or a change in conditions," and also, "The ability of systems, infrastructures, government, business, and citizenry to resist, absorb, recover from, or adapt to an adverse occurrence that may cause harm, destruction, or loss of national significance." Cited in (Fletcher & Ekern, 2017)

The 2009 AASHTO–TRB Transportation Hazards & Security Summit proposed a comprehensive definition of resilience: "The ability of a system to provide and maintain an acceptable level of service or functionality in the face of major shocks or disruptions to normal operations. ° A system of systems characterization across 'lifeline systems' including power, water, connectivity, and mobility with a focus on providing these essential services first. ° Self-diagnosing, self-healing, and self-repairing systems that have fewer long-term service disruptions and lower life-cycle costs. ° Systems that are sustainable, energy efficient and performance-based."  Cited in (Fletcher & Ekern, 2017)

AASHTO's SCOTSEM defines resilience as "the ability to prepare and plan for, absorb, recover from, or more successfully adapt to adverse events" (adapted from (National Research Council of the National Academies, 2012)).  Cited in (Fletcher & Ekern, 2017)

The National Academies of Sciences, Engineering, and Medicine's Resilient America Roundtable has also adopted the National Imperative definition of resilience as "the ability to prepare and plan for, absorb, recover from, or more successfully adapt to actual or potential adverse events."  Cited in (Fletcher & Ekern, 2017)

Federal Highway Administration (FHWA) Order 5520 defines resilience or resiliency as, "…the ability to anticipate, prepare for and adapt to changing conditions and withstand, respond to and recover rapidly from disruptions." Defining Resilience 6 | • The Harbor Safety Committee Conference defined resilience as "The capability to expeditiously recover and reconstitute vital services with minimum disruption." • The non-partisan, not-for-profit Reform Institute suggested resilience was "Mitigating the cascading adverse effects of a terrorist attack or natural disaster so that the nation can quickly recover and resume normal activity after such an episode." Cited in (Fletcher & Ekern, 2017)

## Dictionary Definition

From Mirriam-Webster (https://www.merriam-webster.com/dictionary/resilient)

Resilient - adjective

re·sil·ient | \ ri-ˈzil-yənt \

Definition of resilient: characterized or marked by resilience: such as

a: capable of withstanding shock without permanent deformation or rupture

b: tending to recover from or adjust easily to misfortune or change

## Definitions from Other Domains

The idea of different definitions in different domains is illustrated in the AASHTO report (AASHTO, 2015):

***In Physics***

*“The work done in deforming a body to some predetermined limit, such as its elastic limit or breaking point, divided by the body's volume.”*

***In Ecology***

*“A measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations and state variables.”*

***In Computer Science***

*“The ability of a data processing system to continue to operate correctly even though one or more of its component parts is malfunctioning.”*

***In Psychology***

*“Dynamic process that individuals exhibit positive behavioral adaptation when they encounter significant adversity, trauma, tragedy, threats, or even significant sources of stress.”*

## Appendix B. Practitioner Survey: Questions and Summary Responses

| Question | Response |
|---|---|
| Q1: Definition of resilience | Ability to minimize losses and recovery quickly<br>Ability to rebuilt from storms and resist events. |
| Q2: Measures of resilience | Not very clear. |
| Q3: Do you use any existing resilience measures? | No |
| Q4: What attributes are needed in resilience measures? | Not sure |
| Q5: How to use resilience measures in the future? | Use them perfectly / design infrastructure stronger to resist events |
| Q6: Which apply to resilience? | Systems*<br>Specific types of infrastructure*[i]<br>Particular facilities |
| Q7: Are you interested in an absolute measure of resilience or change in resilience over time? | Both are interested |
| Q8: In which timeframe should resilience be measured? | Short term (1-2 years)<br>Medium term (2-10 years)*<br>Long term (>10 years)* |
| Q9: Resilience has been defined in terms of robustness, rapidity, redundancy, and resourcefulness. | Do these factors have meaning to you as an asset manager?<br>• Positively<br>Are these factors useful to you?<br>• Positively<br>What factors do you think influence resilience?<br>• Initial construction |

[i] * indicated respondents' choices for multiple questions