Texas A&M Transportation Institute

# Resilience Applied to Transportation Policy and Planning

INTERIM MEMORANDUM- DRAFT

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**Environment and Air Quality Division**

# TECHNICAL MEMORANDUM – DRAFT FOR REVIEW

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## Subtask 2.1 Resilience Applied to Transportation Policy and Planning

**DATE:** August 14, 2018

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# 1.0 UNDERSTANDING RESILIENCE IN CONTEXT

## 1.1 The Evolution of the Concept of Resilience

The scientific use of the term "resilience" dates back to the 19th century. Tregold (1818) used the term to describe the property of timber that allows beam to bend to support heavy loads without breaking. Robert Mallet (often referred to as "the father of seismology"), introduced the concept of "modulus of resilience" as a means of assessing the ability of materials to withstand severe conditions (Mallet, 1856). During 1970s, the concept of resilience was used by social scientists, particularly psychologists; for example, Werner, Bierman, and French (1971) used the term to describe individuals' ability to adapt to adverse conditions such as catastrophic life events, poverty, and maltreatment. Holling explicitly linked the concept of resilience to ecosystems by defining it as "the persistence and ability of ecosystems to absorb change and disturbance while maintaining the same relationships between populations or state variables" (Holling, 1973).

More recently, social scientists and urban planners have adopted the concept of resilience for urban planning captured by the phrase "cities of resilience". This perspective distinguishes between ecological resilience and engineering resilience (Holling, 1996). Engineering resilience values efficiency, constancy and predictability. It concentrates on resistance to disturbance and speed of returning to stability near the equilibrium (O'Neill, 1986; Pimm, 1984). According to Hollnagel (2011), there are four cornerstones of resilience from the engineering perspective, as illustrated Figure 1:

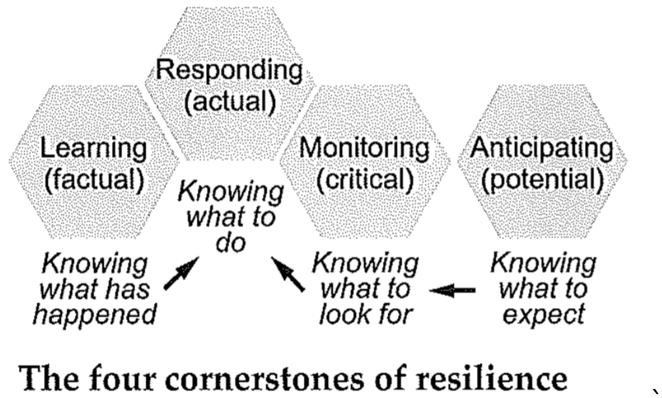


**Figure 1 Four Cornerstones of Resilience**

Source: Hollnagel (2011)

Ecological resiliency, on the other hand, focuses on persistence, change and unpredictability; it emphasizes the existence of instabilities that can flip a system into another stability domain, as well as the magnitude of disturbance that can be absorbed before the system changes its structure (Pimm, 1984). Scholars and practitioners of ecological resilience are concerned with the increasing uncertainty and volatility in the natural and built environment. They study the capacity of systems to reorganize and recover from change.

This focus on uncertainty and adaptability favors systems that are "safe to fail"(Ahern, 2011). In other words, engineering resilience calls for "fail-safe" solutions, while ecological resilience calls for "safe-fail" designs (Holling, 1996).

## 1.2 Resilience Studies on Transportation Systems

Resilience has also been actively studied in the context of urban and transportation planning, partly in response to the growing consensus on climate change, extreme weather and their consequences. Even though attempts to define resilience have yet to fully reconcile the engineering and ecological perspectives, researchers in urban transportation planning are increasingly adopting the ecological resilience model, and by doing so emphasize the need for multidisciplinary collaboration, 'safe-to-fail' solutions, and an understanding of non-linear responses between disturbances and system states. For example, a recent study defines resilience as:

*"…the ability of an urban system-and all its constituent socio-ecological and socio-technical networks across temporal and spatial scales-to maintain or rapidly return to desired functions in the face of a disturbance, to adapt to change, and to quickly transform systems that limit current or future adaptive capacity."(Meerow, Newell, & Stults, 2016)*

An overview of recent research is summarized in Table 1. These studies fall into three groups. The first group of studies focuses on the development of tools, frameworks or methods to assess and/or promote resilience of transportation networks or systems in dealing with disruptions or disasters (Cox, Prager, & Rose, 2011; Croope & McNeil, 2011; Donovan & Work, 2015; Hughes & Healy, 2014; Ip & Wang, 2011; Miller-Hooks, Zhang, & Faturechi, 2012; Osei-Asamoah & Lownes, 2014).

For example, Cox et al. (2011) presents operational metrics to determine a passenger transportation system's resilience to terrorism. They provide a range of strategies to promote resilience, which is quantified using the 2005 London subway and bus bombings. Miller-Hooks et al. (2012) proposes a method for assessing and maximizing the resilience of freight transportation network for scenarios of bombing, terrorist attack, flood, earthquake, and intermodal terminal attack. Their simulation results show that preparedness and recovery options contribute to higher resilience levels. (See Figure 2. Run 4 involves both preparedness and recovery, while Run 1 does not involve either of them.)

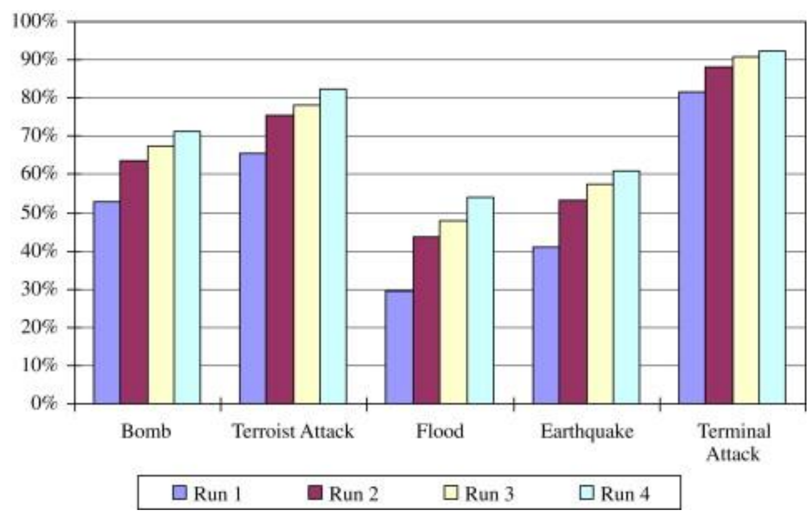


**Figure 2 Network Resilience in Different Scenarios**

Source: Miller-Hooks et al. (2012)

These studies reflect thinking from the engineering resilience perspective, and their resilience measures for a transportation system are based on vulnerability, flexibility and resource availability.  Most of these findings have not been widely adopted by practitioners.

The second group of studies are conceptual or theoretical (Chang, 2014; Glenn Richey Jr, Stewart, Kolluru, & Smith, 2009; Linkov et al., 2014; Mattsson & Jenelius, 2015; Reggiani, Nijkamp, & Lanzi, 2015; Tamvakis & Xenidis, 2012; Wang, 2015; Zhang, Miller-Hooks, & Denny, 2015).  They provide reflection and critical thinking about the incorporation of resilience into transportation planning practice.  While the concept of transportation resilience has a range of meanings such as reliability, variability, vulnerability or fragility, resilience is generally seen as a valuable concept that has an important place in dynamic systems analysis, and is being productively incorporated into mainstream transportation science. (See for example, Reggiani et al. (2015))

The third group of studies are based on empirical evidence and make policy recommendations to transportation decision makers and other relevant stakeholders (Godschalk, 2003; Guthrie & Fan, 2013; Litman, 2006; Nakanishi, Black, & Matsuo, 2014; Ta, Goodchild, & Ivanov, 2010).  For example, Guthrie and Fan (2013) analyzed building permit data in New Orleans, Louisiana after the Hurricane Katrina.  Their empirical findings show that public transportation infrastructure significantly contributed to economic recovery after the disaster. In another example, Ta et al. (2010) conclude that state DOTs need to develop situational awareness, and develop tools for predicting routing changes and the economic impacts of disruptions to a state's freight system.

## Table 1 Summary of Resilience Research Relating to Transportation

| Authors | Type of Study | Measurement/Definitions/Domains of Resilience | Key Findings |
|---|---|---|---|
| Ip and Wang (2011) | Development of tools/frameworks/methods; tested in Sichuan, China | Rail network resilience from earthquakes. Resilience is measured as the number of reliable passageway between any pair of nodes. It represents the ability to recover transportation function once part roads are shut down. | The computational results show that distributed hubs have lower friability than centralized ones, where friability is defined as the reduction of network resilience caused by the removal of nodes or edges. |
| Miller-Hooks et al. (2012) | Development of tools/frameworks/methods; simulations of freight network in Western U.S. | Freight network performance given disruption scenarios: bombing, terrorist attack, flood, earthquake, and intermodal terminal attack. This paper proposes a method for assessing and maximizing the resilience of an intermodal freight transport network. | While improvements in resilience level are obtained from taking preparedness or recovery actions alone, the highest resilience level is attained when both preparedness and recovery options are available. |
| Cox et al. (2011) | Development of tools/frameworks/methods; London, UK | Transportation network resilience, measured in terms of transportation mode shifts applied to passenger-journeys. There are three overarching concepts: vulnerability to unpredictable shocks, resources available to a system, internal controllability of relations in a system. | Resilience was found to be relatively high - the majority of reductions in attacked mode passenger-journeys were offset by increases in alternative transport modes. |
| Chang (2014) | Theoretical and policy-oriented; no specific study site. | Infrastructure resilience to disasters. | The societal disruption caused by infrastructure failures is disproportionately high in relation to actual physical damage. Designing resilient infrastructure systems requires collaboration between engineers and social scientists. |
| Litman (2006) | U.S. regions affected by Hurricane Katrina and Rita (e.g. Louisiana, Texas) | Transportation issues related to responses to disasters: evacuations, delivery of emergency supplies and services, search and rescue operations, quarantine, and transportation infrastructure repair. | Various planning policies and programs can help create a more resilient transport system, by increasing system diversity and integration, improving user information, prioritizing resource use, and providing coordinated services during special events and emergencies. |
| Donovan and Work (2015) | Development of tools/frameworks/methods; New York City | Transportation network resilience to disasters and other extreme events. | Researchers developed a method for measuring resilience of city-scale transportation networks using only taxi GPS datasets. This method is low-cost, because it does not require the installation of any additional sensors. |
| Tamvakis and Xenidis (2012) | Conceptual; no specific study site. | Resilience as the ability of a transportation system to react to stresses that challenge its performance. | Resilience engineering is a rapidly advancing methodological approach, but it has not been adequately applied to transportation systems. |
| Zhang et al. (2015) | Conceptual; no specific study site. | Network resilience. Role of network topology, and characteristics on a transportation system's ability to cope with disaster. | More redundancies built into the network, as indicated by average degree and cyclicity |

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|---|---|---|---|
| | | | metrics lead to the greater the resilience level. |
| Ta et al. (2010) | State of Washington, USA | Reducing consequences of disruption to freight transportation system; three types of resilience: organizational resilience, enterprise resilience, and infrastructure resilience. | State DOTs need to take actions to develop situational awareness and tools for predicting routing changes and the economic impacts of disruptions to a state's freight system. |
| Croope and McNeil (2011) | Development of tools/frameworks/methods; Seaford, Delaware | Protection of critical infrastructure with a focus on decreased vulnerability to disasters. | The CIR-DSS (Critical Infrastructure Resilience Decision Support System) framework can support the integration of mitigation measures into the infrastructure management decision-making process and enhance the resiliency of infrastructure systems. |
| Godschalk (2003) | Nationwide policy narrative. | Being able to withstand an extreme natural event without suffering devastating losses, damage, diminished productivity or quality of life, and with limited external assistance. | Building resilient cities should be a national priority, for which funding is needed for basic and applied urban systems research, support for advanced education programs, and active collaboration among the city planning, design, and construction professions. |
| Guthrie and Fan (2013) | New Orleans, Louisiana | Post-disaster economic recovery. | The post-Katrina building permit frequency changes with distance from streetcar stops. Proximity to stops strongly predict building permits, showing the potential important role of transportation infrastructure in post-disaster economic recovery. |
| Reggiani et al. (2015) | Conceptual; no specific study site. | Resilience is a fashionable concept that has not only assumed an important position in dynamic systems analysis but is increasingly entering the realm of transportation science. It reflects a range of meanings such as reliability, variability, vulnerability or fragility. | The connectivity concept offers an appropriate angle for employing and interpreting resilience and vulnerability as operational research and planning tools for transport systems. |
| Hughes and Healy (2014) | Development of tools/frameworks/methods; New Zealand | The concept of resilience is wider than natural disasters and covers the capacity of public, private and civic sectors to withstand disruption, absorb disturbance, act effectively in a crisis, adapt to changing conditions, including climate change, and grow over time. | The researchers contribute to a framework to measure resilience of transportation systems. Resilience assessment includes technical and organizational dimensions, measured as quantified indicators of robustness, redundancy, safe-to-fail, and change readiness. |
| Linkov et al. (2014) | Commentary; no specific study site. | Resilience is the ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events. A resilience management framework includes risk analysis as a central component. Risk analysis depends on characterization of the threats, vulnerabilities and consequences of adverse events to determine the expected loss of critical functionality. | Resilience management goes beyond risk management to address the complexities of large integrated systems and the uncertainty of future threats, especially those associated with climate change. |

| | | | |
|---|---|---|---|
| Nakanishi et al. (2014) | Japan | Transportation agencies' capacity building to support resilient built environment during pre-disaster phase, the emergency phase, the rebuilding phase and the recovery phase. | The recovery and pre-disaster phases are critical as these are the time to build capacity for resilience. Practical application of the land use and transportation planning process is recommended in forming a transportation master plan. |
| Glenn Richey Jr et al. (2009) | Theoretical; no specific study site. | Economics, behavioral sciences, supply chain management and critical infrastructure protection are integrated to develop a framework for shaping national resilience. | Safety and security of the nation is embedded within a myriad of interdependent systems, therefore public-private partnerships are needed to leverage the adaptive capabilities of public and private sector organizations. |
| Wang (2015) | Theoretical; no specific study site. | Comprehensive resilience in transportation is defined as the quality that leads to recovery, reliability and sustainability. | Transformability, featured in ecological resilience, has been generally overlooked and needs to be incorporated in the analysis framework for comprehensive resilience in transportation. |
| Osei-Asamoah and Lownes (2014) | Development of tools/frameworks/methods; Experimental network developed by using slime mold, to replicate the road network structure in Connecticut. | Preparedness, response, and recovery efforts of state DOTs and MPOs in disaster events; reducing vulnerability. | Compared to the slime mold network, the current road networks exhibit structural vulnerabilities. |
| Mattsson and Jenelius (2015) | Literature study; no specific study site. | The resilience concept offers a broader socio-technical perspective on the transportation systems' capacity to maintain or quickly recover its function after a disruption / disaster. | The cross-disciplinary collaborations between authorities, operators and researchers are desirable to transform resilience knowledge into practical strategies. |

# 2.0 INTEGRATING RESILIENCE FOR TRANSPORTATION POLICY AND PLANNING

Recent resilience research, as summarized above, suggests the following factors will be important for incorporating resilience thinking into transportation policy and planning.

## 2.1 Reconciling ecological resilience with engineering resilience

The complexity of transportation systems is reflected in the interactions between various processes and domains. The engineering process in transportation is concerned with offering safe and efficient mobility solutions; previous studies show that it is currently the predominant resilience paradigm for transportation.

The engineering perspective for transportation needs to remain and be coordinated (reconciled) with the socio-economic and ecological perspectives to provide a meaningful understanding of the nature of the transportation system. Otherwise, the evolution of the transportation system will be cyclical between extremes, and inherently inefficient overall. For example, the construction of highways during 1950s and 1960s gave limited consideration to the community socio-economic fabrics, leading to significant unanticipated negative impacts on the environment, neighborhoods and cultures. The inevitable cyclical backlash resulted in the radical and in some cases abrupt scaling back of highway construction and eventually maintenance, as attention and then funding was diverted into other areas.

The ecological resilience perspective views transportation as an open system, which interacts with the broad environment that includes people, economy, technological developments, and nature itself (Gudmundsson, Hall, Marsden, & Zietsman, 2015). Ecological resilience theory values adaptability and calls for preparedness (i.e., resilience) for systems to reach alternate viable stable states. It has been clearly demonstrated that the inexorable advancement of technology and changing life styles from generation to generation will inevitably change the demands and expectations of society on the transportation system.

Therefore, the reconciliation of the ecological and engineering resilience perspectives is critical for transportation decision makers and other stakeholders to prepare for the inevitable evolution of society's demands on the transportation system.

## 2.2 Measuring Resilience and Prioritizing Adaptation Strategies

The tangible impacts of climate change (weather extremes, sea level rise, etc.) are undeniable, regardless of cause. Transportation agencies at all levels are aware of the impact on the transportation infrastructure. For example, the FHWA plans to increase the health and longevity of highways by assessing vulnerabilities, incorporating resilience in asset management plans, and addressing resilience in project development and design (USDOT, 2017b). In addition, a number of pilot programs have been implemented through collaboration with DOTs across the United States (e.g., Arizona, California, Connecticut, Iowa, Maine, Massachusetts, Michigan, New York State, Oregon, Tennessee, Washington State), as well as several MPOs. These projects take various approaches to the assessment of system vulnerability assessments and/or evaluating options for adaptation (USDOT, 2016). The diversity of the methods used in these pilot programs needs a standardized cost-benefit based framework to assess vulnerability, as well as additional resources to help agencies evaluate the various adaptation strategies.

Several studies reviewed in this report provide input and tools that contribute to the assessment framework. Most notably, Hughes and Healy (2014) developed a standard framework to quantitatively measure the resilience of transportation systems based on their work in New Zealand. Their framework is illustrated in Figure 3.

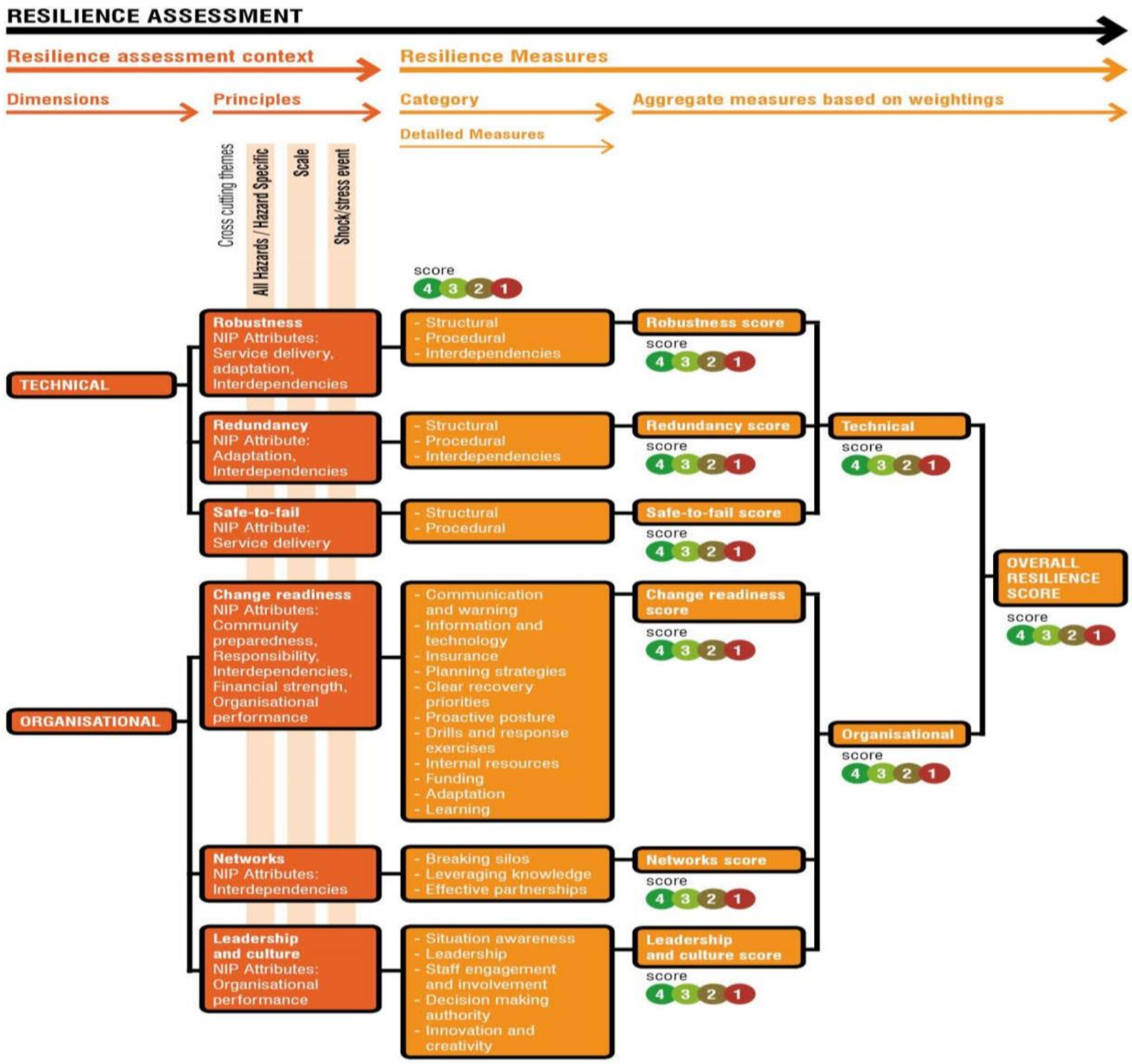


**Figure 3 Framework to Measure Resilience of Transportation Systems**

Source: Hughes and Healy (2014)

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