Characterizing the Dynamics of Vulnerability for Roadway Infrastructure Systems

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ABSTRACT

Critical infrastructure systems, such as transportation, energy, water and communication, are the backbones of sustainable economic and social development. The tragedies and catastrophic events in the past few years have motivated researchers to study the vulnerability of infrastructure systems to disastrous events. A number of existing studies address roadway networks where researchers have characterized the robustness and vulnerability of roadways to earthquakes, floods, and targeted attacks.

However, extreme events with infrequent return periods are not very likely to occur in a 50-60 year analysis period of roadways, while many roadways are located in areas that are not even exposed to floods or earthquakes at all. On the other hand, roadway network endogenous characteristics such the condition and degradation over time not only increases the vulnerability of roadways to disastrous events, but also makes the roadway network vulnerable to disruptions that are caused by maintenance and repair activities on the roadways system. Nevertheless, the impacts of these endogenous network characteristics on roadway vulnerability have not been explicitly addressed in the existing studies.

This dissertation introduces the concept of condition-based vulnerability assessment (CBVA) to capture the effect of roadway endogenous characteristics such as condition and condition uncertainties, roadway network deterioration over time, topological properties of roadways, and travel rate and travel pattern on the dynamics of roadway network vulnerably. First a methodological framework is developed and the method is applied to an illustrative roadway system. The results show that the vulnerability of roadway system is more affected by the average condition of the roadway network than by the condition of individual roads in the system. Moreover, the findings show that small uncertainties associated with the condition of individual roads can significantly increase the variance of the predicated vulnerability.

This initial methodological framework is then enhanced to account for physical degradation of the network over time and network equilibrium, and is applied to a real highway system. For the network studied network degradation increases roadway system vulnerability in a nonlinear mode. The result also suggest that the network vulnerability pattern is not very sensitive to travel pattern and link topological properties when the average network disruption probability (representing average network condition) is less than about 0.5. In other words, at low values of average disruption probability, it does not matter what link has what disruption probability level or how the travelers move across the network. However with further network degradation and as the average network disruption probability increases, the dynamics of network vulnerability depends on travel pattern on the network as well as on the link topological properties.

Glossary of Terms

Dynamics	Behavior and response to different parameters. Dynamics in our study does not imply change with time.
Disruptions	Events such as maintenance activists, structural collapses or failures in the roadway.
Disruption Probability	The probability that a roadway experiences disruption.
Disruption Scenario	The event in which one or several different roads in the network are disrupted.
Efficiency Vulnerability	Vulnerability with respect to efficiency. For example if the efficiency vulnerability is high for a roadway network, it means that the efficiency can decrease significantly if disruptions occur.
Network Status/State	Network in which each link has a particular disruption probability. There are indefinite imaginable states/statuses for a roadway network.
VMT Vulnerability	Vulnerability with respect to VMT. For example if the VMT vulnerability is high for a roadway network, it means that the VMT can increase significantly if disruptions occur.
Vulnerability	The susceptibility to performance reduction after disruptions.
A	Set of all possible disruption scenarios.
d_{ij}	Shortest path between origin-destination *ij*.
d^0_{max}	The maximum shortest path in the undisrupted network.
d^0_{ij}	Shortest path between origin-destination *ij* when network is undisrupted.
$dij(a)$	Shortest path between origin-destination *ij* after scenario *a*.
$E(G)$	Network efficiency (considering travel demand).
$E^0(G)$	Efficiency for undisrupted network.
$EFF(a)$	Network efficiency after disruption scenario *a*.
$E[r(s)]$	Expected value of performance type *r* when the system is in state *s*.
f_{ij}	Hourly flow between origin-destination *ij*.
$G(N,K)$	Network with *N* nodes and *K* links.
l_i	Length of link *i*.
l'_k	Equivalent length of link *k* that has travel time t'_k.
p_i	Disruption probability of link *i*.
$P(a)$	Probability of disruption scenario *a*.
q_{ij}	Daily Travel demand between OD pair *ij*.
r^0	The value for performance measure type *r* when the network is undisrupted.
$r(a)$	Value of performance measure type *r* (can represent efficiency or VMT, or VTT) when scenario *a* happens.
s	Particular state/status of the roadway network.
S	Set of all possible states/statuses for the roadway network.
$T(G)$	Total travel time on the network.

$T^0(G)$	Total travel time on undisrupted network.
t_k	Travel time on link *k* at relatively free flow condition.
t'_k	Travel time on link with capacity reduction of Δc.
$U(G)$	Network efficiency.
$VMT_{ij}(a)$	Resulting VMT between the OD pair *ij* when scenario *a* occurs.
$V_r(s)$	The vulnerability of the roadway system with respect to performance measure type *r* when the system is in state *s*.
$V_{VMT}(s)$	VMT vulnerability of the network at state/status s.
$V_{EFF}(s)$	Efficiency vulnerability of roadway network at state/status *s*.
VTT	Vehicle times traveled.
V_{VTT}	VTT vulnerability.
x_k	Traffic volume on link *k*.
$\theta(a)$	Performance measure of interest (efficiency or VTT) after scenario *a*.
$\tau_k(x_k)$	Travel time on link *k* when there is x_k amount of flow on the link.

To my wife and my parents.

And also,

to the people in less-developed regions of Iran and around the world
who deserve better health, education and life.

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Mohammad Saied Dehghani

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Chapter 1 : INTRODUCTION

BACKGROUND

Critical infrastructure systems, such as transportation, electrical power, water distribution systems and communication networks, form the pillars of economic and sustainable development in any country. With technological advancements in the past few decades these infrastructure systems have become more efficient. Nevertheless, the vulnerability of infrastructure systems has also increased as the systems become more complicated and interdependent.

With the catastrophic events in the past few years such as the 9/11 tragedy (September 2001), hurricane Katrina (August 2005), Japan Tōhoku earthquake and tsunami (March 2011), and hurricane Sandy (October 2012), there has been a lot of interest in understanding infrastructure vulnerability to disaster and failures. As a result, many research studies have addressed the resiliency and vulnerability of critical systems against disasters and extreme events, particularly in roadway network. The disaster-based context in existing studies emphasizes the impact of the characteristics of the disasters, such as their types, magnitudes, and their associated uncertainties, on roadway vulnerably.

PROBLEM STATEMENT

For most roadway systems with an analysis period spanning 50 to 60 years, a severe earthquake, flood, or terrorist attack is not very likely to happen. Moreover, for their geographical locations, many roadways are not exposed to floods, earthquakes, or other disasters at all. However, all roadways deteriorate over time and experience disruption (caused by either disasters or condition related maintenance activities) as a result of the poor condition of their elements. However, endogenous factors such as the physical condition of infrastructure systems and their degradation, and the topological properties of the network not only increase the vulnerably of infrastructure systems to disasters but also to frequent network internal disruption. For example, when a bridge fails structurally, or a road requires maintenance and repair, the traffic flow on the network is disturbed and the roadway system may experiences significant reduction in performance, which could imposes a significant increase of costs to users. The vulnerability caused by these inherent factors and the associated costs are notable over the long term.

On the other hand, the vulnerability of the roadway is assessed based on network performance measures such as mobility and travel time, which depend on travel rate and travel pattern. Nevertheless, the travel characteristics have not been adequately addresses in the past research in roadway vulnerably.

RESEARCH OBJECTIVE

In this research we introduce the idea of condition-based vulnerability assessment (CBVA) of roadway infrastructure systems. We develop both conceptual and computational frameworks to address the impact of roadway network characteristics on its vulnerability. We apply our framework to a real highway system network and specifically evaluate the impact of the following endogenous factors on the vulnerability of roadways to disruptions:

- Physical condition of the roads in the roadway system (reflected in disruption probabilities)
- Uncertainties associated with the condition of roadways (reflected in disruption probability uncertainties)
- Degradation of the roadway network over time
- Travel demand between different origins and destinations
- Travel pattern on the network
- Topological properties of the links, i.e., the relative location of a link in the network.

SIGNIFICANCE

Current studies on roadway vulnerability often focus on characteristics of individual links which does not tell us much about the big-picture network vulnerability. However, it is critical from both engineering and management perspective to observe and study vulnerability at network-scale. Characterizing vulnerability of roadway systems based on various network parameters and characteristics allows us to understand what parameters influence the big-picture of roadway vulnerability.

The framework presented in this study can enhance the existing infrastructure management system by introducing infrastructure vulnerability and risk into the decision making processes particularly at strategic level.

Moreover, the proposed approach can be used by engineers and decision makers to comprehensively evaluate the dynamics of infrastructure vulnerability with respect to the characteristics of the network. Providing this big-picture behavior helps decision makers focus on critical policies and avoid the exhaustive process in optimization problems where almost all solutions are examined.

DISSERTATION ORGANIZATION

This dissertation follows the manuscript format and contains three paper that each form an individual chapter. This Introduction is the first chapter of the dissertation that explains the main problem and objective of this research and outlines the rest of the dissertation. The remainder of the dissertation is organized as follows:

Chapter 2: *Roadway network as a degrading system: vulnerability and system level performance*. In this chapter we review the current literature in roadway vulnerability and identify the areas that have not been addressed so far. We then introduce the idea of condition-based vulnerability assessment (CBVA) of roadways and develop a conceptual framework for it.

Chapter 3: *Impact of road condition and disruption uncertainties on network vulnerability*

In this chapter we build upon the research presented in Chapter 1 and develop a methodological framework for CBVA of roadways. We apply the framework to an illustrative roadway system. In particular, we evaluate the effect of roadway condition uncertainties on roadway network vulnerability.

Chapter 4: *Parametric analysis of roadway infrastructure vulnerability to disruptions.* We enhance our methodological framework developed in Chapter 3 with more realistic assumptions and algorithms. We then apply the framework to a real highway system and evaluate the impact of travel rate and travel pattern, network degradation and link topological properties on roadway vulnerability.

Chapter 5 is the discussion chapter and summarizes the research approach, list the main findings and conclusions and provides recommendations for future research.

Chapter 2 : ROADWAY NETWORKS AS A DEGRADING SYSTEM: VULNERABILITY AND SYSTEM-LEVEL PERFORMANCE[1]

ABSTRACT

Views of both researchers and practitioners towards transportation infrastructure performance have experienced notable changes in the past few years. Strategic-level decision-makers are more interested in knowing the performance of roadways and systems as a whole rather than the performance of the asset-level components. With interdependent and complex infrastructure, many researchers have attempted to study the vulnerability of infrastructure to disasters and catastrophes as an important system-level performance measure. This paper reviews the literature, extends the discussion and proposes new directions on vulnerability and performance evaluation of roadways. The paper reviews how performance assessment in transportation infrastructure – and particularly roadway systems – has been addressed from asset-level to a wider system-level perspective. Infrastructure interdependencies and network science, as two necessary components of system-level performance and vulnerability assessment, are discussed. The significant impact of the condition of the roadway system on its performance and vulnerability is explained and condition-based approaches are proposed. Finally, the advantages of, and contributions derived from, using a condition-based approach to vulnerability assessment with current management systems of roadway infrastructure are explained.

KEYWORDS: Vulnerability, Network, Roadway Infrastructure, System-level Performance, Degradation

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Dehghani, M S; Flintsch, G W; McNeil, S, 'Roadway network as a degrading system: vulnerability and system level performance', *Transportation Letters: the International Journal of Transportation Research*, Volume 5, Number 3, July 2013 , pp. 105-114(10)

INTRODUCTION

A functional and efficient transportation infrastructure significantly contributes to economic growth and prosperity by providing the means for travel, production logistics, and delivery of service in normal daily life. During disasters (such as earthquakes and floods) a functional transportation network is a critical lifeline for damage assessment, search and rescue, emergency medical care, emergency restoration of essential services, fire-fighting, emergency communications, crisis decision-making, evacuation, protection of lives and property, provision of emergency shelter for victims, and debris removal (Martin, 2012). The transportation system, and particularly the roadway infrastructure, must be functional to provide service for people during normal daily life and should be robust against disruptions and disasters. It is thus critical to understand the performance of the roadway infrastructure from a system-level perspective. In other words, for efficient and effective management of the highway infrastructure, it is important to have performance assessment beyond the asset level and have a “system-level” look into the roadway network. The performance of roadways at the system level reflects how the entire roadway network provides service to users. Examples of system-level performance measures are travel time (function of travel length) and travel cost (function of travel length and road condition). In this paper, assets are referred to as specific elements of roads; for example: bridges, pavements, and guardrails. Link, roadway, road, and corridor are used interchangeably, meaning a section or pathway in the network without significant entrances or exits. In addition, terms such as roadway system, roadway network, and roadway infrastructure all refer to a complex network of roadways that are connected and work together.

Researchers have realized the importance of characterizing the performance of roadway systems and a literature review reveals several published studies that identify the vulnerability of roadway networks against different disruptions (Berdica, 2002; Günneç and Salman, 2007; Jenelius et al., 2006; Sohn, 2006; Wu et al., 2007). With advancements in network science and its wide application across different disciplines, transportation research has also employed complex networks to study the vulnerability of transportation systems and, in particular, roadway networks. In this paper, vulnerability is defined as the inability to maintain functionality and performance after a disturbance. According to this definition, vulnerability is related to system performance (travel time, cost, etc. for the roadway system) before and after a disruption. Robustness and resiliency are used as antonyms for vulnerability, capturing the capability of maintaining the system performance after a disturbance. Disturbances or disruptions are referred to in this paper as events that can physically or functionally harm the elements and components within the system. Examples of disturbances or disruptions are targeted attacks or natural disasters.

Several research studies have assessed the robustness and vulnerability of the roadways against different scenarios including floods, earthquakes, terrorist attacks, accidents, and other disasters (Günneç and Salman, 2007; Jenelius et al., 2006; Sohn, 2006; Wu et al., 2007; Chen et al., 2007; Sakakibara et al., 2004; Chang et al., 2012). However, performance and vulnerability assessment of roadway networks can be further extended and not limited to analysis of changes in performance due to disasters or attacks. Along with disasters and their consequences, infrastructure degradation, for instance, is an important factor that can increase infrastructure vulnerability and can reduce performance of roadways. Nevertheless, clear and comprehensive methods that characterize performance dynamics of roadway systems with respect to the condition of their components (individual assets, roadways, bridges, etc.) are still missing. Roads and bridges are often partially or fully closed for maintenance and repair (The Roanoke Times, 2012). It might also happen that roads and, particularly, bridges collapse as a result of poor structural conditions; for example, the Minnesota bridge collapse case (BBC News, 2007). The probability of road closure for maintenance as a result of degraded conditions is typically much higher than the probability of a terrorist attack or a natural disaster. In terms of consequences, frequent road closures for maintenance and repair increase traffic delay and impose enormous costs to users, which is comparable to – or even higher than – the cost of disasters. For instance, one of the biggest earthquakes and tsunamis in history shut down Japan for several weeks and imposed about $309 billion (BBC News, 2011) for reconstruction cost. This high-magnitude earthquake has a return period of about a thousand years and is very unlikely to happen again in decades. Surprisingly, motor vehicle crashes cost the United States about $230 billion every year and the cost of time and fuel wasted in traffic is $78.2 billion each year (ASCE, 2009). Infrastructure condition can be responsible for a significant portion of these costs. On one hand, poor roadway conditions can increase motor vehicle wear and tear, crash rates, and delays

(ASCE, 2009). On the other hand, poor roadway conditions increase the chance of road closure for maintenance and repair (The Roanoke Times, 2012). As a result, many travelers are rerouted, travel times are increased, and significant cost is imposed to users. Therefore, the importance of recognizing road condition in understanding and characterizing the roadway network performance and vulnerability assessment, i.e., “condition-based approach” is evident. Condition-based approach deals with scenarios that continuously happen during the life cycle of the infrastructure, and aims to answer questions such as: How vulnerable is a highway infrastructure system when a portion of its roadways or bridges are in poor or close-to-poor condition? What is the performance of this roadway system? How reliable is such a system? Establishing the link between the condition of roads and the system-level performance and vulnerability can significantly enhance the process of decision making, particularly at strategic levels. As a result, decision-making heuristics not only consider cost-effectiveness but also vulnerability of the infrastructure in the calculations.

This paper reviews how roadway system vulnerability, as a particular system-level performance measure, has been addressed in the literature; it also proposes a new perspective towards roadway vulnerability assessment and describes the significance and potential applications of the proposed approach.

The remainder of the paper is organized as follows. The following section discusses the scope, dimensions, and necessary components of system-level performance evaluation. The paper then develops measures of vulnerability and performance of roadway systems and reviews current research. The main contribution of the paper is then developed in the form of a new perspective and direction on addressing roadway vulnerability and performance problems. The next section discusses how the proposed methods can help in developing more comprehensive management systems. The final section is a discussion.

SYSTEM-LEVEL PERFORMANCE

While the performance of each individual asset is important for project-level practices, the performance of the entire system is particularly important and of high interest for strategic-level decision making. In roadway infrastructure, as shown in Figure 2-1, the system-level performance (and vulnerability) is affected by the performance of individual roadways, and the performance of each roadway or corridor depends on the performance of each asset within the roadway. In several studies researchers have attempted to define an overall performance index for an asset (Litzka et al., 2008; Chin et al., 2011) or develop corridor-level performance measures based on performance of individual assets (such as pavement, bridges, culverts) within the corridor (Verhoeven and Flintsch, 2011; Dehghanisanij et al., 2012). At the system level, examples of studies include the development of a national infrastructure index for the entire U.S. infrastructure (including water, energy, and transportation) (Oswald et al., 2011), the infrastructure report card (ASCE, 2009), and performance measurements of a specific infrastructure such as the transportation system (including air system, highways, and transit) (Li et al., 2011). However, these studies have not clearly addressed the role of each element (such as assets or corridors in a roadway system, or pipelines in a water system) and their interactions to the overall performance and functionality of a system.

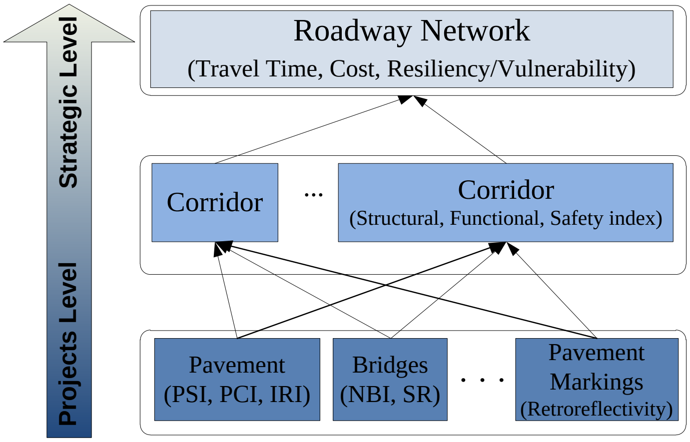

Figure 2-1: Performance measures and organizational level

For a system-level performance and vulnerability assessment of roadway infrastructure, considering it as a complex network of roads and components that work together, it is critical to (1) know the performance of each road, and (2) define, identify, and capture how these roads work and connect to each other. Capturing how the roadways work with each other – in other words, their interdependency – is extremely critical. Network science, an increasingly popular field, can help study and understand the interdependencies between the components of infrastructure systems.

Network science

Network science has seen significant advancements in the past several years. Network science characterizes complex systems by understanding the interaction between the system components and letting us see the whole system that is beyond just a simple model of individual nodes and links (Barabási, 2011). Network science has helped scientists study various properties of human mobility (González et al., 2008), social networks (González et al., 2006), biological networks (Jeong et al., 2000; Ravasz et al., 2002), Web space (Albert et al., 1999), wireless communication (Buldyrev, 2010; Shao et al., 2011), electricity networks (Rosas-Casals et al., 2007; Crucitti et al., 2004a; Albert et al., 2004; Kinney et al., 2005), and many other systems for which a network structure can be imagined. In almost all of such studies, the system is modeled as a graph of nodes and links and is then analyzed to determine the properties of the system that vary based on the network type and functionality. Measures such as degree distribution, cluster size and coefficient, network diameter, centrality measures, and average path length are often used to study the whole complex system (Albert et al., 1999; Buldyrev, 2010; Shao et al., 2011; Albert et al., 2000; Crucitti et al., 2006; Wang et al., 2009). For example, Figure 2-2 shows how urban street networks of Richmond (Virginia), a well-planned city (Figure 2-2a), and Cairo, a self-organized city (Figure 2-2b), have been characterized by betweenness centrality; a measure that shows if a node or link lies between many other nodes or links (Crucitti et al., 2006). Employing network science helps to view the “whole thing” and leads to a better understanding of system performance and how to improve its functionality.

In recent years, network science has been used to analyze the vulnerability in transportation systems, electrical power grids, and communication systems against disruptions (Berdica, 2002; Günneç and Salman, 2007; Jenelius et al., 2006; Chen at al., 2007; Sakakibara et al., 2004; Buldyrev, 2010; Shao et al., 2011; Rosas-Casals et al., 2007; Crucitti et al., 2004a; Albert et al., 2004; Kinney et al., 2005; Latora and Marchiori, 2005; Berdica and Mattsson, 2007; Zio and Sansavini, 2011; Scott et al., 2006). In the majority of these studies, disruptions that represent real-world examples of terrorist attacks, natural disasters, and functional breakdowns are assumed to occur randomly. Often, disruption and failure of one part of the system can cause other parts to fail, and the failure can propagate through the system. Such failure propagation is referred to as “cascading failures” and has been extensively studied in different types of networks such as communication systems and electric power grids (Buldyrev et al., 2010; Albert et al., 2004; Kinney et al., 2005; Albert et al., 2000; Crucitti et al., 2004b; Motter, 2004; Motter and Lai, 2002; Wu et al., 2006; Barrett et al., 2010). Cascading failures often happen in a roadway system as a result of the congestion on one road that can propagate to adjacent roads, and continue until a significant portion of the roadway network is affected. Network science is able to interpret and formulate such interactions in a more tangible way, providing a comprehensive vulnerability and performance assessment of the system.

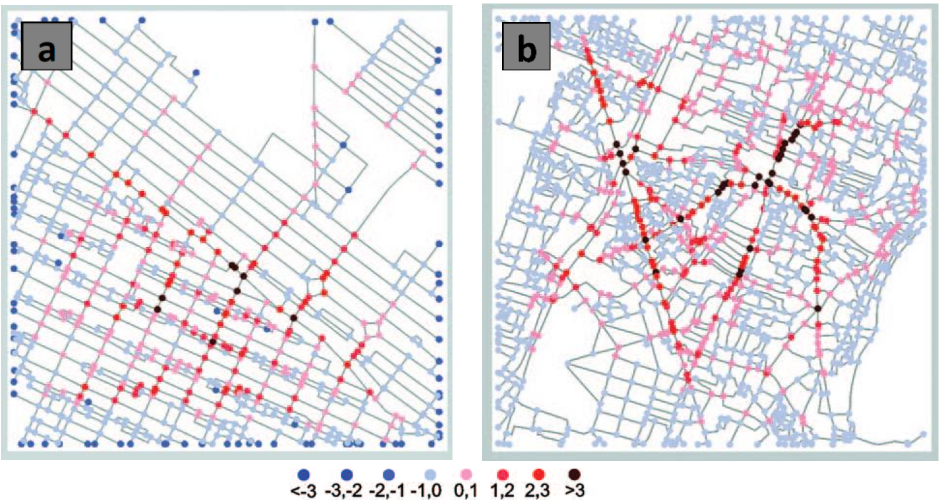

Figure 2-2: Spatial distribution of betweenness centrality based on multiples of the standard deviation from the average: a) Richmond, VA, b) Cairo.

“Reprinted with permission from [Crucitti, P., Latora, V., and Porta, S.Chaos 16, 015113 (2006);]. Copyright [2006], American Institute of Physics”

Interdependencies

Infrastructure systems are becoming increasingly complex. Technological advancements have helped develop infrastructure systems to meet the needs of growing populations but, at the same time, have increased their interdependencies and vulnerabilities (Haimes and Jiang, 2001; McDaniels et al., 2007). For example, more cars and trains are electrified, different sensors are embedded in infrastructure elements to report the condition, and geographic information system

(GIS)-based data are used to monitor and preserve facilities. All these examples show that infrastructure systems are no longer isolated but dependent upon energy, technology, communication, and other systems. Malfunction of any sector, such as energy and power, water distribution, or the communication network, will affect the operation and performance of other systems. Interdependencies, in the context of infrastructure systems, can be physical, cyber, geographical, or logical (Rinaldi et al., 2001). In multi-component systems that consist of many elements the interdependency is classified using structural, stochastic or economic categories (Nicolai and Dekker, 2008). In the context of infrastructure, interdependency can happen at two main levels: within and between the infrastructure systems. For example as shown in

Figure 2-3, the power grids are functionally interdependent within the electrical network. On the other hand, the power network is dependent upon the communication infrastructure, and communication needs power to run. Infrastructure interdependencies have been studied with the purpose of protecting the community and sustaining infrastructure serviceability, particularly during disasters and disruptions. Some studies have used subjective/descriptive methods to define and explain the interdependencies (Rinaldi et al., 2001). Many studies employed graph-theory to model the system and to study the system’s complexities based on the impacts of a change in elements of a network on other sections of the system (Buldyrev et al., 2010; Shao et al., 2011; Zio and Sansavini, 2011; Huang et al., 2011; Ouyang et al., 2009). The main focus of these studies, in general, has been on evaluating the impact on network performance by assessing the consequences of removing nodes or links that represent attacks, natural disasters, or functional loss of system elements (Buldyrev et al., 2010; Shao et al., 2011; Zio and Sansavini, 2011; Huang et al., 2011; Svendsen and Wolthusen, 2007; Rosato et al., 2008). Infrastructure interdependency has also been studied through economical input-output analysis of supply and demand (Chen et al., 2009). The interdependency of sectors is determined based on how much the output of one sector is used as an input in other sectors. Economic concepts such as Leontief input-output models were also used to evaluate the risk in interconnected infrastructure systems (Haimes and Jiang, 2001; Haimes et al., 2005a; Haimes et al., 2005b).

The interconnectivity of networks can increase the overall performance but, at the same time, can make the system more vulnerable to cascading failures and disruptions. Buldyrev et al. (2010) studied the vulnerability of a communication system interconnected to a power system. They found that interdependent networks are more vulnerable to cascade failures as compared to individual networks. Zio and Sansavini (2011) evaluated the cascade-safe thresholds for two interconnected power grid networks below which the system can operate without significant cascade failures when exposed to disruptions. Nozick et al. (2005) modeled a system of a gas distribution network interconnected to an electricity generation/distribution network using graphs. The links carrying gas to different consumers (nodes) had capacity values that stochastically changed over time. They analyzed the system based on two defined performance measures: time to recover (satisfy demands) and probability distribution of product delivery at each node.

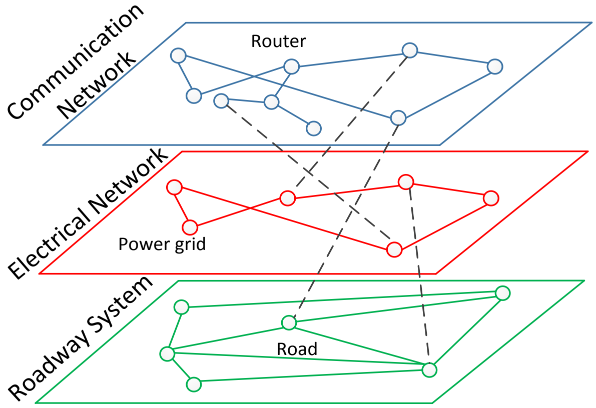

Figure 2-3: Infrastructure interdependencies

Transportation systems such as airports, ports, and railways are dependent on power and other sources of energy. The interconnection of transportation infrastructure to other infrastructure systems (such as the electrical power network) and energy suppliers (such as the oil industry) has also been studied (Chen et al., 2009; Pederson et al., 2006). However, although the vulnerability/performance of roadway networks, considering their interaction with other infrastructure systems, is widely recognized (for example, see Barrett et al. (2010), Heller (2001), Hitchcock et al. (2007), and Giovinazzi and Nicholson (2010)), there are few substantive studies. Moreover, within roadway systems (a subclass of transportation infrastructure), roads are connected to each other as a network and provide service to the users. These roadways are interdependent in a sense that the change in performance of one roadway will change the performance of other roadways and the entire system. Capturing such interdependencies is crucial to proper characterization of roadway performance and vulnerability at a system level. In the next section the context in which this paper defines and formulates vulnerability is explained and studies that have addressed vulnerability of roadway systems are reviewed.

VULNERABILITY

In this section, different components of vulnerability are explained and a definition within that context is provided. The section then reviews current studies of vulnerability and performance of interdependent systems, vulnerability and performance of roadway systems, and some network configuration measures used to characterize roadway system performance.

Defining Vulnerability

Disruptions to different infrastructure systems can have significant short- and long-term effects on serviceability and, consequently, on normal life and the economy. These disruptions might be predictable or not and might be caused intentionally or unintentionally by nature or humans (Berdica, 2002). The need to increase the infrastructure resiliency against disasters and characterize what is called “vulnerability” of infrastructures has gained significant attention over the past few years. For infrastructure systems, the definition of vulnerability depends on infrastructure type and functionality. Vulnerability in roadway systems, according to Berdica (2002), is the susceptibility to incidents that can significantly reduce the network serviceability. Latora and Marchiori (2005) defined the vulnerability of a system as proportional to the maximum performance reduction in the system, which is caused by damage from the class of damages. In other words, the system’s worst performance as a result of damage (from a class of damages) defines the system’s vulnerability. In a similar way, improvability – the ability/capacity to improve a system – is proportional to the best possible improvement of the system after a collapse or failure. The best possible improvement is the maximum performance that can be obtained by an improvement policy (from a class of improvement policies) (Latora and Marchiori, 2005).

In this paper a conceptual context for defining vulnerability is provided and is shown in

Figure 2-4. The framework captures the connection between vulnerability, risk, and system status while taking into account the definitions and dimensions of vulnerability addressed in the past studies (Latora and Marchiori, 2005; Berdica, 2002). Two main aspects/components are considered for vulnerability. The first component is the susceptibility to disruptions or, in other words, "capability of being physically or emotionally wounded" or "openness to attack or damage," according to Merriam-Webster's dictionary. Susceptibility of a system to disruptions depends on both the probability of the disruption, which is an aspect of risk, as well as the system healthiness, which is a function of system condition. For instance, there is a very low probability that a roadway in a desert will be disrupted or damaged by flood (disruption probability), even if the roadway is poorly constructed and is sensitive to moisture (healthiness). The second component is the degree of performance reduction that the system experiences after the disruption. This performance reduction depends on the strength (consequences) of the disruption as well as the preparedness of the system to cope with the disruption (readiness). System readiness can be evaluated based on availability of alternatives in the system (redundancy) and the rapidity in responding to the disruption.

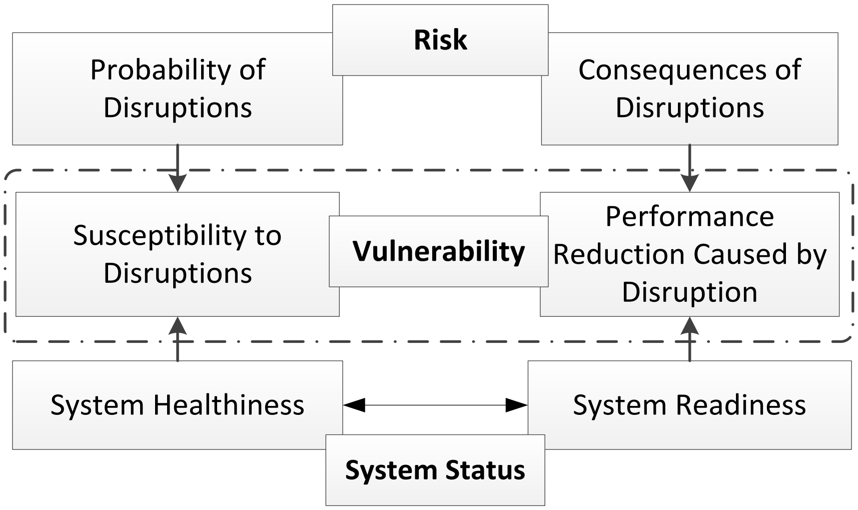

Figure 2-4: Defining vulnerability

From this perspective, vulnerability can be viewed as a system-level indicator which shows the level of exposure of the system to disruptions as well as how performance measures of the system change when disrupted. It captures aspects of both the susceptibility (Berdica, 2002) and the change in performance (Latora and Marchiori, 2005). The diagram also shows how concepts of vulnerability and risk are connected to each other, in addition to the areas where these concepts overlap. The diagram clearly illustrates that risk, in this context, is a characteristic of an event or a disruption while vulnerability is a system attribute.

Vulnerability of Roadway System

With respect to the definition context presented above, measuring the vulnerability of a system depends on the type of performance measures defined for the system and the type of disturbance considered. For example, the structure and topology of a power grid network has significant impact on its vulnerability and, therefore, has been studied by researchers (Rosas-Casals et al., 2007; Crucitti et al., 2004a; Albert et al., 2004; Kinney et al., 2005). For a water distribution system, the critical issue is the vulnerability against different infections that affect the delivery of healthy water to users (Thompson et al., 2007; Propato and James, 2004). For roadway system smooth traffic mobility, travel time and travel cost are important performance measures with respect to which the system vulnerability must be assessed. Different studies have addressed the vulnerability of roadway networks in the past few years (Günneç and Salman, 2007; Jenelius et al., 2006; Sohn, 2006; Chen et al., 2007; Sakakibara et al., 2004; Berdica and Mattsson, 2007; Scott et al., 2006; Chen et al., 1999). In many of these studies the roadway system is modeled with nodes and links using graph theory. An index of vulnerability or robustness is defined and the network is analyzed against the index. The analysis methodology normally includes removing links (roads) or nodes (connections, intersections, etc.) and measuring the network characteristics and already-defined vulnerability indices. Jenelius et al. (2006) defined “importance” and “exposure” for a road network to characterize the vulnerability of the system against disruptions. The link importance basically shows how the travel cost between different origins and destinations changes if one link fails. “Exposure” of nodes in a region was defined as the average expected increase in travel cost between all origins in that region and all destinations over the network as a result of link failures. Scott et al. (2006) defined the Network Robustness Index (NRI) to identify critical links in a roadway network. The concept of NRI was similar to that of “importance” proposed by Jenelius et al. (2006) and the approach was based on the effect of link removals on system performance. Wu et al. (2007) studied the vulnerability of a scale-free type of roadway network. Different link removal strategies (flow-based, betweenness-based, and mixed-based) were considered. They defined an efficiency index as a function of shortest path length and studied how, when a link fails, the traffic distribution causes congestion on other roads and the cascading congestions and traffic failure propagates through the entire system and affects the efficiency.

Some studies assessed the vulnerability of roadway systems to particular disasters. Sohn (2006) defined an accessibility index to assess the significance of highway network links under flood scenarios in Maryland. The index was used to assess the significance of a link based on the distance-only effect and distance-traffic volume criteria. Günneç and Salman (2007) studied the functionality of the Istanbul highway system under earthquake risk by developing probabilistic measures of connectivity and expected travel time. They defined a vulnerability-based dependency between link failures such that, when a link fails, the next vulnerable link close to it has a higher probability to fail. They then characterized the network vulnerability based on the expected travel time and the distance between critical origin-destination pairs with respect to the dirsuption.

Chen et al. (1999) were among the first who took degradation into account to study capacity reliability of roadway networks. They introduced capacity reliability as the probability that a certain level of traffic can be accommodated by the road network; i.e., the roadway network's reserved capacity is greater than the demand. For different levels of degradation (the portion of links in the network that will experience capacity reduction), the capacity reliability of the network was calculated. Instead of using the link removal method, the analysis was based on link capacity reduction which often happens in the roadways. A random link capacity was selected from a probability distribution whenever a link was under degradation. Later, Chen et al. (2007) proposed an accessibility-based vulnerability measure to account for the effect of link failures on increase in travel time. The method considered different possible scenarios based on travelers' behavior, from canceling the trip to choosing another route or mode.

Roadway Network Configuration Properties

Performance and vulnerability of roadway systems have been also characterized based on the network-related properties. Sakakibara et al. (2004) used Topological Index (TI) to study the robustness of the Hanshin roadway network in Japan. Topological Index, first used to classify isomers in molecular chemistry, is a measure of the depressiveness/concentration of a network (Sakakibara et al., 2004). This measure was used to quantify the isolation of the city as a result of roadway breakdowns during disasters. They found that in a roadway network with a similar number of nodes and links, isolation of links is less likely in a network with higher TI. Crucitti et al. (2006) studied the networks of urban streets using centrality measures. In their study they measured degree, closeness, betweenness, straightness, and information centrality for 18 urban street network samples around the world. They found that spatial assessment of the network using multiple centrality measures helps to understand the structure of the urban street network, identifying the central routes and regions.

CONDITION-BASED VULNERABILITY ASSESSMENT

There is no doubt that having a robust roadway system during disasters reduces the hazard mitigation costs while maintaining the continuity of operations for faster recovery (ASCE, 2009). Most studies reviewed in this paper have a “disaster-focused approach” towards the system-level performance and vulnerability assessment of infrastructure systems. For roadways, current research focuses on understanding the vulnerability to events such as terrorist attacks, floods, earthquakes, etc., which have significant consequences. These events disrupt the system and impose significant costs on users and agencies. However, the duration of such events is normally relatively short – from several days to several weeks – in the life cycle of roadway infrastructure, which is normally on the order of 40-50 years. Moreover, disasters, such as earthquakes or floods – depending on their magnitude – have a significantly large return period which is an indication of a very low occurrence probability in a 40-50 year period. On the other hand, roadway degradation happens at all times and for all roadways.

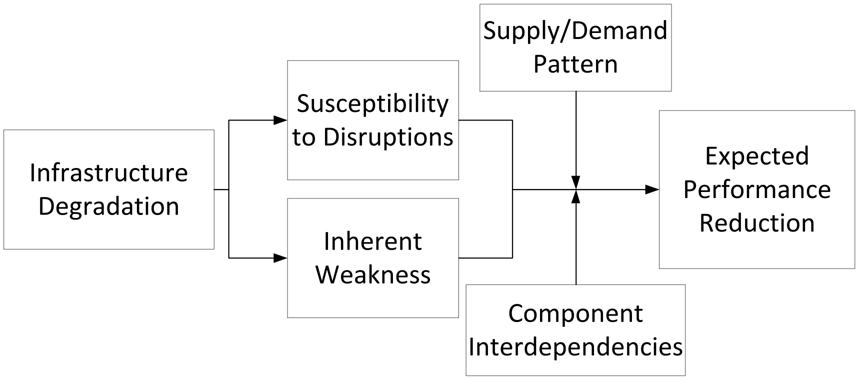

Figure 2-5: Degradation leading to vulnerability

Figure 2-5 shows the logical connection between infrastructure degradation and performance reduction in the system. The effect of degradation on vulnerability of civil infrastructure, particularly roadway systems, can be addressed from two general perspectives: First, the inherent weakness of the system; i.e., the fact that degraded components are more likely to fail or malfunction because of their own poor condition. For example, a pavement with poor condition is more likely to have more cracks or rutting compared to a new pavement. The second perspective is the increased susceptibility to external disruptions; i.e., making it more likely for degraded components to fail or be disrupted by incidents such as natural disasters or attacks. For example, a structurally deteriorated bridge can be more vulnerable to earthquakes or explosions compared to a newly constructed bridge.

For roadway systems, a conceptual framework for condition-based vulnerability assessment (CBVA) can be developed as shown in Figure 2-6, using the concepts and connections shown in

Figure 2-5. The framework actually captures the “inherent weakness” aspect of vulnerability of roadways as a result of degradation. Each road in the system is in a specific condition. Whenever a roadway (or elements in the roadway, such as bridges) reaches the unacceptable condition threshold, it will be fully or partially closed to receive treatment or – in rare cases – the road can fail or collapse (e.g., failure of bridge or culvert in the road). In such cases, travelers will experience delays on their way to the destination, either by getting stuck in traffic or choosing an alternative route. As a result, performance measures such as travel time, travel cost, and level of congestion at the system level will be affected. The condition of roadways determines the remaining time until failure or maintenance, and can predict the likelihood of such an event at any time in the future. In addition to road condition, the framework suggests taking two other important aspects into account: travel patterns and network topography. Travel patterns show how people move across the network; identify important regions, origins, and destinations, and predict road usage and road condition as well as future travel behavior. The network topography shows the position and properties of links and their interconnectedness, and affects the travel behavior and route choice. Although interdependencies, travel behavior, and other uncertainties complicate the observance and characterization of vulnerability, the overall dynamics of vulnerability are imaginable. As the number of roadways that are close to – or are in – poor condition increases the chance of simultaneous roadway collapses or closures increases. Consequently, the system is further exposed (vulnerable) to performance reductions such as increases in travel time and cost. In general, at any time in the life cycle, the system has a level of vulnerability; i.e., the system is expected to experience some maintenance and failures that reduce the system performance and increase cost. The system is more vulnerable if the roadways that are in (or close to) poor condition also have critical locations in the network.

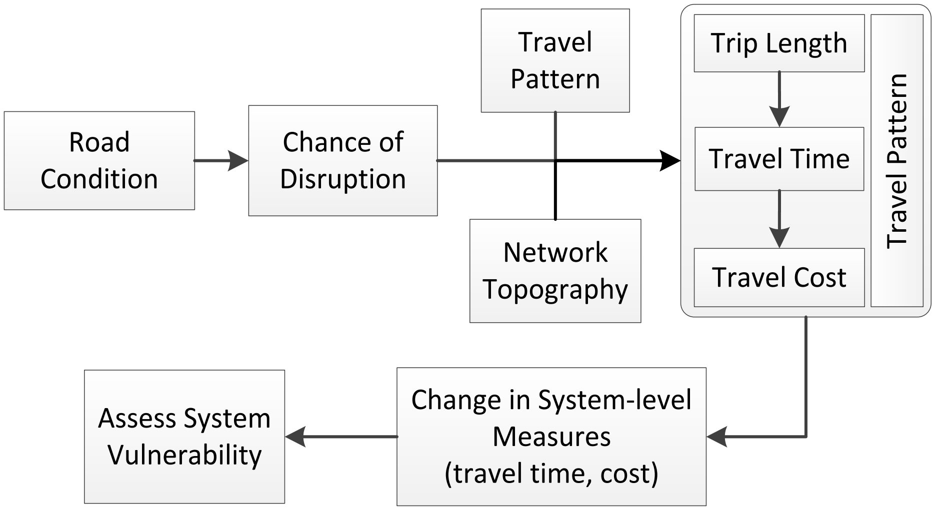

Figure 2-6: A conceptual CBVA framework for a roadway system

Condition-based vulnerability assessment is a step forward in characterizing roadway transportation performance. Instead of modeling failures/disruptions of one link at a time, in the condition-based approach, simultaneous collapses of links are considered. In fact, simultaneous disruptions occur in reality since many roadways in the network might be under treatment at the same time. However, there are few studies that have taken the simultaneous disruption of several roads into account (Günneç and Salman, 2007). Moreover, a condition-based approach requires considering more realistic modeling of disruptions for roads (such as capacity reductions) since roadways are not always completely closed because of poor conditions. Except for a few studies (Chen et al., 2007; Chen et al., 1999; Chen et al., 2002), failure is often the only considered mode of disruption for a road, probably due to the computational simplicities in modeling and analyzing link removal scenarios.

Condition-based vulnerability assessment is a probabilistic approach that can characterize the vulnerability of the roadway network in a wide spectrum of possible outcomes. The transition of road condition from one state to another is probabilistic. The disruptions, i.e., fully/partially closure of roads for maintenance occurs with a probability and depends on the road condition. On the other hand, the impact of a disruption scenario can also highly depend on the road condition. For example, a poor road needs more sophisticated maintenance treatment compared to a fair road and as a result, the disruption impacts (length and magnitude of road closure) can be more severe. Therefore, the condition of the roadways, state transition probabilities, disruption probabilities, and disruption consequence can be interdependent. While the roadway condition and state transitions probabilities are influence by the roadway history, the impact of construction activities and disruption consequences should largely be restricted to the year of decision-making itself.

APPLICATIONS

The condition-based vulnerability assessment attempts to understand the connection between infrastructure condition and degradation with the system-level performance measures (such as travel time and travel cost) from the risk and vulnerability perspective. It is important to note that the CBVA framework is not an optimization algorithm but rather a method to determine how the condition of different roads can affect the overall performance and resiliency of the whole network. The framework, as a supporting tool, can help and guide decision makers in selecting appropriate resource allocation and maintenance policies. Of course, it is ideal to develop an analytical expression of travel time/cost as a function of maintenance strategies and embed it into objective function to find the optimal resource allocation/maintenance policies. However, finding such expression is extremely difficult and computationally intractable and out of the scope of this paper. In CBVA method the impact of the road conditions (and consequently the maintenance strategies) on network performance and vulnerability (travel time +cost) are assessed in a simulation environment. In the first step the disruption probabilities for each roadway should be determined based on their condition. The condition-based reliability models for various assets can be found in the literature (Akgül and Frangopol 2004; Liu and Frangopol, 2006). In the next step different methods can be used to compute travel time/cost for each simulated disruption scenario. Algorithms such user equilibrium (Fisk, 1980; Wu et al. 2007), cell transmission model (Daganzo 1994, 1995) and shortest path approach (Jenelius et al., 2006) have been used in the past for traffic assignment and vulnerability assessment studies. Given the condition/status of the rods as a result of a resource allocation/maintenance policy, the vulnerability of the network can be determined using the CBVA framework. The process can be repeated for a pool of alternative policies to identify options that minimize the network vulnerability. Recently, some studies have tried to capture the roadway network configuration, travel patterns, and system vulnerability to formulate resource allocation and maintenance scheduling problems; examples being: optimizing maintenance and preservation of roadway infrastructure considering traffic dynamics and user cost (Ng et al., 2009), activity interdependencies (Durango-Cohen and Sarutipand, 2007) during maintenance, optimizing roadway maintenance planning to strengthen the roadway network before (Peeta et al., 2010; Miller-Hooks et al., 2012) and after (Chang et al., 2012; Miller-Hooks et al., 2012) a disaster, and bridge network maintenance optimization considering the accessibility and evacuation capacity of the network (Chang et al., 2012; Liu and Frangopol, 2006; Essahli and Madanat, 2012). The significant computational complexities associated with the large size of feasible solutions in such problems often requires simplifying problem formulation or approximating value functions. For example, the computational time for a network with 24 links and 12 OD pairs to find the optimal maintenance planning was about 2 days (Ng et al., 2009). In other studies (Liu and Frangopol, 2006; Essahli and Madanat, 2012;

Peeta et al., 2010) small and simple networks with few OD pairs were considered for computational tractability. The CBVA approach can be used to reduce the feasible solution space and can enhance approximations by allowing us to focus on selective sets of roads throughout the network where the poor condition of those roads can impose a critical impact on roadway network performance and vulnerability. The approximation can be helpful particularly in situations where the limited budget can only cover treatment cost of few links in a large scale network. For example, in a network with100 links and 4 treatment options (including do nothing), 4^{100} possible solutions need to be tested to find the optimal policy which is not practical. Approximation allows us find satisfying solutions that are reasonably close to optimal solution with much less computational effort. However, it is important to note that focusing on a few critical links of the network at the expense of others can create new critical links. Therefore, it is critical to recognize the tradeoff between approximation/cost and optimal results.

DISCUSSION

Engineers and managers are becoming more interested in performance measures that characterize the infrastructure systems as a whole. Roadway systems, along with other infrastructure systems, have become more advanced, interdependent, and sophisticated. As a result, we have more functional and efficient infrastructures that are also more vulnerable to disruptions and disasters. This paper defines vulnerability of roadway systems as a measure that represents the degree of susceptibility of the system to disruptions and shows the level of deviation of system performance from its ideal/original status when it undergoes a disruption or a disaster. Vulnerability and, more generally, performance assessment of roadways at the system level requires capturing their complexities and interdependencies, which has become easier with advancements in network science. In almost all current studies, vulnerability is assessed against disaster scenarios. This paper extends the discussion and proposes new directions towards understanding system-level performance and vulnerability by capturing the degradation of the infrastructure. The main rationale behind this so-called condition-based vulnerability assessment approach is that degradation is a significant threat to robustness of transportation and particularly roadway networks, and an important factor in increasing vulnerability and performance reduction. The poor condition of pavements, bridges, and other assets often causes partial or full closure of the roadways to allow for treatment and repair. The consequences – such as traffic delays, congestion, and travel costs – are often as high as disasters and attacks. This is because road closures for maintenance occur frequently during the life cycle when compared to the much lower chance of collapses and failures as a result of disasters. There are studies that have captured degradation of roadways in resource allocation and maintenance scheduling calculations. However, the behavior of roadways and their condition impact on vulnerability, and other system-level measures have not been clearly studied in the past. The CBVA method can enhance tractability of optimal maintenance planning problems by providing a search heuristic that decreases the solution space. Moreover, this method lets us see the entire roadway network performance based on the properties and interactions of individual components.

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Chapter 3 : IMPACT OF ROAD CONDITION AND DISRUPTION UNCERTAINTIES ON NETWORK VULNERABILITY[1]

ABSTRACT

Researchers have studied the vulnerability of roadway systems to disasters, such as terrorist attacks or natural disasters. However, the literature has not explicitly addressed other factors, such as infrastructure degradation, that can significantly affect the vulnerability of roadway systems. In this study, we developed an algorithmic framework to address how the condition and degradation of a roadway network impacts its vulnerability to disruptions. The vulnerability of the network was computed with respect to two measures: network efficiency and vehicle miles of travel. The results show that the average condition of the roadways in the network, the difference between the conditions of the roads, the uncertainties associated with road disruption probabilities, and link topological positions affect the roadway vulnerability.

Key words: Roadway network, critical infrastructure, vulnerability, condition, disruption, performance, resiliency

INTRODUCTION

Roadway systems are part of the critical infrastructure and a major backbone of economic development in every country. Every day, drivers travel millions of miles on roads to deliver goods and seek services from different destinations. During a disaster, such as an earthquake or flood, the roadway transportation system can support or hinder response operations, such as delivery of medical assistance to victims, and accelerate or slow the rate of recovery through the movement of resources to disrupted areas. To serve the community, particularly during disasters, the roadways should be robust and resilient enough to withstand disruptions.

Researchers have long assessed the vulnerability of infrastructure systems to disasters and attacks. Such events disrupt roadway systems, which can impose enormous cost on users and

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agencies. However, roadway systems with a life span of 50 to 60 years are not very likely to experience a flood, earthquake, or terrorist attack. Moreover, many roadways are not exposed to floods, earthquakes, or other disasters because of their geographical location. The disaster-based vulnerability assessment is a case-specific approach that does not generalize to all roadway systems. Research has not explicitly addressed the impact of other factors, such as condition of the roadway system, on roadway vulnerability. According to the estimates in 2010, deficiencies in the roadway system cost households and businesses in the U.S. about $130 billion (ASCE 2013). On the other hand, construction, maintenance, and repair will likely close, either partially or fully, roadways or bridges in poor condition (The Roanoke Times 2012). Consequently, users have to choose alternative routes to their destinations, which significantly increases the time and miles travelled.

The literature contains a wide spectrum of definitions and methods for the assessment of vulnerability, depending on the type of infrastructure and its expected service. For example, an overload of any power grid in the electrical network can cause cascading failures in the network (Zio and Sansavini 2011). Water distribution systems are critical to public health, so studies have investigated the vulnerability of water networks to infections (Thompson et al. 2007; Propato and James 2004; Haimes et al. 1998; Fowler et al. 2003). Latora and Marchiori (2005) define the vulnerability of infrastructure installations based on how their performance changes before and after a disruption. Berdica (2002) defines vulnerability of roadways as their susceptibility to incidents and disruptions that can significantly affect the functionality of the roadway system. Dehghani et al. (2013) adopted a similar definition and proposed a conceptual framework for condition-based vulnerability assessment (CBVA) of roadways. Fig. 3-1, based on Dehghani et al., shows how the condition of the roads determines the vulnerability of the roadway system to disruptions. Vulnerability assessment in this perspective captures both susceptibility to disruptions, as well as their impact.

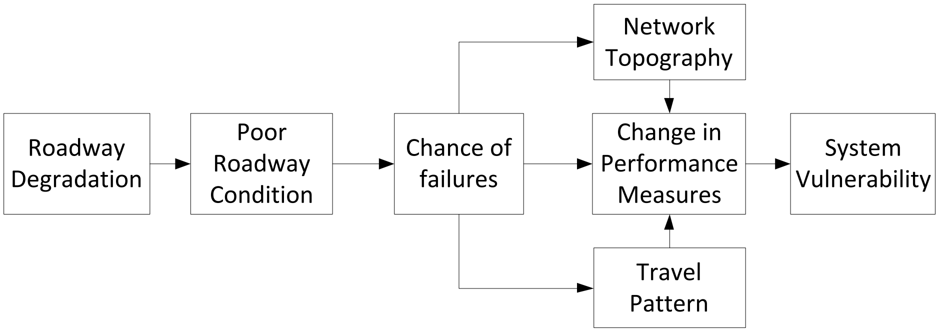

Figure 3-1 Conceptual Link between Roadway Condition and Vulnerability

In this paper we develop an algorithmic approach, based on CBVA framework, to assess the vulnerability of roadway networks and demonstrate its applications. We review current research on roadway vulnerability assessment, present the computational framework and demonstrate its application with a case study, discuss how such an approach contributes to the protection of critical infrastructures, and finally present conclusions.

INFRASTRUCTURE VULNERABILITY IN THE LITERATURE

In the last decade, researchers have significantly increased their attention to the vulnerability of infrastructure systems. Researchers have assessed the vulnerability of power networks to attacks and disruptions (Rosas-Casals et al. 2007; Kinney et al. 2005; Crucitti et al. 2004; Albert et al. 2004). They have also studied the vulnerability of water distribution systems to attacks and contamination by infectious agents (Thompson et al. 2007; Propato and James 2004; Haimes et al. 1998; Fowler et al. 2003). More recently, researchers have characterized the vulnerability and performance of interdependent infrastructure systems such as electricity-electricity (Zio and Sansavini 2011), electricity-communication (Buldyrev et al. 2010) and electricity-gas (Nozick et al. 2005).

In the past few years, researchers have also addressed the vulnerability of roadway systems to disasters, using different performance measures and analysis methods. Günneç and Salman (2007) assessed the vulnerability of the Istanbul roadway network to earthquakes. They classified road links into different sets according to their adjacency and assumed independent failure of links in different sets. They defined vulnerability-based dependency for link failures such that if a link in a set fails, the next weakest links will also fail. Sohn (2006) assessed the vulnerability of the Maryland roadway network to floods. He defined an accessibility index, based on distance-only and distance-traffic volume criteria, to measure the importance of individual links. Jenelius et al. (2006) defined measures of exposure and importance to analyze the vulnerability of roadway networks. The effect of a link's failure on travel cost over the network determines the link's importance. The exposure of nodes in a region shows the effect of link failure on the expected average cost of travel between origins in that region and destinations all over the network. Sakakibara et al. (2004) used the Topological Index (TI), a measure associated with the concentration or diffusion of the network, to study the vulnerability of Japanese roadways to failures. Using the TI, which was first used in molecular chemistry, Sakakibara et al. found isolations are less likely to occur in networks with greater TI.

Fig. 3-2 summarizes the current status of research on vulnerability assessment of roadway networks in terms of the utilized performance measures and analysis methods. Almost all studies have modeled roadways by using a graph of nodes and links. Researchers have then analyzed the performance of roadway systems to capture the impact of disasters, such as floods, earthquakes, and terrorist attacks. The body of research has assumed different types of dependent, independent, targeted, and random failures and capacity reductions for the links or nodes in the network (Chen et al. 2002; Chen et al. 2007; Günneç and Salman 2007; Jenelius et al. 2006; Wu et al. 2007). Some studies have evaluated the network-related measures, such as shortest path or network efficiency (Wu et al. 2007). Other studies have used traffic information, such as accessibility or travel time and cost, to evaluate network vulnerability to disruption (Sohn 2006; Jenelius et al. 2006; Chen et al. 2007).

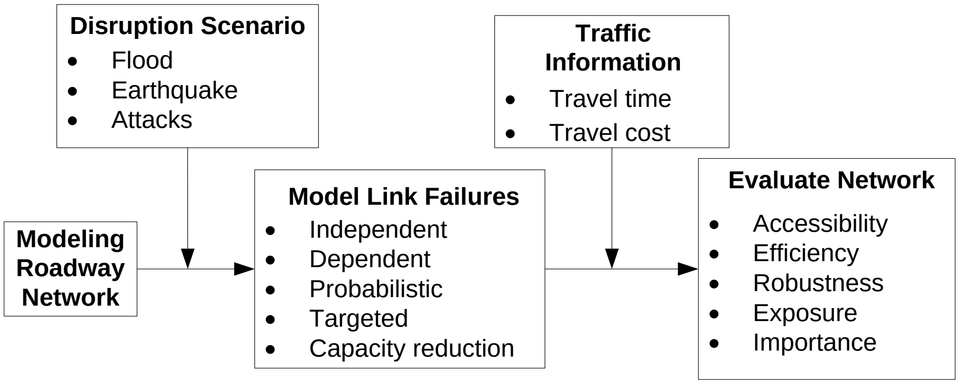

Figure 3-2 Literature Methodology Summary

METHODOLOGY

Algorithmic Approach

The CBVA approach enables the characterization of the vulnerability of a roadway system in which each road has a level of condition and consequently a disruption probability. Fig. 3-3 shows a proposed algorithmic and operational framework for roadway CBVA. The vulnerability assessment process starts by considering disruption scenarios for a particular network status. A network status is a particular state of the network where each road is in a certain condition and has a disruption probability. The network- and transport-related properties of the roadway system are measured for all scenarios. The occurrence probabilities of scenarios are used to compute the expected resulting performance measures (VMT and efficiency). The vulnerability of the network at that particular status is then assessed by computing the change in performance measures, before and after the disruption. The next sections provide the modeling and calculation steps.

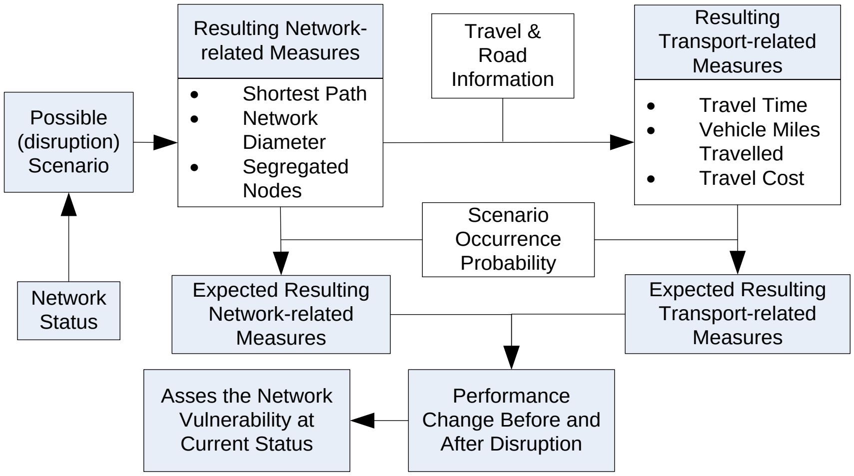

Figure 3-3 Algorithmic Approach for CBVA of Roadways

Modeling Roadway Systems

In this method, roadway systems are modeled with a graph $G(N,K)$, where N and K are the number of nodes and links, respectively. Links (interchangeably used with "roads" in this paper) represent carriageways without major entrances or exits. Nodes are points where links join. In a nationwide roadway system, nodes can represent cities and links can be interstate or primary roads. In urban road networks, nodes and links can represent intersections and streets, respectively. Each link (e.g., the i^{th} link) has a length l_i as well as a disruption probability p_i , as shown in Fig. 3-4. Road disruption probability is the probability that the road will be closed (fully or partially) to receive maintenance or due to failure. With this definition the disruption probability is a function of the condition of the road (i.e., the overall condition of pavements, bridges, culverts, and other assets within the road). Roadway failure is often a result of the failure of assets such as bridges or culverts within the roadway or the poor condition of the pavement. It is not the goal of this study, however, to determine the disruption or failure probability of roads based on their condition where such models can be found in the literature (Liu and Frangopol 2006; Akgül 2004). This study assumes *a priori* that disruption probabilities of the roads are given.

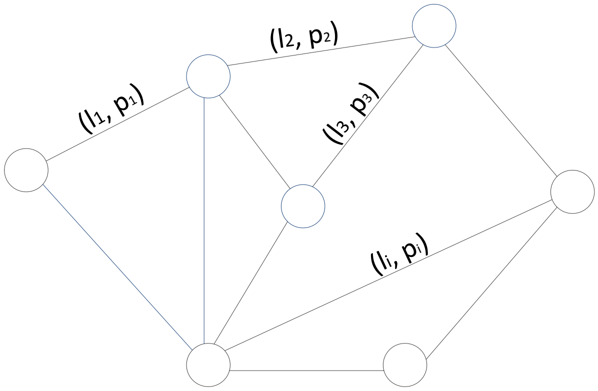

Figure 3-4 Network Illustration

Disruption Scenarios

Many different statuses for roadway networks are possible depending on the condition (disruption probability) of its constituent roads. Likewise, different disruption scenarios are possible for a particular roadway system status, such as that shown in Fig. 3-4. A disruption scenario is the failure, or partial or full closure, of one link or a combination of different links. Removing the links can simulate their full closure or failure. Increasing the length of the link or reducing the link capacity in the model can simulate partial closure of the roads for maintenance purposes. This will increase the travel time on the link and can capture the delays associated roadway maintenance activities. In this study we assume that disruption will result in full closure of roadways. The probability of each disruption scenario for the network is computed based on the disruption probabilities of the roads. For instance, if scenario *a* is the disruption of the i^{th} and m^{th} link in the roadway network (Figure 3-4), the probability of the scenario can be calculated as follows:

$$P(a) = (1 - p_1) \times (1 - p_2) \times \ldots \times p_i \times \ldots \times p_m \times (1 - p_{m+1}) \times \ldots \times (1 - p_k) \qquad \text{(3-1)}$$

where p_i is the disruption probability of link *i*. It can be shown that, for a network with *K* links, there are 2^K possible disruption scenarios.

Network-related Measures

Disruptions can change the performance of the network as well as some of its properties such as network diameter, number of isolated nodes, and shortest path between nodes. Latora and Marchiori (2001) defined the average efficiency, *U(G),* for a generic graph, *G*, as

$$U(G) = \frac{1}{N(N-1)} \sum_{i \neq j \in G} \frac{1}{d_{ij}} \qquad (3\text{-}2)$$

where d_{ij} is the shortest path between origin-destination (OD) pair *ij* and *N* is the number of nodes in the network. This measure reflects how efficiently the information is transferred through the network and has been used in past studies (Wu et al. 2007) to characterize roadway network performance. In this study, we adopt the concept of efficiency and define the network-related performance measure as follows:

$$EFF(a) = \frac{1}{N(N-1)} \sum_{i \neq j \in G} \frac{1}{d_{ij}(a)} \qquad (3\text{-}3)$$

where *EFF(a)* is the resulting network efficiency and $d_{ij}(a)$ is the resulting shortest path between *OD* pair *ij* after scenario *a* has occurred. We also define $EFF^0 = \frac{1}{N(N-1)} \sum_{i \neq j \in G} \frac{1}{d^0{}_{ij}}$ as the original efficiency of the network when undisrupted, where $d^0{}_{ij}$ is the original shortest path between OD pair *ij*.

Transportation-related Measures

Network-related measures provide useful information about the configuration and connectivity of the roadway network. However, transportation engineers are also interested in how transportation and mobility change on the network as a result of disruptions. Various performance measures have been introduced for roadway transportation systems such as travel time, accessibility, and total delay (Berdica 2002). In this study we use Vehicle Miles Travelled (VMT) as the main roadway system performance indicator. VMT is a simple yet informative measure that can approximate travel time and cost on the network, specifically in large-scale networks (i.e., interstates and primary roads). Moreover, the VMT can contribute to the estimation of environmental impacts such as fuel consumption and CO_2 emission.

When one or several links fail (or close fully or partially) in a roadway system, travelers will choose alternate routes to their destination to minimize their travel time and cost. Some studies (Ukkusuri et al. 2007; Ng et al. 2009) employ user-equilibrium (UE) or user-optimal (UO) principles for traffic assignment problems. Other studies (Jenelius et al. 2006; Jenelius 2009) have considered the shortest path between the origin and destination in the traffic assignment. In this study we adopt shortest path traffic assignment approach assuming that the travel time is proportional to the travel distance. The shortest-path approach can provide reasonable results for uncongested networks at the scale of interstates that connect cities or towns (Giaimo 2001).

The resulting VMT after disruption scenario *a* for the entire system, $VMT(a)$, is measured as follows:

$$VMT(a) = \sum_{i \neq j} VMT_{ij}(a) \tag{3-4}$$

$$VMT_{ij}(a) = q_{ij} d_{ij}(a) \tag{3-5}$$

where $VMT_{ij}(a)$ is the resulting VMT between the OD pair *ij* when scenario *a* occurs and q_{ij} is the travel demand between OD pair *ij*.

Expected Network Performance

For a particular state $s \in S$ (where *S* is the set of all possible states imaginable for the network) of the roadway network, each disruption scenario has an occurrence probability. Therefore, the consequences (in terms of new resulting performance levels) are probabilistic and not definite, but are expected to happen. The expected performance measure type *r* (VMT or efficiency) in the roadway system can be computed as follows:

$$E[r(s)] = \sum_{a \in A} P(a) \times r(a) \tag{3-6}$$

where $E[r(s)]$ is the expected value of performance type r when the system is in state s, $r(a)$ is the value of performance measure type r when scenario a happens, and A is the set of possible disruption scenarios.

Measuring Vulnerability

In this proposed method, vulnerability of the roadway is defined for every state s and is measured with respect to the desired performance measures using the following equation:

$$V_r(s) = \left| E[r(s)] - r^0 \right| / r^0 \tag{3-7}$$

where $V_r(s)$ is the vulnerability of the roadway system with respect to performance measure type r when the system is in state s, and r^0 is the value for performance measure type r when the network is undisrupted. Efficiency vulnerability, $V_{EEF}(s)$, shows how the efficiency of the network at state s is vulnerable to disruptions and is expected to decrease. Also, VMT vulnerability, $V_{VMT}(s)$, represents how the VMT of the network at state s is expected to increase as a result of disruptions. Higher values of V_{EEF} and V_{VMT} mean a more vulnerable system.

APPLICATION DEMONSTRATION

This section shows the application of our CBVA algorithmic approach and illustrates how the vulnerability of roadway systems can be analyzed based on the condition of its individual roads.

Consider a hypothetical roadway network with 13 links (roads), shown in Fig. 3-5. The label on each link in Fig. 3-5a is the length of the road. Fig. 3-5b shows the roadway network in a particular status (status I), in which each roadway has an assigned disruption probability. The disruption probabilities were randomly generated from a uniform distribution. The network represents a relatively large-scale roadway system (primary roads or interstates) where the nodes are cities or small towns. As a result, travel times are assumed to be proportional to the length of the links. Table 3-1 shows the random daily travel demands between all OD pairs, which were generated from a normal distribution (μ=15,000 vehicles/day, σ=2,000). In order to reduce computational complexities, some studies (Peeta et al., 2010) considered travel demand only for one OD pair.

A total of 2^{13} disruption scenarios were simulated. If a scenario left an OD pair ij with no remaining path, the distance between that OD pair was set to 10× d_{max}^{0} where d_{max}^{0} is the maximum shortest path in the original network. This represents a penalty, automatically applied by the algorithm, reflecting the amount of effort and cost needed to get from *i* to *j* if no roadway path is available. Estimating the cost of network segregation can be difficult. For example, assigning equal penalties for all segregation scenarios might not be realistic; in this study we adopted this approach for demonstration purposes only.

The vulnerability of the network was calculated based on two measures described earlier: network efficiency and VMT. Table 3-2 shows the vulnerability results. The VMT on the undisrupted network is about 2.099×10^{8} (veh-mile), and the undisrupted network efficiency is 0.0063 (mile^{-1}). The results show that $V_{EFF}(0)$ and $V_{VMT}(0)$ are equal to 0 when the network is undisrupted, which means that the network with no chance of being disrupted is not vulnerable. As shown in Table 3-2, $V_{VMT}(I)$ is equal to 14.5. This means that, considering all possible disruption scenarios with different consequences, the VMT for this roadway network at status I is expected to increase by about 14.5 times the original VMT. The efficiency vulnerability of the roadway network, $V_{EFF}(I)$, is 64%. That is, considering all possible disruption scenarios, the roadway network at status *I* is expected to lose 64% of its efficiency.

Despite the correlation between VMT and efficiency vulnerability (as they are both functions of the distance traveled), each measure sheds light on a particular aspect of the system's vulnerability (see Fig. 3-1). Efficiency accounts for the network configuration, and VMT captures the traffic movement and mobility patterns.

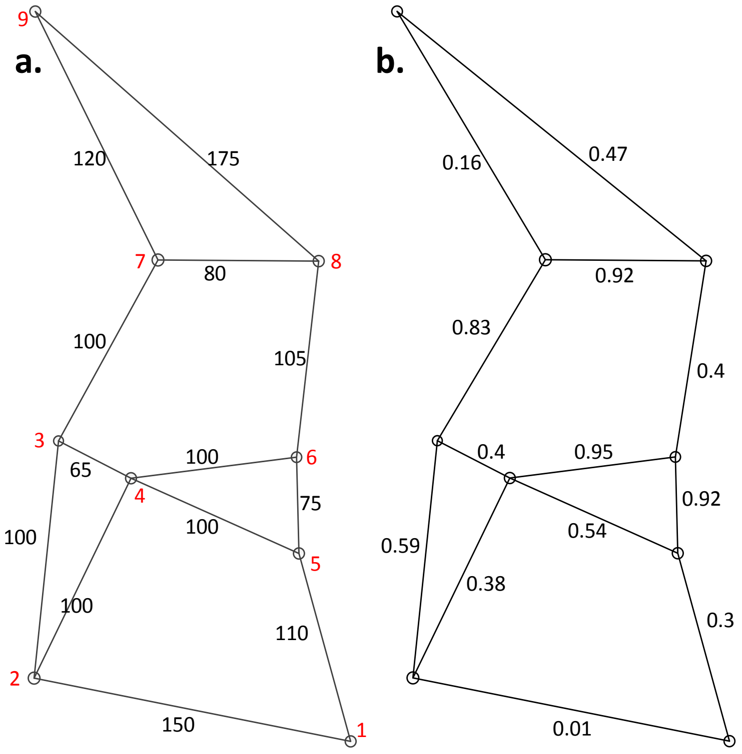

Figure 3-5 Roadway Network: a) Length of the Roads, b) Disruption Probability of the Roads

Table 3-1 Randomly Generated OD Travel Demand (Vehicles/Day)

O/D	1	2	3	4	5	6	7	8	9
1	0	10694	13392	15173	12309	15470	9722	17962	17855
2	12129	0	13944	16919	18820	18355	14141	17948	21029
3	13953	14475	0	15726	17633	13042	13817	12118	12160
4	17788	15960	14473	0	14069	11430	13771	14596	19620
5	16222	15228	17937	16117	0	15246	15150	11370	14577
6	14419	17281	14842	14346	16783	0	13987	15424	13859
7	16930	17139	16838	14567	10628	11626	0	13887	15143
8	12877	16972	15921	16852	14023	11986	14828	0	14566
9	14495	14395	12443	14817	12734	18357	14991	13860	0

Table 3-2 Vulnerability Assessment Result

	Undisrupted Network	Network I Fig 5b
VMT (veh-miles/day)	2.099×10^8	3.2568×10^9
Efficiency	0.0065	0.0023
$V_{VMT}(s)$	0	14.5
$V_{EFF}(s)$	0	0.64

DISRUPTION PROBABILITY UNCERTAINTY

Disruption probabilities reflect the condition of the roadways as well as factors such as the quality of the maintenance, traffic loading, condition of adjacent assets, and environment. These factors increase the uncertainties of determining disruption probabilities. As we mentioned earlier, determining the disruption probabilities of the roadways is out of the scope of this paper, but relevant studies can be found in the literature (Liu and Frangopol 2006; Akgül 2004). In this section we examine how the variations and uncertainties in roadway disruption probabilities affect the vulnerability of the roadway network.

This study included 25 different experiments. In each experiment, the disruption probabilities of the roads in the network shown in Fig. 3-5 were randomly generated from a given distribution. Three different distribution types, three mean values, and three standard deviation (SD) levels were considered. The Uniform distribution with a mean of 0.2 was only used with a standard deviation of 0.05 to avoid negative disruption probabilities. Fig. 3-6 shows the information about each distribution. Each experiment was repeated for 1,500 iterations, and V_{VMT} and V_{EFF} values were computed in all iterations.

The experiments considered a constant and equal travel demand of 100 vehicles per day (veh/day) between all origins and destinations. Equal travel demand eliminates the effect of travel pattern and focuses on the impact of disruption probabilities. Also, we assumed that without changes in land use and roadway constructions, the travel patterns, governed by the demand between different origins and destinations, will remain reasonably unchanged, particularly over an analysis period of several years.

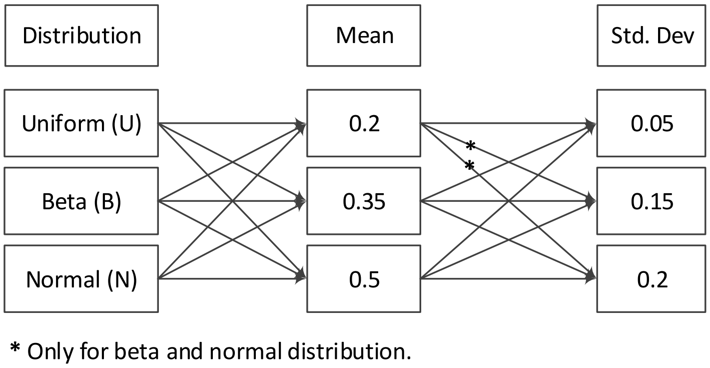

Figure 3-6 Distribution Types, Mean, and Standard Deviation Values for the Experiments

Figs. 3-7 and 3-8 are box and whisker plots showing the simulation results for V_{EEF} and V_{VMT}, respectively for all of the experiments. The figures show the mean, range, and 25th and 75th percentiles for the V_{VMT} and V_{EFF} values for each experiment. Although the scales of V_{VMT} and V_{EFF} differ significantly, the figures illustrate the trends and similarities. As shown in the figures, the average vulnerability values in experiments increase with the mean of the disruption probability distribution. Also, the vulnerability values have more variation as the variance (or equivalently the standard deviation) of the disruption probabilities increases. Theses variations and uncertainties associated with disruption probabilities can complicate the accurate estimation of network vulnerability. In general, regardless of the type of distribution, experiments with probability distributions of similar mean and variance values have very similar results (vulnerability range and mean). In other words, the vulnerability measure is captured by the parameters describing the distribution of failure probabilities across the network and so is not very sensitive to the specific values for each individual link.

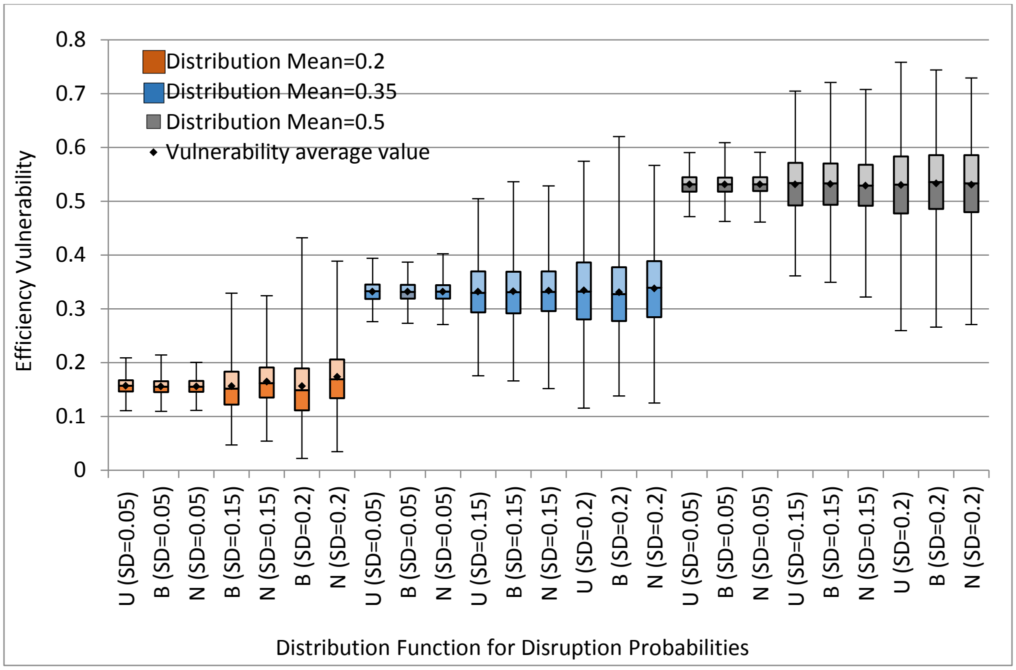

Figure 3-7 The Range of $V_{EEF}(s)$ Values for 1500 Different Disruption Probability Generations for each of 25 Experiements

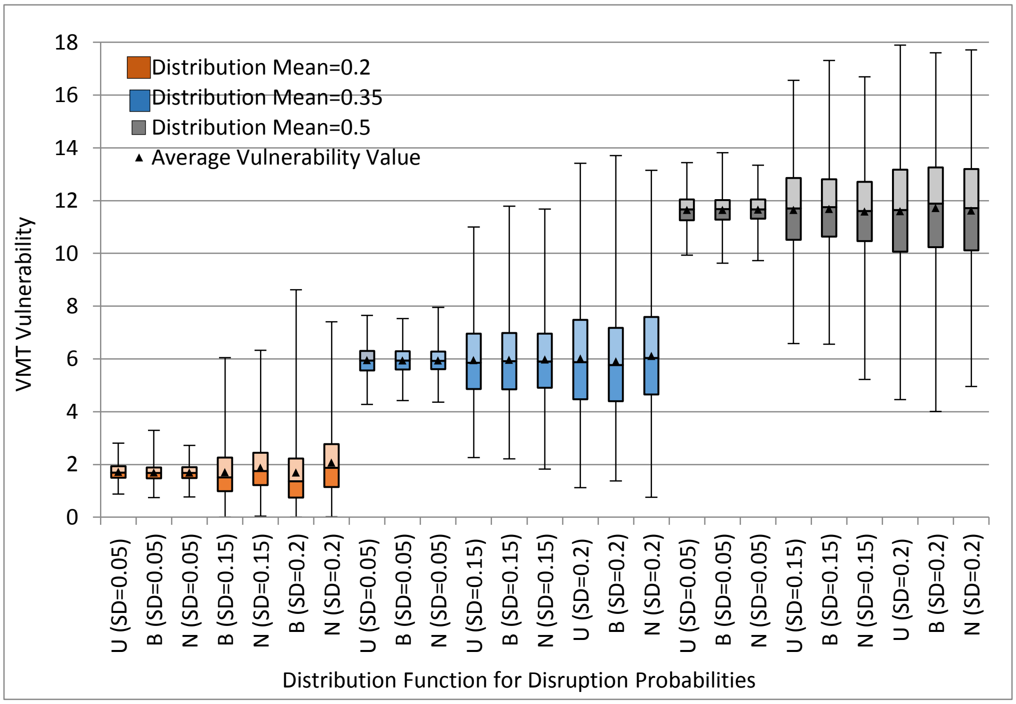

Figure 3-8 The Range of $V_{VMT}(s)$ Values for 1500 Different Disruption Probability Generations for each of 25 Experiements

NETWORK CONFIGURATION

The conceptual framework in Fig. 3-1 includes network configuration and position of the links as important factors that impact the vulnerability of a roadway system. Consider the network shown in Fig. 3-5b. Redistributing the disruption probability values, without any change, across the roads in the network will produce a different network status with a different performance or vulnerability. When redistributing the disruption probabilities without changing their values, one of the main factors that causes a different vulnerability level for the network is the position of each link (in fact the other factor is the length of each link). In other words, redistributing disruption probabilities reveals the impact of link topological positions on the vulnerability of the network.

We conducted a comprehensive analysis using the distributions for the 25 experiments identified in Fig. 3-6. In each experiment, a fixed set of disruption probabilities were generated from the associated distribution. Then using Monte Carlo simulation the disruption probabilities were randomly swapped across the links in 300 different iterations, and V_{VMT} and V_{EFF} were measured. Each experiment was repeated 10 times, and each time the fixed set of disruption probabilities were generated from the associated distribution with a different seed value (a total of 3,000 iterations for each experiment). In all experiments, the travel demands were set to 100 veh/day for all different OD pairs.

Figs. 3-9 and 3-10 show the variability in the efficiency and VMT vulnerability using box and whisker plots. These plots show that the variance of the efficiency measures increases with the variance of the disruption probability distributions. In other words, if the disruption probabilities of the links in a network have high variance, then swapping these disruption probabilities across the links will result in more variation in vulnerability. This means that when the difference (variance) between the link disruption probabilities is high, it matters which link has which disruption probability, and the topological position of the links can be a significant factor to vulnerability. In reality, disruption probability does not change randomly. To illustrate this concept, consider the allocation of treatment resources between two roads, *A* and *B*. Giving more resources to *A* and fewer to *B*, or giving more to *B* and fewer to *A*, is similar to providing excellent condition for A and fair condition for B or vice versa. In this case, positions of links *A* and *B* become important and can help identify the optimal resource allocation.

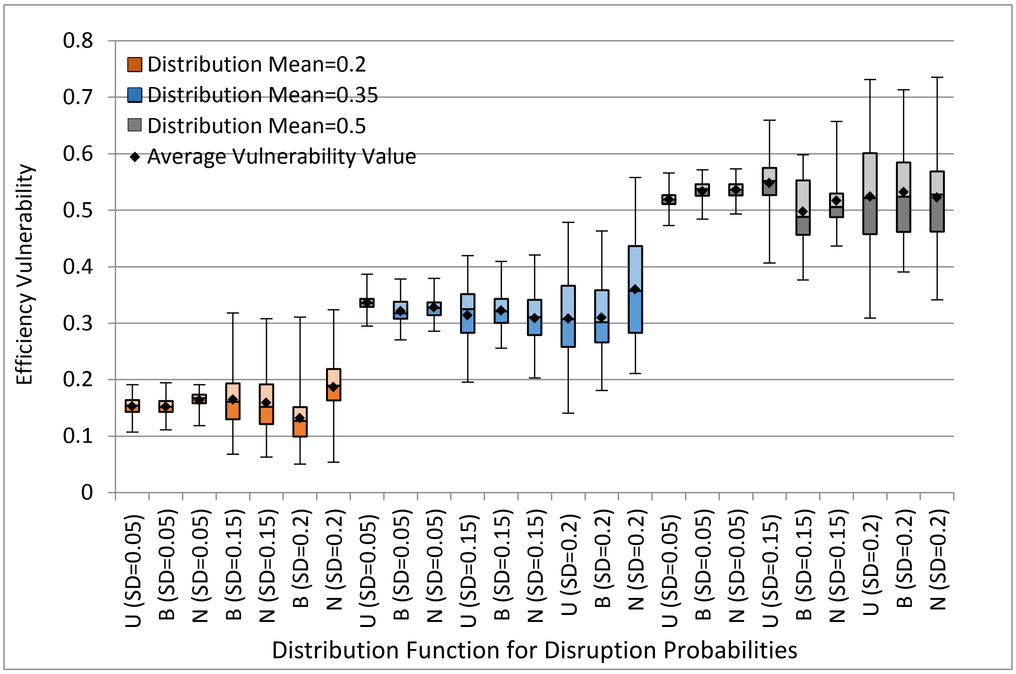

Figure 3-9 **The Range of $V_{EEF}(s)$ Values for 3000 Different Disruption Probability Swapping Iterations for each of 25 Experiements**

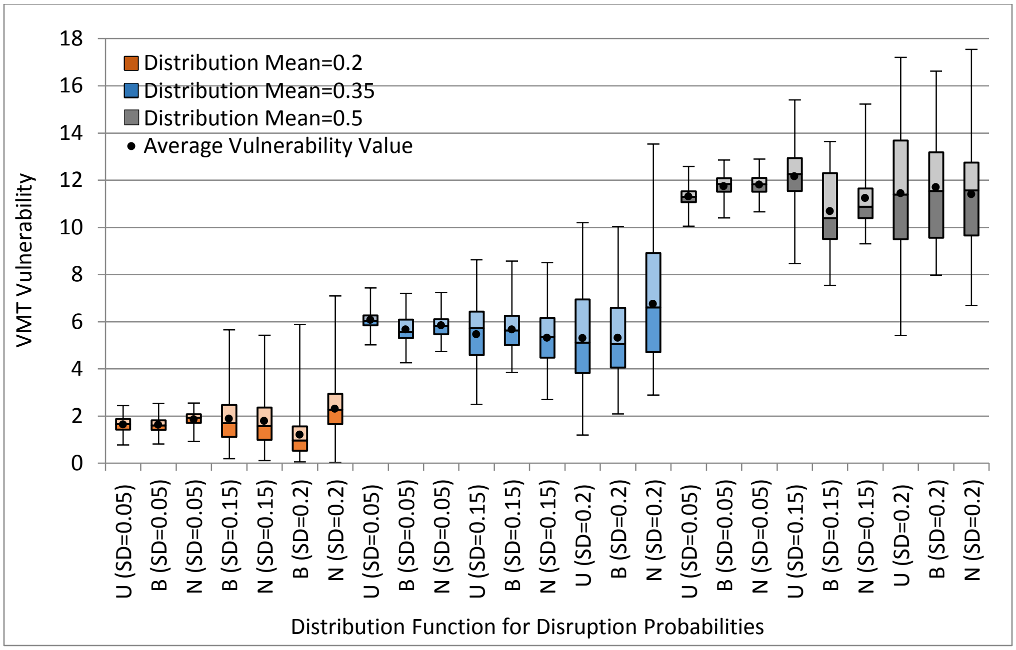

Figure 3-10 **The Range of $V_{VMT}(s)$ Values for 3000 Different Disruption Probability Swapping Iterations for each of 25 Experiements**

Sensitivity Analysis

The results in previous sections show that network vulnerability is sensitive to the parameters that define the distribution of disruption probabilities. As we expected, the greater the disruption probability, the greater the system’s vulnerability. In this section we further analyze the relation between the network vulnerability and disruption probability. Using the network in Fig. 3-5, in several experiments link disruption probabilities were generated from normal distributions with different mean values. For each mean value, the experiments were repeated with several standard deviations. The results in Fig. 3-11 show a nonlinear, s-shaped relation between the average disruption probability and the vulnerability. The vulnerability increases relatively slowly for low and high values of average disruption probability. The vulnerability increases more quickly when the average disruption probability is in the middle range.

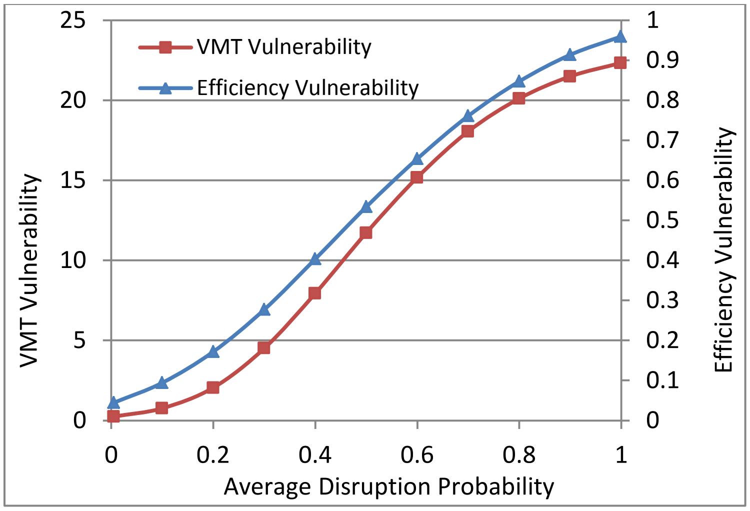

Figure 3-11 The Impact of Expected Disruption Probability of the Network on VMT and Efficiency Vulnerability

CONCLUSION

In this study we develop an algorithmic framework for condition-based assessment of roadway network vulnerability to disruptions. We demonstrated the application of the framework in a case study and computed the vulnerability of the roadway system with respect to two measures: network efficiency and VMT. Network efficiency captures the effect of location and condition (disruption probabilities) of roadways, and VMT accounts for the effect of travel pattern across the network on the vulnerability of the system.

The random failure probability experiments showed that network vulnerability is more sensitive to the mean and variance of disruption probability distributions than to the values of each individual link. As expected, the magnitude and variance of network vulnerability increase with the mean and variance of the disruption probability distribution. However, the relation was not linear. Network configuration and link topological properties also impact vulnerability; when the roadways have significantly different conditions (disruption failures), it might be important to recognize which road has what condition. Link topological properties can have less impact when the road conditions do not significantly vary across the roads. It is noteworthy that the results found in this study are limited to the network shown in Fig. 3-5 and the associated parameters.

More general statements and conclusions require further research and studies considering different types of networks with different parameters.

The CBVA of roadways reveals how and at what level the condition of roadways can make the system vulnerable to disruptions and failures. In this paper we addressed some aspects associated with roadway degradation and disruption that previous research has not explicitly addressed. For example, we considered the simultaneous disruption of different links as well as travel demand for all origins and destinations. However, more accurate prediction of travel behavior after disruptions, the relation between traffic pattern (after disruption) and the roadway network status, appropriate ways to model and simulate disruption events (other than full closure), and defining disruption probabilities with respect to disruption types can provide more realistic and reliable results.

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Chapter 4 : PARAMETRIC ANALYSIS OF ROADWAY INFRASTRUCTUE VULNERABILITY TO DISRUPTIONS[1]

ABSTRACT

In the past few years research studies have assessed the vulnerability of roadways to disasters and extreme event. However, in many of these studies the impact of the endogenous characteristics of the roadway network (such as the condition of the roads, travel on the network) on roadway system vulnerability have not been adequately investigated. In this paper we develop a computational method to assess how the condition of roads in the roadway network, the travel rate and travel pattern on the roadway network, and network topological properties affect the dynamics of vulnerably of the roadway systems. We apply our method to the Istanbul highway system and provide probabilistic assessment of the vulnerability of the network measured using travel time and efficiency. Our findings show that travel time vulnerability depends on the travel pattern on the network and increases with travel rate. We also found that efficiency and travel time vulnerability increase non-linearly with network degradation. When the network deterioration is not severe (disruption probabilities are low) the network efficiency and travel time vulnerability depend on the average disruption probability of the roads within the network. With further degradation (higher disruption probability values), both efficiency and travel time vulnerability not only depend on the average disruption probability of the network but also on what road has what disruption probability.

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INTRODUCTION

Critical infrastructure system, such as transportation, energy, water and communication, are the backbones of a nation's economic development. A functional transportation system, an efficient electrical power network, a fast and reliable cyber system and a sustainable and clean water distribution system can provide high quality service to the community and reduce the chance and consequences of malfunctions.

During the past few years many tragedies and disasters have happened around the world. The September 11th attacks, Japan earthquake, hurricane Sandy, New York power outage, and the 2013 bridge collapse on I-5 in Washington, are only few examples. Therefore, many researchers tried to analyze and address the vulnerability of infrastructure system to catastrophic events. In electrical power networks, studies address the impact of the structure and topology on vulnerability (Rosas-Casals et al. 2007; Crucitti et al., 2004a; Albert et al., 2004; Kinney et al., 2005) or how cascading failures can occur (Buldyrev et al., 2010; Albert et al., 2004; Kinney et al., 2005; Albert et al., 2000; Crucitti et al., 2004b; Motter, 2004; Motter and Lai, 2002; Wu et al., 2006; Barrett et al., 2010). In water distribution systems, the critical challenge is the vulnerability of the network to different infections that affect the delivery of healthy water to community (Thompson et al., 2007; Propato and James, 2004).

A notable number of studies in infrastructure vulnerability relates to roadway networks where researchers have characterized the robustness and vulnerability of roadways to extreme events such as natural disasters (flood, earthquake), terrorist attacks, accidents, and infrastructure degradation (Günneç and Salman, 2007; Jenelius et al., 2006; Sohn, 2006; Wu et al., 2007; Chen et al., 2007; Sakakibara et al., 2004; Chang et al., 2012).

The catastrophic events in general are the result of manmade attacks, natural disasters or the poor condition of the infrastructure. While the majority of the existing literature focus on understanding the infrastructure vulnerability to manmade attacks or natural disasters, there are few studies that take the degradation and poor condition infrastructure systems into account. Degradation of infrastructure systems is a serious challenge. In 2013, the American society of civil engineers (ASCE) reported that infrastructure systems in the U.S. (in four main categories of water and environment section, transportation, Public facilities, and energy) have overall rating of D^+ (ASCE 2013). The report estimates that \$3.6 trillion investment on America's infrastructure is needed by 2020.

Dehghani et al. (2013a) argued that the degradation of infrastructure systems and particularly roadways increase their vulnerability in two ways. First, poor condition of roadways (including bridges, culverts etc.) require treatments with consequent roadway capacity reductions which affects system performance. Second, deteriorated facilities (bridges, viaducts, tunnels) are more likely to fail due to natural disasters or attacks. They proposed the condition-based vulnerability assessment (CBVA) of roadways. Later Dehghani et al. (2013b) used the CBVA approach to evaluate the impact of roadway condition uncertainty on vulnerability of roadways systems.

In this study we build upon our previous work and further characterize the vulnerability of roadway networks. Particularly, our objective is to assess the impact of travel demand, mobility pattern, roadway degradation, and link topological properties on network vulnerability. Moreover, we enhance the CBVA approach as presented in Dehghani et al. (2013b). We employ user equilibrium traffic assignment technique instead of shortest path traffic assignment (all-or-nothing method). We also consider link capacity reduction instead of link removal to simulate disruptions.

On the other hand, currently, computationally intensive problems in pre- and post-disaster planning to protect roadway networks (Peeta et al. (2010), Miller-Hooks et al. (2012)), and in optimal resource allocation in roadway systems (Ng. et al. (2009), Liu and Frangopol, (2006), Essahli and Madanat, (2012), Durango-Cohen and Sarutipand (2007)) are often solved by simplifying assumptions or approximations. Our framework helps in reducing the iterative and exhaustive process of finding the optimal solutions by providing the big picture of network behavior and helps engineers and decision makers to evaluate their overall protection policies for the network and guides them through optimal policies.

METHODOLOGY

Consider a roadway network G(N,K) with N nodes (representing intersections or cities) and K links (representing the roads) as shown in Figure 4-1. Each link (for example, the k^{th} link) has a length, l_k, a capacity, c_k, and a travel time, t_k, which is the required time to travel on the link at relatively free flow condition ($v/c \leq 0.5$). In a particular state of the network, each link has a specific disruption probability, p_k. The disruption probability is the probability that the link is disrupted and loses part, or all of its functionality. The disruption can be the result of a treatment activity that reduces the capacity of the link or it can be caused by a disaster or an attack. Although it can be argued that the probability of disruption by a disaster differs from the probability of getting in poor condition for maintenance, we can assume that we are given a final disruption probability value that takes all those factors into account. Let f_{ij} and d_{ij} be respectively, the travel demand, and the shortest path between a node pair of interest $\{i,j\}$. When a link, say the k^{th} link, is disrupted the capacity of the link is reduced to the extent that depends on the condition of the link, from shoulder closure to full closure of the roadway. As a result the travelers between some node pairs, such as $\{1, 2\}$, has to take alternative routes which will result in higher travel time and cost compared to the original path. We define a disruption scenario as an event in which one or several links are disrupted at the same time. After a disruption scenario, depending on the number of disturbed links, level of disruption (capacity reduction level) and the location of the links, two changes are expected. First, the configuration properties of the network such as the shortest distance between different origins and destinations are affected, i.e., increased. Second, alternative paths with longer distance can significantly increase the cost and time of the traffic flow on the network. If the consequences are high, i.e., shortest distance and travel time and cost increase significantly, then the network is highly "vulnerable" to the disruption scenario. If the consequences are negligible then the network is not significantly vulnerable to the disruption scenario. We 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. Note that a network with K links can have 2^K different disruption scenarios. Each scenario has an occurrence probability since each link is assigned with a disruption probability. For example, for the network shown in Figure 4-1, which is at a certain state with link disruption probabilities equal to $p_1,...,p_k$, assuming the probability of disruption on each link is independent, the probability of scenario a , $p(a)$, in which the i^{th} and j^{th} links are disrupted is

$$p(a) = p_i p_j \prod_{\substack{w=1 \\ w \neq i,j}}^{K} (1 - p_w). \qquad (4\text{-}1)$$

The expected resulting performance, considering all possible disruption scenarios, will be computed as follows:

$$E[\theta] = \sum_{a \in A} p(a)\, \theta(a), \qquad (4\text{-}2)$$

where θ is a performance measure of interest, $\theta(a)$ is the resulting performance measure after scenario a is occurred, and A is the set of all possible scenarios for the network.

We determine the vulnerability of the network at a particular state s based on how a performance of interest changes before and after all conceivable disruption scenarios as follows:

$$V_\theta^s = \frac{|E[\theta] - \theta^0|}{\theta^0}, \qquad (4\text{-}3)$$

where V_θ^s is the vulnerability of the network at status s with respect to performance measure θ, and θ^0 is the original performance of the network where no disruption occurs.

SELECTING PERFORMANCE MEASURES

In order for us to measure the vulnerability, we need to select performance measures with which we compute the consequence of each of the changes. The consequence of first change (associated with the configuration properties of the network) can be computed by measuring the efficiency of the network defined by Latora and Marchiori (2001). Network efficiency is a measure of how the nodes efficiently exchange information and is defined as:

$$U(G) = \frac{1}{N(N-1)} \sum_{i \neq j \in G} \frac{1}{d_{ij}} \qquad (4\text{-}4)$$

Where U(G) is the efficiency of the network.

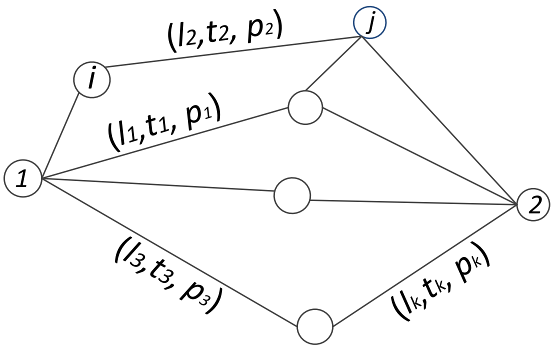

Figure 4-1 Illustrative Network

In this paper we measure the efficiency of the network with the following equation:

$$E(G) = \frac{1}{N(N-1)} \sum_{i \neq j \in G} \frac{f_{ij}}{d_{ij}} \tag{4-5}$$

Where E(G) is the efficiency of the network.

Equation 2 not only considers the effect of distance between node pairs as in Latora and Marchiori (2001) but also takes the amount of flow and mobility between *OD* pairs into account. In other words *E(G)* is a weighted sum of the inverse of the shortest paths where the weights are proportional to the amount of travel between OD pairs. Consideration of f_{ij} is intuitive as if more travelers flow on a shorter distance (and shorter travel time on free flow speed) represents a more efficient network. On the other hand, Equation 5 also shows if the detour has a short distance after disruption, travelers undergo less traveling distance and cost and thus the network is more efficient.

In order to compute the network efficiency after a disruption, we use an equivalent length for the links l' to compute the shortest paths. We assume that when a link, say link *k* is disrupted, its capacity is reduced by an amount, Δc. As a result the required travel time on the link at relatively free flow speed (t_k) increases to t'_k. l'_k is the equivalent length of link *k* with travel time t'_k. Equation 5 uses l'_k to compute d_{ij}.

The consequence of the second change can be simply measured by vehicle travel time (VTT) on the network. When a disruption scenario occurs, the link capacities are reduced and the travelers try to find alternative paths to their destinations (not that here, the link length is not increased to l'). We use the user equilibrium traffic (UE) assignment approach where all passengers or substances will ultimately choose paths that minimizes the travel cost and time. The total travel time on the network can be then computed as follows:

$$T(G) = \sum_{k=1}^{K} x_k \tau_k(x_k) \tag{4-6}$$

Where $T(G)$ is the total travel time on the network, x_k is the amount of flow on link k at equilibrium, and τ_k is the time to travel on link k when there is x_k amount of flow on the link (note that t_k is the travel time on link k at relatively free flow condition).

Using Equation 3, we then determine the efficiency vulnerability (V_{EFF}) and travel time vulnerability (V_{VTT}) as follwos:

$$V_{EFF} = \frac{\left|E[E(G)] - E^0(G)\right|}{E^0(G)}, \tag{4-7}$$

$$V_{VTT} = \frac{\left|E[T(G)] - T^0(G)\right|}{T^0(G)}. \tag{4-8}$$

Note that efficiency vulnerability lies in (0,1] range while VTT vulnerability can take on any positive value.

APPLICATION

In this section we demonstrate the application of our method to a real highway network. For our case study we consider the highway network in Istanbul, Turkey, as shown in Figure 4-2. The network is important because it connects the Asian side of Istanbul to the European side. Moreover, the poor and risky structures of the highway such as the bridges have made this network a suitable case for condition-based vulnerability analysis. A 12-link network of Istanbul highway system was selected for our study and is shown in Figure 4-2. All links are highways (two lane two way limited access road) except link 9 which is an arterial. Information about the length, capacity, and disruption probability of each link is shown in Table 4-1.

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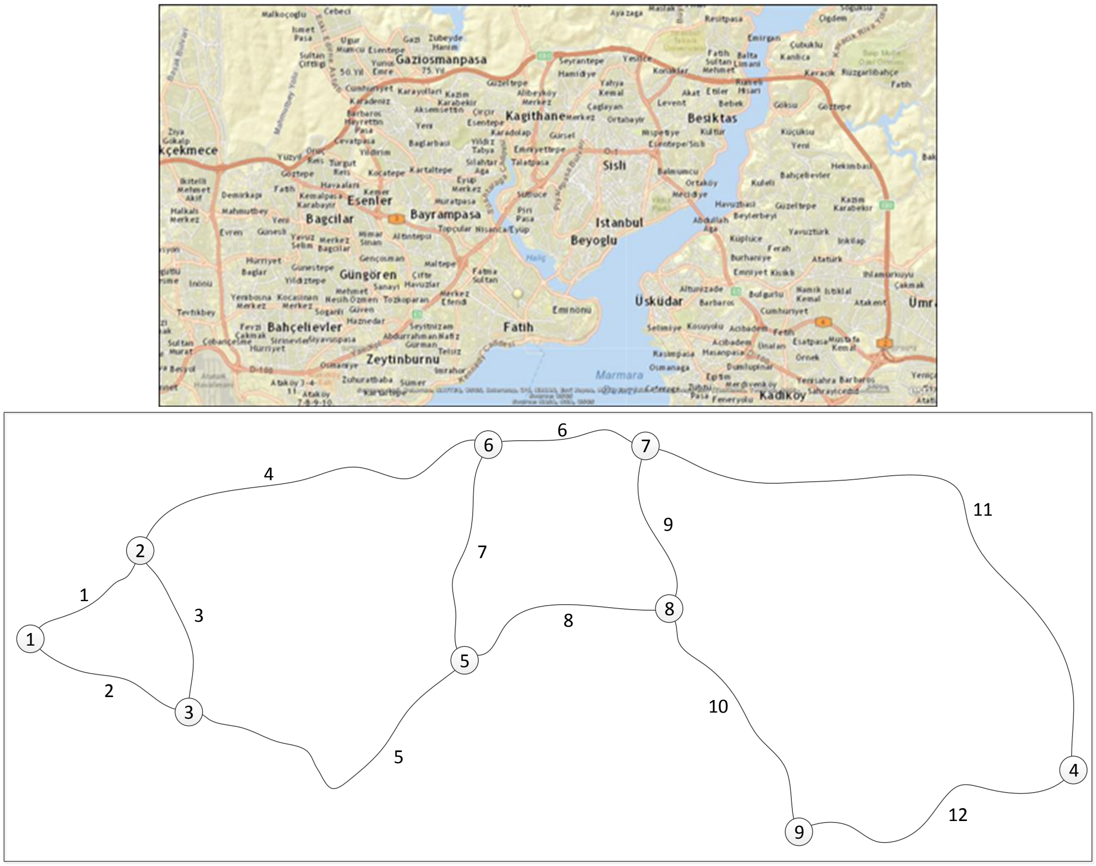

Figure 4-2 Istanbul Highway System

A capacity of 2000 veh/hr and 1000 veh/hr were assigned to highway-type links and arterials, respectively. The disruption probability of each link is a representation of the condition of the road and the structures within the road such as the bridges and tunnels. Determining the disruption probabilities based on the condition of the road (and its containing assets) is out of the scope of this paper. However, relevant studies that model the reliability of structures based on their condition can be found in the literature. We determined the disruption probability values of each link based on their associated survival probability values that were computed by Peeta et al. (2010) for the Istanbul highway system. They assigned a survival probability value to each link based on the risk of the bridges/viaducts within each link.

Table 4-1 Link Information

Link	length	Capacity	Disruption probability
1	3.5	2000	0.4
2	4.3	2000	0.2
3	4	2000	0.2
4	8.7	2000	0.45
5	8.5	2000	0.25
6	3.6	2000	0.5
7	4.8	2000	0.4
8	5	2000	0.45
9	4.4	1000	0.3
10	5.8	2000	0.35
11	15.1	2000	0.3
12	6.8	2000	0.4

For the travel demand on the network, we considered several major origin-destination pairs of interest and assumed that the OD matrix is symmetric. The travel demands for these OD pairs are shown in Table 4-2 which represents an uncongested network. For all other OD pairs we assume an hourly travel demand of 10 Veh/hr.

Table 4-2 OD Travel Rate

Origin-Destination	Traffic (Veh/hr)
1-4	1000
1-8	500
2-4	750
2-9	350
3-7	900
4-5	500
4-6	350
6-9	480

We computed all 2^{12} different possible disruption scenarios and measured the consequences in each scenario. The results for efficiency and VTT vulnerability are shown in Table 4-3. The original (undisrupted) efficiency and VTT of the network are 7.68 and 5055 units respectively. As a result of all possible scenarios and their consequences, the expected efficiency will decrease to 7.33 and the expected VTT will increase to 6272 units. The network at the state described in Table 1 is therefore, expected to have an increase of about 24% in VTT and a decrease of 5% in efficiency, i.e., the efficiency and VTT vulnerability of the network are 0.05 and 0.24 respectively.

Table 4-3 Efficiency and VTT Vulnerability of Istanbul Network

Measure	Original	Expected	Vulnerability
Efficiency	7.68	7.33	0.05
VTT	5055	6272	0.24

Probability Density of Vulnerability

Since we analyzed all disruption scenarios and computed their associated occurrence probability we are able to construct the exact probability density functions (pdf) for VTT and efficiency vulnerability. These pdfs are shown in Figure 4-3. It is important to note that VTT and efficiency vulnerability are discrete random variables but a continuous curve is fitted to develop smooth pdf curves. Also the pdfs shown in Figure 4-3 are exclusive to the network at the state with characteristics described in Table 4-1.As the results show, VTT vulnerability will be in the range of 0-0.2 with probability of 0.45 or in the range of 0.2-0.4 with probability of 0.35. The efficiency vulnerability of the network is not expected to exceed 0.12 and is more likely to be between 0.04-0.06 with 35% chance. Probabilistic evaluation of roadway vulnerability provides a general information on where the network lies in the range from being very resilient up to being extremely vulnerable to disasters and disruptions.

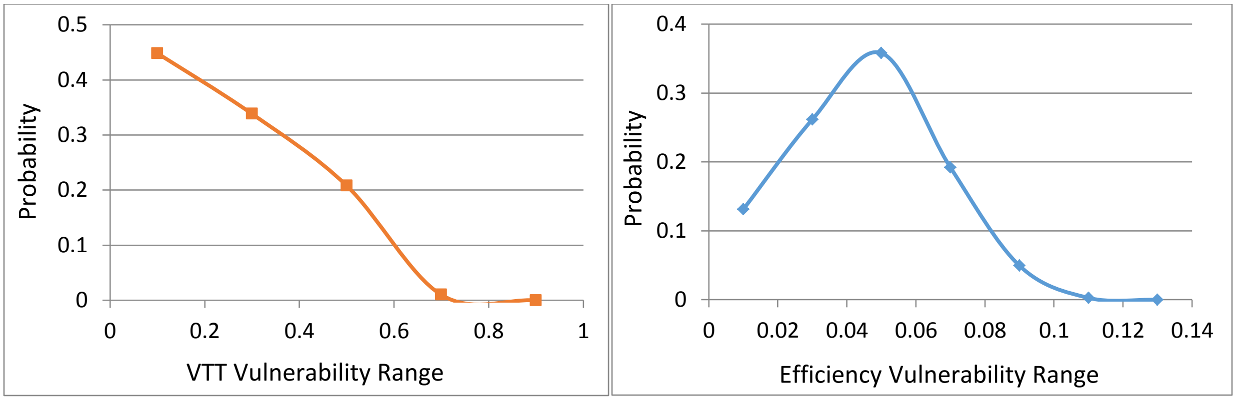

Figure 4-3 Probablity Density Fucniton for Efficiency and Travel Time Vulnerablity

Impact of Mobility on Roadway Vulnerability

Network efficiency and network VTT are two indicators that we used to measure vulnerability. Both measures take the traffic flow into account. It is evident from Equations 3 and 5 that efficiency vulnerability is independent of traffic flow and only captures the network configuration. However, VTT vulnerability is directly influenced by the movement of travelers on the network.

In this section, we evaluate the impact of travel pattern and travel magnitude on VTT vulnerability. In the first experiment, we multiplied the travel demands between all OD pairs (Table 4-2) with a factor α which changed from 0.25 to 7.5 in several iterations and measured the characteristics of the network such as the original VTT, expected VTT and VTT vulnerability. As the results show in Figure 4-4, with the increase in travel rate, both expected VTT and original VTT increase. The VTT vulnerability increases rapidly until when the travel rates is about 2.5-3.5 times the initial travel rate. With further increase in travel demand both expected VTT and original VTT increase at a fairly constant (not similar) rate. As a result, VTT vulnerability stabilizes around 0.85. This means that when the traffic demand on the network is relatively very high, the change in network performance after a disruption is not significantly affected by travel rate on the network.

We also studied the impact of travel pattern on the vulnerability of the network in two additional experiments. In each experiment, we randomly re-assigned the OD travel demands shown in

Table 4-2 across the OD pairs. Then with the new resulting travel pattern, we increased the travel rates with factor α in several iterations and measured network vulnerability in each iterations. Figure 4-4, compares VTT vulnerability of the network for all the three different travel patterns (including the original in Table 4-2). The results show that the network can have significantly different levels of VTT vulnerability depending on the travel pattern. However, the trend with respect to travel rate is similar in all experiments, i.e., vulnerability increases significantly and then stabilizes at high traffic rates.

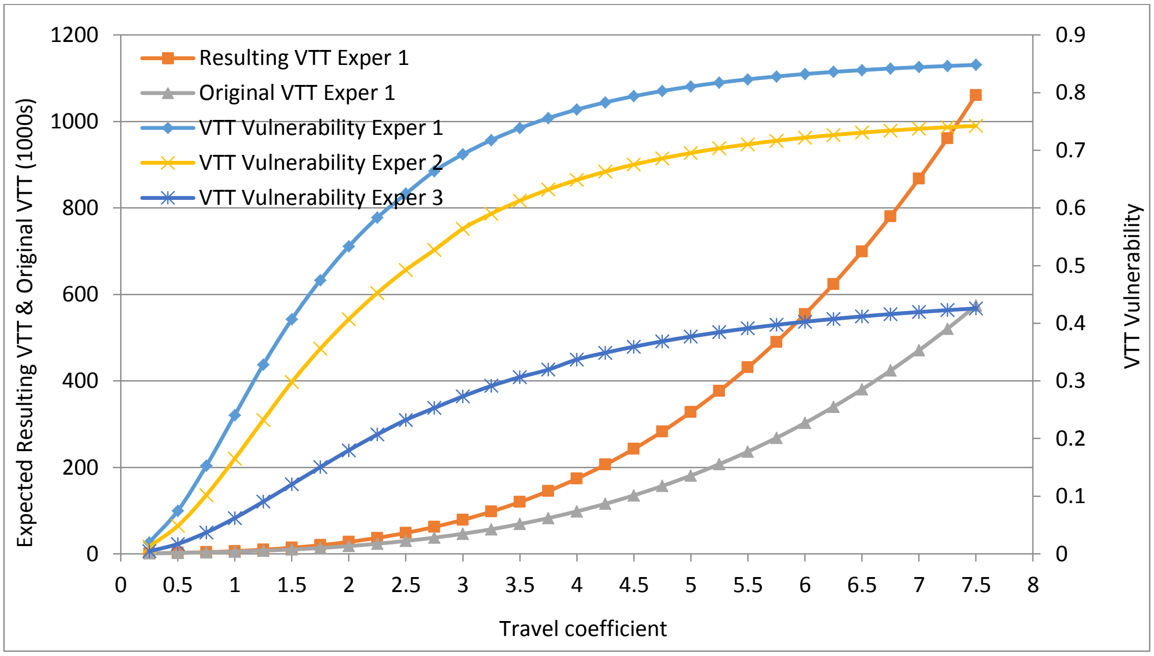

Figure 4-4 The Impact of Travel Rate and Travel Pattern on VTT Vulnerability

The results imply that accurate OD travel estimation is significantly important in the determination of network vulnerability. Although it is unlikely to have dramatic change in travel patterns on the network in short period of time, miscalculations can result in a huge different analysis and evaluation of network vulnerability.

Network Deterioration and Configuration

When the roads (and their encompassing components such as bridges and tunnels) in the network deteriorate, they are more likely to get closed for treatment purposes or get disrupted by disasters. Therefore, in general, it is reasonable to assume that disruption probability increases with deterioration. As a result the vulnerability of the network can change as the network degrades over time.

In this section we evaluate how degradation impacts network vulnerability through several experiments. In the first experiment, the new-linked network degradation (NND), we assumed that all links in the Istanbul network are relatively new. We generated the disruption probabilities for all links from a normal distribution with mean of 0.05 and standard deviation of 0.01, *N(0.05,0.1)*. In order to simulate deterioration, we generated disruption probabilities for all links from normal distribution with mean 0.15, 0.2, 0.3, up to 0.99 (with SD equal to 0.01 for all distributions) in consecutive iterations and measured the efficiency vulnerability. Without loss of generality, we assumed that disruption probabilities for all links increase with the same constant rate.

In the second experiment, the original disruption probability deterioration (ODPD 2), we assumed that the disruption probabilities of the network are those shown in Table 4-1. We simulated network deterioration in several iterations by assuming a constant deterioration rate and increasing the disruption probabilities with that rate. We again considered a constant deterioration rate for all links in the network (the upper bound on disruption probability was set to 0.999). We also used the same constant rate to backcalculate network failure probabilities in previous stages. We measured efficiency vulnerability in all iterations.

In the third and fourth experiments, the swapped original disruption probability deterioration 3 & 4 (SODPD3&4), we swapped the original disruption probabilities (Table 4-1) across the links to form a different network status as compared with the original network status. We then followed the procedure in ODPD experiment. The only difference in SODPD3&4 experiments is that the links have swapped their disruption probabilities. Therefore, the factors that impact network vulnerability in these two experiments are associated with the link configuration properties and characteristics.

We used the fixed travel rate in Table 4-2 in all experiments and iterations in order to eliminate the impact of travel rate and only focus on deterioration and failure probability.

The results for all four experiments are shown in Figure 4-5, where the efficiency vulnerability is plotted against average network disruption probability. The findings can be summarized as follows:

- In all experiments, the efficiency vulnerability increases with network degradation with a non-linear, s-shape pattern.
- The network shows similar behavior in terms of vulnerability value and pattern in all experiments when the average disruption probability is fairly low (below 0.5).
- The efficiency vulnerability increases more rapidly when the average disruption probability is between 0.5 and 0.8, particularly for OPDP2, SOPDP3 & 4 experiments. The network shows different behavior in OPDP2, SOPDP3 & 4 experiments when the average disruption probability is higher than 0.5. This means that swapping failure probabilities can change vulnerability level and pattern. An interpretation of this finding is that when the network starts to deteriorate further, it is not enough to know the overall network condition but is necessary to consider the impact of link configuration. In other words in this case it is important to know that where the link is located and what is its exact failure probability.
- When the average disruption probability is high (greater than 0.5), the vulnerability of the network in OPDP2, SOPDP3 & 4 experiments (with original or swapped failure probabilities) is higher than that in the NND experiment in which all links in the network have similar probability values.
- Further degradation increases the network vulnerability to its maximum but with much lower rate in all experiments, particularly in OPDP2, SOPDP3 & 4.

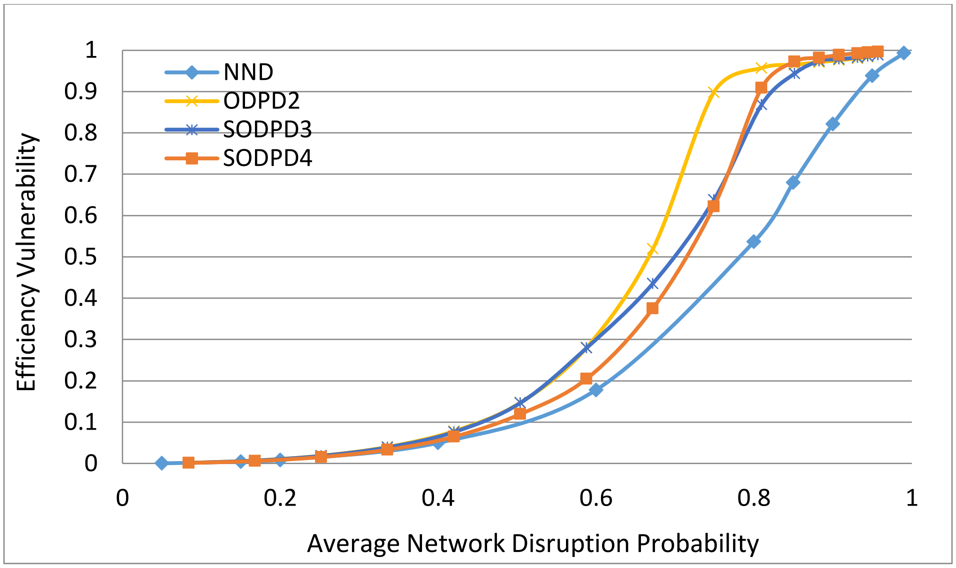

Figure 4-5 The Impact of Network Degradation and Topography on Efficiency Vulnerability

In order to evaluate the impact of deterioration on VTT vulnerability we conducted similar experiments discussed above and measured the VTT vulnerability. However, we assumed that while the capacity of roadways in disruption simulations will be reduced proportional to their disruption probability values, they will not fall below 30% of their original capacity. This might be a more realistic assumption as full closure of roadways does not often occur for maintenance purposes. Even in disastrous events it sometimes happens that the roadway still has some minimum capacity for passage and evacuation purposes.

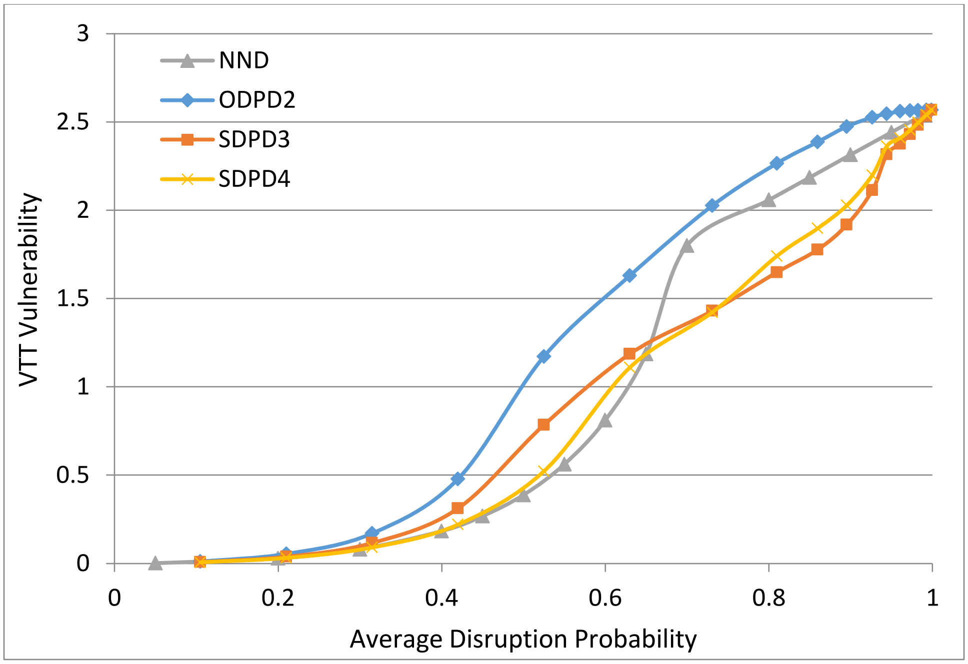

Figure 4-6 The Impact of Network Degradation and Topography on VTT Vulnerability

The VTT vulnerability results for all four experiments are displayed in Figure 4-6. We summarize our findings as follows:

- In all experiments, the VTT vulnerability has a nonlinear behavior with respect to the average disruption probability.
- When average disruption probability is small (less than 0.3) the network shows similar behavior in all experiments. With further increase in average disruption probability the VTT vulnerability increase but with considerably different behavior. Swapping disruption probabilities across the links appear to change the network behavior particularly at high average disruption probability values (greater than 0.3).

Overall, both VTT and efficiency vulnerability increase with network deterioration in a nonlinear format. However, our findings show that the average disruption probability of the network is not the only factor that conditions the dynamics of network vulnerably. For a particular average disruption probability value, the network shows a different vulnerability behavior (with regard to both performance measures) depending on how these disruption probability values are distributed over the network. In other words in some circumstances, the network configuration and the fact that what link has what disruption chance can be a critical parameter.

DISCUSSION

While many researchers have studied roadway network vulnerability to disasters and extreme events, few have studied the impact of condition and other parameters such as travel pattern and demand on vulnerability behavior of the network. In this paper we argued that roadway condition and degradation is an endogenous characteristics of the roadway that can make it vulnerable. We explained that a roadway network is vulnerable if the network performance is decreased after a disruption which is any event that reduces the functionality (capacity) of one or multiple links in the roadway. We then proposed a computational framework for CBVA of roadway infrastructure systems that computes the expected efficiency and VTT vulnerability of the network based on the disruption probability values of the network links. The framework uses equivalent link length values to determine efficiency vulnerability and uses UE traffic assignment technique to estimate the resulting travel time on the network after each simulated disruption scenario.

We applied our framework to the Istanbul highway system. We selected disruption probabilities based on survivability values reported in past studies that represented the structural condition and health of the assets within each roadway. We provided a probabilistic evaluation of roadway vulnerability by computing the probability density function for VTT and efficiency vulnerability of the Istanbul highway system.

We analyzed the impact of the travel pattern and travel volumes on vulnerability of the network. The results show that the vulnerability increases with travel volumes until some point (where the network becomes congested) and stabilizes with further increase in travel rate. Although network vulnerability changes with travel pattern it has similar increasing trend with travel rate in all experiments. This implies that the OD travel demands must be predicted accurately, otherwise, the analysis can provide different and misleading estimation for network vulnerability.

The impact of degradation on network efficiency and VTT vulnerability was evaluated in several experiments. The results show that when the average disruption probability of the network is less than about 0.5 the network shows similar behavior regardless of how the disruption probability values are distributed across the network. However, as the network degrades (disruption probabilities increase) further, the network vulnerability behavior depends on both the average disruption probability of the network as well as on how the disruption probability values are scattered. In other words, at high average disruption probabilities of the network, topological properties of the network links are more critical and it is important to distinguish what link has what level of disruption probability. It is noteworthy that the results found in this study are limited to the case study network and its associated parameters. For more general findings, networks of different size with different parameters should be analyzed.

For an accurate characterization of network behavior we simulated all 2^k different possible disruption scenarios in each vulnerability computation attempt in this study. It is evident that this is not computationally possible for large scale networks and the network behavior should be approximated using techniques such as Monte Carlo simulation.

Without loss of generality we made assumptions that can be relaxed in future studies. For example, we assumed that the capacity reduction is linearly proportional to the link failure probabilities, or that degradation has a linear and similar trend for all links. These assumptions can be improved based on accurate treatment history and structural and performance characteristics of the roadways. In addition using accurate models to estimate disruption probability values for each roadway as a function of roadway condition and disaster types, real OD travel matrix can provide more realistic evaluations on network vulnerability.

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Chapter 5 : SUMMARY, FINDINGS, CONCLUSIONS, AND DIRECTIONS FOR FUTURE RESEARCH

SUMMARY

Roadway condition and other roadway endogenous characteristics such as link topological properties and travel patterns, can significantly affect roadway systems vulnerably. However, little effort has been made to address the impact of these parameters on roadway vulnerability behavior.

This dissertation introduced the concept of condition-based vulnerability assessment of roadways. We first developed a conceptual framework that captures the effect of roadway endogenous characteristics on its vulnerably. The framework evaluates how roadway condition and condition uncertainties, roadway network deterioration over time, topological properties of roadways, and travel rate and travel pattern impact the dynamics of roadway vulnerability.

We then developed a methodological framework and applied the method to a hypothetical roadway system. We later improved the methodological framework by using user equilibrium traffic assignment to predict travel behavior and simulating disruptions with capacity reduction (rather than complete failure) and applied the method to Istanbul highway system and provided probabilistic evaluation of roadway network vulnerability.

FINDINGS

The analysis of roadway vulnerability behavior with respect to different parameters suggests that vulnerability of roadway system is more affected by the average condition of the roadway network than by the condition of individual roads in the system. Moreover, small uncertainties associated with the condition of individual roadways in the network can cause large variance in the predicated vulnerability of the roadway network. Another finding was that when the conditions of roads on the network are significantly different (high variance) the link topological properties become more important. In these cases, it is important to identify what link has what condition.

More specifically, the application of our method to the Istanbul Highway system shows that for the network studied:

- The roadway network vulnerability increases nonlinearly with the average network disruption probability (which is a representation of roadway network condition and degradation).
- When the roadway deterioration is not severe (low average disruption probability) the link topological properties have less impact on network vulnerability dynamics. In other words, the network shows similar behavior regardless of what link has what condition level.
- When the network degradation is high (average disruption probability greater than about 0.6) the network can show different vulnerability trends and behaviors depending on what link has what condition.
- Roadway vulnerability increases with total travel rate on the network but it does not change significantly after a certain travel rate.
- Even small uncertainties in road condition (reflected in variance of disruption probability values) estimation can increase the variance of predicted vulnerability.

CONCLUSION

This study is amongst very first attempts to characterize the behavior of roadway vulnerably with respect to different parameters. Available literature includes several studies on determining the vulnerably of roadway networks. However, our work takes a step forward and tries to answer more fundamental questions; what parameters impact roadway vulnerability? how vulnerability of a roadway changes? and how sensitive is roadway network to changes in those parameters? The proposed method not only allows us to measure vulnerability of the roadway network at a snapshot of time, but also lets us monitor network vulnerability behavior over time. This allows engineers and decision makers to evaluate the long-term impacts of their policies on network vulnerability. In other words, the developed framework provides heuristics for selecting best preservation policies and thus can contribute to developing strategic-level policy and decision making guidelines for critical infrastructure protection against disruptions. In addition, the heuristics and observations provided by using this framework can enhance pre-, and post-disaster management operational activates.

This study paves the road for the integration of vulnerability minimization, as a critical objective, into transportation infrastructure management systems by providing guidelines that help in selecting appropriate maintenance and resource allocation policies. For example, there are often several simultaneous maintenance activates on a roadway network that, depending on their location, can significantly reduce network performance, and consequently increase roadway vulnerability. Departments of Transportation (DOTs) can apply the proposed methodology to examine the impact of simultaneous maintenance operations on network performance and synchronize maintenance activities in order to minimize roadway vulnerability.

DIRECTIONS FOR FUTURE RESEARCH

In this research we incrementally improved our framework proposed in Chapter 3 by incorporating UE technique for traffic assignment and link capacity reduction to simulate road disruption. However, the framework can be furthered improved and account for more realistic assumptions. The recommendations for framework improvement and for future research directions include the following:

- For accurate vulnerability assessment and exact probabilistic evaluations, we simulated all possible disruption scenarios (2^k) each time we computed vulnerability. However, in reality, and in large scale networks, simulation of all scenarios is computationally intractable. In such cases, the vulnerability can be estimated via Monte Carlo simulation or other approximation techniques.
- Determining the disruption probabilities of roads based on their condition was out of the scope of this research and was assumed a *priori.* Although there are existing studies that model failure probabilities based on the structural condition of facilities, an accrue estimation of roadway disruption probability based as a combined function of the road (and its containing elements) condition and disaster type can result in more realistic vulnerability estimations.

- We estimated the OD travel matrix for our case study network. However, the findings show that travel pattern and travel rates should be precisely projected in order to reduce the error in estimating the vulnerability.

It is noteworthy that, the specific findings in this dissertation are limited to the network studied. Future research studies can apply the framework to different roadway systems with different size and scale to assess more general interpretations and guidelines on roadway vulnerability behaviors. Moreover, the generic structure of CBVA framework enables engineers and decision makers to apply the method to other critical infrastructure systems as for future research directions.