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Transportation Network Resiliency: A Study of Self-Annealing

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TRANSPORTATION NETWORK RESILIENCY: A STUDY OF SELF-ANNEALING

by

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A thesis submitted in the partial fulfillment
of the requirements for the degree

of

MASTER OF SCIENCE

in

Civil and Environmental Engineering

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ABSTRACT

Transportation Network Resiliency: A Study of Self-Annealing

by

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Utah State University, 2012

Major Professor: Dr. Kevin Heaslip
Department: Civil and Environmental Engineering

Transportation networks, as important lifelines linking communities and goods, are indispensable for the smooth functioning of society. These networks are, however, fragile and vulnerable to natural and manmade disasters, which can disrupt their vital functionality. The role of the transportation sector becomes more crucial during disasters due to its role in pre-disaster evacuation as well as post-disaster recovery.

The ability of transportation systems to retain performance during and after disasters undergoing little to no loss and their ability to return to the normal state of operation quickly after disasters defines their resilience. Authorities need to understand the degree of resilience within the transportation system under their jurisdiction and plan for improvements. In this research, attempts have been made to deal with resilience in quantitative ways to provide defensible data to decision makers to support investment strategies.

Total loss in the network performance can be quantified by dealing with the variation of network performance over time after disasters and the network resilience can be measured by the ability to minimize this loss. It has been shown that robust networks retain better performance after disruptions and recovery works, which follow optimized recovery paths, in spite of constraints of resources and time, help to minimize the total losses and enhance the network resilience.

The objective of this research is to create a conceptual framework to quantify resilience and discuss quantitatively the properties determining resilience of transportation networks. The concepts presented are applied to a test network to illustrate the mathematical procedures. Such methods can help decision makers analyze relative improvements in resiliency as a consequence of proposed project alternatives and help to perform benefit-cost analysis for such projects.

(110 pages)

PUBLIC ABSTRACT

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Disasters have the potential to hit any geographical location with or without warning. As such, it is desirable that transportation networks are able to withstand the adverse effect of disasters and maintain the normal functioning of all sectors of society. Resilient transportation networks are least affected by disruptions created by natural and manmade disasters and are still able function with an acceptable level of service. Such networks also have ability to return earlier from disrupted state to the normal functioning state. Resilience possessed by a transportation network measures the ability of networks to maintain functionality despite adverse conditions posed by disruptions as well as the ability to return quickly to normal operating conditions. Measurements of resilience can be important in assessing the degree of preparedness against disasters and act as guidelines for making improvements or providing extra security to critical network pathways. This research attempts to identify properties that determine resilience and presents a method to measure the resilience of a network for disaster scenarios.

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Sunil Babu Pant

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CHAPTER 1

INTRODUCTION

The efficient transportation of goods, people, and services is a fundamental need for modern society. Dependence on the transportation sector is increasing, contributing to growing demand for travel and trade by an increasing population. This increased demand has highlighted a need to seek for increased reliability in transportation networks. Disruptive events, either natural or human caused, affect the functionality and performance of transportation systems contrary to societal necessity requiring transportation networks to perform well under adverse conditions. In an ideal transportation network, losses during disasters should be minimized and the network should quickly recover in order to provide an acceptable level of service to society.

Disastrous events often affect multiple aspects of society, including transportation itself. Examples of such events are: the 9/11 terrorist attacks, Hurricanes Katrina and Rita in 2005, Ike and Gustav in 2008, Christchurch, New Zealand's earthquake in 2011, Japan's earthquake and Tsunami in 2011, and the most recent hurricane Sandy 2012, affecting Northeastern United States. Pre-disaster evacuation and post-disaster recovery efforts require functional transportation networks in order to facilitate access to disaster areas for evacuation and recovery efforts. Inability to meet these needs often results in an increase in fatalities and economic degradation. The overarching goal for this research of transportation resiliency is to minimize losses through targeted intervention. This is accomplished by analyzing the network's ability to function during and after extreme events, and ability to respond quickly and effectively to facilitate recovery. The analysis is performed with the ultimate objective of devising methods and targeted investment strategies to minimize the loss of operational capacity over time.

Previous research in the field of transportation network resiliency (e.g. by Freckleton et al., 2012, Heaslip et al., 2009, 2010, and Serulle et al., 2011) has defined metrics and proposed methodologies used to quantitatively measure the resiliency of transportation networks. The result of research is an index called the Transportation Network Resiliency Index (TNRI), which is a quantitative measure of resilience. This index provides valuable insight into resiliency but is dependent upon the discretion of analyst. The objective of this research is to refine the previous research to remove judgment and discretion and to provide a quantitative approach to measuring resiliency.

1.1 Research Questions

This research attempts to address three questions: 1) What are the properties of a transportation network that determine its performance?; 2) How can a network's performance be measured at each stage of the network lifecycle?; and 3) Given the answers to the first two questions, how can resilience best be quantified? Performance of network depends upon factors determining capacity, which are mathematically quantifiable, but recovery depends upon management factors, many of which are subjective and difficult to quantify mathematically. The rate of recovery depends upon availability of resources and ability to optimize the use of resources. The development of a methodology for resiliency computation can be a useful tool for planning improvement projects and in the formulation of disaster preparedness plans to minimize losses and optimize resources for accelerated recovery.

1.2 Research Problem and General Approach

In the methodology proposed by this research, measurement of resilience requires an estimation of network capacity and performance, loss of transportation network performance caused by disruptive events, and the real-time rate of recovery in performance. Disruptive events often result in partial or total loss of availability or capacity of network elements. Some events may also overwhelm the network with excess traffic demand instantly. Prediction of the actual losses corresponding to the magnitude of such events on a network provides a significant challenge. Capacity modeling is difficult in transportation networks, as transportation involves flows of people and also the human route choice behavior is involved (Yang et al., 2000). Level of service needs to be specified while describing capacity. Congestion and travel delay occur with the increase of traffic flow on specific routes and affects the level of service (Yang et al., 2000). The data for the capacity estimation of all elements of a transportation network may not be available. Travel demand has spatial and temporal variation provides an additional difficulty in the prediction of demand. Computation of resiliency involves measurement of network performance before, during, and at different stages after a destabilizing event. Measurement of performance, which is related to the demand, capacity, and level of service, is a difficult task.

The amount of loss of functionality within the transportation network caused by disruptive events is a function of the fragility of network elements and the magnitude of events. The effect of these losses is reflected on the capacity and performance of the network. Self-annealing occurs after the disruption when the available capacity is optimized by users, and extent of self-annealing depends upon network redundancy and length of time before external recovery efforts becomes available. Recovery begins once external support to increase functionality of the network is available. Total recovery time is the sum of self-annealing and recovery time. Resilience is a function of the ability to resist events without any loss or with only little loss in performance and the ability to recover rapidly. In this research, measures such as reserve capacity and network route diversity whose magnitude differs depending upon capacity and/or availability of each element of the network are chosen. Metrics explaining qualitative attributes like managerial aspects, resourcefulness, and technology availability that cannot be mathematically quantified to a specific value are also considered. Total loss of performance over time is used as the ultimate measure to quantify network resilience. Using this methodology, authorities gain the knowledge to evaluate network resilience for probable scenarios of disruption and improvements in the resiliency by the addition of new elements, improvement of existing elements, changes to the technical and managerial capacities, and supply and flow rate of resources to speed recovery.

1.3 Past Research

This thesis is a extension of research performed by Serulle et al. (2011) which built upon work by Heaslip et al. (2009, 2010) by refining key variables, adjusting modal interactions and the adjusting the whole process to include more transparent resilience metrics. Heaslip, et al.'s work referenced Murray-Tuite (2006), which focused on measures of capacity flexibility which was again based on previous compilation of variables related to resiliency created by Godschalk (2003). The concept of resilience triangle presented by Bruneau et al. (2003) also affords this thesis with key concept in network resiliency. Past researches have been dealt in detail in the section of literature review compiled in Chapter 2.

1.4 Anticipated Contribution

This thesis seeks to identify a quantitative method for the computation of transportation network resilience using well-defined metrics. Mathematical expressions will be incorporated into the analysis to identify properties affecting capacity and performance. In short, this research seeks to provide a method of evaluation for transportation network resilience using simple and well-known tools from network analysis.

CHAPTER 2

LITERATURE REVIEW

2.1 Defining Resilience

The term “resilience” comes from the Latin etymology “resilire” that means to “rebound” (Laprie, 2008). In material science, resilience is the ability of a material to absorb energy when it is deformed elastically and then, upon unloading, to have this energy recovered. It is represented by the modulus of resilience which is calculated by the area under the curve in the elastic region of the stress-strain curve (Campbell, 2008) The concept of resilience has been studied in a large number of fields such as engineering, psychology, sociology, ecology, business, and economics. Typical definitions of resilience as it relates to well-known fields are presented below.

- In ecology, resilience is defined as, “a measure of persistence of systems and their ability to absorb changes and disturbances and still maintain the same relationships between populations or state variables” (Holling, 1973).
- In economics, resilience is defined as, “‘nurtured’ ability of an economy to recover from or adjust to the effects of adverse shocks to which it may be inherently exposed” (Briguglio et al., 2006).
- In social science resilience is defined as, “the capacity of a system, community or society potentially exposed to hazards to adapt, by resisting or changing, in order to reach and maintain an acceptable level of functioning and structure” (Huiping et al., 2005).

- In earthquake engineering, “community seismic resilience is defined as the ability of social units (e.g., organizations, communities) to mitigate hazards, contain the effects of disasters when they occur, and carry out recovery activities in ways that minimize social disruption and mitigate the effects of future earthquakes” (Bruneau et al., 2003).
- “Infrastructure resiliency is the ability to reduce the magnitude and/or duration of disruptive events” (NIAC, 2009).

In the field of transportation engineering, research has been performed regarding resilience and definitions have been proposed. Some of the definitions are listed below.

- “Resilience is the ability for the system to maintain its demonstrated level of service or to restore itself to that level of service in a specified timeframe” (Heaslip et al., 2010).
- “Resilience is a characteristic that enables the system to compensate for losses and allows the system to function even when infrastructure is damaged or destroyed” (Battelle, 2007).
- “Resilience is a characteristic that indicates system performance under unusual conditions, recovery speed, and the amount of outside assistance required for restoration to its original functional state” (Murray-Tuite, 2006).
- “Resilience is the ability of systems to accommodate variable and unexpected conditions without catastrophic failure” (VTPI, 2010b).

- Freight transportation system resilience is defined as "the ability for the system to absorb the consequences of disruptions, to reduce the impacts of disruptions, and maintain freight mobility" (Goodchild et al., 2009).
- Transportation resiliency is defined as "a system's ability to function before, during and after major disruptions through reliance upon multiple mobility options" (Amdal and Swigart, 2010).
- Resilience in freight context is defined as "ability for the transportation system to absorb the consequences of disruptions, to reduce the impact of disruptions, and to maintain freight mobility in the face of such disruptions" (Adams et al., 2010).

2.2 Measuring Resilience

As discussed previously, the topic of resilience has been studied in many different disciplines. Literature within various disciplines explains the concepts of resilience and methods of measuring resilience in some qualitative or quantitative ways. Some of the literatures explaining methods providing conceptual framework of measuring resilience on a number of available subjects are summarized below.

2.2.1 Conceptual Frameworks

Bruneau et al. (2003) proposed both a conceptual framework and quantitative measures in an effort to define the seismic resilience of communities. Their research named the infrastructural qualities used to define resilience in term of four R's that are listed and defined in the bullets below.

- Robustness: "The inherent strength or resistance in any system to withstand a given level of stress or demand without degradation or loss of functionality"

- **Redundancy:** “Ability of a system to satisfy the functional requirements using alternate options, choices, and substitutions in event of disruption, degradation, or loss of functionality”
- **Resourcefulness:** “The ability to identify problems, establish priorities, and mobilize resources and services in emergencies to restore the system performance”
- **Rapidity:** “The speed with which losses are overcome and safety, serviceability, and stability are re-achieved”

These four R’s are integrated into the conceptual framework to provide four dimensions of community resilience including Technical, Organizational, Social, and Economic (TOSE), each of which are defined in the bullets below.

- **Technical:** “This dimension refers to the physical properties of the system or its components to resist the loss in functionality when a disruptive event occurs. It also includes physical components that add redundancy to the system.”
- **Organizational:** “This dimension refers to the capacity of institutions or organizations to manage the physical components of system and improve disaster related organizational performance and problem solving.”
- **Social:** “This dimension is formed by measures concerned with lessening the negative consequences due to loss of critical services following a disaster upon a community.”
- **Economic:** “This dimension is related to capacity to reduce both direct and indirect disaster induced economic losses.”

In their framework, resilience of a community is measured by the difference between the ability of community's infrastructure to provide services prior to the occurrence and expected ability of infrastructures to perform after an earthquake.

The ability of a system on a global basis as well as in single components is defined within the terms of four R's and TOSE. Each of these dimensions can be used to quantify measures of resilience for various types of physical and organizational systems.

Bruneau et al. (2003) defined community seismic resilience as "the ability of social units (e.g., organizations, communities) to mitigate hazards, contain the effects of disasters when they occur, and carry out recovery activities in ways that minimize social disruption and mitigate the effects of future earthquakes." They conceptualized the broader definition of resilience in terms of system performance, which states, "resilience can be understood as the ability of system to reduce the chances of a shock, to absorb a shock if it occurs (abrupt reduction of performance), and to recover quickly after a shock (reestablish normal performance)." Additionally, the research presented the resilience triangle concept, as shown in Figure 2.1, to represent the loss of functionality from damage and disruption. The triangle's depth represents severity of system performance loss and the length of the triangle shows the time needed for recovery. The area within the resilience triangle relates directly to the resiliency with smaller areas indicating greater resilience. Actions, behaviors, and properties of social units, organizations and networks all contribute to reducing the area of the resilience triangle.

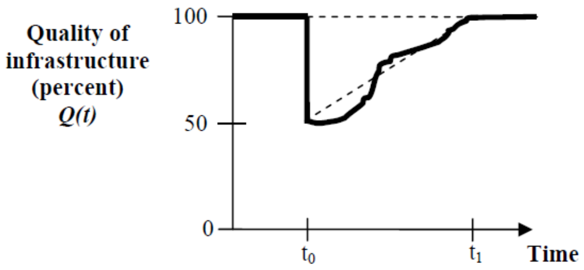

Figure 2.1 Original resilience triangle (Bruneau et al., 2003).

Battelle (2007) defined resiliency as synonymous to a transportation system's redundancy. Transportation system redundancy was defined as the resiliency that enables the system to compensate for losses and allows the system to function even when infrastructure is damaged or destroyed. This resiliency comes from excess capacity that is obtained by over capacitating routes, providing alternate routes, and optimizing the capacity of an existing system with proper coordination and management. Proper integration of multiple modes of transportation within a network also helps to maximize the system redundancy.

Transportation chokepoints or bottlenecks represent vulnerabilities where redundancy is particularly critical. According to Battelle, qualities such as presence of extra capacity, alternate routes, intermodality between multiple modes, and efficient coordination, cooperation and information sharing in the dynamically changing environment are crucial. These activities need to exist among Transportation/Traffic Management Centers (TMCs), Emergency Operations Centers (EOCs), and Incident Command Systems (ICSs) and the use of advanced technologies like Intelligent Transportation Systems (ITS), Advanced Traveler Information Systems (ATIS) for traffic control and incident/emergency management lead to enhancement of system redundancy and increase resiliency.

Murray-Tuite (2006) defined resilience as “a characteristic that indicates system performance under unusual conditions, recovery speed, and the amount of outside assistance required for the restoration to its original functional state.” She identified ten dimensions of resilience for a transportation system: redundancy, diversity, efficiency, autonomous components, strength, collaboration, adaptability, mobility, safety, and the ability to recover quickly. By using simulation, Murray-Tuite’s research attempted to examine the influence of System Optimum (SO) and User Equilibrium (UE) traffic assignments on the last four comparatively simple to quantify dimensions of adaptability, safety, mobility, and recovery. The SO assignment minimizes the travel time for all vehicles in the network, while the UE assignment minimizes travel time for individuals. Results of this simulation in the test network showed that the UE traffic assignment performed slightly better than SO in terms of adaptability and safety while SO performed better with respect to mobility and recovery.

Mostashari et al. (2009) defined two resilience metrics and proposed a modeling framework for assessing the resiliency of regional road networks. The first metric, travel time, is used to measure the impact of disruptions to travel time between network nodes. The second metric is environmental resiliency that is used to capture the increase in environmental impact due to delays. The researchers used multiple performance and level of service metrics, taking into consideration the impact of recovery and adaptation time. They defined four ways that resiliency can be integrated into a system including a

Table 2.1 Networked Infrastructure Resilience Assessment
(Mostashari et al., 2009).

System Mapping	Network Risk Analysis	Network Resiliency Assessment	Resiliency Strategy Evaluation
Logical Mapping of Network	Threat Identification	Link Resilience Simulation	Identification of Resiliency Strategies
Network Resiliency Metric Definition	Likelihood and Impact assessment	Resilience Metric Analysis	Simulation and Evaluation of Resiliency Strategies
OD Demand and Network Flow Analysis		Critical Mode Identification	

reduction in vulnerability, an increase in adaptive capacity, agile response, and effective recovery. The resilience measurement process for regional networks is called the Networked Infrastructure Resilience Assessment (NIRA). This process is displayed in Table 2.1. The research addressed the vulnerability aspect of resilience and investigated the consequence of network vulnerability.

Sudakov and Vu (2008), though not directly linked to transportation networks, proposed a definition of resilience using graph theory. The local resilience of a graph with respect to a particular property measures the degree to which the graph possesses that property and then measures the amount of change required locally in order to destroy it. If removal of two edges is required to disconnect a vertex of the graph, then the graph has a resilience of two with respect to connectivity. Using this method, each graph will produce different values of resilience with respect to different properties. A graph with a low resilience related to a specific property can lose that property because few edges require removals. Resilience of a transportation network with respect to a certain property can be increased by adding redundancy with respect to that property. Such as, adding capacity to important links may add reserve capacity to the network and help maintaining adequate levels of performance even when link capacity is degraded.

Vugrin et al. (2011) developed a comprehensive framework for the evaluation of the resilience of infrastructure and economic systems. System performance metrics and measurement methodologies from this framework are applicable for both natural and artificial disrupting events affecting all 18 critical infrastructure and key resources defined by DHS (2012). They defined resilience this way: “Given the occurrence of a particular disruptive event (or a set of events), the resilience of a system to that event (or events) is the ability to efficiently reduce both the magnitude and duration of the deviation from targeted system performance levels.” The difference between targeted system performance level and actual system performance after a disruptive event is defined as system impact while the amount of resources expended during the recovery process following a disruption defines total recovery effort. The sum of system impact and total recovery efforts is used to quantify the resilience with lower value implying higher resilience. Vugrin et al. also listed three fundamental system capacities that determine system resilience: absorptive capacity, adaptive capacity, and restorative capacity. Application of this framework for resilience assessment enables to perfrom comprehensive evaluation of system resilience and guides how to further enhance system resilience.

The Victoria Transport Policy Institute (VTPI, 2010a) described the concepts of basic access and basic mobility which are defined as, “Basic access refers to ability of people to access goods, service, and activities essential for any society. Basic mobility refers to physical travel that provides basic access.” and stated that, “Transportation systems may be evaluated in terms of their ability to provide basic access, even under unusual or difficult conditions.” That is, the system quality is measured based on the quality of the transportation service it can offer under the worst conditions rather than under the best conditions.

In a seperate article, the Victoria Transport Policy Institute (VTPI, 2010b) clarifies that transportation resilience can be evaluated differently at various levels. These levels include the individual level, the community level, the design level, the economic level, and the strategic planning level. A system with more diversity, redundancy, efficiency, and strength in critical components will exhibit a higher resiliance because such features help the system to accommodate a wide range of user needs and conditions. Mobility can be an important strategy for increasing resilience because it permits easier movement away from adverse conditions or towards areas of greater need. Similarly ability of system to collect and distribute critical information under extreme conditions, effective ways of identifying problems and communication and prioritization of resources for repairs and corrections will make a system more resilient.

Gunderson and Pritchard (2002) stated that resilience of a transportation system depends on two system properties: vulnerability and adaptive capacity and they defined vulnerability as the ease with which a disturbance may cause the system to deviate from its normal behavior. In other words it is the sensitivity of a system to a disruption. Similarly they defined adaptive capacity as the ability of the system to devote resources to respond to a disturbance. The magnitude of disruptions it can withstand is greater for systems with higher adaptive capacity.

Litman (2011) discussed the concept of accessibility and how it can be incorporated into transport planning. Litman describes accessibility as “people’s ability to reach desired goods, services, activities, and destinations.” Quality of accessibility has important impacts on transport quality so better accessibility can help identify optimal solutions to transport problems. The factors affecting accessibility are transport demand, mobility, transportation options, user information, integration, affordability, mobility substitutes, land use factors, transport network connectivity, roadway design and management, prioritization, and inaccessibility. Resilience of a transportation system can be improved by improving performance through improvements in measures of accessibility.

Heaslip et al. (2010) presented a sketch level method for assessing transportation resiliency at regional levels. A formal definition of transportation resilience was introduced as, “the ability for the system to maintain its demonstrated level of service or to restore itself to that level of service in a specified timeframe.” The conceptual basis of this methodology draws on the concepts of “resiliency cycle” and “transportation system performance hierarchy.” The framework developed by Heaslip, et al. brings the “resiliency cycle, resiliency cycle time, and performance hierarchy together into a Cartesian plane.” A network performance index as a measure of resilience was obtained by defining the combined relationship between variables having impacts on resilience by Fuzzy Inference System (FIS). Subsequently Serulle et al. (2011) "redefined the dependent variables, adjusted the model interactions with increasing transparency between metrics and thus refined the method to be applicable for measuring resilience quantitatively at the pre-event level."

Ip and Wang (2011) proposed a quantificational resilience evaluation approach. Their methodology states that resilience depends on three critical factors: redundant resources, distributed supplies, and reliable delivery lines. In their approach, a transportation network is represented by an undirected graph with nodes as cities and the edges as roads. Higher number of independent paths between of a pair of cities relates to a higher survival ability of transportation system between them. Their method used the weighted average number of reliable independent paths from a city node to other city nodes in the network to evaluate the node resilience and the weighted sum of resilience of all nodes to evaluate the resilience of transportation network.

Cox et al. (2011) presented a set of operational metrics to determine resilience of a passenger transportation system to terrorism with reference to the real world case of the 2005 London subway and bus bombings. The measures are based on vulnerability, flexibility, and resource availability to cope with a terrorist attack or natural disaster. They defined risk perception by users of a transportation system as an important factor affecting the system's vulnerability and a crucial predictive measure for resilience. Similarly, flexibility of a system allows it to respond to a shock and adjust its internal mechanisms to survive under duress while better availability of resources allows it to organize resources and maintain its integrity. They introduced the term Direct Static Economic Resilience (DSER) as “the percentage of avoidance of the maximum economic disruption that a particular shock can bring about.” Maximum disruption refers to the reduction in passenger journeys for the attacked modes and resilience behaviors refer to the increase in passenger journeys for alternative modes. The higher value of resilience is supposedly achieved if individuals are able to switch to substitute modes in order to offset the passenger journey reductions on attacked modes in order to fulfill their travel demand.

Adams et al. (2010) presented a method to evaluate the resilience ratings of road corridor segments. Metrics for resilience include alternate route distance, alternate route travel time, change in traffic volumes on the alternate routes, and the change in traffic level of service. ArcGIS was used to identify alternate routes in the corridor. They calculated a vulnerability rating of road segments and existing structures on the road segments in form of a Risk Priority Number (RPN) on a scale with values ranging from one to 10 using the failure mode and effects analysis (FMEA) method for hydrologic, overloading, and weather related modes of failure. Finally, resilience rating of road corridor segments was determined using the RPN, the economic importance of segments and metrics for evaluation of resilience based on alternate routes.

Croope and McNeil (2011) developed a Critical Infrastructure Resilience-Disaster Support System (CIR-DSS) framework to support in the infrastructure repair, replacement, and serviceability in the post disaster scenario. CIR-DSS deals with strategies to reduce vulnerability of infrastructure systems and increase resistance of systems towards stresses created by disasters. It supports in the integration of mitigation measures into the infrastructure management decision-making process with the objective of increasing the system resilience. The CIR-DSS is divided into subsystems which are a) Spatial Decision Support System (SDSS) implemented using GIS and HAZUS; b) Critical Infrastructure Management System (IMS) which is based on benefit-cost analysis principles; c) Resilience Management Information System (MIS) which is based on resilience principles, and finally d) Results Presentation System(RPS) which also imbeds a resilience evaluation subsystem within it. CIR-DSS features are presented by the system dynamics diagram, which is a way to represent the sequence of events, relationship among the people and organizations playing important roles for operating and restoring the system and policies helpful to understand complexities of the system.

Miller-Hooks et al. (2012) formulated a two stage stochastic program to measure a resilience level of a network and simultaneously determine of the optimal set of preparedness and recovery actions required under budget and service quality constraints. Resilience is defined as the expected fraction of post disaster demand compared to the original pre-disaster demand that can be satisfied by the network for a given budget level. The first stage of the program includes decisions on pre-disaster preparedness actions, taken before the disaster is realized by authorities. The second stage of the program involves selection of actions for post-disaster recovery, which need to be taken in the aftermath of disruption, once the impact of disruptions on the network performance is known. The problem is solved using integer L-shaped method, which decomposes a problem for a disaster scenario into a set of master problem and sub problems.

Montecarlo simulation is used to generate disaster scenarios. The results help to develop optimal investment allocation of a fixed budget between preparedness and post disaster recovery stages to improve the resilience of a network to the maximum value.

2.2.2 Resilience Index Calculation

Todini (2000) studied pipe network design for urban water distribution and tried to apply the resilience concept on it. According to Todini, looped topology adds redundancy, and helps to ensure sufficient capability to the system to overcome local failures and to guarantee the distribution of water to all nodes. He defined resilience as the ability of overcoming stress or failure in the water supply system. Todini used a heuristic optimization approach to explain resilience index of looped water distribution networks. The study also showed that resilience can be increased given a higher investment but it is not directly proportional to cost. In some cases, large increases in resilience can be achieved with small increases in investment.

Hamad and Kikuchi (2002) proposed a new approach to measure the degree of congestion on arterial highways. The proposed measure uses three data inputs that are travel speed, free flow speed, and the proportion of very low speed in the total travel time. These inputs are then processed through a fuzzy rule based inference and a single congestion index value ranging from 0 to 1 is obtained. Values of congestion index are interpreted with zero as the best and one as the worst condition. Practically, the congestion index values remain somewhat midway between these two values.

Briguglio et al. (2006) developed conceptual and methodological aspects associated with the economic resilience measurement of a country using an index called the Economic Resilience Index. They adopted a working definition of economic resilience as, “the nurtured ability of an economy to recover from or adjust to the effects of adverse shocks to which it may be inherently exposed.” They defined two terms: vulnerability index and resilience index. Vulnerability index refers to, “permanent or quasi permanent features over which a country can practically exercise no control.” Similarly, resilience index refers to, “what a country can do to mitigate or exacerbate its inherent vulnerability.” The overall risk of harms on the system by external shocks is indicated by the combination of the vulnerability index and resilience index. Resilience index is assumed dependent on four areas: macroeconomic stability, microeconomic market efficiency, good governance, and social development and is computed by taking a simple average of those four components. Results of the analysis show that GDP per capita, vulnerability, and resilience hold a linear relationship and thus confirmed the fact that per capita GDP is found to be more sensitive to resilience than to vulnerability.

Huiping et al. (2005) studied effect of disasters on the resilience of metropolitan areas made up of smaller communities. They defined resilience as, “the capacity of a system, community, or society potentially exposed to hazards to adapt, by resisting or changing, in order to reach and maintain an acceptable level of functioning and structure.” Recovery of socioeconomic activities and the workforce after a community wide disruption is used as a proxy for resilience in their analysis. Five social and economic indicators are selected to measure the amount of recovery named as population return, employment, severance tax, re-opened school, and building permit. Measurement of these indicators was combined using three different methods: method of simple summation, sum of standardized values and principle component analysis to create a socioeconomic resilience index. Results of the analysis revealed that, “the existence of segregated micro ethnic communities negatively correlates with socioeconomic resilience, and that economic capability has a positive correlation with it.”

Zhang et al. (2009) developed a framework for calculating the Measure of Resilience (MOR) to disasters for intermodal transportation systems. Intermodal network consists of two components: the road network and intermodal terminals. They defined intermodal network resilience as, “the ratio of reduction of the intermodal system performance after a disaster with respect to the system performance before a disaster.” Combining the results from performance indicators related to travel speed using a regression model, a Performance Index (PI) was developed which measures the ratio of travel speed to the free flow speed (FFS) weighted by truck miles travelled. The value of PI ranges from 0 to 1 with higher values indicating better network performance in terms of mobility. Resilience is then measured based on the value of PI before and after the disaster.

Scott et al. (2006) proposed a concept of Network Robustness Index (NRI) in order to identify the critical links inside a network and evaluate the performance of the network. They defined Network Robustness Index for a link as, “the change in travel time-cost associated with the rerouting all traffic in the system should that segment become unusable.” The NRI is a measure that focuses on maximizing travel timesaving over the entire network, and is based on the capacities of individual highway segments, the routing options for the origin-destination pairs using a particular segment, as well as the topology of the entire network. Scott et al. selected three hypothetical networks and proved through calculations that the links with higher values of NRI are more critical than the links with higher values of V/C ratio as their removal causes greater impact to the network in terms of increase in total travel time. In addition, same amount of investment for making improvements on link with higher NRI often provides system wide more benefits than for improvements on the links with higher V/C ratio.

Nagurney and Qiang (2009) proposed an index called the relative total cost index for evaluating the robustness of transportation networks. This index allows for the quantitative assessment of changes in the relative total cost of a transportation network in case of alternative travel behaviors including user-optimal traffic flows, or system optimal traffic flows when the link practical capacities are decreased or increased. The relative total cost index for a transportation network is calculated by the ratio of increase in total cost of the network over the original cost to the original total cost under a given capacity retention ratio. This index is expressed as percentage. Capacity of all links in the network is supposed to be decreased by a uniform factor lying between 0 and 1 to calculate the increase in total travel cost. This factor is known as capacity retention ratio. A network is more robust given a lower relative total cost index.

Serulle et al. (2011) based on the works by Heaslip et al. (2010) as their foundation, expanded and refined the concepts on measurement of transportation network resiliency at the pre event level. The methodology contains four tiers as shown in Figure 2.2. In total nine variables, which summarize the important infrastructure qualities and

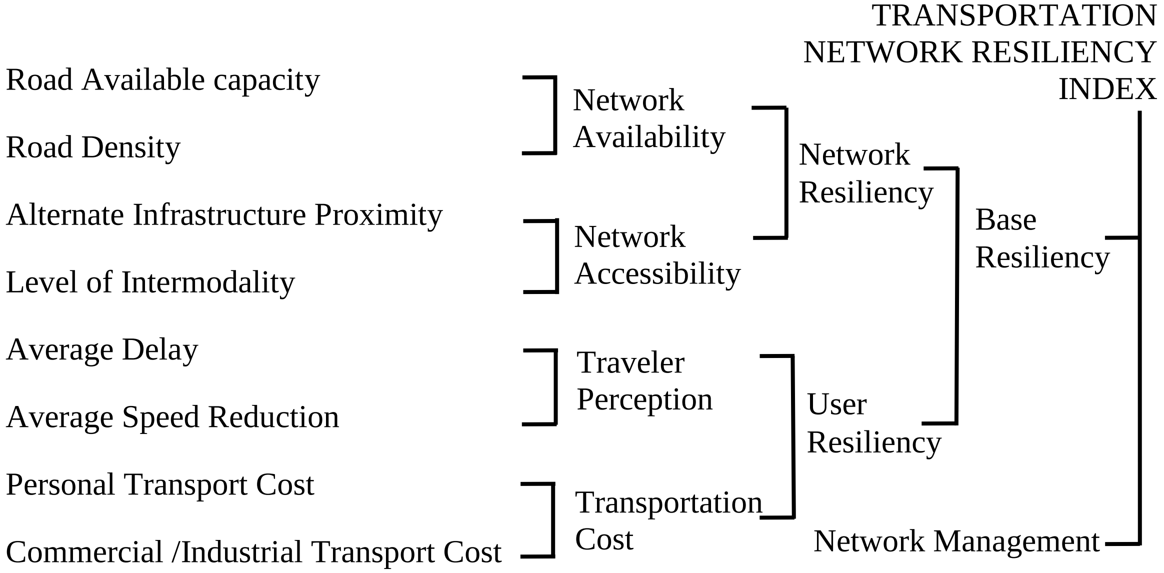

Figure 2.2 The dependency diagram as the basis for fuzzy inference (Serulle et al., 2011).

user behaviors inside a transportation system were selected to serve as metrics for resiliency. These variables are processed using Fuzzy rule based inference into an index called Transportation Network Resilience Index (TNRI) whose value ranges from 0 to 9 with value closer to 9 representing a more resilient system.

2.3 Conclusion

Resilience has been defined in many different fields including transportation engineering and many attempts to measure resilience are made in each of those fields. Many researchers tried to measure resilience in terms of various resilience indexes. Only some methods present well-defined metrics or suitable approaches in order to quantify system resiliency as a whole while in most of other methods, either the metrics used to measure resilience are incomplete as values assigned to the metrics depend upon the discretion of the analyst or the methods of using the metrics to obtain a resilience index are subjective. A clear and concise method to calculate resilience, which explains the metrics determining resilience in the context of transportation networks, is desirable. The objective of this research is to develop a method of measuring resilience based on well-accepted and widely used concepts and tools in transportation network analysis.

CHAPTER 3

METHODOLOGICAL FRAMEWORK

This chapter describes the research approach that will be implemented in this thesis. The research premise, research questions, theoretical concepts behind the resilience, and explanations of the variables and formulations used for the mathematical analysis of resilience will be provided in detail.

3.1 Research Premise

Disruptions caused by disasters initially reduce the performance of transportation networks. In the absence of external support for recovery, users redistribute onto functional routes and the network eventually reaches a new equilibrium. At this point, network maintains a new performance level depending upon the magnitude of disaster and the robustness of network. Upon availability of external support, the recovery process begins at a speed dependent on the flow rate of resources external to the system. The amount of degradation of the network performance caused by disasters and the speed of recovery are important in measuring resilience. Resilience can be measured by the area of curve under the plot of network performance measure against the time dimension starting from the beginning of disruption to the completion of recovery process.

3.2 Research Question

The overarching question that this research attempts to address is, “How can resilience of road transportation networks be quantified against disastrous events?” This question is best addressed through two questions presented below.

1) What are the properties of transportation networks essential to retain acceptable level of performance during disruption and what determines the post-disruption speed of recovery?
2) How can data relating to network performance be used to measure the resilience of transportation networks?

3.3 Research Conceptual Framework

The basis of the research methodology is founded on the concept of the resiliency cycle. It is based upon the assumption that networks within different regions or localities have characteristic degradation and response profiles, which can be evaluated within the resiliency cycle.

The concept of the resilience cycle was introduced by Heaslip et al. (2009). There are four stages in the resilience cycle: normality, breakdown, self-annealing, and recovery. The resiliency cycle has been shown diagrammatically on Figure 3.1. These stages are briefly described below.

- **Normality:** When the network is functioning under normal or standard conditions without the effect of any disturbances or disruptions, this phase is called normality (Heaslip et al., 2010). A system operates with maximum efficiency in this stage.
- **Breakdown:** When disruptions or disturbances occur within the system, the network experiences a reduction in performance. This stage is called the breakdown stage. Disruptive events may be sudden or gradual. After the system breakdown, performance drops to its minimum level. The ability to resist this

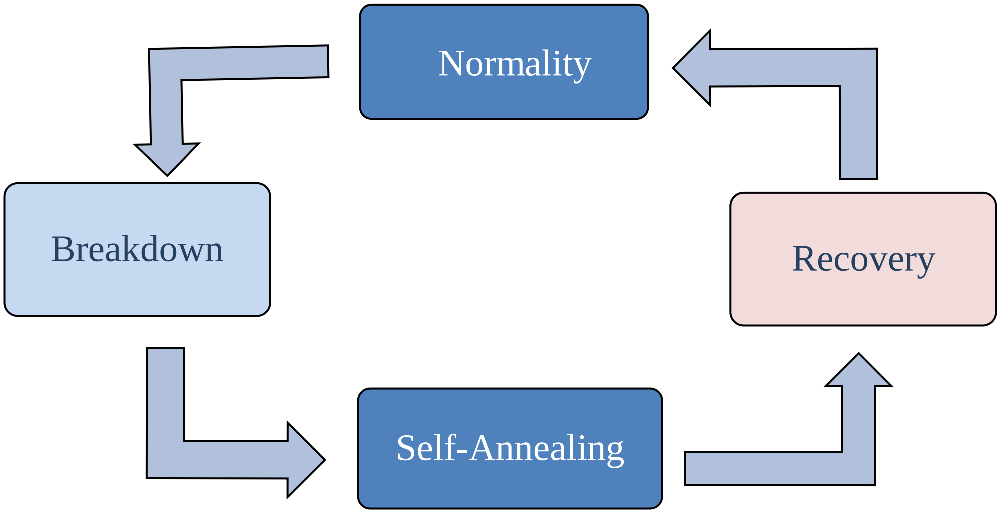

Figure 3.1 Transportation network resilience cycle (Heaslip et al., 2009).

performance loss is defined as robustness.

- **Self-annealing:** After breakdown, network users attempt to carry on their movements by attempting to identify alternate routes or alternate modes of transport. Emergency management practices put into place by network authorities may ease their movements in this stage compared to the breakdown. The self-annealing stage is described in detail in Section 3.4.1.
- **Recovery:** During this stage, damages caused by disruptive events are repaired, obstructions are removed, and facilities are restored or replaced. The speed of recovery or rate of improvement with respect to recovery time can be defined as rapidity. The rate of recovery depends upon resourcefulness, which is defined as the availability of both resources and technology, and the ability or managerial capacity to mobilize them with a reasonable speed to repair, renovate, rehabilitate,

replace, and restore the facilities in the system. The recovery stage results in a new normality, which may or may not have the same level of performance as the pre-event normality. Some systems may even use consequent recovery works required after disruptions as an opportunity to fix the preexisting deficiencies in the system leading to a performance level better than the preexisting system (Cimellaro et al., 2010). The recovery phase is described in detail in Section 3.4.2.

A graphical diagram with ‘transportation network performance’ against the ‘transportation network resilience cycle placed in the time dimension’ is presented in Figure 3.2. In this graph, the area bounded between the normal functioning curve, or the curve that network performance would follow given no disturbance to the network, and the curve of reduced system performance following the breakdown, self-annealing, and recovery stages provides the total loss in system performance. Once breakdown occurs, network managers begin efforts to bring back the system to new normality. Depending upon the promptness of response, recovery efforts may start at any point following a disruptive event.

Different regions have varied degradation and response profiles that can be evaluated through the resiliency cycle. This evaluation will account for the network topology and travel patterns prior to a disruptive event and network losses following an event. Estimating demand variation phenomenon following destabilizing events is very complex, therefore, is not considered for analysis in

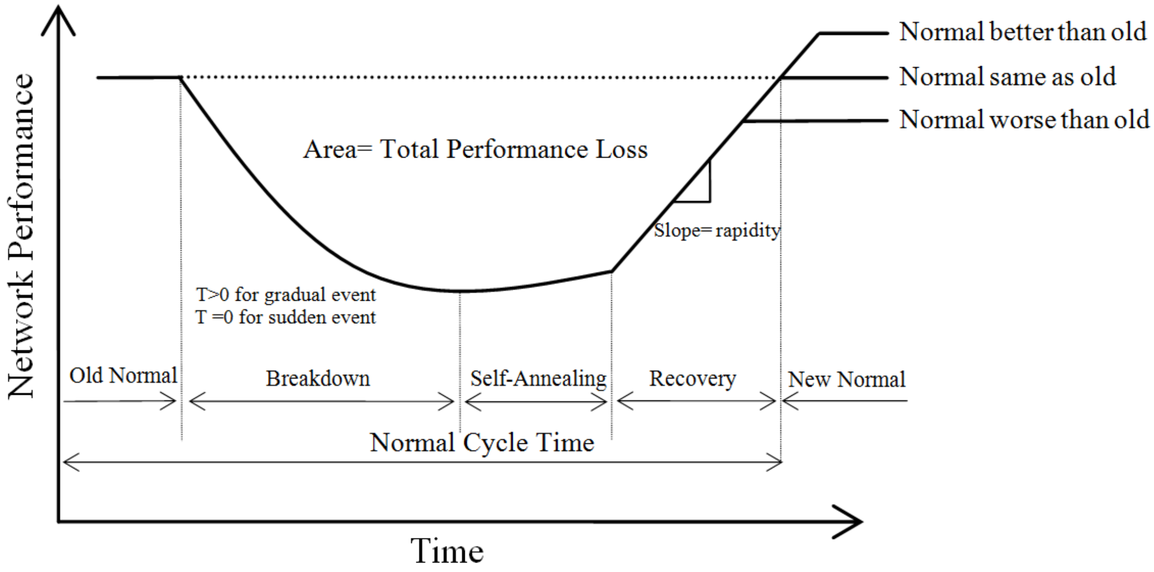

Figure 3.2 Performance of transportation network against network resilience cycle.

in this research. Modal shift, which can occur within the system with multiple transport modes choice, however, is considered for the analysis. In the resilience triangle, the length of time from the breakdown stage to the completion of recovery stage is important. Shorter length results in reduced total loss in performance but a higher flow rate of resources into the system is required to achieve that. Given a network, managers can determine an optimum length of time for completing recovery works for various disaster scenarios. Completion of recovery within this optimum time curbs detrimental effects on the local, regional, and national economies caused by slow recovery.

3.4 Theoretical Framework and Formulations

Road functionality may be severely affected by the physical damage experienced in disruptive events. Disruptions may also be caused by the failure of structures adjacent the roads. Breakdown events can remove or reduce the capacity of network elements. In this case, network users redistribute over alternate routes based on a perception of travel cost. Assuming that no external assistance is provided to the network for recovery, the redistribution behavior of travelers helps in regaining performance lost due to breakdown. Once external assistance is provided to a disrupted network in the form of incoming resources, the actual recovery process begins. The speed of recovery is dependent not only on the rate of resource supply but also depends upon the optimized use of resources.

3.4.1 Self-annealing

When disruptions occur over a network, affected travelers choose alternative paths, or modes to fulfill their travel demands, assuming an inelastic demand. The effect of network disruption degrades the network performance to a minimum level and as travelers redistribute using alternate paths or modes, the level of performance starts to improve gradually. In absence of external resources to support recovery, this improvement continues until a new equilibrium is achieved. The process can be named as self-annealing of networks. Robust networks are able to regain performance during self-annealing comparable to pre-event normal performance. Depending upon the promptness of response by the authorities, actual recovery may start anytime before, after, or exactly at the point when the network acquires equilibrium during the self-annealing stage. Depending upon where the starting point of actual recovery is, a conceptual performance curve against time can assume different shapes as provided in Figure 3.3 to Figure 3.7

In Figure 3.3, it is assumed that the duration of disruptions is long enough for a new user equilibrium to form prior to the commencement of externally assisted recovery. It is also assumed that disruptive events do not significantly affect the travel demand, resulting in an inelastic demand scenario. Figure 3.4 represents a situation of passive network management, who starts recovery efforts late after equilibrium. Figure 3.5 represents a responsive network management who start recovery efforts soon before equilibrium. Figure 3.6 presents very responsive network management starting recovery efforts even before the breakdown stage is complete. Figure 3.7 shows a stage when network becomes fully non-functional by suffering complete breakdown and starts to recover only after a period of time.

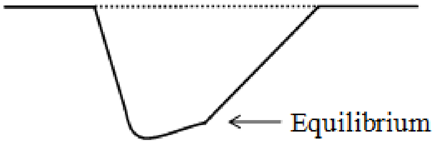

Figure 3.3 Recovery begins when equilibrium is just reached.

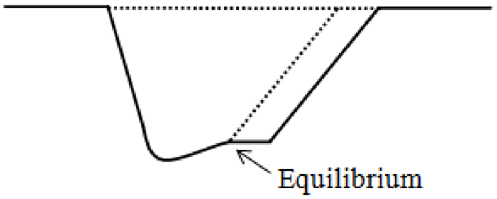

Figure 3.4 Recovery begins only after some time equilibrium is reached.

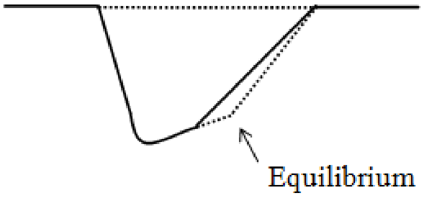

Figure 3.5 Recovery begins before equilibrium is reached.

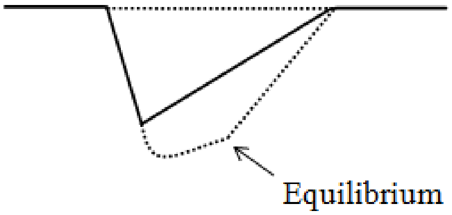

Figure 3.6 Recovery begins before the breakdown stage ends.

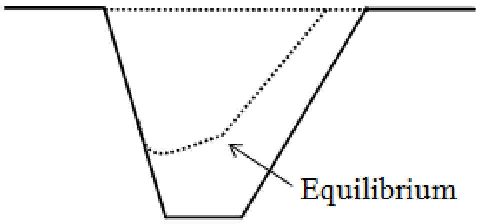

Figure 3.7 Recovery starts only after complete breakdown.

Since self-annealing involves only the redistribution of traffic into alternate routes or modes, it takes a much shorter time compared to the actual maintenance work in the recovery process. Self-annealing enables to gain higher performance and takes place quickly on more redundant networks having more surplus capacity and numerous route and mode choice alternatives.

Researches have defined various measures for redundancy. Bruneau et al. (2003) presented the definition of redundancy as described in Section 2.2.1. Cimellaro et al. (2010) stated that redundancy represents ability to use alternative resources to maintain functionality when the major resources become insufficient or missing. Laprie (2008) defined redundancy in the earthquake engineering as the quality of having alternate paths in the structure by which the lateral forces can be transferred, which keeps the structure stable after the failure of any single segment. Snelder (2012) classified redundancy into two categories: named as active and passive redundancy. Active redundancy like alternate routes is redundancy in the network that can be used in regular situations. Passive redundancy refers to the backup options that are only used in case of disturbances. Xu et al. (2012) described two measures for characterizing the redundancy of road networks: route diversity and network spare capacity.

In this research, we consider the variables network spare capacity, network route diversity, and alternative mode availability as the measures of redundancy. The variables considered responsible for self-annealing include these redundancy measures and additionally other variables named as level of travel time information and network management. A rational measure of network performance is also chosen to determine the effect on performance of the network due to the change in values of the self-annealing variables. The variables and performance measure are explained in the following sections.

3.4.1.1 Network Spare Capacity

The concept of network spare capacity (alternatively network reserve capacity) was proposed by Wong and Yang (1997) in order to calculate the reserve capacity of a signal controlled road network. In their method, the reserve capacity is given by the value of a common multiplier (μ) applicable to the existing origin destination matrix (q) that can be allocated to the network without exceeding a specific degree of saturation, which determines the level of service. In other words, reserve capacity provides information about the maximum allowable increase in original demand volume the network can handle without violating the constraint of level of service. Using this method, values of μ

greater than 1 indicate that the network has spare capacity amounting to (μ-1)*100 % of the current demand q. A network with reserve capacity value greater than 1 may still be able to handle the existing demand within the assumed level of service in case capacity of some links are fully or partially compromised. Value of μ less than 1 indicates the network is already congested with (1-μ)*100% demand more than the capacity.

Concept of network reserve capacity takes into account both the route choice behavior of travelers and congestion effect on networks (Xu et al., 2012). It is based on the assumption that users try to minimize their travel time by choosing the shortest route among all available routes. If that shortest route no longer remains shortest due to the congestion effect, then users choose another shortest route. This behavior is based on the concept of user equilibrium.

The mathematical formulation for calculating the network-reserve capacity (μ) given by Wong and Yang is a bi-level programming problem with upper-level formulation for the network flow maximization and the lower-level problem for traffic assignment based on concept of deterministic user equilibrium. This method is based on conserving existing O-D pattern and then determining capacity by scaling all O-D demands by a common multiplier (Kasikitwiwat and Chen, 2005). The upper program for network reserve capacity formulation given by Wong and Yang (1997) is represented in Equations 3.1a and 3.1b.

$$\text{Maximize } \mu, \tag{3.1a}$$

subject to

$$X_a(\mu q) \leq \theta_a C_a, \forall a \in A \tag{3.1b}$$

where

A is the set of links,

θ_a is a parameter denoting the pre- specified LOS on link a

C_a is the capacity of link a, and $x_a(\mu q)$ is the flow on link a which is obtained by solving the lower user equilibrium(UE) assignment problem under the given reserve capacity multiplier μ.

Similarly, the lower user equilibrium assignment problem of formulation by Wong and Yang (1997) is given in Equations 3.1c, 3.1d, 3,1e, and 3,1f

$$\text{Minimize } Z\big(X(\mu q)\big) = \sum_{a\in A} \int_0^{X_a} t_a(w)dw \tag{3.1c}$$

subject to

$$\sum_{k\in K_n} f_k^{rs} = \mu.q_{rs}, \forall r \in R, s \in S, \qquad \text{3.1d)}$$

$$X_a = \sum_{r\in R}\sum_{s\in S}\sum_{k\in K_{rs}} f_k^{rs}\delta_{ak}^{rs}, \forall a \in A \tag{3.1e}$$

$$f_k^{rs} \geq 0, \forall k \in K_{rs}, r \in R, s \in S \tag{3.1f}$$

where

R and S are sets of origins and destinations, respectively

t_a is the travel time on link a

q_{rs} is the assumed demand between OD pair (r, s)

f_k^{rs} is the flow on route k between OD pairs (r, s)

δ_{ak}^{rs} is the link-route incidence indicator with $\delta_{ak}^{rs} = 1$ if the link a is on route k between OD pair (r, s), $\delta_{ak}^{rs} = 0$ otherwise

In the above formulation, the upper objective function is used for maximizing the multiplier μ and constraints for this expression are related to the level of service. The lower program objective function is strictly for deterministic user equilibrium used to minimize total travel time for each user. Constraints for this are referred to as demand conservation constraints, constraint that sums up all route flows that pass through a given link to define the link flow, and the last constraint defines the non-negativity of route flows.

3.4.1.2 Network Route Diversity

For every Origin-Destination (OD) pair, there may be one or more connecting routes. Unlike the case of having a single route only between an OD pair, where connectivity is lost if the route fails, multiple routes help to reduce the impact of disruptions by providing alternative paths to the users when some of these routes are obstructed. Diversity of connections for an OD pair is defined simply by the number of available routes connecting them. A problem arises when multiple routes share some common links. Failure of shared links will disconnect all routes sharing such links. The route diversity needs to be corrected with a factor that accounts for route overlaps. This factor, called the strength of connection factor, is obtained using the equations given by Di Gangi and Luongo (2005). When this factor is multiplied through the available number of routes, it gives corrected route diversity for each OD pair within the network. Each OD pair is provided with some weight in proportion of network demand carried by them. The ratio of OD demand to the total network demand gives the weight. The weighted route diversity of each OD pair is obtained by multiplying the corrected route diversity with its weight. Weighted route diversities of all OD pairs are added to get a single number, which gives the average route diversity for the whole network. The formulations for calculating the above described terms is shown below.

Let us consider N be the set of nodes, A the set of links, and G (N, A) the graph representing the considered road network system. There are n numbers of OD pairs. For any OD pair connecting origin r to destination s, there are k_{rs} number of paths. Let a_k be the sum of number of links for each path between an OD pair where $k \in k_{rs}$. Let $\gamma_{ij} = 1$ for a link connecting any node i of network to node j of the network if the link belongs to at least one of the paths between the considered OD pair. Otherwise $\gamma_{ij} = 0$

The total of sum of number of links (T_{rs}) involved for all paths between an OD pair connecting origin r to destination s is given by Equation 3.3a

$$T_{rs} = \sum_{k \in K_{rs}} a_k \tag{3.2a}$$

Additionally, the actual number of links (A_{rs}) used in the paths connecting the considered OD pair is presented in Equation 3.3b.

$$A_{rs} = \sum_i \sum_j \gamma_{ij} \tag{3.2b}$$

The strength of connection (S_{rs}) for the considered OD pair can be calculated through Equations 3.2c and 3.2d.

$$S_{rs} = 1 - \left\{ \frac{\frac{T_{rs}}{A_{rs}} - 1}{k_{rs} - 1} \right\} \; if \; k_{rs} > 1 \tag{3.2c}$$

$$S_{rs} = 0 \; if \; k_{rs} = 1 \tag{3.2d}$$

The value of S_{rs} ranges from 0 to 1, with a value of 0 indicating the weakest connection and value 1 for the strongest connection. A connection is strong if links are not shared by paths, and each path is independent of another. Connections become weaker if links are shared between different paths such that failure of shared links affects all paths using the shared links.

The mathematics behind route diversity is provided below. Given n numbers of OD pairs, for the OD pair connecting origin r to destination s, let there be k_{rs} number of paths. Thus the route diversity of OD pair r-s is k_{rs}. The corrected route diversity (C_{rs}) is obtained by multiplying with S_{rs} as shown in Equation 3.3a.

$$C_{rs} = k_{rs} * S_{rs} \tag{3.3a}$$

The weighted route diversity factor (W_{rs}) for OD pair r-s is calculated in Equation 3.3b.

$$W_{rs} = C_{rs} * \frac{demand\ for\ OD\ pair\ r{-}s}{\sum_{rs} Demand\ for\ OD\ pair\ r{-}s} \tag{3.3b}$$

A single numerical value for route diversity (R) of the whole network is then calculated by summing the weighted route diversity factor for all OD pairs as shown in Equation 3.3c.

$$R = \sum_{rs} W_{rs} \tag{3.3c}$$

3.4.1.3 Alternative Mode Availability

Multiple modes of transportation within the transportation system increase redundancy by providing options to maintain service if the capacity of one or more modes is restricted by disruptions. One mode can accommodate and fulfill the demand of users from another disrupted mode and help to maintain system performance. For example in the Northridge 1994 earthquake that affected the Los Angeles highway network, the transit system helped to alleviate some of the initial congestion. During interstate reconstruction, transit usage tripled on selective rail and bus lines; however, transit usage reduced to pre-earthquake ridership levels one year after the disruption

(Deblasio et al., 2003). The variable of alternate mode availability represents the capacity of a mode to accept demand shifts from another mode. In this analysis, it is assumed that when a hazard produces disruptions on one mode of a multimodal network, e.g. auto mode, the network for another mode e.g. transit remains intact.

To calculate the shift of demand between modes, let us assume a network with some OD demand assigned as shown on Figure 3.8. This network has two auto links between origin and destination, also provided with a parallel transit line on dedicated guide way such that disruption on auto line may not affect the transit line of network. Disruption on an auto link may cause the OD travel time of auto mode to increase. This may result in a shift of some flow to the transit mode and decrease of demand in the auto mode assuming total network demand remains unchanged. This shift reduces the load of auto network and increases its reserve. According to Sheffi (1985), the issue of mode choice between transit and automobile results from a complex decision process influenced by a large number of quantifiable and unquantifiable factors. Transit and auto

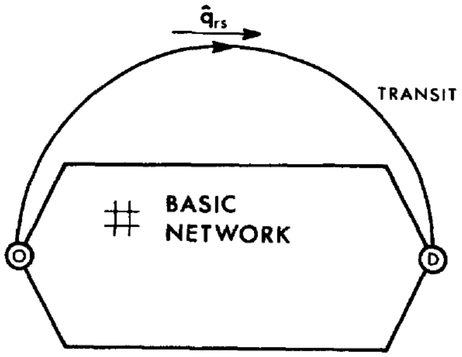

Figure 3.8 Basic auto network with parallel transit line on a dedicated guide way (Sheffi, 1985).

travel time is only one of the factors among them. Logit formula is a widely used mode split function to predict flows on auto and transit modes and is as given in Equation 3.4a and 3.4b below (Sheffi, 1985). Respective flows can be found out by solving equilibrium between auto and transit modes using the combined modal split/traffic assignment problem. For computational simplicity, some assumptions are made as described below.

- Transit vehicles move on dedicated guide ways so that transit flow is independent of auto flow. There is no interaction between transit and auto links.
- The level of service offered by the transit system is assumed independent of either automobile or the transit flow. This is possible when transit capacity is large enough to accommodate increasing demand without occurrence of any congestion. In other words, transit travel time between the origin and destination is a fixed quantity say $\hat{u}_{rs}$ where r and s are origin and destination. Transit service normally offers vehicles at fixed frequencies. When a transit service is using dedicated guideways, there is no congestion effect affecting the travel time of transit vehicles. Following demand rise, if the transit authority can introduce more vehicles into the transit system for service, or increase service frequency of existing vehicles in a demand responsive way, they can accommodate increasing demand also without any congestion.
- Total demand for an OD pair is assumed fixed though mode change may take place.
- The automobile and transit flows both are expressed as persons per unit of time with vehicle occupancy factor for auto mode assumed as 1.

- The transit and automobile trip rates between each OD pair are given by a logit equation and flows over each mode's network are distributed in accordance with user equilibrium (UE) conditions.

A mathematical presentation of mode split is defined in the logit formula provided in Equation 3.4a and 3.4b below.

$$q_{rs} = \bar{q}_{rs} \frac{1}{1+e^{\theta(u_{rs}-\hat{u}_{rs}-\varphi_{rs})}} \; \forall \, r, s \tag{3.4a}$$

$$q_{rs} + \hat{q}_{rs} = \bar{q}_{rs} \; \forall \, r, s \tag{3.4b}$$

where

φ_{rs} and θ are non-negative valued empirical parameters.

$\hat{q}_{rs}$ and q_{rs} are flows over transit and auto mode.

$\bar{q}_{rs}$ is the total OD flow.

$\hat{u}_{rs}$ and u_{rs} are travel time over transit and auto network.

φ_{rs} stands for the effects of all other factors other than the travel time difference on the modal split. For example, a positive value of φ_{rs} can be interpreted as an automobile preference factor which means that the share of automobile trips between OD pair r-s is greater than transit share between this OD pair even in cases in which travel time are equal for both mode as given by $u_{rs} = \hat{u}_{rs}$

The equilibrium traffic assignment can be found by the minimization of the program based on user equilibrium conditions (Sheffi, 1985) as presented in Equation 3.5a, 3.5b, 3.5c, 3.5d and 3.5e below.

$$\text{Min } Z(X, \hat{q}) = \sum_{a \in A} \int_{o}^{X_a} t_a(w) dw + \sum_{rs} \int_{0}^{\hat{q}_{rs}} \left(\frac{1}{\theta} ln \frac{w}{\bar{q}_{rs} - w} + \hat{u}_{rs} + \varphi_{rs} \right) dw \tag{3.5a}$$

subject to

$$\sum_k f_k^{rs} + \hat{q}_{rs} = \bar{q}_{rs} \ \forall\, r \in R, s \in S \tag{3.5b}$$

$$X_a = \sum_{r \in R} \sum_{s \in S} \sum_{k \in K_{rs}} f_k^{rs} \delta_{ak}^{rs}, \forall a \in A \tag{3.5c}$$

$$f_k^{rs} \geq 0 \ \forall\, k \in K_{rs}, r \in R, s \in S \tag{3.5d}$$

$$0 < \hat{q}_{rs} < \bar{q}_{rs} \ \forall\, r \in R, s \in S \tag{3.5e}$$

where

A is the set of auto links.

R and S are sets of origins and destinations, respectively.

t_a is the travel time on auto link a.

$f_k^{rs}$is the flow on route k between OD pair (r, s)

X_a is the flow on auto link a.

φ_{rs} , θ, $\hat{q}_{rs}$, q_{rs}, $\bar{q}_{rs}$, $\hat{u}_{rs}$, u_{rs}, and φ_{rs} carry same meaning as defined for Equations 3.4a, and 3.4b.

This minimization program can be used as the lower level program of bi-level reserve capacity formulation to calculate the reserve capacity of the network having a mode choice option with the transit network provided on dedicated guide ways, and independent of auto links.

3.4.1.4 Network Management

Network management refers to the activities, methods, procedures, and tools related to the operation, administration, maintenance, and provision of network systems (Clemm, 2006). There are four major traffic management measures named as operational measures, regulatory measures, information measures, and measures to encourage modal change (Williams, 2007). Operational measures involve activities to improve operational efficiency like redesigning of links and intersections, reallocations of road space, traffic signaling and speed reduction by traffic calming measures etc. Regulatory measures involve the use of national and local regulations to support operational measures. Information measures involve providing traffic information to users such as road markings, direction signings, parking guidance and information, real-time traffic and travel information, and variable message signs about delays and alternate routes to name a few. Information helps users to take appropriate decisions such as choosing alternate routes, shifting to alternate mode of transport, delaying, or canceling their journey, choosing a different parking etc in response to both recurring as wells as disastrous incidents in the networks. Measures to encourage modal change help to increase ridership of transit mode over the auto mode.

The objective of a network management process is to assure effective, efficient, and standardized operations within and among modes of transportation (TSA, 2012). The management of traffic conditions that occur after natural disasters is more complex than ordinary traffic management which is based on handling of relatively stable traffic conditions (Iida et al., 2000). Traffic management systems must be able to respond adequately to conditions changing over time caused by unexpected disruptive events. Advanced network management helps on the redistribution of resources and demands on the existing network in the real time, and reduces the impact of a disruptions by helping annealing to begin (Serulle et al., 2011). Better network management during disasters help users by providing different levels of traffic information and trip advisory so that they can make timely and informed decisions to travel through the alternate functional routes. This helps in the optimum utilization of available reserve capacity of functional network. Thus, a good network management practice, important throughout the life cycle of a transportation network, becomes more important after the breakdown for the successful self-annealing process. A good network management team must ensure redundancies in several important areas of emergency response and recovery (Deblasio et al., 2003). The examples of such areas are workforce, communications, utilities, control centers, equipment, and supplies.

3.4.1.5 Network Performance Measures

Performance measures can be used to evaluate the change in quality of service delivered by the network that is caused by disruptions or improvements. Total travel cost of the network is a widely used measure of network performance as the degradation of network links or nodes causes a decrease in network capacity and an increase in the total travel cost of users. It is calculated as the total sum of product of link flows and link travel times over the network as given in Equation 3.6 below.

$$Total\ Travel\ Time = \sum_a X_a * t_a(X_a) \tag{3.6}$$

where

X_a is the flow on link a.

$t_a(X_a)$ is the travel time on link a.

Relative change in total travel cost before and after a breakdown, event or improvement can be used as an index of network performance. However, there arises a computational problem if a disaster results into removal of links or nodes causing the disconnection of certain OD pairs within a network. In this case, after event travel cost for the disconnected OD pair would become infinite and incomparable to the before event travel cost, extinguishing the ability to compare performances. To account for this problem, a performance index is required which is well defined even when certain OD pairs get disconnected. Nagurney and Qiang (2007) presented a unified network performance measure named as the Nagurney and Qiang (N-Q) Network Efficiency/ Performance measure which is described below and will be used in this research as a measure of performance. This measure considers demands, flows, costs, as well as users route choice behavior in addition to the network topology, and hence is a suitable measure.

Consider a network with topology G with a fixed demand vector q, then the N-Q performance measure denoted by ε is defined in Equation 3.7.

$$\varepsilon = \varepsilon(G, q) = \frac{\sum_{rs} \frac{q_{rs}}{\lambda_{rs}}}{n_{rs}} \tag{3.7}$$

where

q_{rs} is the equilibrium (or fixed) demand for OD pair r-s
$\lambda_{rs}$is the minimum equilibrium travel time or cost for OD pair r-s, and
n_{rs} is the number of OD pairs in the network

This equation shows that the performance/efficiency measure ε is the average demand to price ratio for the OD pairs. For a fixed demand q for a network G, the network is more efficient if it can satisfy a higher demand at a lower price. Disasters often result in link removals or link capacity reductions. Enhancement projects may involve new link additions or capacity additions to the existing links. Comparison to the original performance for both disruptions and enhancements can be done by calculating the ratio of performances. The average demand to price ratio decreases for a disrupted network assuming the demand remains constant since the cost of travel increases with disruptions. This shows that the value of N-Q performance measure decreases with disruptions. Similarly, it is expected to increase with capacity enhancement to the network. When some OD pairs are disconnected, the disconnected OD pairs have unfulfilled demand q_{rs} but the cost of travel λ_{rs} is infinity. In this case, still the ratio $\frac{q_{rs}}{\lambda_{rs}}$ is calculable and equals 0.

Let $\varepsilon(G, q)$ is considered the original performance of the network. If a component or a set of components $g \epsilon G$ are removed from the network and the performance measure attains the value $\varepsilon' = \varepsilon(G - g, q)$ then the relative performance $R(g)$ is given by ratio in Equation 3.8a.

$$R(g) = \frac{\varepsilon'}{\varepsilon} = \frac{\varepsilon(G-g,q)}{\epsilon(G,q)} < 1 \tag{3.8a}$$

If the capacity of component g is reduced to, g' leading to the performance drop to $\varepsilon'' = \varepsilon(G - g + g', q)$ then the relative performance $R(g)$ is given by the ratio in Equation 3.8b.

$$R(g) = \frac{\varepsilon''}{\varepsilon} = \frac{\varepsilon(G-g+g',q)}{\epsilon(G,q)} < 1 \tag{3.8b}$$

Demand q is assumed constant in both cases presented above and the ratio attains value less than 1 in both cases because there is a drop in performance. The addition of new links or more capacity to the existing links can increase the performance resulting in a performance ratio that will be more than 1 in this case. If the elimination of nodes due to disasters occurs, it can be modeled by the removal of links entering and exiting the node.

3.4.2 Recovery Phase

The Federal Emergency Management Agency (FEMA) has identified four phases of disaster related planning as mitigation, preparation, response, and recovery and defined recovery as the process of restoring components of transportation networks to their the pre-event conditions (Mehlhorn, 2009). Similarly, Cova (1999) stated that recovery phase is distinguished by activity to bring life back to normal or more improved levels. Recovery of transportation networks must involve rebuilding the network beyond its pre-event condition to a higher standard making them more resistant against future disasters (USDOT, 2009). In this research, recovery is considered as restoration of service of transportation networks affected by disasters to normal conditions. It is very difficult to calculate the time needed for recovery before it is actually completed. The actual time required for the recovery process depends upon several factors which cannot be mathematically estimated without knowing the exact amount of damage suffered (USDOT, 2009).

Since no comprehensive model exists that describes the recovery process, Cimellaro et al. (2010) developed three simplified recovery functions based on system and society preparedness against disasters. These functions are shown in Figure 3.9. The linear recovery function is used when there is no information available regarding the preparedness, resources availability, and societal response. The exponential recovery function can be used when society responds to a disaster with a high recovery speed due to good influx of resources required but the recovery speed goes on decreasing, as the process approaches completion. Finally, the trigonometric recovery function can be used when response and recovery are initially affected by limited organization and limited resources but recovery gains rapid speed in the later phase after the society gets support in resources and management from other societies outside (Cimellaro et al., 2010).

The recovery patterns described are also valid for the transportation networks. In general, recovery depends upon resourcefulness, one of the four R’s of concept by Bruneau et al. (2003). The addition of more resources to a system will enable the system to achieve earlier recovery but even the addition of infinite resources cannot reduce length of recovery time to zero because human limitations necessitate at least certain minimum time for recovery (Bruneau and Andrei, 2004). The metrics for recovery time are more specifically categorized below.

3.4.2.1 Emergency Response Time

Barbarosoglu and Arda (2000) defined response as the set of activities carried out during the initial impact of disasters to prevent further property damage. Disrupting events require a coordinated and simultaneous response by different layers of federal, state, regional, and local jurisdictions. Freckleton et al. (2012) defined emergency response as, the capacity of a region to mobilize response efforts without taking the help of outside regions and stated that response time is measured by the time it takes for the first responders to react to an event. Quicker response can help to prevent failure of further more components of the infrastructure systems, which may otherwise occur in a cascading sequence after the failure of some components (Ouyang et al., 2012).

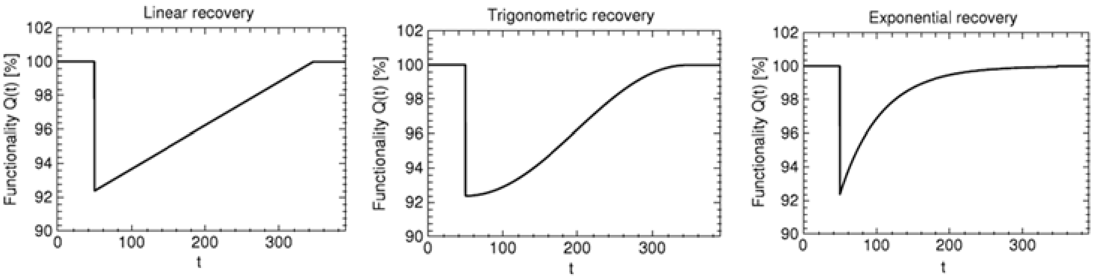

Figure 3.9 Functionality curve for different community preparedness level (Cimellaro et al., 2010).

3.4.2.2 Resource and Technology Availability

The variable of resource includes a broad range of things including manpower, finances, materials, and equipments. Depending upon the amount of resources possessed by both government and contracting agencies involved and their ability to mobilize those resources for maintenance, recovery time, and serviceability after maintenance vary. The use of advanced technology can expedite the speed of reconstruction and enhance service quality of facilities. Agencies need to be strong on financial resources. The sufficiency of available funds facilitates the speed of reconstruction.

3.4.2.3 Maintenance Prioritization and Schedule Management

The identification of routes whose capacity reduction causes the largest impact on the network is important to guide investment using available resources to help maintain performance during and following disasters. Available resources need to be allocated for restoration of the most critical portions of transportation system, to maintain minimum service level as per the community needs (USDOT, 2009). A rating list for the importance and condition of each link can assist in determination of the sequence of link restoration. Available resources need to be allocated to restore the highest number of important links to the minimum operating standards and the surplus funds then can be used to prioritize the links again and repair to the pre-event conditions or better (Karlaftis et al., 2007).

CHAPTER 4

METHODOLOGICAL IMPLEMENTATION AND DATA ANALYSIS

This chapter illustrates the concepts for measuring the resilience as discussed in Chapter 3 and provides analysis of the data outputs of the methodology. The procedure for performing the analysis is described so other researchers can replicate it. All assumptions made within calculations, description of calculations performed, along with results and findings are explained and interpreted in this chapter.

4.1 Basic Concept Illustration

Consider a one-link and one-way freeway segment connecting origin 1 to destination 2 shown on Figure 4.1, with the link capacity of 1600 vehicles/hour, peak hour demand of 1200 vehicles/hour and free flow speed of 60 miles/hour. Since there is only one link between the OD pair, all traffic must pass through the same link to reach their destination. The traffic volume to capacity ratio (v/c) at peak demand is 1200/1600=0.75. In this case, the v/c ratio is between 0.68 to 0.88 which corresponds to level of service (LOS) D as defined in Exhibit 23-2 of the Highway Capacity Manual (HCM, 2000).

Figure 4.1 A one-link network.

Since the link can still carry more volume for the assumed level of service, the reserve capacity of the network is (1600*.88)/1200=1.173 for LOS D. If level of service E is considered, reserve capacity of the network is (1600*1)/1200=1.333 as the v/c ratio for level of service E as given by HCM (2000) is between 0.88-1.00.

If the link is closed due to an incident, then users cannot reach their destination until it reopens because there is no alternate route. Therefore, despite having a high reserve capacity, the network does not have any route diversity. This network does not ensure connectivity if an incident removes the connectivity of the link.

Now consider a three-link network connecting origin 1 to destination 2 shown on Figure 4.2 with link capacities and free flow travel time shown in Table 4.1 and a peak hour demand of 5500 vehicles/hour. Since the three links create three different paths between the OD pair, users have route choice options to reach their destination.

Table 4.1 Link parameters for three-link network.

Link	Free Flow Travel Time (Min)	Link Capacity (Veh/Hr)
1	21	1600
2	15	1500
3	18	1400

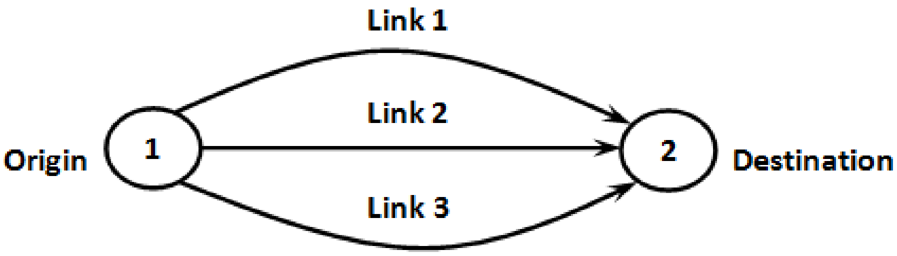

Figure 4.2 Three link network.

The function used for defining link travel time is the standard Bureau of Public Road (BPR) function given in Equation 4.1.

$$t_a(x_a) = t_a(0) * \left(1 + 0.15 * \left(\frac{X_a}{C_a}\right)^4\right) \tag{4.1}$$

where X_a, $t_a(0)$, and C_a are flow, free-flow travel time, and capacity of the link a. Assuming deterministic user equilibrium travel behavior, the flows, travel time, and v/c ratio on the links are calculated and tabulated in Table 4.2. The equilibrium results show that links 1, 2, and 3 are all over capacity and the level of service according to HCM (2000) falls in LOS F. Since this network has three route choices for users, it has a route diversity value of two, which helps to ensure connectivity even when destabilizing events remove one or more links. However, the total sum of capacity of three links is less than demand, and the network is over saturated. In such networks where capacity is lower than demand, the performance is poor. In other words, users have to bear unreasonably higher travel cost in the form of congestion. Under normal circumstances, surplus reserve capacity is enough to ensure adequate performance of the network. However, for successful adaptation to conditions when the capacity of some links or nodes is compromised due to destabilizing events, a network needs to possess reserve capacity as well as route diversity. Such networks

Table 4.2 Equilibrium flow parameters on three-link network.

Link	Link Flow (Veh/hr)	Link Travel Time (Min)	V/C ratio
1	1625	24.35	1.015
2	2141	24.35	1.428
3	1734	24.35	1.238

ensure that the capacity reduced under the effect of disruptions is still above the threshold capacity required to fulfill the demand with an accepted level of service. Multimodality further increases reserve capacity of the network and the ability to reach the new equilibrium by the optimum use of the functional network in the disrupted state is enhanced by better network management practices.

4.2 Test Network, Data Description, and Methodology

In this research, a network derived from Nguyen and Dupuis (1984), widely used in transportation literature, is chosen for the analysis. Details of this network and the methodology of analysis have been described in this section. The analysis and interpretation of the results of implementation are dealt with in the subsequent sections.

This network as shown in Figure 4.3 consists of 13 nodes, 19 links, two origins, two destinations, and four Origin-Destination (OD) pairs. The link travel time function used is a linear function of link flows provided in Equation 4.2.

$$t_a(x_a) = \alpha_a + \beta_a * X_a \tag{4.2}$$

where α_a and β_a are the link cost parameters provided in Table 4.3 along with assumed values of link capacities for this research, and X_a is flow on link a. Similarly, the hourly OD demand for the network is provided in Table 4.4

Table 4.3 Link characteristics for test network 1.

(O,D)	Link #	β_a	α_a	Link Capacity/Hour
1,5	1	0.0125	7	800
1,12	2	0.01	9	750
4,5	3	0.01	9	200
4,9	4	0.005	12	850
5,6	5	0.0075	3	750
5,9	6	0.0075	9	500
6,7	7	0.0125	5	500
6,10	8	0.005	13	500
7,8	9	0.0125	5	250
7,11	10	0.0125	9	500
8,2	11	0.0125	9	750
9,10	12	0.005	10	750
9,13	13	0.005	9	750
10,11	14	0.0025	6	1000
11,2	15	0.005	9	750
11,3	16	0.01	8	750
12,6	17	0.0125	7	250
12,8	18	0.01	14	500
13,3	19	0.01	11	750

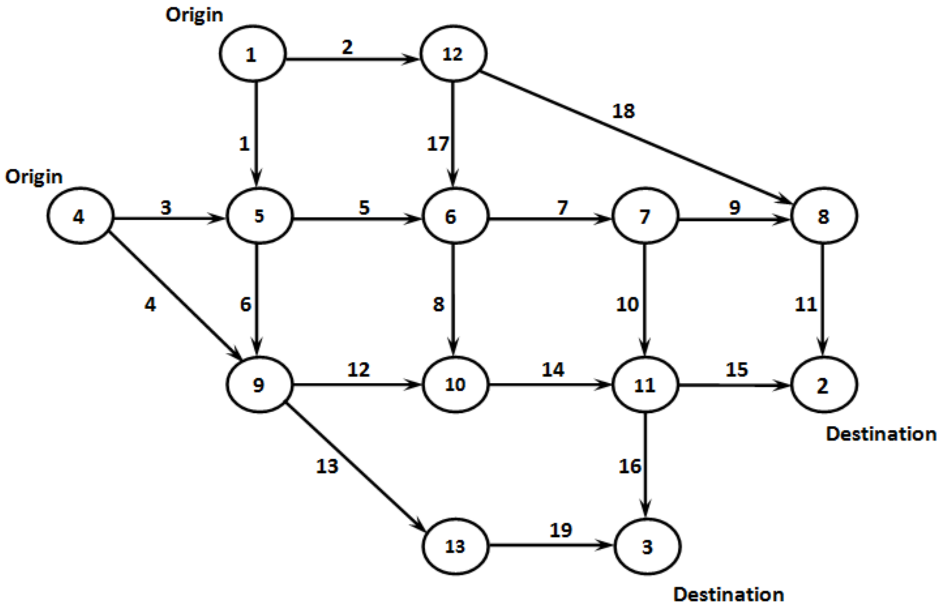

Figure 4.3 Test network 1.

Table 4.4 Hourly OD demand for test network 1.

	Destination 2	Destination 3
Origin 1	400	800
Origin 4	600	200

The addition of transit links to the network from origin 1 to destination 3, and from origin 4 to destination 2 in Section 4.3.4 illustrates the redundancy that the addition of transit links can provide. The travel time for the transit links, model constants, and auto preference factors are defined in Table 4.12 in Section 4.3.4.

This test network is analyzed to illustrate the concepts presented in Chapter 3. Excel 2007 and its solver functionality is the mathematical tool used for the analysis. Use of Excel for this type of analysis is a heuristic method which gives a near optimal or optimal solution.

Calculation of Network Spare Capacity: Steps followed in Excel 2007 to calculate the network reserve capacity by solving a bi-level program in this analysis are expressed in the flowchart form shown in Figure 4.4.

Calculation of Network Route Diversity: The calculation of network route diversity requires the enumeration of all possible paths between the origin and destination nodes. For small neworks, a hierarchical tree diagram of links can be drawn to enumerate all paths. The tree starts from the origin node and all possible branches able to reach destination node are drawn. In order to draw the branches, the tail node of i+1th step is given by head node of ith step. The number of branches starting at origin and ending at destination can be counted and detail of links on each route can also be determined in that way. For bigger networks, this method becomes tedious and should be automated through an algorithm and criteria should be used to filter all possible paths to a set of feasible paths using sets of criterion. The steps for calculation of network route diversity are shown in the Figure 4.5.

Calculation of Network Performance: Evaluation of network performance requires the traffic assignment in the network and calculation of cost for each link using link performane functions. Steps for the calculation of measure of network performance are shown in Figure 4.6

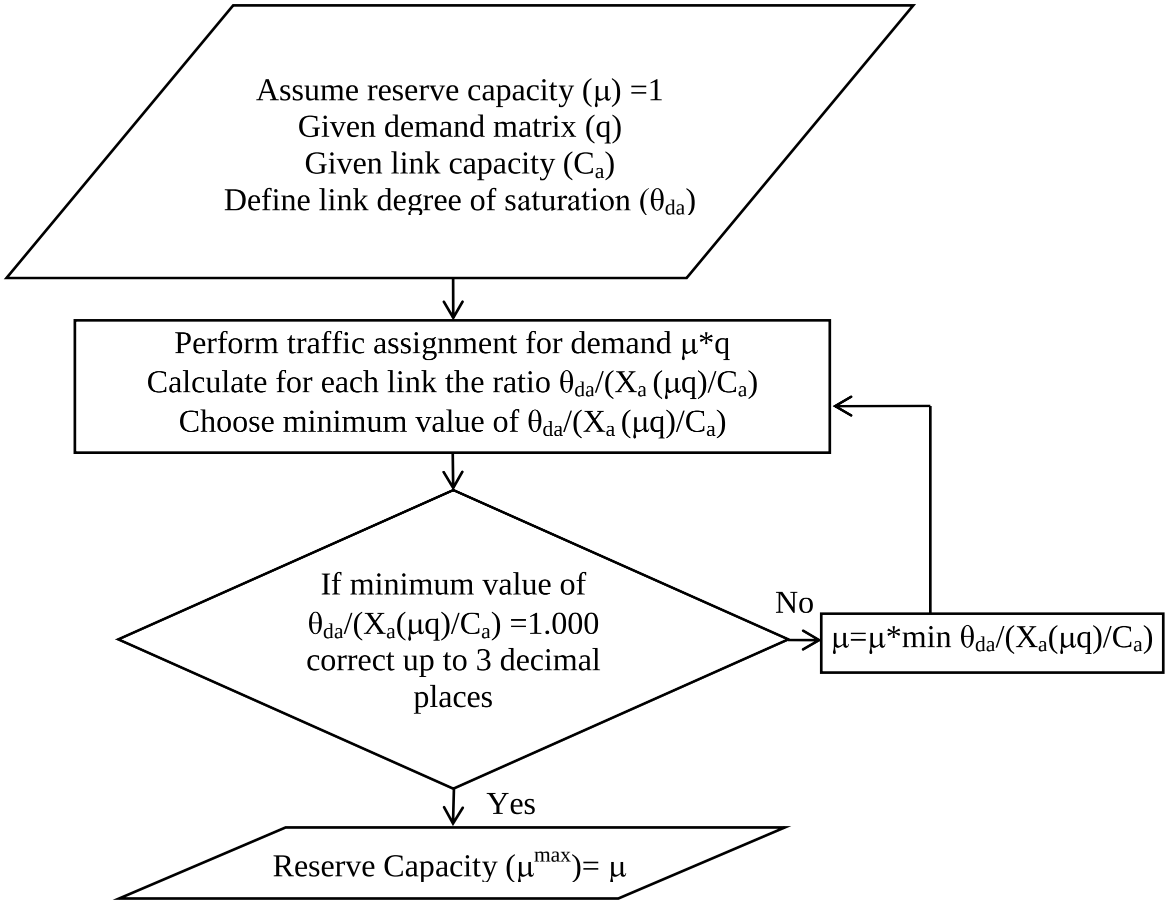

Figure 4.4 Steps for calculation of network reserve capacity.

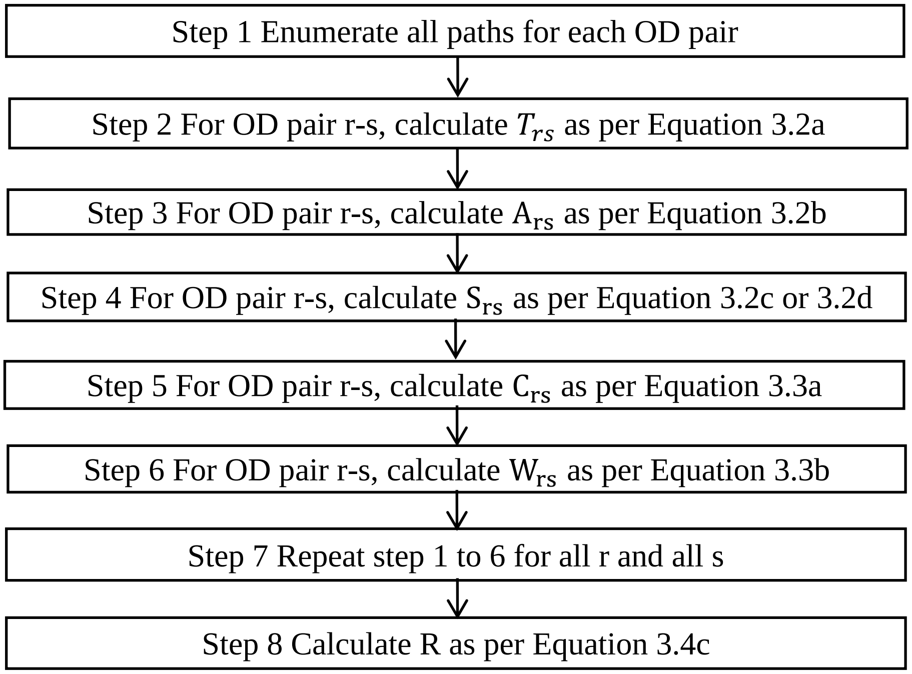

Figure 4.5 Steps for calculation of network route diversity.

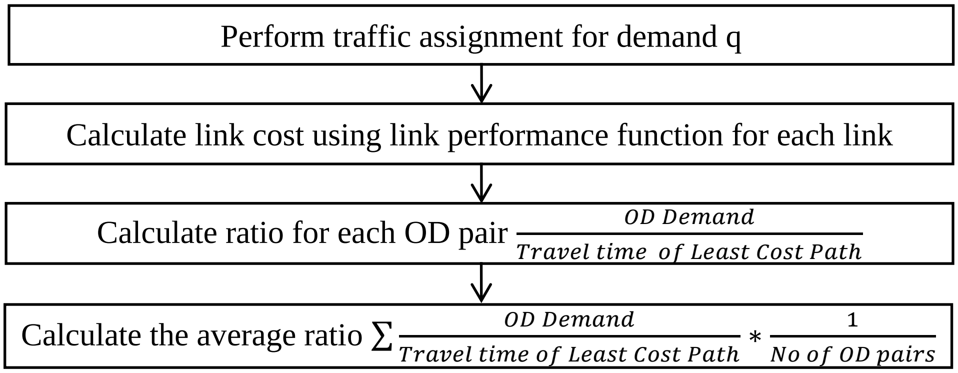

Figure 4.6 Steps for calculation of performance (N-Q).

4.3 Network Analysis and Numerical Results

The network is subjected to different scenarios of disruptions or improvements to see the effect on the equilibrium performance. Disasters may either completely block or reduce the capacity of the links. The complete blockage of links can be modeled as the removal of the affected links from the network. Out of 19 total links, there can be in total 524,287 combinations for cases of link removal as shown in Equation 4.3. Similarly, the total number of combinations becomes several times more than that if partial link capacity reductions are included in addition to link blockages.

$$\sum_{i=0}^{19} \binom{19}{i} = 524{,}287 \tag{4.3}$$

In the real world, however, the exact nature of a disaster cannot be prognosticated so the impact of the disaster on the links is impossible to forecast completely. Sample cases of closures were selected for the purposes of illustrating the methodology. In this example, the effect on the network properties of reserve capacity, route diversity, and network performance were initially studied through the removal of each link, one at a time. Then the three most important and the three least important links were selected based upon the magnitude of reduction on those properties because of link removal. The deterministic user equilibrium traffic assignment method was then used to investigate the reserve capacity and network performance values.

4.3.1 Single Link Removals

At first, the base network is analyzed using the deterministic user equilibrium traffic assignment to calculate the N-Q performance measure value. Then, after using the bi-level reserve capacity formulation, the reserve capacity of the base network is found by following steps in Figure 4.4. Similarly, the route diversity of each OD pair and the overall network route diversity are also calculated using steps in Figure 4.5. For each link removal scenario, the values of N-Q performance, network reserve capacity, and network route diversity are calculated. Results of the analyses are provided in Table 4.5. The first column of this table enumerates the link identification number of the removed link. The second column depicts the reserve capacity of the network. The assumed level of service for capacity is E in this analysis corresponding to the value of v/c ratio of 1. The route diversity value for the whole network is shown on the third column. Values of the N-Q performance are shown on fourth column. The relative network performance (decimal ratio to the performance of the base case) with respect to the base network performance for different scenarios is shown on column six, which is calculated using Equation 4.4.

$$Relative\ \ Performance\ \ (N-Q) = \frac{N-Q\ meaure\ for\ Scenraio\ Considered}{N-Q\ measure\ for\ network\ base\ case} \qquad (4.4)$$

When links are removed from a network, number of available paths between origin and destination for different OD pairs may change, resulting in a decrease in the overall network route diversity. The changes to the number of routes between each OD pair, the strength of connections for each OD and the overall network route diversity is illustrated in Table 4.6 Based on the reduction of the values of relative network performance, reserve capacity, and route diversity, links may be ranked in order of their importance. With respect to a given property, the link whose removal creates the greatest reduction on the value of the considered property is the most important. Plots of network degradation with the removal of one link with respect to network performance (N-Q), network reserve capacity, and network route diversity are given in Figure 4.7, Figure 4.8, and Figure 4.9. As seen from the results, links 15, 14, 2, 4, and 1 are the five most important links with respect to the network performance (N-Q). Similarly based on network reserve capacity, the five most important links in order include 4, 1, 15, 12, and 14. Based on network route diversity the five most important links are 14, 16, 5, 15, and 7. This analysis shows that links 14 and 15 are two of the top five links with respect to all three measures. This shows that the disruption of these links will degrade the performance of the network; the network will have little reserve capacity to absorb demand from these links, and have fewer route choice alternatives for people to utilize.

Table 4.5 Network properties under single link removal scenarios.

Removal of Link #	Reserve Capacity	Network Route Diversity	Performance (N-Q)	Relative Performance (N-Q)
Base Network	1.17	4.60	10.00	1.00
1	0.31	2.77	8.87	0.89
2	0.63	3.38	8.79	0.88
3	1.06	3.14	9.96	1.00
4	0.25	4.19	8.82	0.88
5	0.93	2.63	9.73	0.97
6	0.94	3.29	9.67	0.97
7	1.00	2.77	9.83	0.98
8	1.13	3.43	9.90	0.99
9	1.10	4.03	9.97	1.00
10	1.17	3.41	9.93	0.99
11	0.75	3.79	9.03	0.90
12	0.33	3.42	9.29	0.93
13	0.75	4.09	9.11	0.91
14	0.33	2.13	8.73	0.87
15	0.33	2.68	8.69	0.87
16	0.63	2.38	9.65	0.96
17	1.00	3.60	9.94	0.99
18	0.63	4.40	9.27	0.93
19	0.75	4.09	9.07	0.91

Table 4.6 Route Diversity: OD pair wise for single link removal scenarios.

	OD Pair 1-2			OD Pair 1-3			OD Pair 4-2			OD Pair 4-3				
Removal of Link #	# of Routes Available	Strength	OD Route Diversity	# of Routes Available	Strength	OD Route Diversity	# of Routes Available	Strength	OD Route Diversity	# of Routes Available	Strength	OD Route Diversity	Total # of Routes on the Network	Network Route Diversity
Base Network	8	0.76	6.04	6	0.75	4.52	5	0.75	3.75	6	0.77	4.60	25	4.60
1	4	0.73	2.93	2	0.75	1.50	5	0.75	3.75	6	0.77	4.60	17	2.77
2	4	0.73	2.91	4	0.76	3.03	5	0.75	3.75	6	0.77	4.60	19	3.38
3	8	0.76	6.04	6	0.75	4.52	1	0.00	0.00	2	0.60	1.20	21	3.14
4	8	0.76	6.04	6	0.75	4.52	4	0.73	2.91	4	0.76	3.03	24	4.19
5	5	0.81	4.04	4	0.81	3.22	2	0.50	1.00	4	0.57	2.29	17	2.63
6	7	0.71	4.96	4	0.67	2.67	4	0.76	3.03	4	0.82	3.27	21	3.29
7	4	0.79	3.15	4	0.76	3.03	3	0.63	1.88	5	0.73	3.63	17	2.77
8	6	0.77	4.62	4	0.76	3.03	4	0.76	3.03	5	0.77	3.86	20	3.43
9	6	0.77	4.62	6	0.75	4.52	4	0.70	2.80	6	0.77	4.60	22	4.03
10	6	0.77	4.62	4	0.76	3.03	4	0.76	3.03	5	0.73	3.63	20	3.41
11	5	0.68	3.41	6	0.75	4.52	4	0.70	2.80	6	0.77	4.60	21	3.79
12	7	0.71	4.96	5	0.75	3.75	3	0.67	2.00	4	0.82	3.27	21	3.42
13	8	0.76	6.04	5	0.73	3.65	5	0.75	3.75	4	0.76	3.03	24	4.09
14	5	0.68	3.38	3	0.72	2.17	2	0.57	1.14	3	0.83	2.50	16	2.13
15	3	0.69	2.06	6	0.75	4.52	1	0.00	0.00	6	0.77	4.60	16	2.68
16	8	0.76	6.04	1	0.00	0.00	5	0.75	3.75	2	0.25	0.50	20	2.38
17	5	0.81	4.04	4	0.76	3.03	5	0.75	3.75	6	0.77	4.60	20	3.60
18	7	0.72	5.03	6	0.75	4.52	5	0.75	3.75	6	0.77	4.60	24	4.40
19	8	0.76	6.04	5	0.73	3.65	5	0.75	3.75	4	0.76	3.03	24	4.09

Improvements should be made to ensure that these links are protected and to add additional route diversity and reserve capacity to ensure better performance even in absence of these links. For normal situations, enough reserve capacity alone ensures good performance, but when link(s) or node(s) capacity are compromised due to disrupting events, the survival of network depends on the ability to divert traffic to the alternate routes. Therefore, networks with both good capacity as well as good connectivity are required to ensure good performance under adverse conditions. It is also necessary to protect the more important links with respect to each property from being disrupted and give higher priority in the early maintenance of such importance links after disruptions.

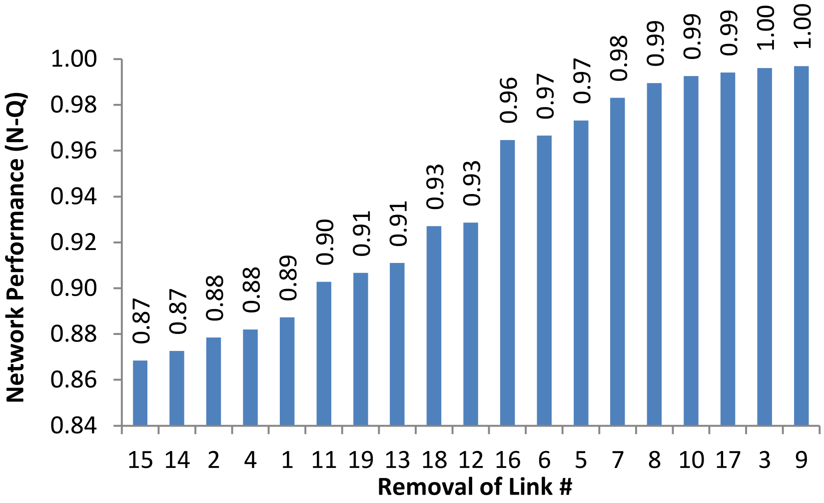

Figure 4.7 Network performance (N-Q) after the removal of a given link.

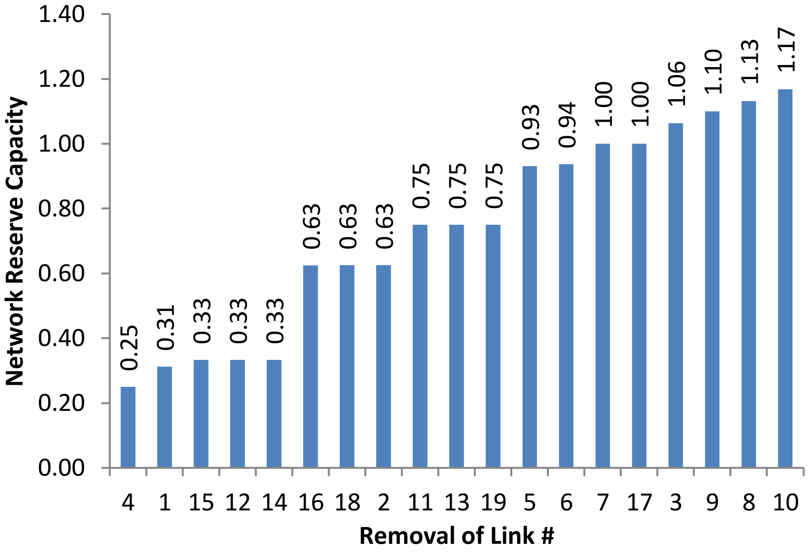

Figure 4.8 Network reserve capacity after the removal of a given link.

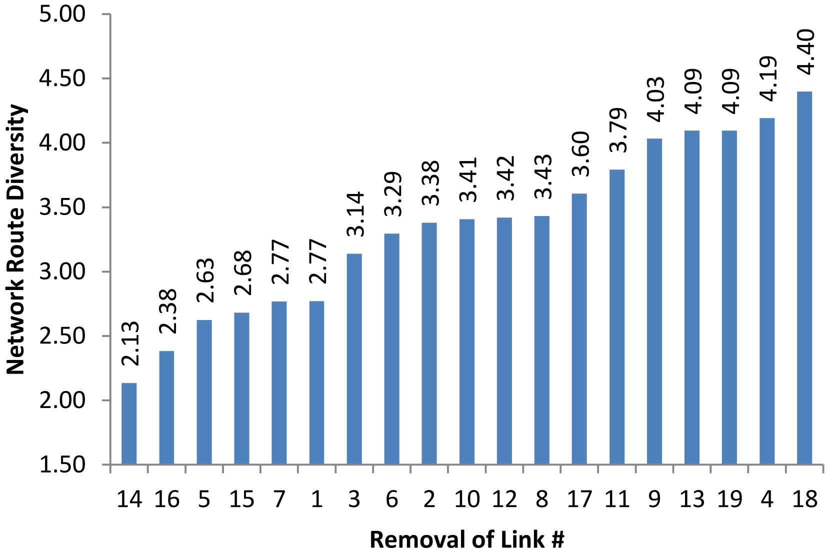

Figure 4.9 Network route diversity after the removal of a given link.

4.3.2 Link Combination Removals

As discussed previously, disasters can result in the removal or capacity reduction of any combinations of links, a phenomenon that is unpredictable for most incidents. In this study, some important combinations are considered by selecting the top three most important links for each property and taking all possible combination between the most important three links. Likewise, three least important links are chosen for each property and all possible combination between them is taken. As depicted by Figure 4.7, Figure 4.8, and Figure 4.9, the most important three links for network performance (N-Q) are 15, 14, and 2, for network reserve capacity are 4, 1, and 15, and for network route diversity are 14, 16, and 5. Similarly the least important three links for network performance (N-Q) are 3, 9, and 17, for network reserve capacity the links are 10, 8, and 9, and for network route diversity the links are 18, 4, and 19. The most important and least important three links based on network total VHT are also identified to consider for this analysis. The most important three links based on network total VHT are 1, 15, and 14 and the least important three are 9, 3, and 17. The possible combinations between the three links either most or least important for each category are taken with three links out of three at a time and two links out of three at a time. The results of the analysis performed for all possible combinations are shown in Table 4.7, sorted in the increasing order of equilibrium network performance (N-Q). The results show that out of the selected links, the most detrimental link removal combination consists of links 5, 14, and 16. If all of these three links are removed at once, the connectivity of OD pair 4-2 is lost and the equilibrium network performance drops to 0.63 times the base network performance. To avoid such link removal combinations additional security measures need to be arranged in the network. The combination of links 1, 14, and 15 is the second most harmful combination, reducing the performance to 0.67 times the base network performance. Similarly, the combination of links 14 and 5 is the third most harmful combination, and causes the drop of relative performance to 0.67 as well as a disconnection of the OD pair 4-2. The effect of all other link combinations in the decreasing order of reductions in network performance is sorted in the Table 4.7. Similarly, for each link removal combination, the decrease in number of routes between OD pairs, strength of connection and route diversity for each OD pair as well as the overall network route diversity are listed in Table 4.8. Analysis results show that removal of link combination 14, 16, and 5 disconnects OD pair 4-2. Similarly, removal of link combination 14 and 5 also disconnects OD pair 4-2. Removal of the link combination 1, 14, and 15 is the most harmful combination, which at minimum keeps all OD pairs connected. Link removal

Table 4.7 Network properties under link removal combinations.

Removal of Link	Reserve Capacity	Network Route Diversity	N-Q Performance	Relative Performance
5,14,16	*0.62*[1]	*NA*[1]	6.28	0.63
1,14,15	0.31	0.52	6.71	0.67
5,14	*0.93*[1]	*NA*[1]	6.71	0.67
2,14,15	0.25	0.82	6.81	0.68
1,14	0.31	1.01	7.14	0.71
2,15	0.25	1.67	7.26	0.73
1,4,15	0.25	1.17	7.27	0.73
2,14	0.33	1.39	7.28	0.73
4,18,19	0.25	3.56	7.51	0.75
1,15	0.31	1.33	7.73	0.77
1,4	0.25	2.36	7.86	0.79
4,18	0.25	3.99	8.11	0.81
4,19	0.25	3.76	8.15	0.82
4,15	0.25	2.52	8.22	0.82
18,19	0.62	3.89	8.31	0.83
14,15	0.33	1.53	8.61	0.86
14,16	0.33	1.07	8.64	0.86
5,16	0.62	1.16	9.33	0.93
8,9,10	0.62	1.33	9.39	0.94
8,10	0.62	2.02	9.54	0.95
9,10	1.00	2.77	9.83	0.98
8,9	1.06	2.92	9.88	0.99
3,17	1.00	2.14	9.92	0.99
3,9,17	1.00	2.00	9.92	0.99
9,17	1.00	3.18	9.92	0.99
3,9	1.06	2.85	9.96	1.00

combinations shown to have more severe effects are listed in the table in decreasing order of severity.

In the realistic networks, disasters may remove or reduce capacity of any number of links from the network at once. Some combinations may have a much greater impact

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[1] OD pair 4-2 get disconnected when link combination 14, 5 and 14,16,5 are removed so Reserve Capacity and N-Q performance are calculated by omitting the demand of disconnected pair. Total VHT cannot be computed because of an infinite path cost for the disconnected OD pairs.

Table 4.8 Route diversity: OD pair wise for link removal combinations.

Removal of Link #	OD Pair 1-2			OD Pair 1-3			OD Pair 4-2			OD Pair 4-3			Total # of Routes on the Network	Network Route Diversity
	# of Routes Available	Strength	OD Route Diversity	# of Routes Available	Strength	OD Route Diversity	# of Routes Available	Strength	OD Route Diversity	# of Routes Available	Strength	OD Route Diversity		
5,14,16	3	0.69	2.06	1	0.00	0.00	0	NA	NA	2	0.25	0.50	6	NA
5,14	3	0.69	2.06	2	0.88	1.75	0	NA	NA	2	0.25	0.50	7	NA
1,14,15	2	0.67	1.33	1	0.00	0.00	1	0.00	0.00	3	0.83	2.50	7	0.52
2,14,15	1	0.00	0.00	2	0.71	1.43	1	0.00	0.00	3	0.83	2.50	7	0.82
1,14	3	0.69	2.06	1	0.00	0.00	2	0.57	1.14	3	0.83	2.50	9	1.01
14,16	5	0.68	3.38	1	0.00	0.00	2	0.57	1.14	2	0.25	0.50	10	1.07
5,16	5	0.81	4.04	1	0.00	0.00	2	0.50	1.00	2	0.25	0.50	10	1.16
1,4,15	2	0.67	1.33	2	0.75	1.50	1	0.00	0.00	4	0.76	3.03	9	1.17
1,15	2	0.67	1.33	2	0.75	1.50	1	0.00	0.00	6	0.77	4.60	11	1.33
8,9,10	2	1.00	2.00	2	0.50	1.00	2	0.50	1.00	4	0.57	2.29	10	1.33
2,14	2	0.57	1.14	2	0.71	1.43	2	0.57	1.14	3	0.83	2.50	9	1.39
14,15	3	0.69	2.06	3	0.72	2.17	1	0.00	0.00	3	0.83	2.50	10	1.53
2,15	1	0.00	0.00	4	0.76	3.03	1	0.00	0.00	6	0.77	4.60	12	1.67
3,9,17	4	0.83	3.33	4	0.76	3.03	1	0.00	0.00	2	0.60	1.20	11	2.00
8,10	4	0.83	3.33	2	0.50	1.00	3	0.80	2.40	4	0.57	2.29	13	2.02
3,17	5	0.81	4.04	4	0.76	3.03	1	0.00	0.00	2	0.60	1.20	12	2.14
1,4	4	0.73	2.93	2	0.75	1.50	4	0.73	2.91	4	0.76	3.03	14	2.36
4,15	3	0.69	2.06	6	0.75	4.52	1	0.00	0.00	4	0.76	3.03	14	2.52
9,10	4	0.79	3.15	4	0.76	3.03	3	0.63	1.88	5	0.73	3.63	16	2.77
3,9	6	0.77	4.62	6	0.75	4.52	1	0.00	0.00	2	0.60	1.20	15	2.85
8,9	4	0.83	3.33	4	0.76	3.03	3	0.72	2.17	5	0.77	3.86	16	2.92
9,17	4	0.83	3.33	4	0.76	3.03	4	0.70	2.80	6	0.77	4.60	18	3.18
4,18,19	7	0.72	5.03	5	0.73	3.65	4	0.73	2.91	3	0.75	2.25	19	3.56
4,19	8	0.76	6.04	5	0.73	3.65	4	0.73	2.91	3	0.75	2.25	20	3.76
18,19	7	0.72	5.03	5	0.73	3.65	5	0.75	3.75	4	0.76	3.03	21	3.89
4,18	7	0.72	5.03	6	0.75	4.52	4	0.73	2.91	4	0.76	3.03	21	3.99

to the network functionality compared to others. An analysis can be conducted to identify potential risk to the network components and put the links into different risk categories. The analysis of disruptions on different combinations of the high-risk links is meaningful as that may help to make decisions regarding mitigation and preparedness against disasters and recovery plans after the disasters.

4.3.3 Addition of Links to the Network

As shown in Figure 4.8, links 4, 1, and 15 are the most critical links in terms of reserve capacity. Similarly as seen, from Figure 4.9, links 14, 16, and 5 are the most critical in terms of network route diversity. In order to make sure the network has sufficient redundancy to perform successfully in events of potential disruptive events, the following links can be added to the base network as shown on Figure 4.10 below. Role of added links is described in the bullets below.

- Link 1 is critical for reserve capacity and link 5 is critical for route diversity so a new link labeled 20 is added connecting nodes 1 and node 6. From this new link, it can be expected that more capacity as well as more route diversity will be produced.
- Similarly, by adding a new link labeled 21 and connecting it to nodes 4 and 10, it can be expected that more capacity and route diversity be added to supplement link 4, which is critical for reserve capacity, and link 5, which is critical for route diversity.
- The addition of a new link labeled 22 joining nodes 7 and 2 can also supplement link 14 and link 15 which are critical for route diversity and reserve capacity respectively.
- The addition of a new link 23 joining nodes 10 and 3 can add more routes to the network by supplementing link 14 and link 16 which are both critical for route diversity.

The link cost parameters along with link capacities for the of proposed link additions are presented in Table 4.9 and the link travel time function for these links are assumed to be given by the linear travel time function as given on Equation 4.2 for all other links. For real world networks, link travel times, and link capacities may depend on several factors. Topography of the area, length, and gradient of alignment, design speed, pavement quality, and right of way availability are a few to name.

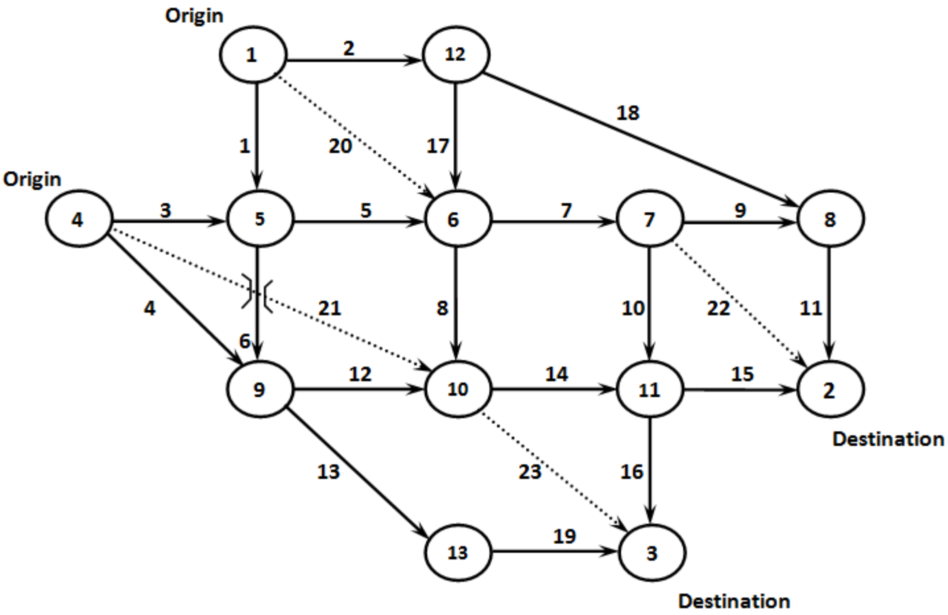

Figure 4.10 Addition of links to improve network redundancy.

Table 4.9 Link characteristics for proposed link additions.

Link		β_a	α_a	Link Capacity
1,6	20	0.0125	12	600
4,10	21	0.0125	21	400
7,2	22	0.0125	15	250
10,3	23	0.0125	15	400

In transportation planning process, projects for capacity expansions and new link additions are selected based on the needs to address the traffic demand and based on the availability of funds and other resources. Several alternatives may come into consideration and prioritization of projects out of the alternatives is based on the principle of benefit to the cost ratio maximization within the constraints of limited available resources. For this test network, all possible scenarios created by the addition of some or all of above-mentioned four links are analyzed to find out which option provides the highest benefits. The link additions can be carried out with any one, any two, any three, or all four of the proposed links at a time. Results of the analysis for all possible scenarios are given in Table 4.10 with link addition scenarios arranged in the descending order of equilibrium network performance (N-Q). Increase on route diversity due to the link addition is shown in Table 4.11. Similarly, a plot of reserve capacity, network route diversity, and network performance relative to the base network against different link addition scenarios are shown in Figure 4.11, Figure 4.12, and Figure 4.13 respectively. Analysis of results depict that the addition of all four links 21, 21, 22, and 23 at once results in the highest increment of performance. At the same time, network reserve capacity and network route diversity both attain a maximum value when these four links are added at once. Link addition scenarios in the descending order of increase of performance are shown in Table 4.10 but this order does not match with link order based on reserve capacity as shown in Figure 4.11. In some cases, addition of bypass links may even reduce the network reserve capacity. Adding bypass links that create new routes with relatively shorter travel time leads to the increased preference of users to choose the shorter routes resulting in early saturation of critical links in that route while capacity of longer routes may still remain under utilized. This results in the reduction of reserve capacity value for such networks in spite of link additions. Though reserve capacity decreases just because one or more links are saturated earlier, overall network performance may still improve by such additions.

In this network, we see that addition of links 20, 22, and 23 results in the lowering of reserve capacity value to 0.87 as opposed to a base network reserve capacity of 1.17.

Table 4.10 Network properties under different link addition scenarios.

Addition of Link #	Reserve Capacity	Network Route Diversity	Performance (N-Q)	Relative Performance (N-Q)
Base Network	1.17	4.60	10.00	1.00
20,21,22,23	1.34	8.47	10.97	1.10
20,21,23	1.23	7.70	10.85	1.08
20,21,22	1.18	6.87	10.79	1.08
20,22,23	0.87	7.99	10.77	1.08
20,21	1.25	6.10	10.64	1.06
20,22	0.80	6.49	10.60	1.06
20,23	1.22	7.23	10.58	1.06
21,22,23	1.20	6.83	10.50	1.05
21,23	1.17	6.35	10.42	1.04
20	1.25	5.72	10.39	1.04
21,22	1.18	5.58	10.36	1.04
22,23	1.07	6.35	10.29	1.03
21	1.15	4.99	10.26	1.03
22	0.98	5.19	10.17	1.02
23	1.18	5.76	10.15	1.01

Table 4.11 Route diversity: OD pair wise for different link addition combinations.

Removal of Link #	OD Pair 1-2			OD Pair 1-3			OD Pair 4-2			OD Pair 4-3			Total # of Routes on the Network	Network Route Diversity
	# of Routes Available	Strength	OD Route Diversity	# of Routes Available	Strength	OD Route Diversity	# of Routes Available	Strength	OD Route Diversity	# of Routes Available	Strength	OD Route Diversity		
20,21,22,23	14	0.78	10.97	12	0.78	9.31	7	0.80	5.58	11	0.80	8.80	44	8.47
20,21,22	14	0.78	10.97	8	0.77	6.12	7	0.80	5.58	7	0.79	5.56	36	6.87
20,22,23	14	0.78	10.97	12	0.78	9.31	6	0.77	4.62	9	0.77	6.92	41	7.99
21,22,23	10	0.77	7.70	9	0.76	6.83	7	0.80	5.58	11	0.80	8.80	37	6.83
20,21,23	11	0.77	8.43	12	0.78	9.31	6	0.78	4.71	11	0.80	8.80	40	7.70
20,21	11	0.77	8.43	8	0.77	6.12	6	0.78	4.71	7	0.79	5.56	32	6.10
20,22	14	0.78	10.97	8	0.77	6.12	6	0.77	4.62	6	0.77	4.60	34	6.49
20,23	11	0.77	8.43	12	0.78	9.31	5	0.75	3.75	9	0.77	6.92	37	7.23
21,22	10	0.77	7.70	6	0.75	4.52	7	0.80	5.58	7	0.79	5.56	30	5.58
21,23	10	0.77	7.70	9	0.76	6.83	6	0.77	4.62	9	0.77	6.92	34	6.35
22,23	10	0.77	7.70	9	0.76	6.83	6	0.77	4.62	9	0.77	6.92	34	6.35
20	11	0.77	8.43	8	0.77	6.12	5	0.75	3.75	6	0.77	4.60	30	5.72
21	8	0.76	6.04	6	0.75	4.52	6	0.78	4.71	7	0.79	5.56	27	4.99
22	10	0.77	7.70	6	0.75	4.52	6	0.77	4.62	6	0.77	4.60	28	5.19
23	8	0.76	6.04	9	0.76	6.83	5	0.75	3.75	9	0.77	6.92	31	5.76

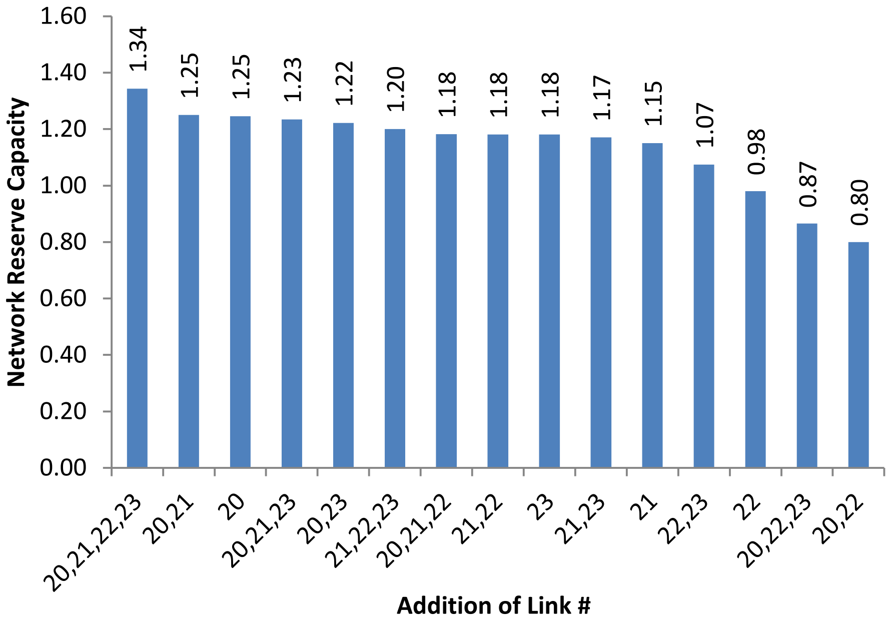

Figure 4.11 Network reserve capacity after link addition (descending order).

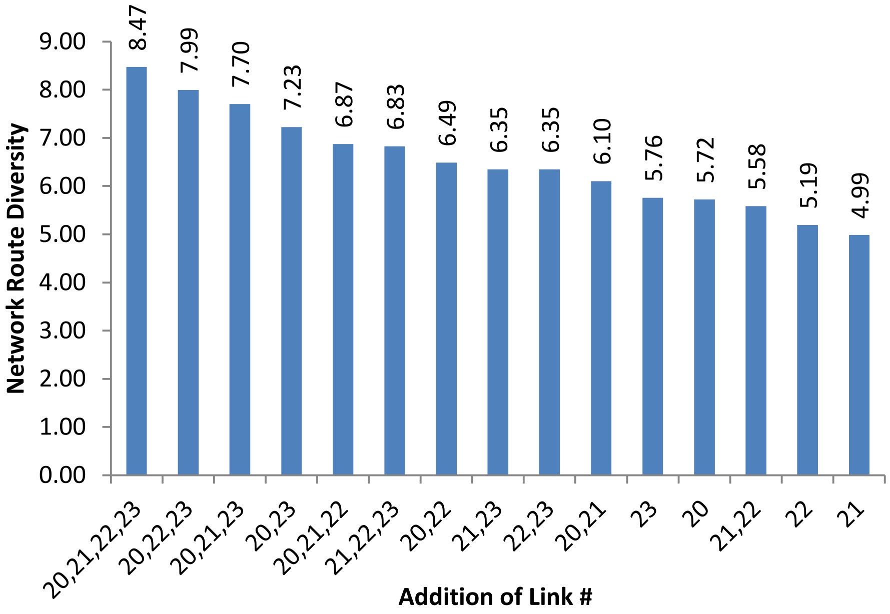

Figure 4.12 Network route diversity after link addition (descending order).

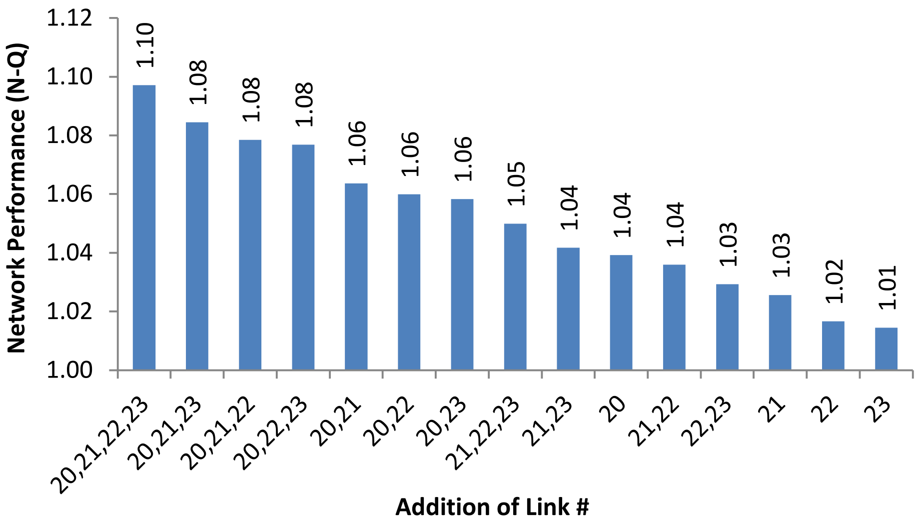

Figure 4.13 Relative network performance after link addition (descending order).

Despite this, the performance improves to 1.08 times the base network performance. In this case, the major affecting change is the addition of link 22 forming a new route consisting of links 3-5-7-22 for OD pair 4-2 that is shorter than all other routes except route with links 3-5-7-9-11. Both shorter routes pass through link 3. This link is also critical in capacity so it gets saturated earlier leading to the reduction in reserve capacity of the network. Saturation of some links and the underutilization of capacity of most other links of the network are not desirable for sustainable networks. If changes are made such that the network becomes more congruent to the demand pattern, then traffic is more evenly distributed over all links of the network and all links tend to saturate at once. Addition of links increasing the diversity of routes is desirable because this provides more number of alternative paths at least some of which may remain functional during disasters to ensure connectivity.

4.3.4 Analysis for a Bimodal Network

Transportation networks in the real world are complex network systems with interaction between different modes, which compete or complement one another. In this analysis, transit links on dedicated guide ways are added to the base network, from origin 1 to destination 3 and from origin 4 to destination 2 as shown in Figure 4.14. Providing a transit link on a dedicated guide way prevents any interaction between the auto and transit link. The addition of links 20, 21, 22, and 23 as shown on Figure 4.10 is also taken into consideration for this bimodal network analysis. All assumptions made in the Section 3.4.1.3 of Chapter 3 for bimodal network are assumed valid for this analysis.

Assumptions are made for the values of transit link travel time, constant parameter (θ), and auto preference factor (φ) which are shown in Table 4.12 below. Transit travel time of 50 units considered for both OD pairs 1-3 and 4-2 are higher than corresponding auto free flow travel times.

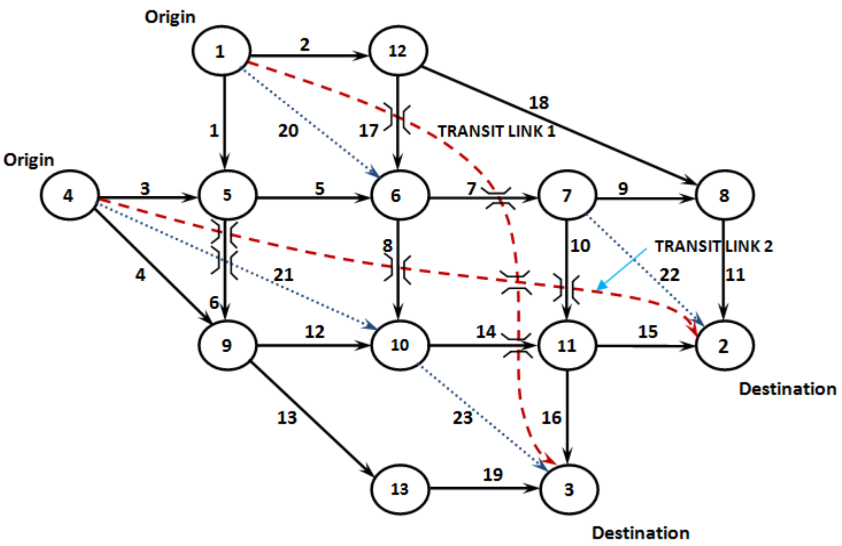

Figure 4.14 Addition of auto and transit links to the base network.

Table 4.12 Characteristics after transit links addition.

Transit Link#	Origin	Destination	Transit Travel time	Parameter (θ_{ij})	Auto Preference Factor (φ_{ij})
1	1	3	50	0.10	10
2	4	2	50	0.10	10

Assuming people are more inclined towards the auto mode, an auto preference factor of 10 is chosen for both OD pairs.

The network is now analyzed to find equilibrium flows for different scenarios. All scenarios as analyzed on Section 4.3.1, 4.3.2, and 4.3.3 for single link removals, link combination removals, and link combination additions to the base network respectively are considered again for analysis of the bimodal network. The total demand after the addition of transit links is assumed constant. This transfers some of the network load fully carried by the auto links in earlier scenarios to the new transit links. After the addition of transit links, users have option to choose both modes and routes. The values of transit link flows, network reserve capacity, and network performance for basic and combination link removals are shown in Table 4.13. Similarly, Table 4.14 displays calculated values of all those parameters for different combinations of link-additions. The purpose of the analysis is to show that networks with multiple mode choice are more redundant and under similar disruptions, networks with greater redundancy values can retain better performance.

Table 4.13 Properties of bimodal network under different link removals.

Removal of Link #	Transit Link 1 (O1-D3) Flow	Transit Link 2 (O1-D3) Flow	Auto Network Reserve Capacity	Performance (N-Q)	Relative Performance (N-Q)
Base Network	241	113	1.25	10.55	1.00
1	425	109	0.48	9.91	0.94
2	328	128	0.63	9.64	0.91
3	237	123	1.25	10.53	1.00
4	262	213	0.28	9.61	0.91
5	250	122	1.25	10.35	0.98
6	300	119	1.25	10.40	0.99
7	249	128	1.25	10.44	0.99
8	249	113	1.25	10.52	1.00
9	237	123	1.25	10.54	1.00
10	253	109	1.25	10.49	0.99
11	283	146	0.86	9.71	0.92
12	255	189	0.41	10.05	0.95
13	331	128	1.20	9.90	0.94
14	285	217	0.41	9.78	0.93
15	246	262	0.42	9.73	0.92
16	318	100	1.08	10.29	0.98
17	241	113	1.25	10.55	1.00
18	277	129	0.62	9.93	0.94
19	331	128	1.20	9.90	0.94
1,4	434	200	0.28	9.09	0.86
1,15	425	249	0.41	9.19	0.87
4,15	254	282	0.28	9.34	0.89
1,4,15	424	266	0.28	8.80	0.83
8,10	297	107	0.99	10.29	0.97
8,9	243	122	1.25	10.51	1.00
9,10	249	128	1.25	10.44	0.99
8,9.10	303	128	1.01	10.18	0.96
1,14	505	238	0.42	9.11	0.86
14,15	270	269	0.42	9.63	0.91
1,14,15	484	271	0.42	9.00	0.85
3,9	237	123	1.25	10.53	1.00
9,17	237	123	1.25	10.53	1.00
3,17	237	123	1.25	10.53	1.00
3,9,17	237	123	1.25	10.53	1.00
2,14	376	277	0.40	8.72	0.83
2,15	332	351	0.28	8.58	0.81
2,14,15	360	355	0.28	8.44	0.80
14,16	318	187	0.39	9.75	0.92
5,14	250	600	1.25	7.18	0.68
5,16	318	122	1.07	10.14	0.96
5,14,16	318	600	1.07	6.99	0.66
4,18	301	241	0.29	9.03	0.86
18,19	374	144	0.63	9.27	0.88
4,19	346	230	0.29	9.18	0.87
4,18,19	390	256	0.29	8.60	0.81

Table 4.14 Properties of bimodal network under different link additions.

Addition of Link #	Transit Link 1 (O1-D3) Flow	Transit Link 2 (O1-D3) Flow	Auto Network Reserve Capacity	Performance (N-Q)	Relative Performance (N-Q)
Base Network	241	113	1.25	10.55	1.00
20,21,22,23	181	87	1.41	11.32	1.07
20,21,22	196	88	1.31	11.20	1.06
20,22,23	180	98	1.16	11.14	1.06
21,22,23	230	87	1.30	10.95	1.04
20,21,23	175	94	1.40	11.19	1.06
20,21	192	95	1.42	11.04	1.05
20,22	195	99	1.05	11.02	1.04
20,23	174	109	1.31	10.96	1.04
21,22	244	88	1.29	10.87	1.03
21,23	225	95	1.25	10.87	1.03
22,23	232	99	1.25	10.77	1.02
20	190	111	1.32	10.83	1.03
21	239	96	1.25	10.78	1.02
22	244	100	1.16	10.70	1.01
23	227	112	1.25	10.64	1.01

A comparison of relative performances between the bimodal and auto only forms of the test network is presented graphically in Figure 4.15, Figure 4.16, and Figure 4.17 respectively. This comparison uncovered some important information that is described below.

- Both the reserve capacity and performance for the bimodal base network is found to be higher than the base auto network. Reserve capacity of bimodal network for the base case is 1.25 but is 1.17 for auto network. Similarly, N-Q performance for bimodal network is 10.55 whereas for unimodal it is 10.00. This is because transit links attract some demand out of the total demand and reduce the load of the auto network creating a less dense flow on the auto network. This improves both the reserve capacity and the performance of the network.

- For all link removal scenarios, comparison of relative performance of the bimodal network with respect to the bimodal base case to that of the unimodal network with respect to the unimodal base case shows that the bimodal network suffers lesser loss in relative performance. The retention of relative performance is found to be more for the more important links or link combinations compared to less important links or link combinations. This leads to a general conclusion that a bimodal network can perform better even when important network components fail to function. This is an important property desired for resilient networks.
- For all link addition scenarios, the comparison of the relative performance of the bimodal network to the relative performance of the auto only network shows that there is an increase in relative performance for each link combination addition for both networks. However, an increase in the relative performance for each link combination addition is lesser for the bimodal network. From this, it is concluded that bimodal networks are more stable in terms of performance for both disruption and enhancement scenarios. More stability in performance helps to increase the resilience so multimodality is a desirable quality for higher resilience of the networks.

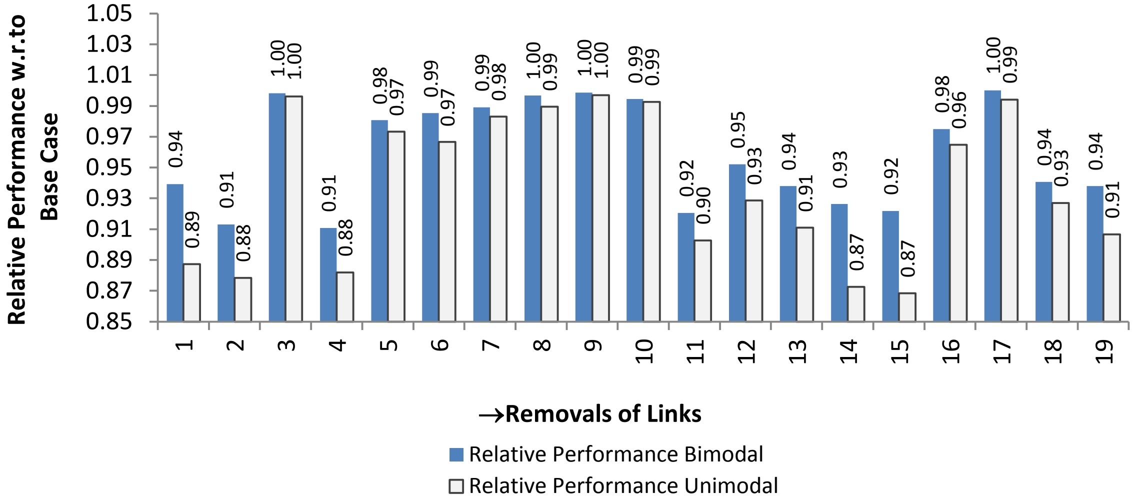

Figure 4.15 Network relative performance comparison 1: Bimodal and unimodal network for basic link removals.

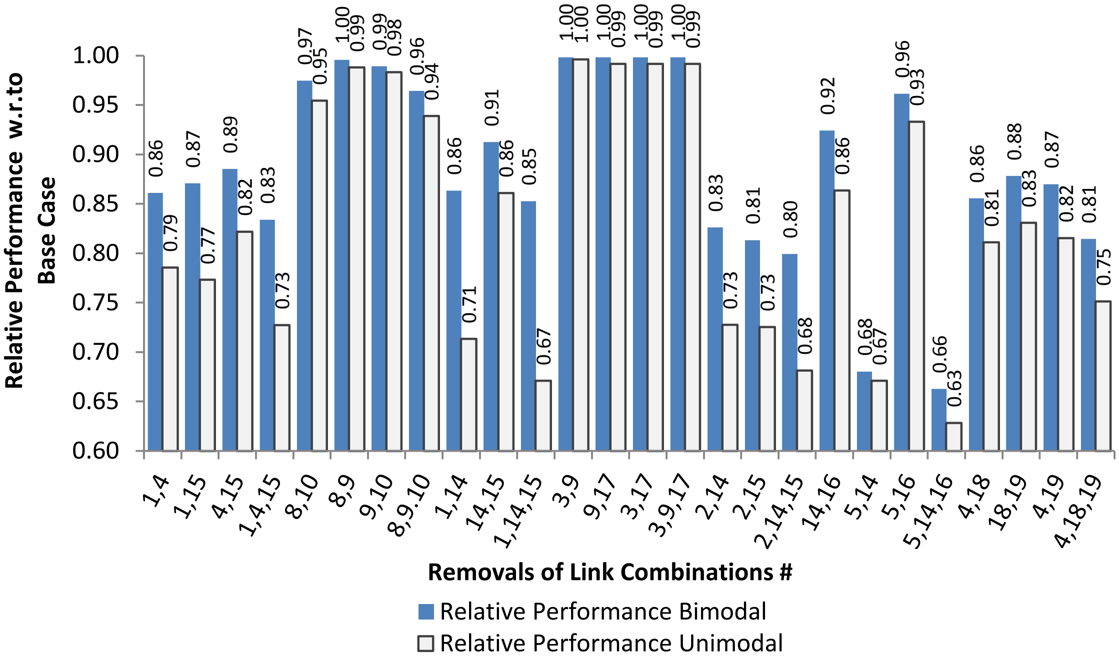

Figure 4.16 Network relative performance comparison 2: Bimodal and unimodal network for link removal combinations.

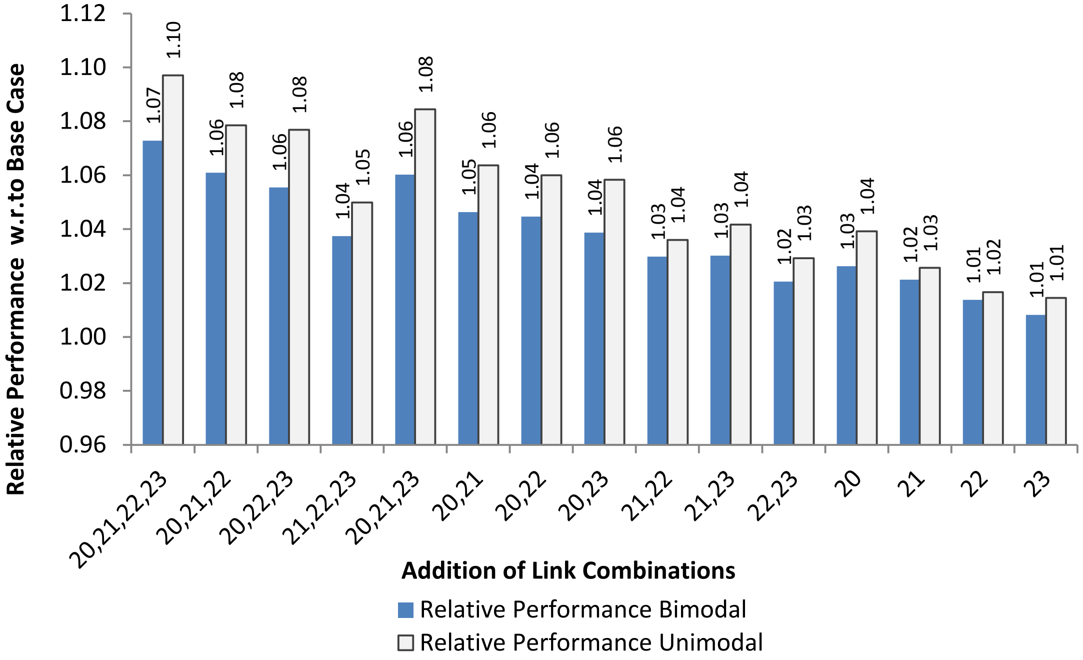

Figure 4.17 Network relative performance comparison 3: Bimodal and unimodal network for different link addition combinations.

4.3.5 An Example of Network Resiliency Evaluation

An example in which a set of links are removed from the test network by some disaster is considered in this section and different possible recovery scenarios are analyzed in an attempt to illustrate the concept of transportation network resilience using the concept of resilience triangle. Consider the removal of an important combination of links 1, 14, and 15 from the base auto network and bimodal base network. As seen from Table 4.7, the performance of an auto network at post-disaster equilibrium after the removal of the above mentioned link combination is 0.67 times the base network performance. Similarly, from Table 4.13 the bimodal network performance at equilibrium after link removal is 0.85 times the original bimodal network performance at base conditions. It has already been shown that the equilibrium network performance of a bimodal network for the base condition itself is higher than the performance at the base condition of an auto only network. Networks, able to maintain higher level of network performance in disrupted states are called robust networks in terms of performance. Depending upon the resource and technology availability, and maintenance prioritization and schedule management, the links can be restored to functionality within a scheduled period in different ways. Assuming the total period allowed for completing the recovery process is constant, different priorities are analyzed within a single period. This assumption is made also assuming that the total time within which recovery is to complete is 1 unit long. Three possible combinations are assumed including recovering a single link at a time with each link taking one third of total time, recovering two links on the first half and the third link on the second half time, recovering all three links at once taking a full period for each link. All possible scenarios each with the order and combination of links with equilibrium performances at different stages of time are enumerated in Table 4.15 and Table 4.16 for the auto network and bimodal network respectively. As listed on the tables, there are six possible combinations for recovery by restoring one link at a time, three possible combinations for recovery by restoring two links at a time, and only one combination for recovery by restoring all three links at a time. Once the restoration of a link/links takes place, performance is assumed to increase up to a new equilibrium level. Assuming the performance of the network at base case is 1, relative performance at all subsequent stages can be calculated. A plot of this performance against time is in form of the resilience triangle. Resilience triangles for all scenarios are presented in Figure 4.18 to Figure 4.27, respectively, in the ascending order of the number of scenarios. For the resilience-triangles, both performance and time are on the scale of 1 indicating that the area of the resilience triangle would be 1 if the network were completely nonfunctional.

Additionally, the area would be zero if there were no effect at all in the performance even after disruption in the network. Assuming the resilience is 0 for a completely nonfunctional case and 1 for full functionality even after disruptions caused by disaster; resilience can be numerically calculated by the area of the polygon under the resilience triangle and above the time axis.

Table 4.15 Recovery scenarios for auto network after removal of links 1, 14, and 15.

Alternate Scenario#	Link# Recovered in the Time			Relative Performance for Auto Network				
	First One Third	Second One Third	Last One Third	Before Disaster	Beginning of First One Third	Beginning of Second One Third	Beginning of Last One Third	End of last One Third
1	1	14	15	1	0.67	0.86	0.87	1
2	1	15	14	1	0.67	0.86	0.87	1
3	14	1	15	1	0.67	0.77	0.87	1
4	14	15	1	1	0.67	0.77	0.89	1
5	15	14	1	1	0.67	0.71	0.89	1
6	15	1	14	1	0.67	0.71	0.87	1

Alternate Scenario#	Link# Recovered in the Time		Relative Performance for Auto Network			
	First Half	Second Half	Before Disaster	Beginning of First Half	Beginning of Second Half	End of Second Half
7	1,14	15	1	0.67	0.87	1
8	1,15	14	1	0.67	0.87	1
9	14,15	1	1	0.67	0.89	1

Alternate Scenario#	Link# Recovered in the Time	Relative Performance for Auto Network		
	During Full Time	Before Disaster	During Full Time	After Full Time
10	1,14,15	1	0.67	1

For each of the recovery scenarios discussed above, network resilience is computed using the area of the polygon and the values of resilience computed are shown in Table 4.17

Results show that for the auto only network, resilience is highest for recovery scenario 9 with value of 0.861. Similarly, if transit links are added to this network as discussed on Section 4.3.4, then resilience increases and the maximum value of resilience is 0.933 for the recovery scenario 9.

Table 4.16 Recovery scenarios for bimodal network after removal of links 1, 14, and 15.

Alternate Scenario#	Link# Recovered in the Time			Relative Performance for Bimodal Network				
	First One Third	Second One Third	Last One Third	Before Disaster	Beginning of First One Third	Beginning of Second One Third	Beginning of Last One Third	End of last One Third
1	1	14	15	1	0.85	0.91	0.92	1
2	1	15	14	1	0.85	0.91	0.93	1
3	14	1	15	1	0.85	0.87	0.92	1
4	14	15	1	1	0.85	0.87	0.94	1
5	15	14	1	1	0.85	0.86	0.94	1
6	15	1	14	1	0.85	0.86	0.93	1

Alternate Scenario#	Link# Recovered in the Time		Relative Performance for Bimodal Network			
	First Half	Second Half	Before Disaster	Beginning of First Half	Beginning of Second Half	End of Second Half
7	1,14	15	1	0.85	0.92	1
8	1,15	14	1	0.85	0.93	1
9	14,15	1	1	0.85	0.94	1

Alternate Scenario#	Link# Recovered in the Time	Relative Performance for Bimodal Network		
	During Full Time	Before Disaster	During Full Time	After Full Time
10	1,14,15	1	0.85	1

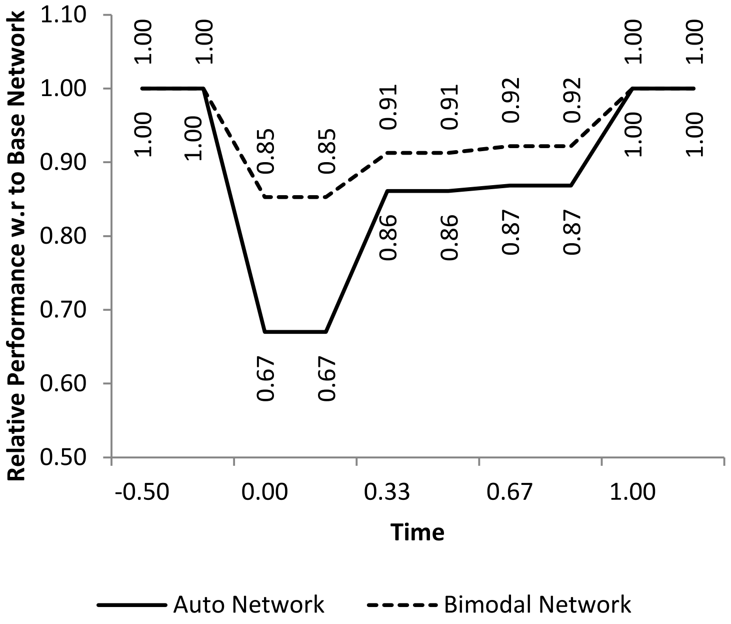

Figure 4.18 Resilience triangle for recovery scenario 1.

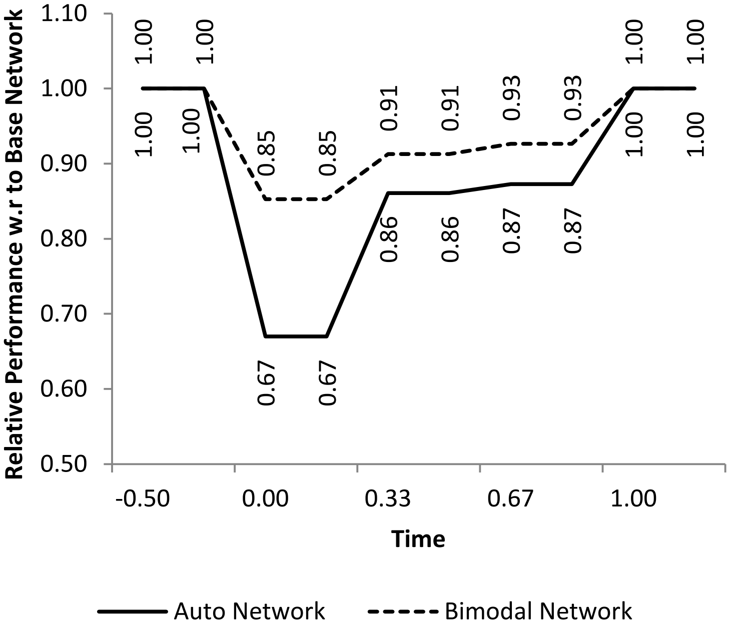

Figure 4.19 Resilience triangle for recovery scenario 2.

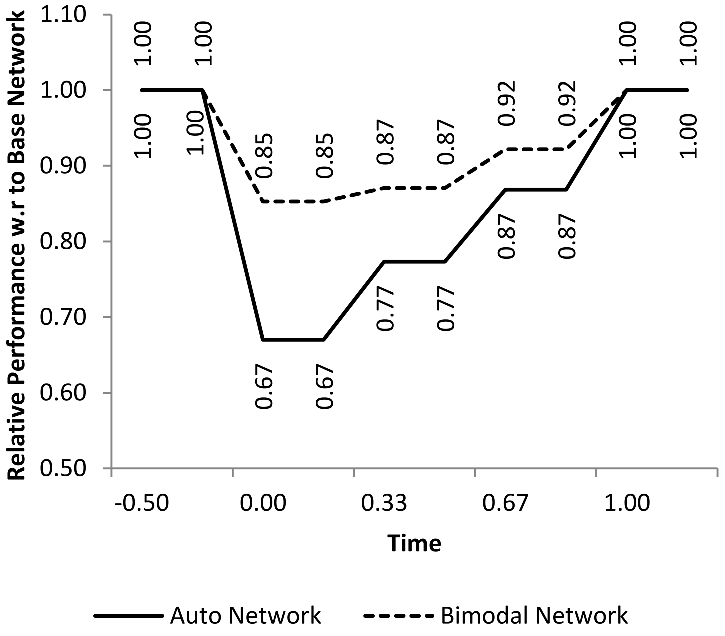

Figure 4.20 Resilience triangle for recovery scenario 3.

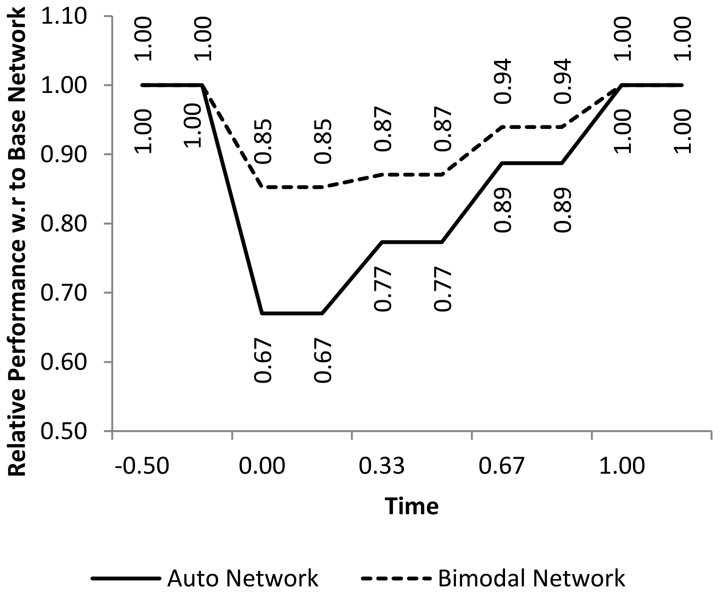

Figure 4.21 Resilience triangle for recovery scenario 4.

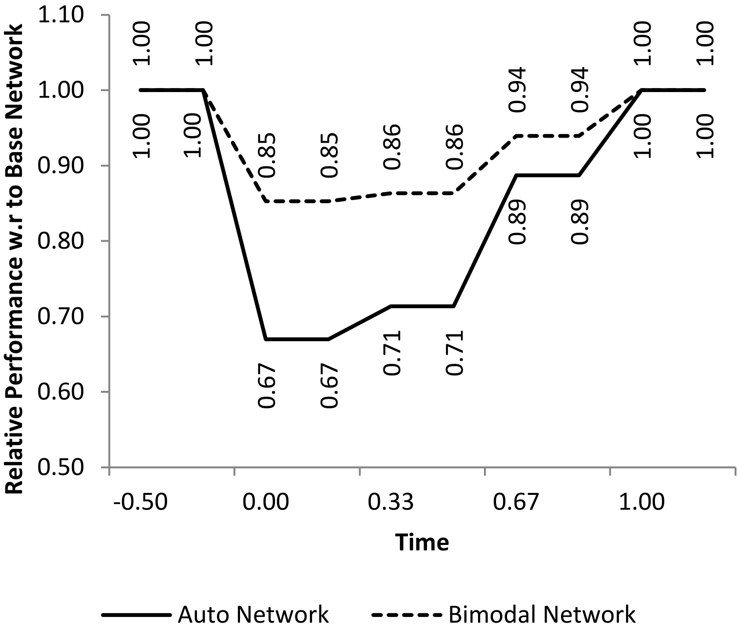

Figure 4.22 Resilience triangle for recovery scenario 5.

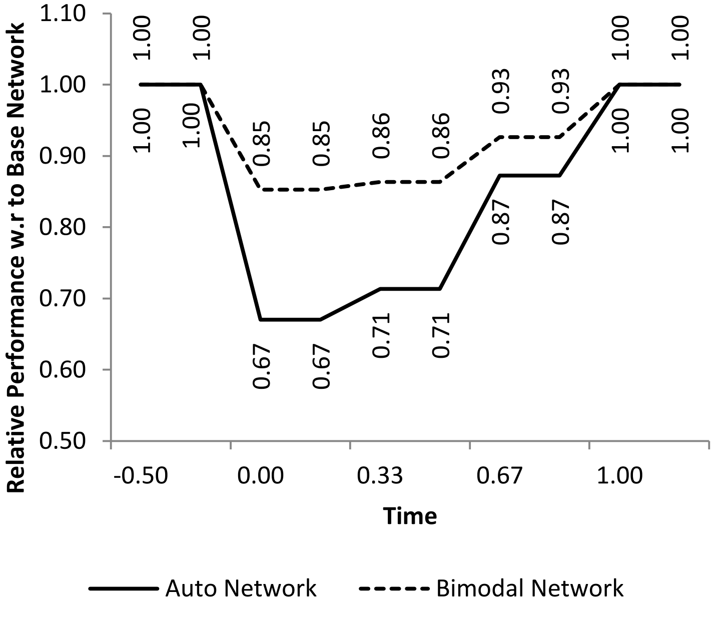

Figure 4.23 Resilience triangle for recovery scenario 6.

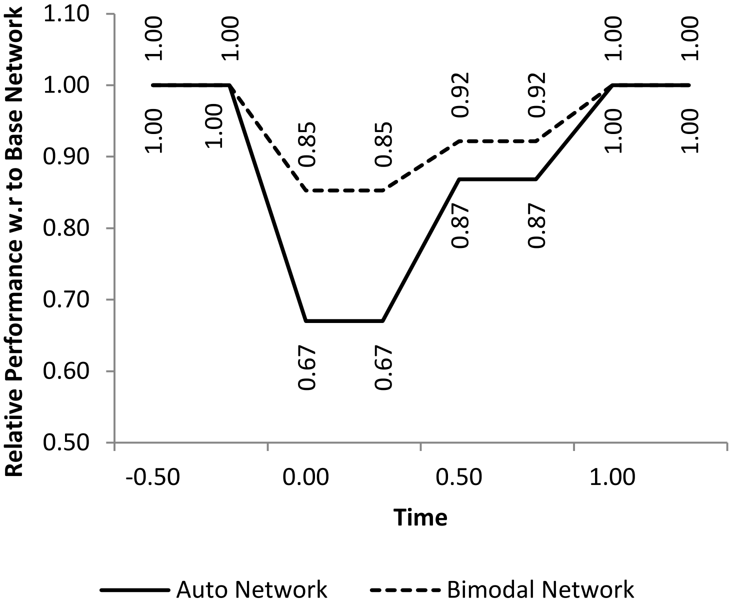

Figure 4.24 Resilience triangle for recovery scenario 7.

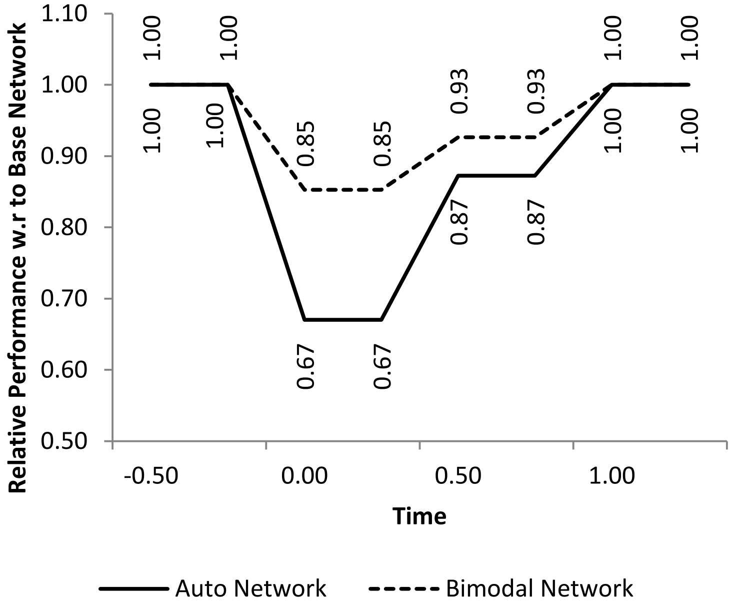

Figure 4.25 Resilience triangle for recovery scenario 8.

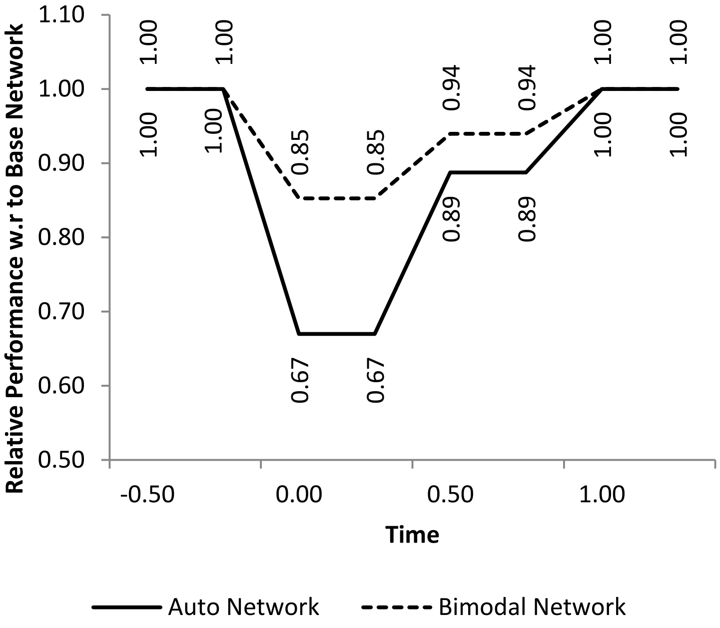

Figure 4.26 Resilience triangle for recovery scenario 9.

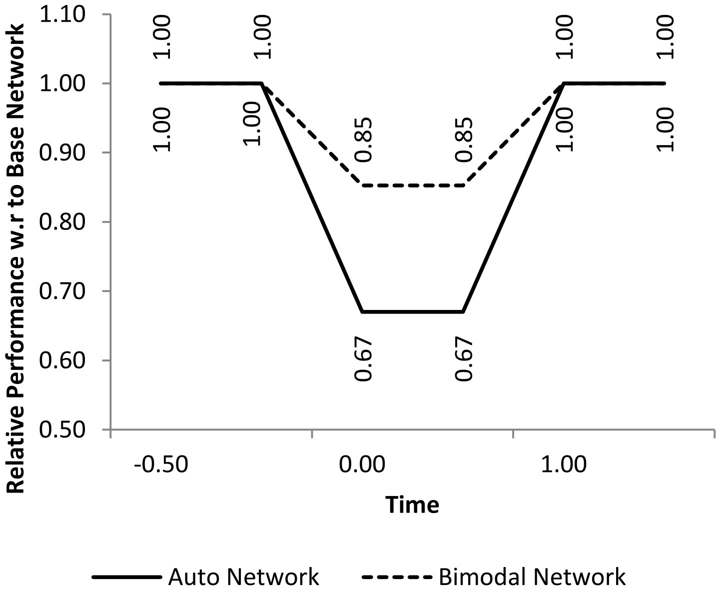

Figure 4.27 Resilience triangle for recovery scenario 10.

Table 4.17 Resilience of the test network under recovery scenarios.

Scenario#	1	2	3	4	5	6	7	8	9	10
Resilience of Auto Network	0.855	0.856	0.826	0.832	0.812	0.807	0.852	0.854	**0.861**	0.835
Resilience of Bimodal Network	0.920	0.922	0.906	0.912	0.910	0.905	0.924	0.926	**0.933**	0.926

Higher value of resilience after adding transit links to the auto network shows that mode choice is an important measure of redundancy and bimodal networks are more resilient than auto only networks. This result is only specific to the considered test network under the given assumptions. If the transit travel time, transit capacity, transit preference factors, and characteristics of auto network are simultaneously changed to different levels, we will get different results. In spite of that, it is a fact that availability of functional transit service adds option of mode choice and adds more ability into the network to resist the shocks created by disasters. Analysis in this particular case showed the effect of transit link additions to the network is more beneficial in terms of achieving higher resilience. Stating in the reverse way, removal of transit links form a network due to some disasters have detrimental effect over the network performance and results in the reduction of network resilience.

This implies that transit links are more important components requiring extra protection against potential disruptions in the network. Transit service usually has lesser flexibility in terms of route choice so the effect of disruptions at some specific points of the links only may also be enough to shut down the service completely. This necessitates more protection to the transit links than auto links. Resilience can be better achieved in the realistic networks if we can protect more the more critical network components like transit links and more important auto links from undergoing any losses and the losses if any need to be repaired faster with the highest priority.

This calculation also depicts the role of availability of resources as well as role of resource prioritization and recovery work-schedule management in the process of recovery. Better availability of resource enables to conduct recovery works more rapidly, which minimizes the duration for which network must remain in the disrupted state of performance. In the above example, we choose the recovery period to be 1 unit on some appropriate scale. Depending upon the level of resource availability, the length of recovery period may vary. The more there are resources, the shorter the length of this period can be. On the other hand, within the constraints of limited available resources, a good project prioritization and schedule management can optimize the performance and thus minimize the total loss in performance, which increases resilience of the networks.

CHAPTER 5

CONCLUSION AND FUTURE INVESTIGATIONS

5.1 Conclusion

Resilience has been studied in the field of transportation engineering but many of the research to date builds a conceptual framework of resilience using descriptive means, rather than using widely accepted quantitative measuring techniques. Some quantitative methods rely on soft computing techniques and the output of the analysis for a network varies upon the discretion of the analyzer. Some quantitative techniques focus on specific components of transportation resilience such as robustness and redundancy separately. This research supports the definition of resilience proposed by Heaslip et al. (2009) which defines resilience as “the ability of the system to maintain its demonstrated level of service or to restore itself to that level of service in a specified time frame.” In this research, resilience of test network was measured by evaluating the total loss on a network based on the changes in the values of widely accepted performance measures. Assuming more robust networks such as auto-transit network in this specific can retain better performance after disruptions and the rate of flow of resources into the network following optimized recovery paths enable the network to attain faster recovery speed, it has been shown through examples that a good robustness in terms of performance and optimized recovery process helps to minimize the overall loss in network performance and enhance the network resilience. This research also assumes that better measures of redundancy provide higher robustness in terms of performance that in turn provides the ability to undergo faster self-annealing and higher performance retention after disasters.

The analysis method used in this research is derived from traffic assignment techniques and is based on the equilibrium analysis of transportation networks. Both of these are accepted concepts in network science and provide results independent of analyzer discretion.

Though the results shown in this thesis are specific to the test network chosen, the techniques described in this thesis are useful for making a detailed analysis of network enhancement as well as repair and replacement strategies with respect to specific properties such as reserve capacity, route diversity, and network performance or all at once. The results of analysis for the existing networks and disruption scenarios can help to measure the preparedness of existing networks to the potential disasters. This may help in making decisions to provide extra security to the relatively more important components of the network, which may help to minimize the debilitating effects of potential future disasters. Analysis of different types of network improvement scenarios can help to perform benefit cost analysis of improvement projects and help in the prioritization of such projects. The overall network resilience can be maximized with the help of such analyses.

5.2 Future Investigations

Methods illustrated in this research are provided only at the basic level. Improvements in the approach defined through this work can be made to enable it to address more aspects stemming from the complex nature of transportation networks in the real world. The following details in the bullets provide topics for future investigation:

- The calculation of route diversity takes into account the overlap of links between routes within an OD pair number wise only but does not take into account the relative length of overlapped links compared to non-overlapped links. This method also does not address the effect of link sharing between paths of different OD pairs. The method in this thesis may be improved to address these facts also.
- Reserve capacity, route diversity, and modal choice are measures of redundancy discussed separately in this work. A single unified measure of redundancy which combines all these measures into a single measure is needed for better analyzing response of networks against disruptions or improvements.
- Measures of resourcefulness that can be used to determine the rapidity of recovery process and total time for the recovery process need to be developed.
- Network performance discussed in this research is a measure of performance at equilibrium. The instance that a disruption occurs, the network is no longer in a state of equilibrium. In order to predict the actual performance at that point, methods need to be developed to determine non-equilibrium performance. Additionally, methods to determine the time it takes to bring disrupted networks to a new equilibrium need to be defined.
- Demand considered in this research is fixed and independent of network capacity. Development of a method of resilience analysis for variable demand is needed where demand is a function of network capacity.

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