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Transportation Network Resiliency: A Fuzzy Systems Approach

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TRANSPORTATION NETWORK RESILIENCY: A FUZZY SYSTEMS APPROACH

by

Nayel Urena Serulle

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

of

MASTER OF SCIENCE

in

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Approved:

Kevin Heaslip Major Professor	Anthony Chen Committee Member
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ABSTRACT

Transportation Network Resiliency: A Fuzzy Systems Approach

by

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Utah State University, 2010

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Department: Civil and Environmental Engineering

Every day the dependence on transportation grows as local, regional, national, and international independence increases. Resilient transportation systems are needed to secure the highest possible level of service during disruptive events, including natural and man-made disasters. Because of limited resources, decision makers need guidance on how, when, and where to invest to improve resiliency of their networks. The research objective is to develop a method to assess and quantify resiliency, at pre-event conditions, using a fuzzy inference approach. This research expands previous work, refining key variable definitions, adjusting model interactions, and increasing transparency between metrics. This thesis presents the method and provides an illustrative example of the methodology using the Dominican Republic as a case study. The example explains how a transportation network responds to a disruptive event and how specific investments can increase resiliency of the network. The result of this research is a quantitative basis for decision makers to conduct cost-benefit analysis of resiliency increasing projects.

(106 pages)

DEDICATION

This thesis is dedicated to my mother, Aida, for her unconditional love and support. To my father, Ramón, for being an example of what dedication and hard work can accomplish. To my little sister, Carmen Rosa, who always saw me as a role model, inspiring me to be the best person and professional that I can be. To my remaining brothers (Juan, Angel, and Enmanuel) and sisters (Diana and Marlenny), whom I deeply love. To my uncle “Rafaelito,” for being a role model and showing me the magnificence of civil engineering. To Marie Claire, for always being there for me, providing love, support, and motivation. Finally, to all my family and friends that have motivated, supported, and believed in me throughout my life. I will be eternally grateful for having all of them; I love you all.

Nayel Urena Serulle

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Nayel Urena Serulle

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CHAPTER 1

INTRODUCTION

Dependence on transportation grows each day as local, regional, national and international societal interactions and economic activities become more fully integrated. The ability for the transportation system to perform under adverse conditions and recover to acceptable levels of service is fundamental to the viability of society. This notion is true for a region such as the United States with more over 4,000,000 roadway miles (USDOT, 2008); or a smaller system such as the Dominican Republic, with approximately 20,000 roadway miles (CIA, 2010).

The United States is the largest greenhouse gas emitter worldwide, with transportation accounting for one third of the US's carbon dioxide emissions. The impact of transportation on worldwide climate is significant, leading to observable changes such as: variations on rainfall patterns, the rising of sea levels, and increase in the intensity and frequency of extreme weather events (Oswald, 2009). In 2005, Hurricane Katrina illustrated the impact of climate-driven events on transportation system performance during, immediately following, and long after a disaster event. Fragility was revealed as evacuation and recovery efforts were limited by the transportation system. The aftermath of Katrina spawned research efforts on the nature of the breakdown and recovery. Work in this field led to the formalization of a definition of the service breakdown and restoration phenomena. In this regard, transportation resiliency was defined as "the ability for the system to maintain its demonstrated level of service or to restore itself to that level of service in specified timeframe" (Heaslip et al., 2009).

Prior research is valuable in setting a basis for assessing resiliency. However, it lacks specificity in measures and quantitative values needed to provide quality information to those faced with transportation investment decisions. The objective of this research is to extend prior investigations (e.g. Heaslip et. al., 2009, 2010) and to propose a more clear and detailed methodology for sketch-level assessment of resiliency at pre-event condition. This objective will provide decision makers with a quantitative basis for their analysis. This research will provide decision makers with a robust but intuitive methodology to conduct 'what-if' analyses on alternative projects. The methodology employs a fuzzy inference approach that recognizes that available data is ambiguous and incomplete. The approach identifies currently defined transportation measures and sketch-level assessments that can be made by local and regional experts. The method provides the decision makers with insight into the magnitude of performance degradation and sensitivity to various input variables. This helps identify points of weakness, supporting development of a rank ordered mitigation strategy.

1.1 Research Question

The central question this research revolves around is: *"How can transportation resiliency be quantified on a regional level?"* The ability to answer this question will enhance decision makers' ability to make informed decisions regarding the prioritization of projects that enhance resiliency and enable recovery. A variety of methodologies currently exist that help decision makers quantify risks, locate vulnerabilities within a system, and create and evaluate evacuation plans. The limitations of these methodologies are that most analyses do not take into consideration the resilience of the entire system. In this matter, it is assumed that funds are limited and it is necessary to choose between projects. Thus, decision makers need guidance in how, when, and where to invest funds in order to improve their network's resiliency and, as a consequence, make the network less vulnerable to the increasing threats, such as climate change and man-made disasters.

1.2 Research Problem and General Approach

Currently, there is difficulty determining a network's level of resiliency because of a lack of measures of effectiveness needed to explain the effect that transportation has over a region's economy and society. Additionally, human behavior and perception are a very important metrics of resiliency, making modeling a challenging endeavor. Furthermore, data at the network level is not easily obtained, hence proxy measurements need to be suggested and/or developed.

The methodology detailed in this report employs a fuzzy inference approach based on its flexibility and ability to embrace the data ambiguity and incompleteness. The approach defines the variables in an empirical manner, using expert knowledge to inform the model. The fuzzy numbers-based approach allows the method to progressively respond to an increasing data quality environment by gradually raising the 'fineness' of the fuzzy numbers used in the inference engine.

1.3 Major Research Theories

The conceptual basis for the methodology presented in this research draws on the concepts of a "resiliency cycle" and a "transportation system performance hierarchy." Each region and locality will have a different characteristic degradation and response profile. For this research, all regions will be evaluated within the construct of a “resiliency cycle”. In addition, the proposed methodology for measurement of network resiliency is based upon the notion that the degrees of transportation system performance can be stratified.

1.4 Past Research

The research in this thesis is an extension of Heaslip et al.’s (2009 and 2010) research work on transportation network resiliency. Their work generated a compilation of previous research in different fields of knowledge, especially in civil engineering, and created the base for the conceptual framework used in this research. Correspondingly, Heaslip et al.’s work is a continuation of past studies performed by Murray-Tuite (2006), focused on capacity flexibility measuring only a sub-group of variables based on the fact that no accurate metric exists for the non-selected variables. Congruently, Murray-Tuite’s investigation was based on the previous compilation of variables related to resiliency created by Godschalk (2003). More information about past researches can be found in the literature review compiled in Chapter 2.

1.5 Anticipated Contribution

This proposed research would contribute to the state of the knowledge of transportation resilience by providing both a clear and detailed conceptual framework, based on the hierarchy of transportation network performance and resiliency cycle, and a more lucid methodology on the measurement of the metrics needed in order to quantify resiliency at a pre-event state. This research would help obtain an accurate value of resilience, based on a combination of quantitative and qualitative variables. A fuzzy inference approach will provide a new perspective of transportation network resilience measurement process by taking under consideration the ambiguity that the human interaction with the transportation network contributes to the measurement of resiliency. Finally, from the analysis of resiliency under normal conditions, an assessment on projects alternative can be made, taking into consideration the networks characteristics that poorly contributes to the networks ability to overcome disaster events.

CHAPTER 2

LITERATURE REVIEW

2.1 Defining Resilience

The concept of resilience is broadly applied throughout the different fields of study (e.g., engineering, psychology, sociology, and economics). The definition also can be associated to similar concepts like flexibility, redundancy, reliability, elasticity, and risk management. In economics, the term resilience is related to the ability to recover quickly from a shock (shock-counteraction), to withstand the effect of a shock (shock-absorption), and to avoid the shock altogether (vulnerability) (Briguglio et al., 2005). In social science, resilience can be defined as the capacity of a system 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, researchers have defined seismic resilience, particularly, 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 reduce the effects of future earthquakes (Bruneau et al., 2003). Community seismic resilience can be acknowledged as the capacity to absorb stress, manage it and recover from it (RTF-URR, 2008). As a more general definition, resilience can be defined as the capacity to absorb shocks gracefully (Foster, 1993).

The concept of resilience has been studied in the field of transportation engineering as well. Conceptual frameworks have been created in order to define and “measure” resilience within the area of transportation. Transportation resilience can be defined in different ways:

- 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., 2009).
- 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).
- A system’s ability to accommodate variable and unexpected conditions without catastrophic failure (VTPI, 2008 A).
- The ability for the system to absorb the consequences of disruptions to reduce the impacts of disruptions and maintain freight mobility (Ta et al., 2009).

2.2 Measuring Resilience

As stated previously, the concept of resilience is consistently applied in research of different disciplines. Methods to measure resiliency, either in a quantitative or qualitative manner, can be found across disciplines. In this section, a variety of conceptual frameworks presented in the literature are summarized and associated with the ongoing investigation of transportation network resilience.

2.2.1 Conceptual Frameworks

Bruneau et al. (2003) researched resilience in the area of community seismic resilience. The research provided a conceptual framework to define the seismic resilience of communities and quantitative measures of resilience that can be useful for a coordinated research effort focusing on enhancing this resilience. Earthquakes have been given high priority in efforts to enhance community disaster resistance because of their potential to produce extensive losses and community disruption. The authors focused on the need to move beyond qualitative conceptualizations of disaster resilience to more quantitative measures, both to better understand factors contributing to resilience and to assess, more systematically, the potential contributions and benefits of various research activities. The researchers supported this statement by explaining how returning to 100% pre-event levels may not be sufficient in many instances, particularly in communities where the existing seismic resiliency is low, and how post-event recovery to more than 100% pre-event levels are often desirable. Therefore, specific metrics are needed to objectively assist decision makers about where, when and how to invest. The conceptual framework proposed by Bruneau et al. is built upon two sets of resilience dimensions, the four R’s (robustness, redundancy, resourcefulness, and rapidity) and TOSE (technical, organizational, societal, and economic). The authors implemented these sets in a series of scenarios and found that well-defined and consistently applied quantifiable measures of resilience permit carrying out various kinds of comparative studies to determine why some systems are more resilient than others, and to assess changes in system resilience over time (e.g., to assess the effectiveness of various loss-reduction measures, such as structural and nonstructural retrofit systems).

In a briefing paper prepared for the National Surface Transportation Policy and Revenue Study Commission, Battelle (2007) stated that “resiliency… enables the system to compensate for losses and allows the system to function even when infrastructure is damaged or destroyed.” The research focused on the importance of redundancy in the case of a network’s disruption or in its normal usage condition. Battelle pointed out the existence of vulnerabilities within a network (e.g., chokepoints) and suggested action steps for those chokepoints. Battelle explains that redundancy must be measured as a whole, considering the entire network, in order to fully obtain all the information needed, such as excess capacity, intermodality, vulnerabilities, and variations due to the stochastic behavior of the network’s users and the effects of state of the art network management techniques.

Murray-Tuite (2006) conducted a thorough compilation of different transportation resiliency dimensions (variables) based on previous research in the area. Her research established ten dimensions that characterize transportation resiliency: redundancy, diversity, efficiency, autonomous components, strength, collaboration, adaptability, mobility, safety, and the ability to recover quickly. Murray-Tuite examined the influence of the ‘system optimal’ and ‘user equilibrium’ traffic assignments on the last four dimensions. The limitations on this research were caused by the lack of widely accepted measurement of resilience for transportation systems at the time, although it should be noticed that these limitations are still present. Murray-Tuite found that user equilibrium results in better adaptability and safety, while system optimum yields better mobility and faster recovery. The key point of Murray-Tuite's research is the compilation of resiliency dimensions and the idea of assigning quantitative metrics to them. This broadens the concept of transportation resiliency and helps identify the characteristics that should be investigated in the future.

The Victoria Transport Policy Institute (VTPI, 2008 B) described the concepts of "basic access" and "basic mobility" by making reference to transport activities that are considered socially beneficial. They defined "basic access" as "people's ability to access goods, services and activities that society considers particularly important (also called essential or lifeline)," whereas "basic mobility" is explained as "the physical travel that provides basic access." The VTPI paper shows that as a community becomes more automobile-dependent, an increasing portion requires motorized travel (e.g., public transit, private vehicles, etc.). VTPI also states that no universal standard exists for determining exactly the basic transportation activities or level of accessibility, and they will tend to vary depending on geographic, demographic and social factors. In addition, the paper suggests an alternative to measure accessibility and mobility. It explains how these concepts can be defined by land use patterns and transport options (mode choices).

In the same manner, Litman (2008) explains with more detail the concepts of accessibility and mobility. Moreover, he discusses transportation planning techniques and characteristics that directly influence accessibility, such as demand, level of service and user information (see Table 2.1). These characteristics, combined with the set of variables presented by Murray-Tuite, are transformed into the initial phase of resiliency variables of the present research, since they embrace all the basic notions that are assumed to affect resiliency.

Table 2.1 Factors Affecting Accessibility (Litman, 2008).

Name	Description
Transport Demand	The amount of mobility and access that people and businessses would choose under various conditions (times, prices, level of service, etc).
Mobility	The distance and speed of travel, including personal mobility (measured as person-mile) and vehicle mobility (measured as vehicle-mile).
Tranportation Option	The quantity and quality of access options, including walking, cycling, ridersharing, transit, taxi, delivery services, and telecommunications. Qualitative factors include their availability, speed, frequency, convenience, comfort, safety, price and restige.
User Information	The quality (convenience and reliablity) of information available to users on their mobility and accessibility options.
Integration	The degree of integration among transport system links and modes, including terminals and parking facilities.
Afordability	The cost to users of transport and location options relative to incomes.
Mobility Substitutes	The quality of telecommunications and delivery services that substitute for physical travel.
Land Use Factors	Degree that factors such as land use density and mix affect accessibility.
Transport Network Connectivity	The density of connections between roads and paths, and therefore the directness by which people can travel between destinations.
Roadway Design and Management	How road design and managemente practices affect vehicle traffic, mobility and accessibility.
Prioritization	Various strategies that increase transport system efficiency.
Inaccessibility	The value of inaccessibility and external costs of increased mobility.

Heaslip et al. (2009) researched how to measure transportation resiliency at a regional level. Their paper presented the importance of transportation systems in response and recovery strategies, and the importance of the presence of resiliency in the system. One of their main contributions was the presentation of a formal definition of transportation resiliency, stated 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.” In addition, they introduced for the first time the concepts of “resiliency cycle” and “hierarchy of transportation network’s ability to fulfill societal needs.” This innovative conceptual framework was combined with a fuzzy inference system (FIS) for measuring transportation resilience based on a set of variables that relate to the impact of resiliency at individual, community, economic and recovery levels.

2.2.2 Resilience Index Calculation

Todini (2000) applied the definition of resilience to water distribution design to increase hydraulic reliability and the availability of water during pipe failures. He explained the advantages of redundant designs as they assist the network to overcome local failures and ensure sufficient capability for the distribution of water to users. Whenever the demand of a network increases or a failure occurs, the flow of water changes and the original network is transformed into a new one with higher demand. In this scenario, the new network might not be able to offer the desired capacity, unless already existing “excess capacity” is available. Todini used the resilience concept to develop a heuristic optimization approach that allows the designer to identify reasonable solutions within computational limitations. His study suggests that the relationship that exists between resilience and cost is direct, but not proportional, since there are wide ranges for which a small increase in cost can result in a large increase in resilience.

Hamad and Kikuchi (2002) developed a measure of traffic congestion based on two conventional transportation metrics, travel speed and delay. Their study identifies the ambiguity problem that the two traditional congestion measurement approaches have, based on the imprecision of measurement, variation in sample data, and the analyst’s uncertainty about casual relations. In other words, the problems are the inevitable existence of vagueness in the real world and the difference between a transportation network’s users and analysts. Because of this ambiguity, a fuzzy inference approach was implemented to combine travel speed and delay into one single index. The result was a congestion index that ranges from 0 to 1, where 0 is the best condition and 1 the worst. The authors contributed to the resiliency literature by using fuzzy inference to combine different types of metrics into a unique index, while taking into consideration the distortion of the truth provoked by the ambiguity in the real world.

Brenkert and Malone (2004) combined the concept of resilience with vulnerability to climate change and suggested a methodology to perform vulnerability assessment using indicators. The researchers identified three distinct cluster definitions of vulnerability based on: risk exposure to hazards, capability for social response, and attribute of places. Their paper focused on how to apply the vulnerability-resilience index to societies and individuals. The study presents a set of seventeen quantitative indicators that allow comparisons of different levels of localities (regional, states, cities, etc.) in terms of their vulnerability and resilience to current and changing climate. The indicators affect the final index in a positive and negative manner; hence, positive and negative values will exist within the data set. The methodology consists of first, scaling all indicators' sub-variables to the same range (e.g., 0 to 1), then calculating each indicator as a geometric mean of its sub-variables, and finally calculating the net vulnerability-resilience index value as the simple algebraic summation. Although focusing strictly on climate related disasters, Brenkert and Malone presented a different alternative for the formulation of a resilience index, but more importantly, they provided specific guidelines for the creation of indicators and management of the results.

Briguglio et al. (2005) stated the importance of an economic resilience index since it enlightens a country's options of how to mitigate or exacerbate its inherent vulnerability, hence, reflecting the appropriateness of policy measures. This concept is important for small states because, inherently, they tend to be more economically vulnerable. The research team suggested the use of macroeconomic stability, microeconomic market efficiency, good governance, and social development as the components of the resilience index. The economic resilience index was computed using the average combination process of the four components after all observations of the components were standardized. Briguglio et al. confirmed the hypothesis that the performance of a country, measured as the GDP, has a negative dependence on their inherent vulnerability and a positive dependence on their nurtured resilience, being the last one of the more influential on total performance.

Huiping et al. (2005) attempted to characterize the effect on the resilience of metropolitan areas with the presence (or absence) of separate small communities within a larger jurisdiction. These communities can be based on many different social cleavages (ethnic, racial, economic, social, geographic, linguistic, etc.). In their paper 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. The authors emphasized the ability of a community to restore essential socioeconomic functions after a community-wide disruption. This disruption leads to the use of the recovery of socioeconomic activities and the workforce as a resilience proxy. A resilience index was created following the Political, Security, Economic, Social, Infrastructure, and Informational frameworks, and using the socioeconomic data from Katrina-affected areas in Mississippi and Louisiana. Biloxi-Gulfport-Pascagoula, MS Metropolitan Area and New Orleans Metropolitan Area were their selected cases. To create a socioeconomic resilience index, these five measurements were combined in three ways: 1) simple summation, 2) sum of the standardized values, and 3) principle component analysis.

Joseph Mayunga (2007) explained how communities are becoming more vulnerable to everyday threats, and in particular, climate related drastic events as the Indonesian Tsunami in 2004 and Hurricane Katrina in 2005. His study suggests that there has been a shift to focus research on building resilience and creating an accurate measuring technique. Mayunga explained that resilience could be divided into five elements: social capital, human capital, economic capital, physical capital and natural capital. His proposed methodology suggested the use of a weighted average of these elements in order to obtain a single community disaster resilience index (CDRI).

Although practical, Mayunga's study did not emphasize in how to accurately measure each individual element.

The Asia Regional Task Force on Urban Risk Reduction (RTF-URR, 2008) is an initiative that attempts to answer the queries of how to enhance and locate indicators and create an effective CDRI. Its main focus is disasters related to climate change, especially hydro-meteorological disasters (e g., cyclone, flood, heat wave, etc.), since their impacts and variability post the most threat to exacerbate existing vulnerabilities and further entrench development disparities. Their study looked at different dimensions of resilience from the lens of urban communities, by focusing on fifteen Asian communities. The report defined community resilience as the capacity to absorb stress (hydro-meteorological disasters), manage it and recover from it. Their basic assumption is that if a community enhances its climate resilience, their disaster risk resilience would enhance as well.

Similarly to Mayunga (2007), the climate disaster resilience is assessed considering natural (environment and disasters), physical (infrastructure), social (population characteristics), economical (livelihood), and institutional (organization) dimensions. The data was obtained through surveys filled out by city officials, which makes the results biased to human perception and therefore incomplete. The methodology consists in mapping each previously mentioned dimension and then combining them into a single resilience map that ranges from 0 to 12. In this scale, the higher the value, the higher preparedness to cope with climate-related disasters. The final result is a five-point radar map that illustrates the city's state on each dimension, hence, locating the vulnerabilities on which the city officials (decision makers) should focus their attention. Figure 2.1 illustrates the resulting resilience index of Bangkok city. Both studies, Mayunga (2007) and RTF-URR (2008), contribute a conceptual and methodological framework to measure resilience from a community risk assessment viewpoint. The findings (methodology and conceptual framework) can be reallocated to transportation engineering by defining variables that explain the characteristics of a transportation network.

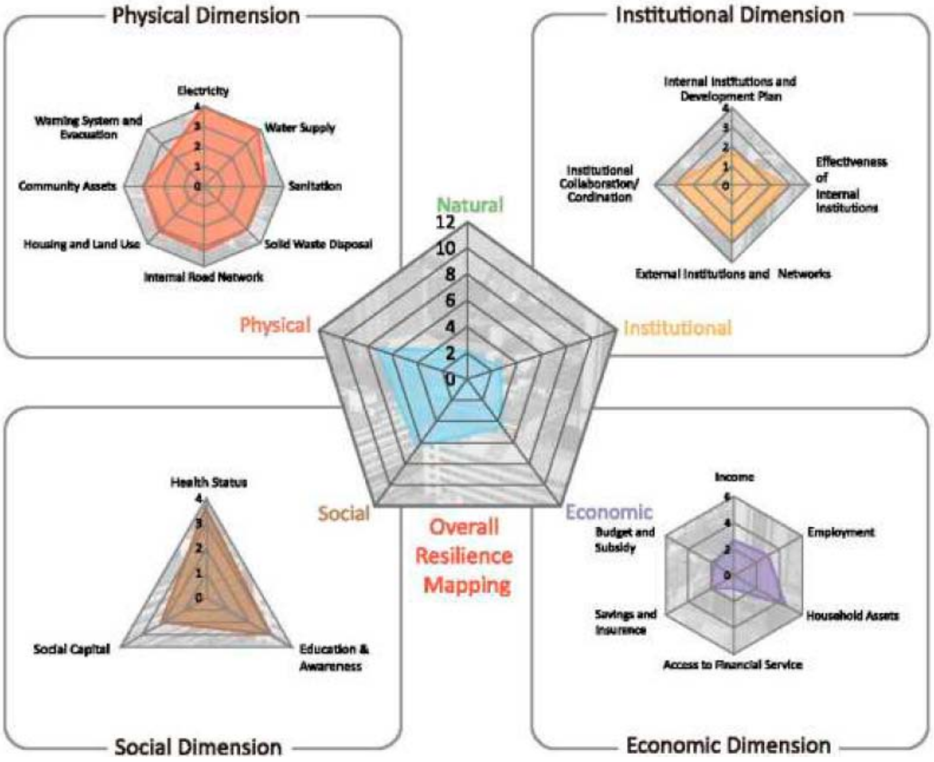


Figure 2.1 Resilience Analysis Result for the City of Bangkok (RTF-URR, 2008).

Scott et al. (2006) used a “gamma index” in their proposed methodology to identify critical links and evaluate the performance of a transportation network. This index measures the connectivity of a network considering the relationship between the number of links and the number of possible links. They based their research on the concepts of network flexibility and reliability and their effects on a network’s “ability to adapt to external changes while maintaining a satisfactory level of performance” (Morlok & Chang, 2004). Scott et al. (2006) stated that the common and broad approach of using the volume to capacity ratio (V/C) may not enable traffic engineers and planners to identify the most critical highway segments or corridors to maximize system-wide travel-time benefits associated with a highway improvement project. Additionally, their research suggested that a transportation network should not only meet origin-destination (OD) demand, but should also provide ample connectivity to avoid being overly vulnerable to disruptions on individual segments within the system. Moreover, they introduced a new methodology that takes into account the networks’ connectivity. The network robustness index (NRI) was defined as the change in travel-time cost associated with rerouting all traffic in the system, should that segment become unusable. Their results showed that evaluating a transportation system as a whole using the NRI provides better planning solutions than those obtained using the traditional localized V/C approach applied to the most congested segments. This is the outcome because the NRI takes into account the spatial relationships and rerouting possibilities associated with the network’s topology, the OD demand and the capacity of individual highway segments.

Heaslip et al. (2010) expanded their previous research in resilience by refining key variable definitions and value ranges, making adjustments to model structures, and making computational processes transparent. The researchers combined a total of eleven variables using the FIS to measure network resiliency. Ten measurable variables where used to define four basic network performance indexes (network availability, traveler perception, transportation cost, and network accessibility). These four indexes are then combined into a single network performance index, which serve as a base resilience index. This index is subsequently coalesced with a leveraging variable (network management) to obtain a more realistic result. Heaslip et al. serves as part of the foundation of this thesis work by providing the most up-to-date information through a conceptual measuring approach.

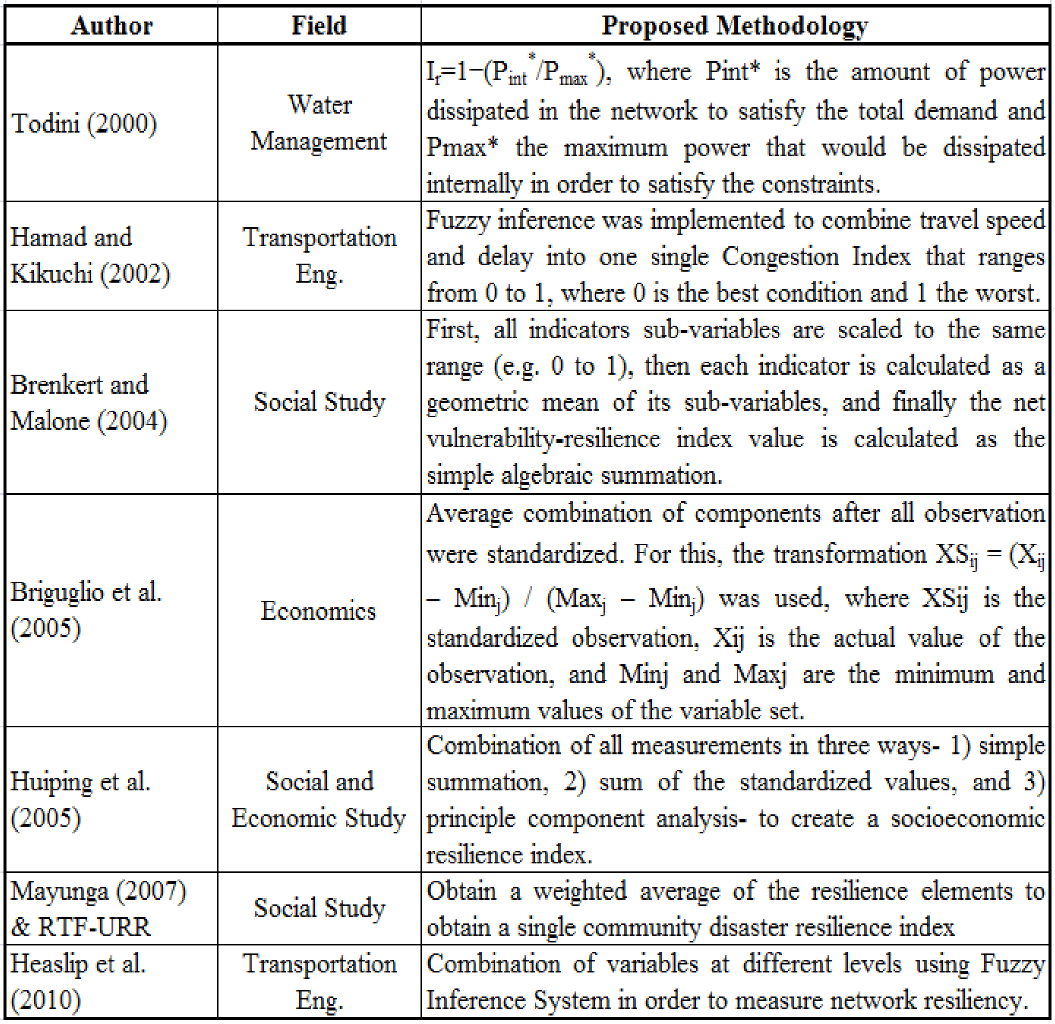
A compilation of the previously presented methodologies is shown in Table 2.2. This table provides a general overview of the methods, presenting information about the authors, field of application and a general description of each approach.

2.3 Conclusion

The previous literature review provides insight on earlier conceptual and technical methodologies proposed by several authors in different fields. The discussed studies showed a deficiency in quantitative measuring techniques of resilience in the field of transportation engineering. The concept of resilience is well-defined and applied in most of the areas of knowledge; however resilience measurement is generally limited to a conceptual box, being characterized mainly in a qualitative manner. Hence, a clear need for quantitative approaches for measuring resilience can be recognized.

The papers analyzed presented the essential knowledge needed to tackle the resilience problem and achieve the goals defined in Chapter 1. For the rest of this research, transportation network resilience will be understood 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” (Heaslip et al., 2009).

Table 2.2 Summary of Previously Proposed Methodologies to Measure Resilience.



Author	Field	Proposed Methodology
Todini (2000)	Water Management	$I_r=1-(P_{int}^{*}/P_{max}^{*})$, where Pint* is the amount of power dissipated in the network to satisfy the total demand and Pmax* the maximum power that would be dissipated internally in order to satisfy the constraints.
Hamad and Kikuchi (2002)	Transportation Eng.	Fuzzy inference was implemented to combine travel speed and delay into one single Congestion Index that ranges from 0 to 1, where 0 is the best condition and 1 the worst.
Brenkert and Malone (2004)	Social Study	First, all indicators sub-variables are scaled to the same range (e.g. 0 to 1), then each indicator is calculated as a geometric mean of its sub-variables, and finally the net vulnerability-resilience index value is calculated as the simple algebraic summation.
Briguglio et al. (2005)	Economics	Average combination of components after all observation were standardized. For this, the transformation $XS_{ij} = (X_{ij} - Min_j) / (Max_j - Min_j)$ was used, where XSij is the standardized observation, Xij is the actual value of the observation, and Minj and Maxj are the minimum and maximum values of the variable set.
Huiping et al. (2005)	Social and Economic Study	Combination of all measurements in three ways- 1) simple summation, 2) sum of the standardized values, and 3) principle component analysis- to create a socioeconomic resilience index.
Mayunga (2007) & RTF-URR	Social Study	Obtain a weighted average of the resilience elements to obtain a single community disaster resilience index
Heaslip et al. (2010)	Transportation Eng.	Combination of variables at different levels using Fuzzy Inference System in order to measure network resiliency.

CHAPTER 3

RESEARCH APPROACH

This chapter describes the research approach based on a defined premise, research question, hypotheses, data (variables) explanation and analysis. The following discussion will provide the informational basis for understanding the problem.

3.1 Research Premise

The research is centered on the following premise:

A network's ability to overcome failure while working at a minimum desirable level of service can be quantitatively measured based on key indexes of transportation performance. These key indexes can be calculated using quantitative proxies, which can be obtained from commonly used transportation measurements (data).

This premise allows the development of the algorithm that will be tested with data.

3.2 Research Question

The central question this research revolves around is: *"How can one quantify transportation resiliency on a regional level?"* To effectively answer this question one must address several other queries that would give sufficient insight on resilience and the metrics to be used. These queries can be broadly categorized into two questions:

1) What are the basic indices of transportation performance?
2) How can these indices be quantitatively measured or approximated using real data?

3.3 Research Conceptual Framework

The conceptual basis for the methodology presented in this research draws on the concepts of a definable "resiliency cycle" and "transportation system performance hierarchy". While each region and locality will have a different characteristic degradation and response profiles, for this research it is assumed that they can be evaluated within the construct of a "resiliency cycle." In addition, the proposed methodology for measurement of network resiliency is based upon the idea that the degrees of transportation system performance can be stratified at various levels. The main theory is that "resiliency cycle" affects the resiliency stratification of performance and the performance of the network.

3.3.1 Resilience Cycle

The concept of the resiliency cycle was introduced in a previous research in an earthquake context (Bruneau et al., 2003). Key findings by Bruneau et al., especially those dealing with impacts and response to natural disaster events, are incorporated in an extension of the concept posited by Heaslip et al. in 2007.

The "resiliency cycle" consists of four stages: Normality, Breakdown, Self-Annealing, and Recovery. The flow between these stages is illustrated in Figure 3.1. The cycle begins with the network at the normality stage. Normality occurs when the network operates under standard and sustained conditions. The breakdown stage takes place when the network experiences a failure due to loss of a transportation facility or reduced access to portions of the servicing network. The self-annealing stage refers to the process of strengthening the damaged network performance as a function of transportation management practices and alternative behaviors by travelers. The last phase of the cycle is recovery. In this phase facilities are replaced or restored and full network access is restored providing a return to normality or, in the case where restoration improves the network, to a new normality.

While each region and locality will have a different characteristic degradation and response profiles, they can be evaluated within the construct of a "resiliency cycle" in which the assessment methodology has the ability to recognize the differing nature of the networks and the varying travel patterns at pre-event conditions. It must be stated that the proposed methodology is not case-dependent, since it is limited to the normalcy stage, therefore obtaining a resiliency value that helps locate the current level of preparedness of the network for a disruptive event. The different demand variation associated with disruptive events are taken into consideration in the subsequent stages, but are not explained in this research.

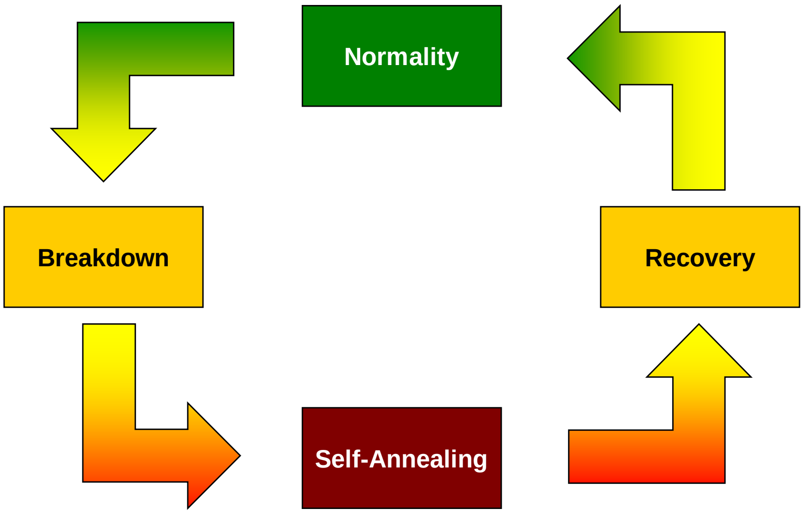


Figure 3.1 Transportation Network Resiliency Cycle.

In addition to scale of influence and event severity, time is a very important characteristic in resiliency assessment. Time characteristics associated with components of the cycle recognize decay patterns, self-annealing patterns, and recovery patterns requiring a discrete assessment at appropriate time intervals. In some cases, the scale of influence and the degree of impact can generate negative stability behaviors as the effects of the breakdown spread across a wider area than where the breakdown occurred. The longer it takes for the self-annealing process to begin, the greater the possibility of significantly lengthening the self-annealing time, and ultimately also extensively increasing the time to recover. The consequences for a slow recovery time may be devastating to the local, regional, and national economies. The calculation of resiliency will provide decision makers with the opportunity to plan effectively for breakdown events of all kinds.

3.3.2 Transportation Performance Hierarchy

The goal of any transportation system is to serve societal needs and to enable social interaction and commercial activity. As such, its performance is judged based on the degree to which societal needs and commercial activities are supported by the interacting physical network components and the transportation management components. To help stratify the transportation system performance, Heaslip et al. (2009) developed a hierarchal representation of transportation system performance patterned after the work of Maslow and his development of the hierarchy of human needs. Maslow explained human needs and behavior motivations by grouping needs into those related to deficiency and those related to growth (Huitt, 2004). The hierarchy ranged from the basic levels of fulfillment −characterized by activities to ensure safety−to the highest levels −characterized by self-actualization. Similarly, the transportation hierarchy defines easily observable levels of performance and ranks them from lowest to highest (see Figure 3.2). The hierarchy defines performance levels in terms of activities and capabilities related to the safe and efficient movement of people and goods. In this matter, five levels are identified:

The hierarchy is useful as a benchmark in assessing the resilience of a regional transportation network as analysts use data to inform decision makers of an objective measure of ‘current conditions’ and estimate the degree of degradation caused by specific events.

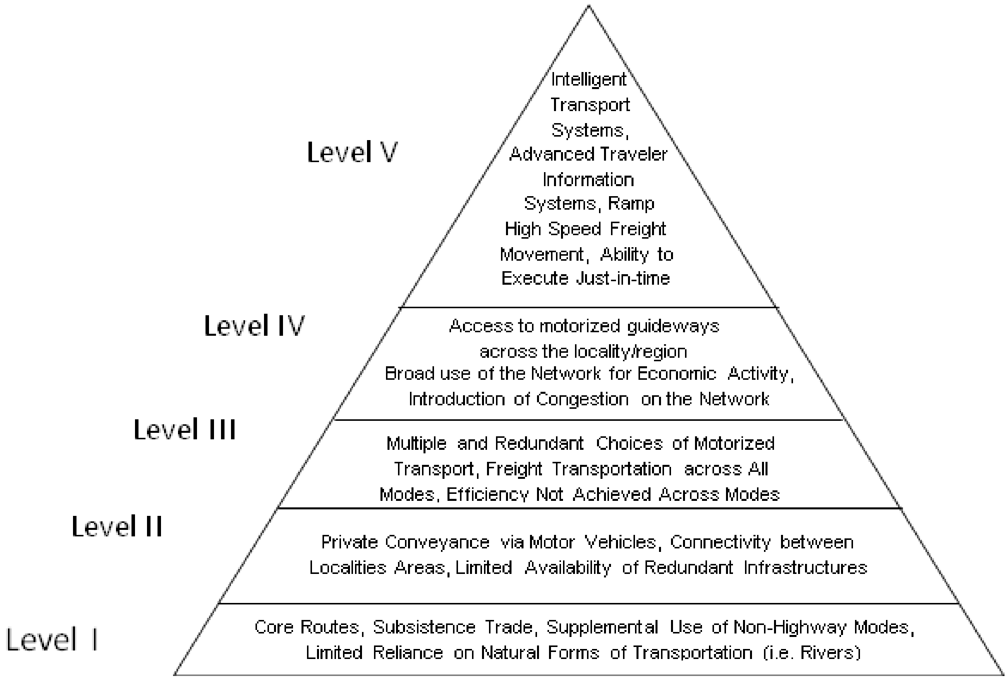


Figure 3.2 Transportation System Performance Hierarchy. Heaslip et al. **(**2010**)**.

3.3.3 Combining Resiliency Cycle and Transportation System Performance Hierarchy

The concepts of resiliency cycle, resiliency cycle time, and performance hierarchy were combined together into a Cartesian plane supporting a discrete event-based assessment framework by Heaslip et al.'s (2010) research in transportation network resiliency (see Figure 3.3). This Cartesian plane was slightly modified to include the case when the newly obtained network normality is lesser than or surpasses the previous normality level of performance (the dash line that starts before achieving the system's pre-event normal level of performance). The framework, as depicted, supports an intuitive understanding of the depth of degradation during the breakdown phase and the time required to self-anneal and recover.

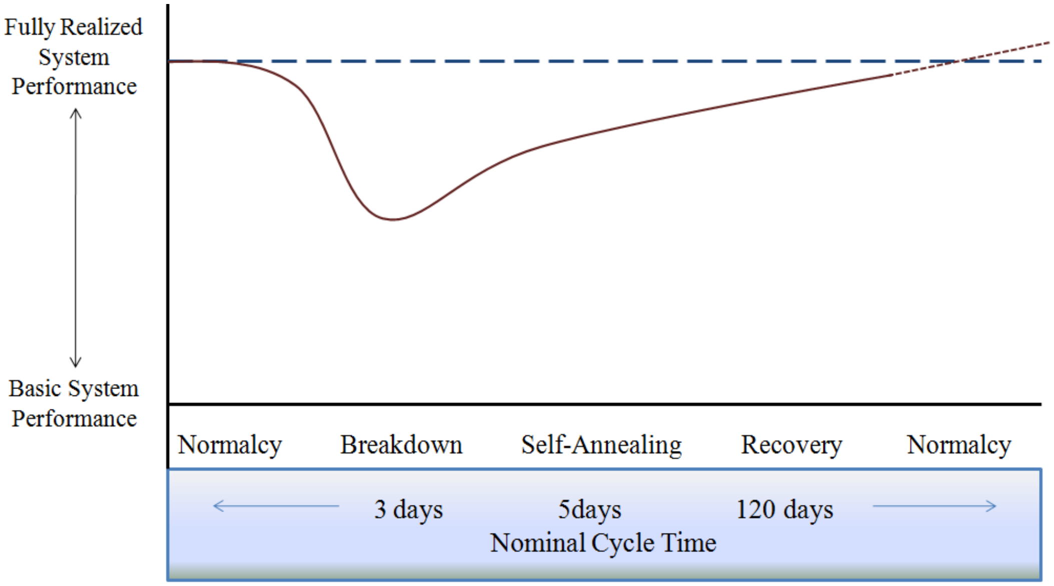


Figure 3.3 Resiliency Assessment Framework.

Also, Figure 3.3 shows the important concept within the research of a new normal. The new normal is at the point where the recovery is complete. As stated before, this new normal may be of a higher or lower caliber than the old one. Depending on the nature of the disruptive event, the infrastructure may be built to be more robust or it may not be built to the previous levels. An example of this is the area of the lower 9th Ward in New Orleans, which was not rebuilt to the levels previous to Hurricane Katrina.

3.4 Variables of Interest

Within the structure of the methodology, there are four tiers. At the lowest tier, are the eight measureable input variables, these variables aggregate at the intermediate tier into four inference-derived values that represent physical attributes of the network (i.e., availability and accessibility, and traveler tolerance and demand attributes, cost of travel and delay perception). The four intermediate values aggregate into two resilience groups, Network and User Resiliency, from which the Base Resilience value is obtained. This value, indexed from 0 to 9, is leveraged by an auxiliary variable, Network Management, which represents the ability of the existing Traffic Management Center to control network performance by maximizing the utility of the existing physical network while favorably affecting the traveler’s tolerance and perception.

The set of variables was obtained from an analysis of previous researches. The variables would represent important characteristics of a transportation system, such as redundancy, cost, and available and accessible capacity. The eight measureable input values, along with the auxiliary variable, are defined as follows:

Road available capacity. The available road capacity of a network explains the infrastructure usage and its performance. This variable represents a weighted average of realized traffic density, which can be obtained from analyzing the key links across the various time-of-day based demand patterns (peak and off-peak). This variable can be measured using the Highway Capacity Manual (HCM) methods, which ranges the level of service (LOS) from A to F values (A being the best and F being the worst).

Road density. This variable measures the territorial occupation of a transport network (Rodrige, 2009); providing a clear idea of the network's transportation infrastructure availability, indicating capacity and, furthermore, redundancy within the system (micro level). For this research, the range of this variable is set from 0 to 100 lane miles per square mile (ln-mi/mi^2). The value can be found by a GIS data survey of the travel demand avenue of interest.

Alternative mode availability. This variable represents the capacity that non-auto modes of transportation (e.g., rail and air) have in order to accept demand shifts from the auto to alternate forms of transportation. This is measured as a percentage of demand shift acceptance capacity (percentage of contribution) that ranges from 0 to 100. The value can be generated as a weighted average of all available alternatives unused under prevailing conditions and, if applicable, under conditions in which new capacities are added in the course of event management.

Average delay. This variable represents the delay of traffic due to recurring, non-recurring, and traffic signal-generated delay that a traveler expects to experience (Litman, 2008). Delay increases the time for annealing to begin, especially in unpredictable events (e.g., earthquakes). Since delay is defined in time measures, average delay (hours or minutes) under “normal conditions” of a specific time of day (AM-PM Peaks, off peak, etc.) is used as a measure of this property. Again, because of the difficulty to measure the delay of an entire network, especially under extreme conditions, a proxy can be used to obtain such a value. For this research, it is proposed that the delay time ranges from 0 to 6 hours.

Average speed reduction. This variable represents the link performance curve driven by the response to link loads. The value is measured as a percentage reduction from Free Flow Speed. It is associated with prevailing conditions in a base case and with expected link loads under duress. Highway Performance Measuring Systems can be used as the source of input values.

Personal transportation cost. This variable represents transportation costs incurred by individuals under prevailing and duress conditions. The variable considers the price of fuel and supporting commodities and services. The value ranges from US$0.50/mi to US$0.75/mi and can be computed using typical cost of travel “calculator wizards” and planning program components available to Metropolitan Planning Organizations (MPOs).

Industrial/commercial transportation cost. This variable represents transportation costs incurred by firms under prevailing and duress conditions. It considers the price of fuel and supporting commodities and services. The value ranges from US$1.00/mi to US$2.00/mi and can be computed using typical cost of travel “calculator wizards” and planning program components available to MPOs.

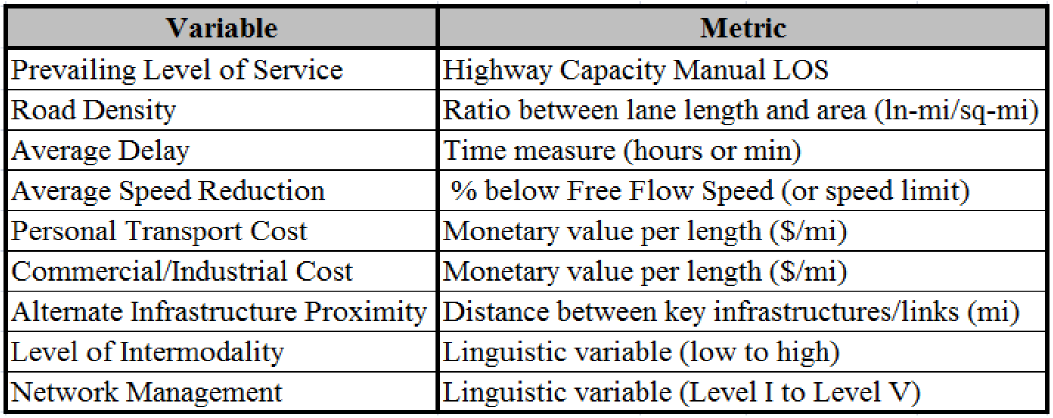
Alternate infrastructure proximity. This variable represents the ability for a traveler to adjust routes (i.e., to detour around an affected roadway section or affected sections), and it also gives an idea of the level of redundancy within the system at a macro level. The unit of measure used is miles of separation between the primary and alternate infrastructure (it goes from 1 mile to 30 miles). The selection of the distance was made taking into consideration recent events, such as the January 12th, 2010 Haiti earthquake, which struck with a magnitude of 7.0 on the Richter scale. Even though the epicenter was located 15 miles away from the capital city, Port-Au-Prince, the ramifications of its vibrations caused devastating effects to the city. The variable is then considered to be most appropriate at an intermediate distance (10-20 miles), recognizing, on the one hand, that too short distances make the variable unfavorable due to the likely inclusion in the distressed area, and, on the other hand, that too long distances reduce the utility of the alternative.

Level of intermodality. This variable represents the ability of a traveler or shipper to make a mode change considering sub-variables such as parking availability at the transfer site, the cost of transfer in time and dollars, and safety and security of transfer activities. Good integration secures accessibility to all different modes of conveyance, resulting in an optimization of networks capacity and performance (Litman, 2008). The variable is expressed as a Linguistic Value ranging from Low to High based upon review of the sub-variables.

Network management (leveraging variable). This variable refers to the activities, methods, procedures, and tools that pertain to the operation, administration, maintenance, and provision of network systems (Clemm, 2006). Increased network management provides real time shifting of resources and demands on the network, which enables the annealing process to begin and minimizes the intrusiveness of recovery activities. By the time of completion of this research, no quantitative value could be obtained to measure how well a network is being managed. To date, qualitative information is necessary to evaluate the network management under its specific condition. Each network has a particular behavior and demand, but they can be stratified by their fulfillment of societal needs. The measure employed is qualitative and it is scaled from the provision of Basic Mobility Services (Level I) to Advanced Management (Level V) in four increments, following the hierarchy presented in Figure 3.2. The score within the scale is determined by reference to a catalog of traffic management capabilities and associated features that are mapped to the qualitative values. This variable is used as a leverage of the network's base resiliency value because of its secondary contribution to the network's performance optimization, and consequently the network's resiliency. It should be noted that in instances when the Base Resiliency value is small, then Network Management has great influence on the final Network Resiliency Index. On the contrary, when the Base Resiliency value is large or above the medium level, the Network Management variable no longer has a significant effect over the Network Resiliency Index.

All variables, and their proposed metrics, are summarized in Table 3.1. It should be stated that the proposed metrics are mostly proxies of the variables,

Table 3.1 Summary of Variables' Metrics.



Variable	Metric
Prevailing Level of Service	Highway Capacity Manual LOS
Road Density	Ratio between lane length and area (ln-mi/sq-mi)
Average Delay	Time measure (hours or min)
Average Speed Reduction	% below Free Flow Speed (or speed limit)
Personal Transport Cost	Monetary value per length ($/mi)
Commercial/Industrial Cost	Monetary value per length ($/mi)
Alternate Infrastructure Proximity	Distance between key infrastructures/links (mi)
Level of Intermodality	Linguistic variable (low to high)
Network Management	Linguistic variable (Level I to Level V)

3.5 Conclusion

This chapter presented the conceptual basis of this research, "resiliency cycle" and "transportation system performance hierarchy," and explained their interaction. Furthermore, it detailed the set of variables that would form part of the Transportation Network Resiliency Index model. The next chapter will describe the model and its components with greater detail, as well as the interaction between the variables and their effect on the Base Resilience Index.

CHAPTER 4

TRANSPORTATION NETWORK RESILIENCY INDEX MODEL

In the creation of a model that combines qualitative and quantitative data, a variety of algorithms were examined (e.g., neural systems, regression analysis, heuristic model), and Fuzzy Algorithm was selected because of its capability of managing the ambiguity and incompleteness of the data. This chapter, first, explains the model's methodology; second, defines the relationships between each variable and the resilience index; third, the model's framework is explained providing details about the FIS logic; and finally, presents a practical example to illustrate the model's ample application range, using the Dominican Republic as a case study.

4.1 Methodology

4.1.1 Fuzzy Sets and Numbers

Classical set theory reaches its limits when the property that determines the membership of an element to a set is defined in such a way that a clear distinction between membership and exclusion is no longer possible (Hanss, 2005). Figure 4.1 compares classical set with fuzzy sets, representing the levels of network management.

As can be seen, classical sets have rectangular-shaped groups, where the end of one group is the beginning of the next. On the other hand, fuzzy sets have triangular-shaped groups that overlap with each other.

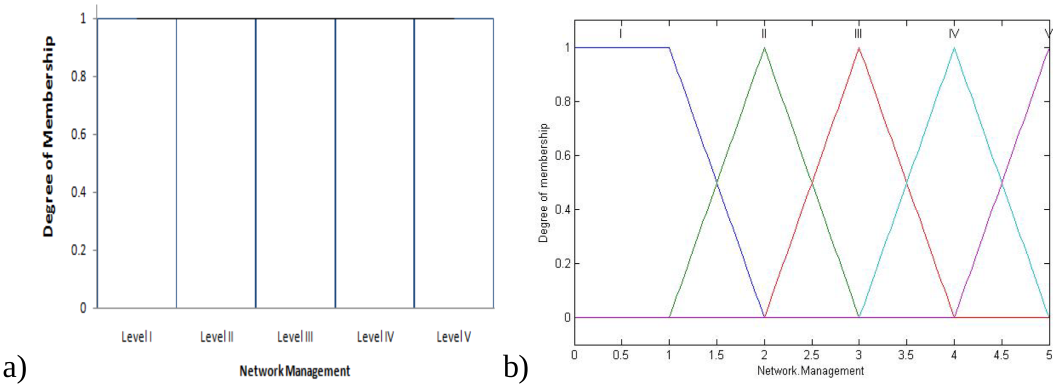
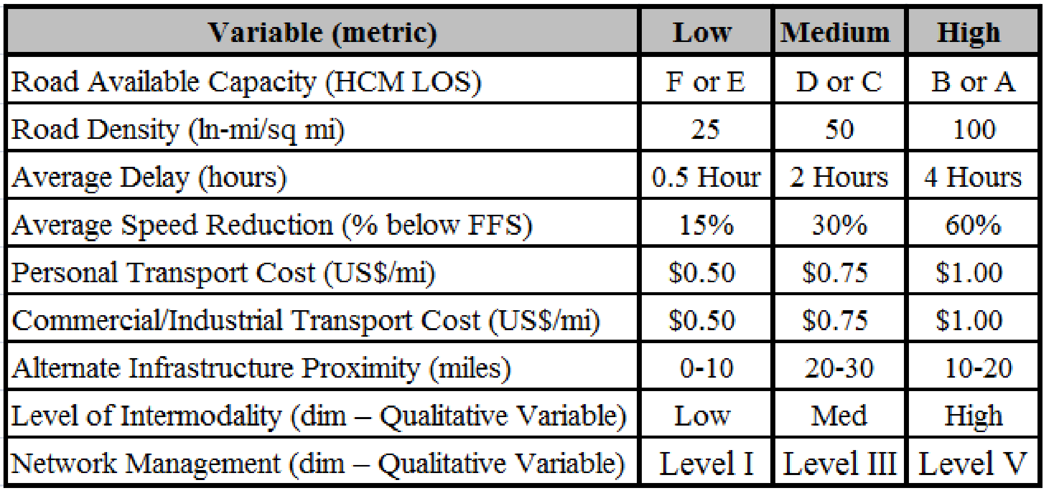


Figure 4.1 A Comparison of a) Classical and b) Fuzzy Sets.

The base of the triangle and the degree of overlap (softness) characterize the degree of "fuzziness" in parsing the values to be used in the FIS computational environment. These triangular regions are called membership functions. Fuzzy numbers can be represented in a variety of shapes that exhibit different degrees of "softness."

A clear necessity of the extension of classical set theory towards a generalized set theory – in which additionally to membership and exclusion there is also the possibility to provide gradations between the two groups – can be acknowledged. This type of set is known as a Fuzzy Set. This set can be understood as a generalization of a conventional set, because it allows elements of a universal set not only to belong entirely or not to a specific set, but also to belong partially to it. Fuzzy numbers allow for mathematical processes to recognize different type of values: those that are estimates, those representing ambiguous data, and those that are qualitative measures. Fuzzy numbers are an extension of conventional numbers that permit assigning order to real life situations that have a natural variation, with input values between 0 and 1 (or any other scale). Therefore, the main advantage of fuzzy numbers is that they can represent a wider range of values than conventional numbers.

Table 4.1 Example of Values for the Fuzzy Numbers Data Ranges.



Variable (metric)	Low	Medium	High
Road Available Capacity (HCM LOS)	F or E	D or C	B or A
Road Density (ln-mi/sq mi)	25	50	100
Average Delay (hours)	0.5 Hour	2 Hours	4 Hours
Average Speed Reduction (% below FFS)	15%	30%	60%
Personal Transport Cost (US$/mi)	$0.50	$0.75	$1.00
Commercial/Industrial Transport Cost (US$/mi)	$0.50	$0.75	$1.00
Alternate Infrastructure Proximity (miles)	0-10	20-30	10-20
Level of Intermodality (dim – Qualitative Variable)	Low	Med	High
Network Management (dim – Qualitative Variable)	Level I	Level III	Level V

As values are placed into the FIS, they must be translated from the raw measure into a fuzzy number. Table 4.1 above illustrates an example of the assignment of range values for each variable to the fuzzy numbers used in this research.

4.1.2 Fuzzy Inference System (Models)

Fuzzy ruled-based models can effectively combine measured quantitative data with operational experience and with qualitative and imprecise information (Babuska et al., 1999). They are transparent and capable of expressing and incorporating human preferences, perceptions and subjectivity. FISs have the biggest success when the actions, outcomes, or consequences are not precisely known (Singpurwalla & Booker, 2004). This is unquestionably the case in regards to transportation resiliency, especially when the event that will trigger the system's breakdown is uncertain. Within a FIS, all rules are called on simultaneously, generating an approximate output value for each applicable rule. The output from each partially fulfilled rule is a contribution to the aggregate output, which is represented in a shape with a measurable area.

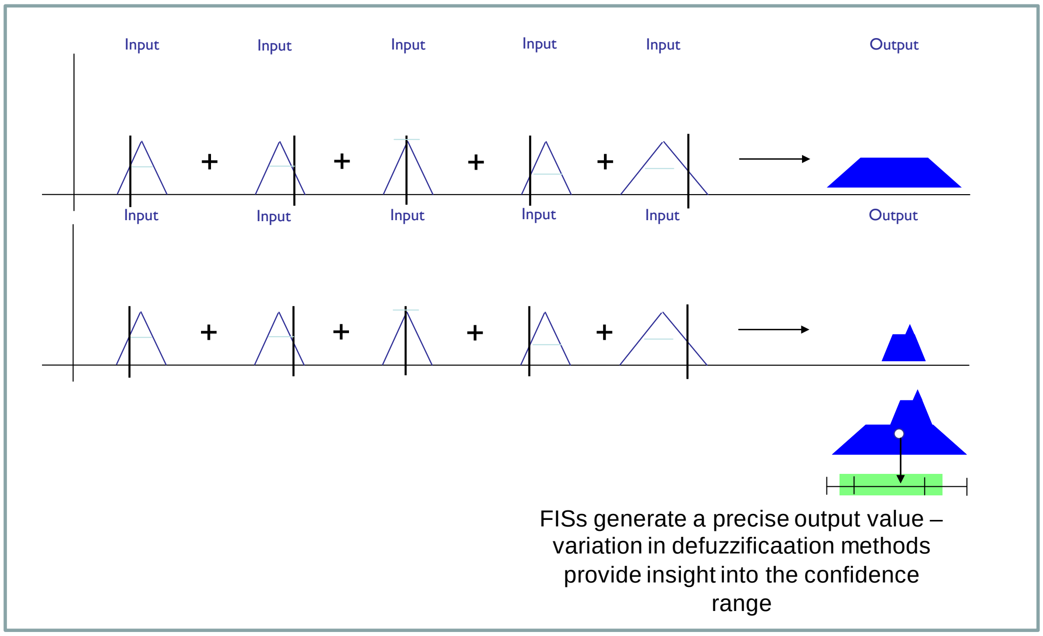


Figure 4.2 Illustration of the Geometric FIS Computational Method.

In the example illustrated in Figure 4.2, the inference operator is ‘and’, implying that the rules read as, “if Input 1 is X and Input 2 is Y and … then, the output is Z.” The figure shows that the output range is dependent on the location of the inputs on their membership functions.

4.2 Interaction of Variables

The proposed methodology for generating a measure of network resiliency is based on a dependency relationship between variables, as represented in the hierarchical structure illustrated in Figure 4.3. Candidate variables were identified in the literature review section, and particularly, they were taken from Heaslip et al. (2009, 2010). The candidate list was reduced to the 8 child nodes on the left hand side of the diagram. These variables were selected via a subject matter expert-based pair-wise process.

Following the development of the dependency diagram, each variable was categorized according to the availability of quality data to support valuation within the process. Findings suggested that several variables would involve a range rather than precise values and that, at this time, some would require qualitative measures. All of this would lead to the conclusion that variation in data quality would be best handled if researchers were to use soft computing techniques instead of conventional expert system or probabilistic/statistical techniques (Kaufmann & Gupta, 1988).

The FIS method used in this thesis follows the dependency diagram presented in Figure 4.3. Each node in the system, which is the point where two or more variables combine, is represented by a FIS. The FISs are used in a feed-forward method that arrives at a value that places the performance index on the previously introduced scale from Level I −the lowest or the basic performance level− to Level V, the advanced performance level.

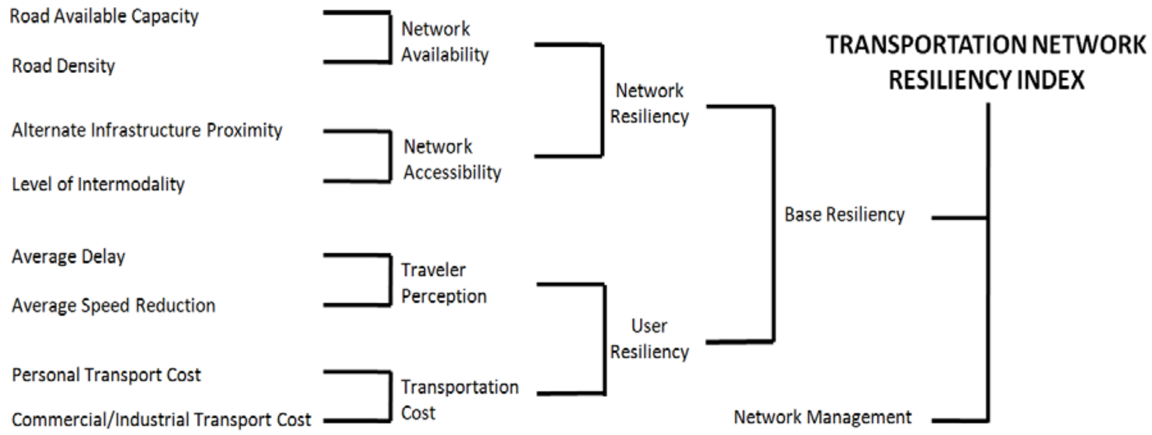


Figure 4.3 The Dependency Diagram as the Basis for Fuzzy Inference.

As can be seen in the dependency diagram, there are eight fundamental variables and one leveraging variable. These variables are combined to create four metrics that are the main indicators of the networks' performance, such as its availability, accessibility, travelers' usage cost and perception of efficiency. These variables define two general groups of resiliency, network- and user- resiliency. The next section would expand the explanation of each metric and the description of network- and user- resiliency groups.

4.3 Framework

This section focuses on expanding the concept of each metric and the interaction of the variables that form them. In the Resiliency Index Model, each variable has a different weight over the designated metric, making the metric less or more affected by their changes. The weight is reflected in the FIS rule set. The range of values for each metric goes from 'Extremely Low' to 'Extremely High' in eight increments. The weight of each variable and the grouping logic for the metrics of the different tiers are explained next.

4.3.1 Network Availability

Network availability refers to the existent level of capacity of the network. This metric depends on the Road Available Capacity (RAC) and Road Density (RD). The level of importance of each variable and its effect on the Network Availability metric can be summarized as follows:

- RD represents the level of micro-redundancy and capacity of the network. Hence, it is fair to assume that RD has a significant effect on the availability of the network. Nevertheless, this variable presents the second level of importance, since it only gives virtual information of capacity.

- RAC is the most important variable. It is sound to say that capacity becomes irrelevant if the network is working at or near maximum level. Consequently, all cases containing LOS F or E would place Network Availability at its lowest stages. Also, each positive or negative change in the LOS would have drastic effects on the Network Availability metric.

The interaction among these two variables and their effect on the Network Availability metric is presented in Table 4.2.

Table 4.2 Network Availability Set of Rules.

IF	Road Ava. Cap.	AND	Road Density	THEN	Network Availability
If	F	and	25	then	Extremely Low
If	E	and	25	then	Low
If	D	and	25	then	Medium Low
If	C	and	25	then	Medium
If	B	and	25	then	Medium High
If	A	and	25	then	High
If	F	and	50	then	Very Low
If	E	and	50	then	Medium Low
If	D	and	50	then	Medium
If	C	and	50	then	Medium High
If	B	and	50	then	High
If	A	and	50	then	Very High
If	F	and	100	then	Low
If	E	and	100	then	Medium
If	D	and	100	then	Medium High
If	C	and	100	then	High
If	B	and	100	then	Very High
If	A	and	100	then	Extremely High

For this study, RAC explains 70% of Network Availability, whereas RD explains the remaining 30%. Also, when RAC is LOS F it has no effect on Network Availability, since when a network reaches LOS F it collapses.

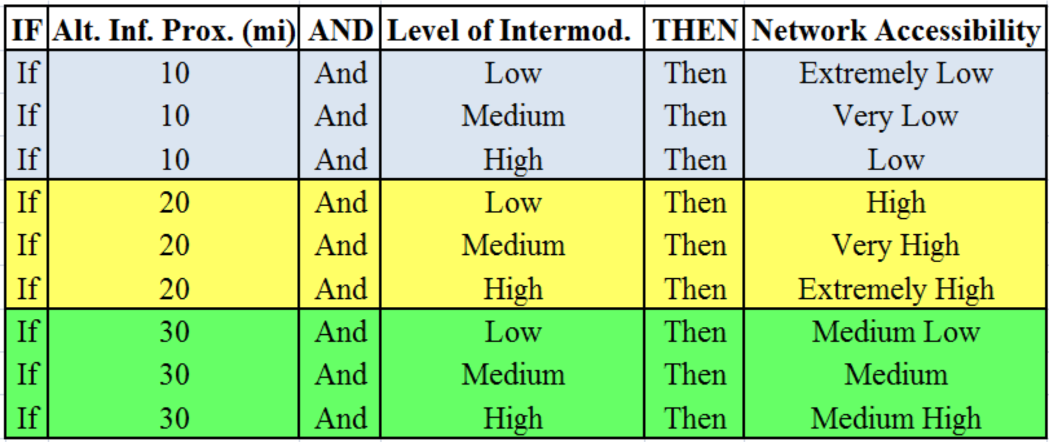
4.3.2 Network Accessibility

Network accessibility refers to the ease of access to the different modes of conveyance within a network. This metric is obtained by the combination of the variables Alternate Infrastructure Proximity (AIP) and Level of Intermodality (LIM). An explanation of the level of importance of each variable and their effect on the Network Accessibility metric is presented next:

- LIM is the least important since it would depend on the existence and availability of transferring options and mode after a disturbing event. This makes the variable extremely sensitive to the magnitude of the disturbing event.
- AIP presents the highest level of importance since high values of it would secure redundancy and intermodality after the disturbing event. Securing secondary infrastructure for the different types of conveyance (e.g., freight, public, private) is eminent for the recovery process.

The interaction between these variables and their effect on the Network Accessibility metric is illustrated in Table 4.3.

Table 4.3 Network Accessibility Set of Rules.



IF	Alt. Inf. Prox. (mi)	AND	Level of Intermod.	THEN	Network Accessibility
If	10	And	Low	Then	Extremely Low
If	10	And	Medium	Then	Very Low
If	10	And	High	Then	Low
If	20	And	Low	Then	High
If	20	And	Medium	Then	Very High
If	20	And	High	Then	Extremely High
If	30	And	Low	Then	Medium Low
If	30	And	Medium	Then	Medium
If	30	And	High	Then	Medium High

4.3.3 Traveler Perception

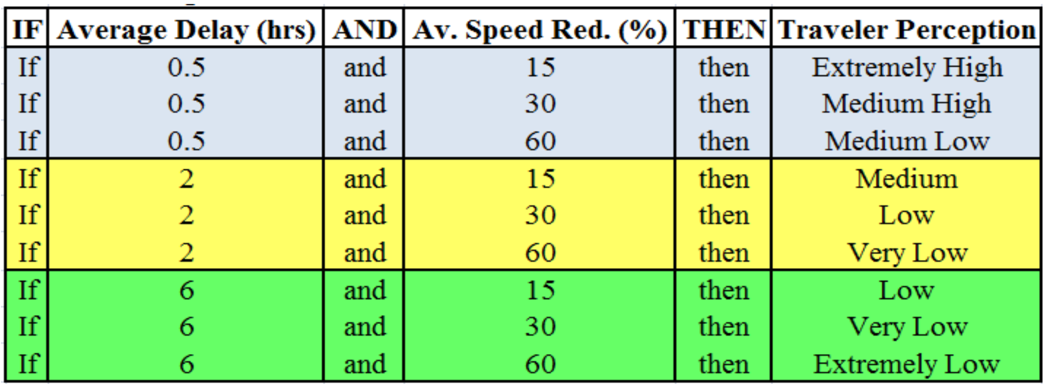
Traveler Perception defines the level of stress and dissatisfaction that a user may experience while voyaging through a network. The opinion of travelers has been linked to and measured within the concept of level of service. However, recent research by Washburn and Kirschner (2006) explains that drivers are less tolerant to traffic congestion than what is currently suggested by the Highway Capacity Manual. To secure a more realistic effect caused by drivers' perceptions, this metric is measured by combining the variables Average Delay (AD) and Average Speed Reduction (ASR), which are the two most important characteristics.

Each variable has a different level of importance and a different effect on the Network Availability metric. These distinctions are explained next:

- ASR presents the lowest level of importance. It is known that traveling at speeds bordering the speed limit helps maintain the drivers' high satisfaction level. Nonetheless, for this research it is assumed that traveling below the speed limit would not affect greatly the traveler perception, as long as he/she does not reach stop-and-go or a full stop for most of the travel time.
- AD, on the contrary, comprises the highest level of importance. The assumption is that drivers prefer trips that are less time-consuming, which, in case of an obstruction in the normal behavior of a network, might not always be the one with the highest permitted speed. Hence, the traveler perception metric would reach its highest level when delay is at its minimum.

The interaction between these two variables and their effect on the Traveler Perception metric is presented in Table 4.4.

Table 4.4 Traveler Perception Set of Rules.



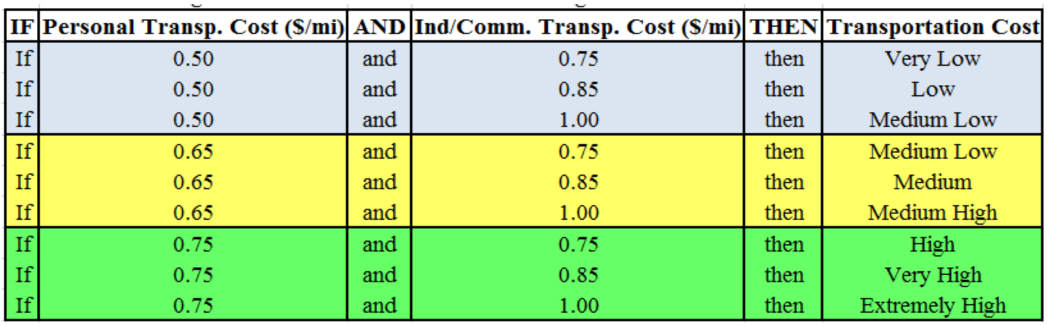
IF	Average Delay (hrs)	AND	Av. Speed Red. (%)	THEN	Traveler Perception
If	0.5	and	15	then	Extremely High
If	0.5	and	30	then	Medium High
If	0.5	and	60	then	Medium Low
If	2	and	15	then	Medium
If	2	and	30	then	Low
If	2	and	60	then	Very Low
If	6	and	15	then	Low
If	6	and	30	then	Very Low
If	6	and	60	then	Extremely Low

4.3.4 Transportation Cost

Transportation cost directly affects the usage of a network's facilities, since high cost for transport limits travel options when individuals react to the destabilizing event. The information presented by the United States Department of Transportation's Research and Innovation Technology Administration (RITA) about the variation of the Transportation Service Index (TSI) between the years 2000 and 2009 illustrates the impact of the economy on transportation. A clear example of this is the 5.9% reduction of the Combined TSI in the year 2008 (Reseach and Innovative Technology Administration, 2010), which most likely responds to the explosion of the economic crisis during the end of the 2008 summer.

For this research, auto-based trips were divided in two general groups: personal- and industrial/commercial- based trips. These two types of trips are the basis for the creation of the Personal Transport Cost (PTC) and Industrial/Commercial Transport Cost (ICTC) variables. The Transportation Cost metric can be measured by combining these two variables. The effect of the variation in values of the variables is presented in Table 4.5.

Table 4.5 Transportation Cost Set of Rules.



IF	Personal Transp. Cost ($/mi)	AND	Ind/Comm. Transp. Cost ($/mi)	THEN	Transportation Cost
If	0.50	and	0.75	then	Very Low
If	0.50	and	0.85	then	Low
If	0.50	and	1.00	then	Medium Low
If	0.65	and	0.75	then	Medium Low
If	0.65	and	0.85	then	Medium
If	0.65	and	1.00	then	Medium High
If	0.75	and	0.75	then	High
If	0.75	and	0.85	then	Very High
If	0.75	and	1.00	then	Extremely High

In addition, it is assumed that the economic crisis that sequels a disturbing event affects both personal- and industrial/commercial-based trips similarly. Therefore, both variables are assigned with an equal level of importance

4.3.5 Network and User Resiliency

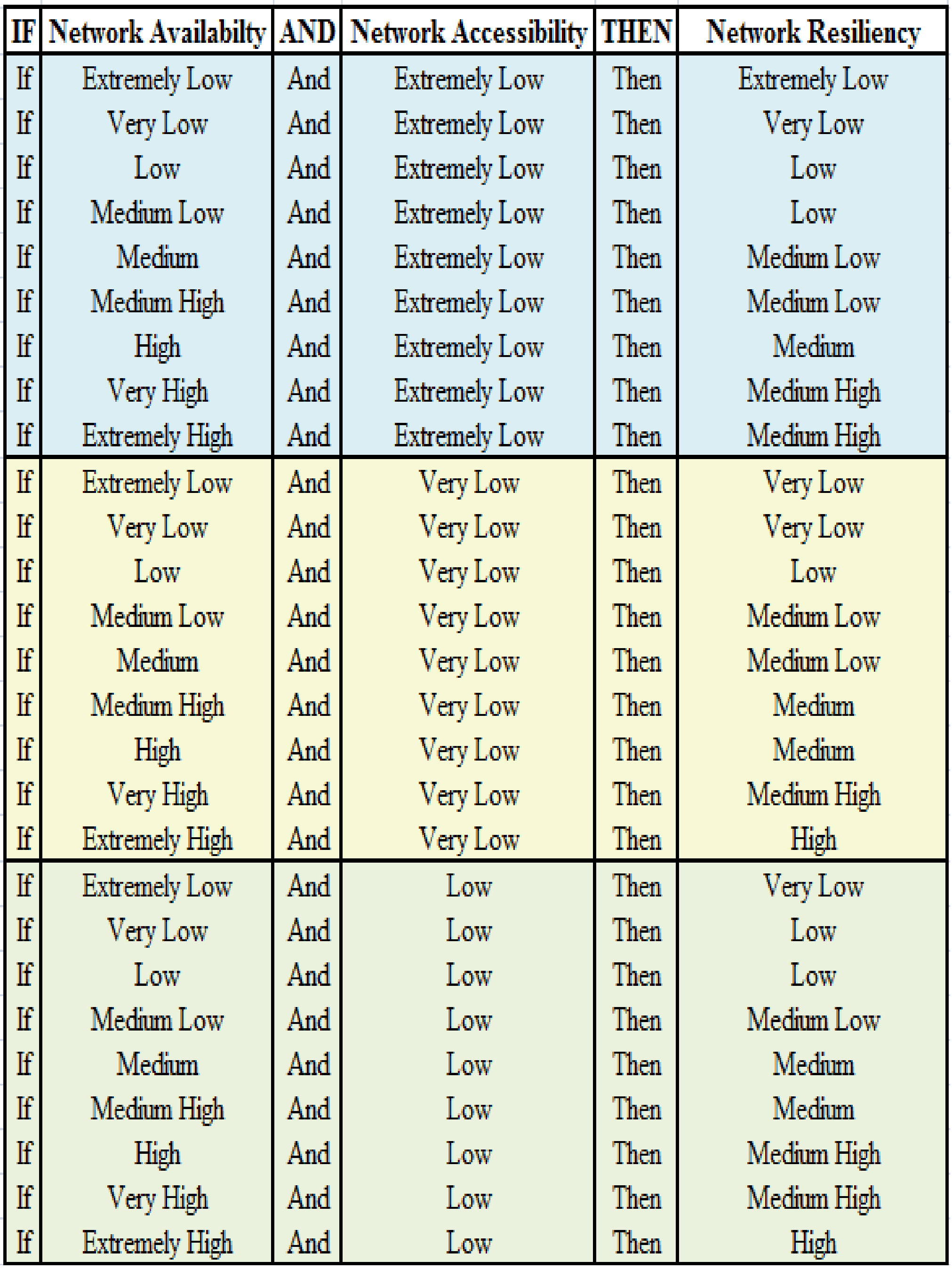
Network Resiliency explains how capable the network is; based on capacity, alternate modes, etc., whereas User Resiliency indicates the network's efficiency level and traveler's commodity, based on indicators such as time consumption and cost.

For this research's purposes, network availability is assumed to explain 60% of Network Resiliency. This assumption is based on the premise that the question "what is the gain from accessing a congested network?" is more important than its counterpart, "what is the gain of having inaccessible network availability?" The set of rules for combining network accessibility and network availability into Network Resiliency is presented in Table 4.6, (a) through (c).

Subsequently, the set of rules for combining traveler perception and transportation cost into User Resiliency is presented in Table 4.7, (a) through (c). Here, traveler perception was assumed to explain 60% of User Resiliency based on the idea that users would more easily pay an increase in cost than having to wait longer periods of time (i.e., US$6/gal vs. a 6 hours delay).

Table 4.6 Network Resiliency Set of Rules.

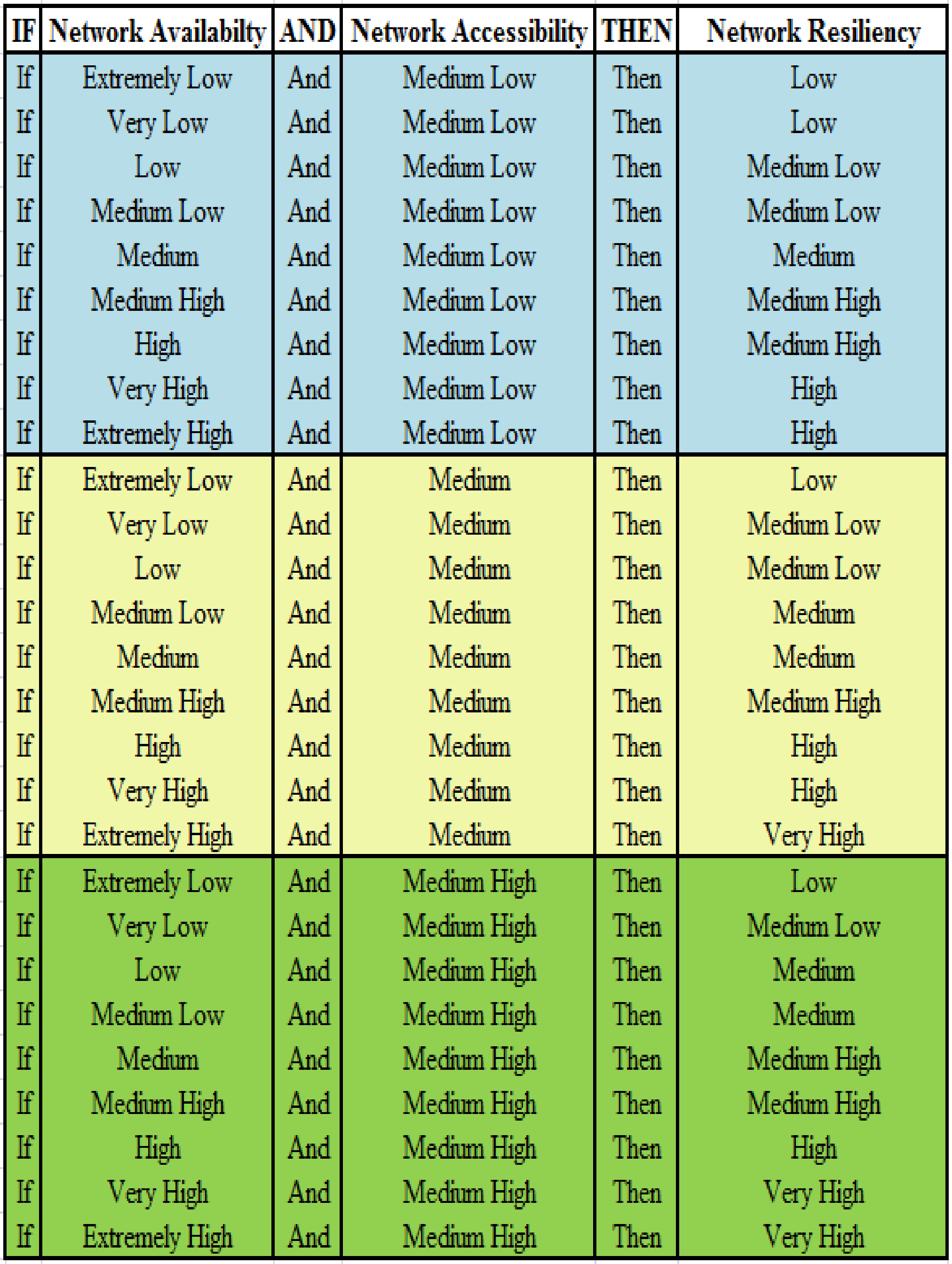
a) Low Values



IF	Network Availabilty	AND	Network Accessibility	THEN	Network Resiliency
If	Extremely Low	And	Extremely Low	Then	Extremely Low
If	Very Low	And	Extremely Low	Then	Very Low
If	Low	And	Extremely Low	Then	Low
If	Medium Low	And	Extremely Low	Then	Low
If	Medium	And	Extremely Low	Then	Medium Low
If	Medium High	And	Extremely Low	Then	Medium Low
If	High	And	Extremely Low	Then	Medium
If	Very High	And	Extremely Low	Then	Medium High
If	Extremely High	And	Extremely Low	Then	Medium High
If	Extremely Low	And	Very Low	Then	Very Low
If	Very Low	And	Very Low	Then	Very Low
If	Low	And	Very Low	Then	Low
If	Medium Low	And	Very Low	Then	Medium Low
If	Medium	And	Very Low	Then	Medium Low
If	Medium High	And	Very Low	Then	Medium
If	High	And	Very Low	Then	Medium
If	Very High	And	Very Low	Then	Medium High
If	Extremely High	And	Very Low	Then	High
If	Extremely Low	And	Low	Then	Very Low
If	Very Low	And	Low	Then	Low
If	Low	And	Low	Then	Low
If	Medium Low	And	Low	Then	Medium Low
If	Medium	And	Low	Then	Medium
If	Medium High	And	Low	Then	Medium
If	High	And	Low	Then	Medium High
If	Very High	And	Low	Then	Medium High
If	Extremely High	And	Low	Then	High

Table 4.6 Continued

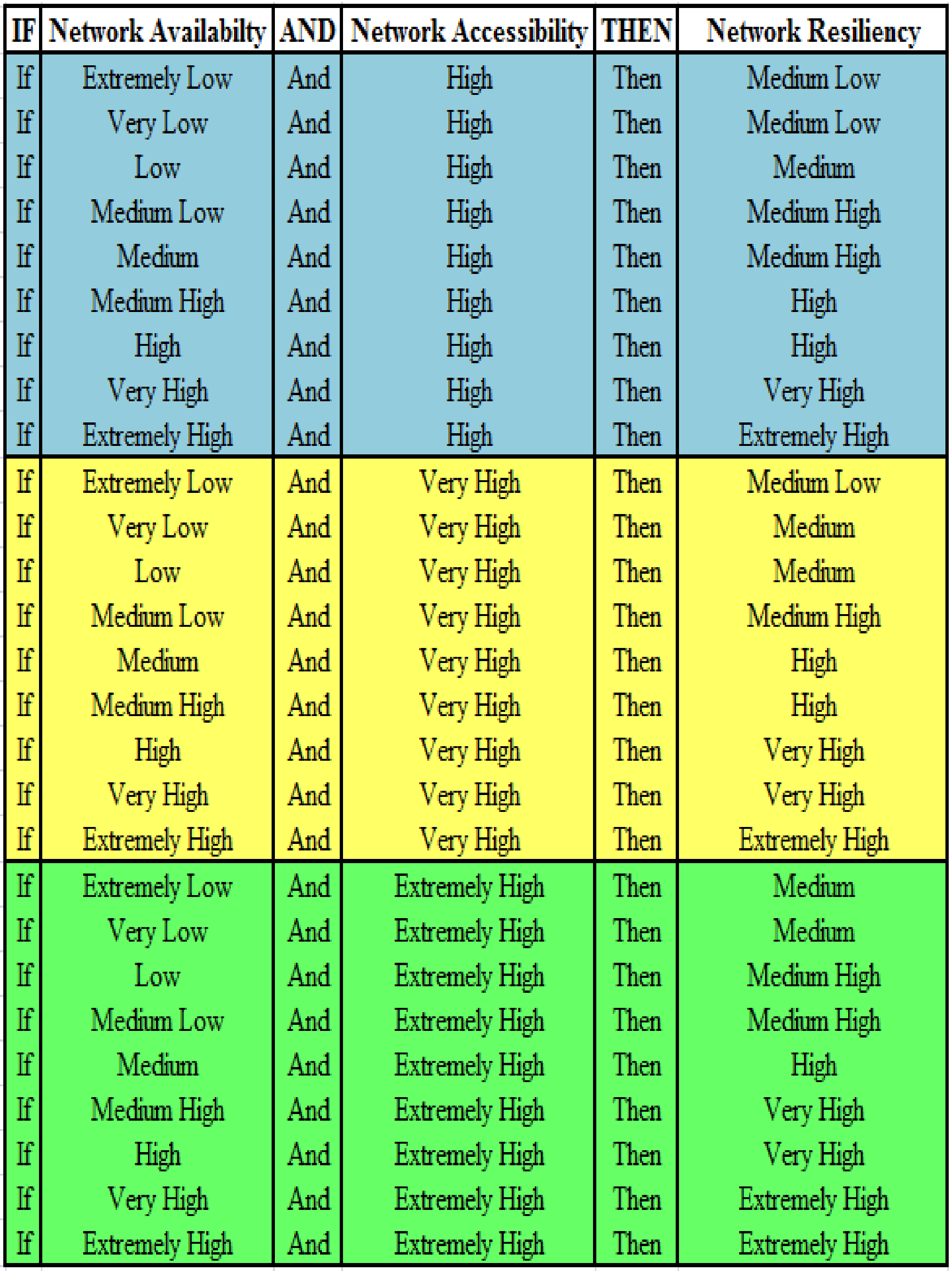
b) Medium Values



IF	Network Availabilty	AND	Network Accessibility	THEN	Network Resiliency
If	Extremely Low	And	Medium Low	Then	Low
If	Very Low	And	Medium Low	Then	Low
If	Low	And	Medium Low	Then	Medium Low
If	Medium Low	And	Medium Low	Then	Medium Low
If	Medium	And	Medium Low	Then	Medium
If	Medium High	And	Medium Low	Then	Medium High
If	High	And	Medium Low	Then	Medium High
If	Very High	And	Medium Low	Then	High
If	Extremely High	And	Medium Low	Then	High
If	Extremely Low	And	Medium	Then	Low
If	Very Low	And	Medium	Then	Medium Low
If	Low	And	Medium	Then	Medium Low
If	Medium Low	And	Medium	Then	Medium
If	Medium	And	Medium	Then	Medium
If	Medium High	And	Medium	Then	Medium High
If	High	And	Medium	Then	High
If	Very High	And	Medium	Then	High
If	Extremely High	And	Medium	Then	Very High
If	Extremely Low	And	Medium High	Then	Low
If	Very Low	And	Medium High	Then	Medium Low
If	Low	And	Medium High	Then	Medium
If	Medium Low	And	Medium High	Then	Medium
If	Medium	And	Medium High	Then	Medium High
If	Medium High	And	Medium High	Then	Medium High
If	High	And	Medium High	Then	High
If	Very High	And	Medium High	Then	Very High
If	Extremely High	And	Medium High	Then	Very High

Table 4.6 Continued

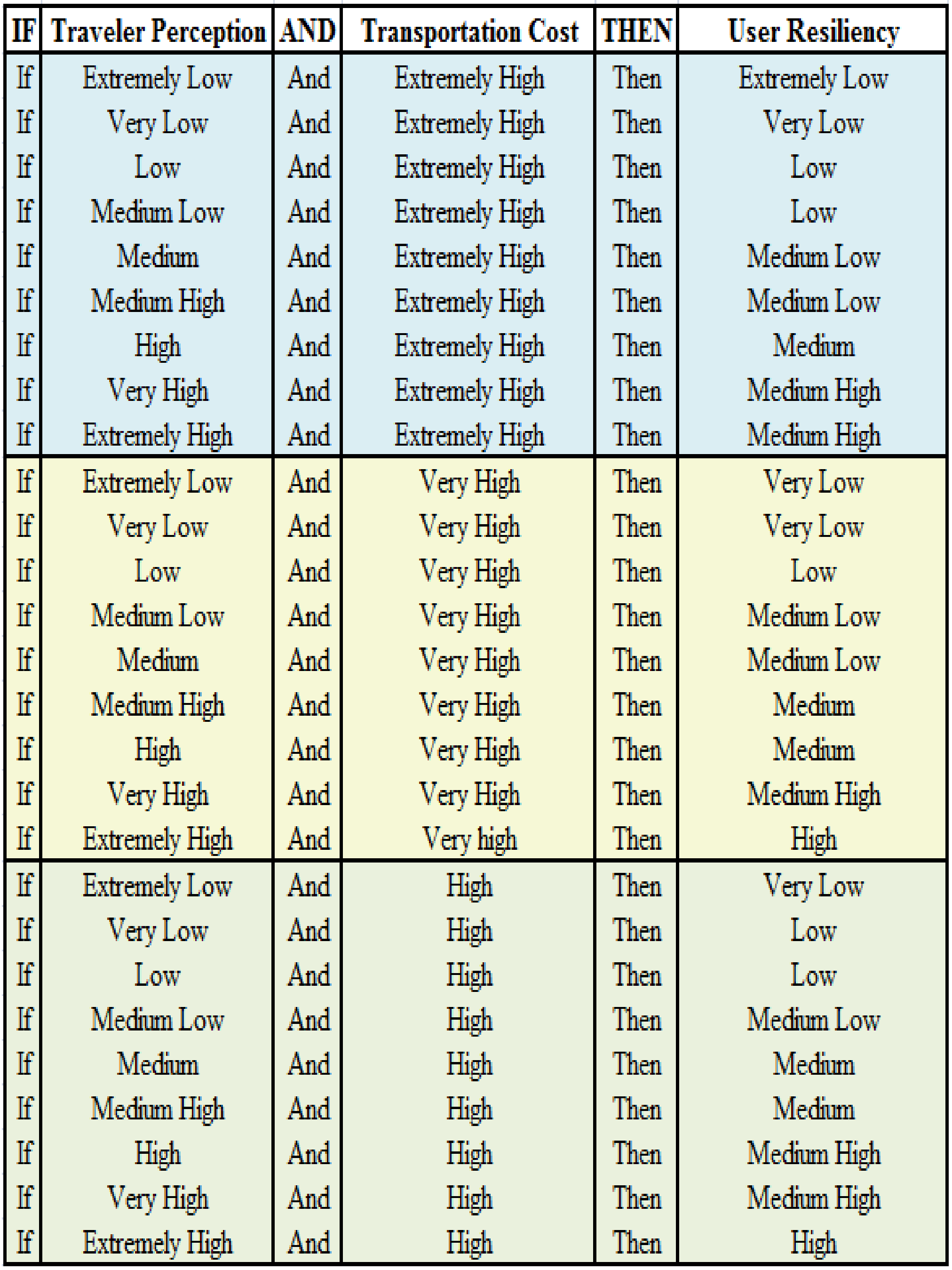
c) High Values



IF	Network Availabilty	AND	Network Accessibility	THEN	Network Resiliency
If	Extremely Low	And	High	Then	Medium Low
If	Very Low	And	High	Then	Medium Low
If	Low	And	High	Then	Medium
If	Medium Low	And	High	Then	Medium High
If	Medium	And	High	Then	Medium High
If	Medium High	And	High	Then	High
If	High	And	High	Then	High
If	Very High	And	High	Then	Very High
If	Extremely High	And	High	Then	Extremely High
If	Extremely Low	And	Very High	Then	Medium Low
If	Very Low	And	Very High	Then	Medium
If	Low	And	Very High	Then	Medium
If	Medium Low	And	Very High	Then	Medium High
If	Medium	And	Very High	Then	High
If	Medium High	And	Very High	Then	High
If	High	And	Very High	Then	Very High
If	Very High	And	Very High	Then	Very High
If	Extremely High	And	Very High	Then	Extremely High
If	Extremely Low	And	Extremely High	Then	Medium
If	Very Low	And	Extremely High	Then	Medium
If	Low	And	Extremely High	Then	Medium High
If	Medium Low	And	Extremely High	Then	Medium High
If	Medium	And	Extremely High	Then	High
If	Medium High	And	Extremely High	Then	Very High
If	High	And	Extremely High	Then	Very High
If	Very High	And	Extremely High	Then	Extremely High
If	Extremely High	And	Extremely High	Then	Extremely High

Table 4.7 User Resiliency Set of Rules.

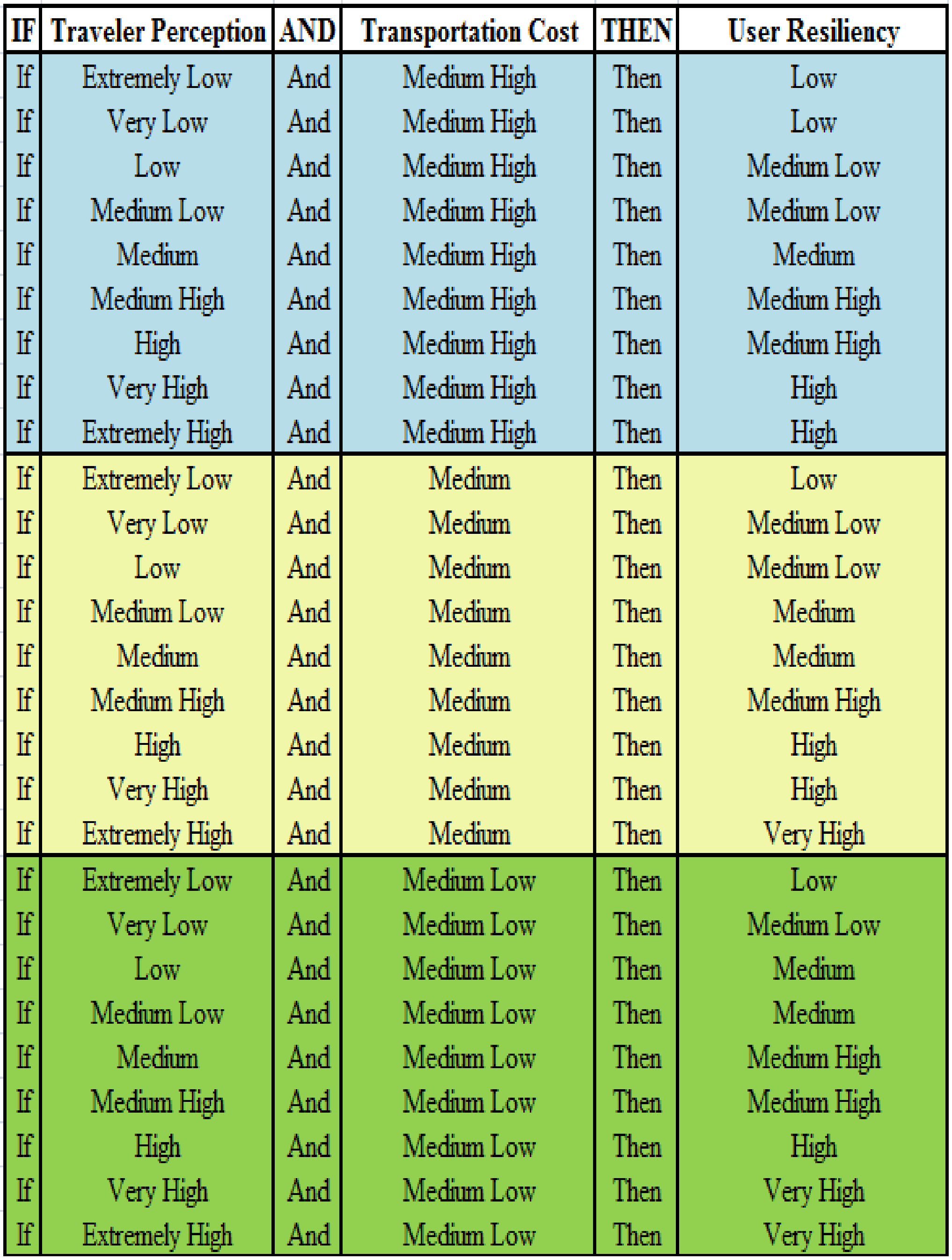
a) Low Values



IF	Traveler Perception	AND	Transportation Cost	THEN	User Resiliency
If	Extremely Low	And	Extremely High	Then	Extremely Low
If	Very Low	And	Extremely High	Then	Very Low
If	Low	And	Extremely High	Then	Low
If	Medium Low	And	Extremely High	Then	Low
If	Medium	And	Extremely High	Then	Medium Low
If	Medium High	And	Extremely High	Then	Medium Low
If	High	And	Extremely High	Then	Medium
If	Very High	And	Extremely High	Then	Medium High
If	Extremely High	And	Extremely High	Then	Medium High
If	Extremely Low	And	Very High	Then	Very Low
If	Very Low	And	Very High	Then	Very Low
If	Low	And	Very High	Then	Low
If	Medium Low	And	Very High	Then	Medium Low
If	Medium	And	Very High	Then	Medium Low
If	Medium High	And	Very High	Then	Medium
If	High	And	Very High	Then	Medium
If	Very High	And	Very High	Then	Medium High
If	Extremely High	And	Very high	Then	High
If	Extremely Low	And	High	Then	Very Low
If	Very Low	And	High	Then	Low
If	Low	And	High	Then	Low
If	Medium Low	And	High	Then	Medium Low
If	Medium	And	High	Then	Medium
If	Medium High	And	High	Then	Medium
If	High	And	High	Then	Medium High
If	Very High	And	High	Then	Medium High
If	Extremely High	And	High	Then	High

Table 4.7 Continued

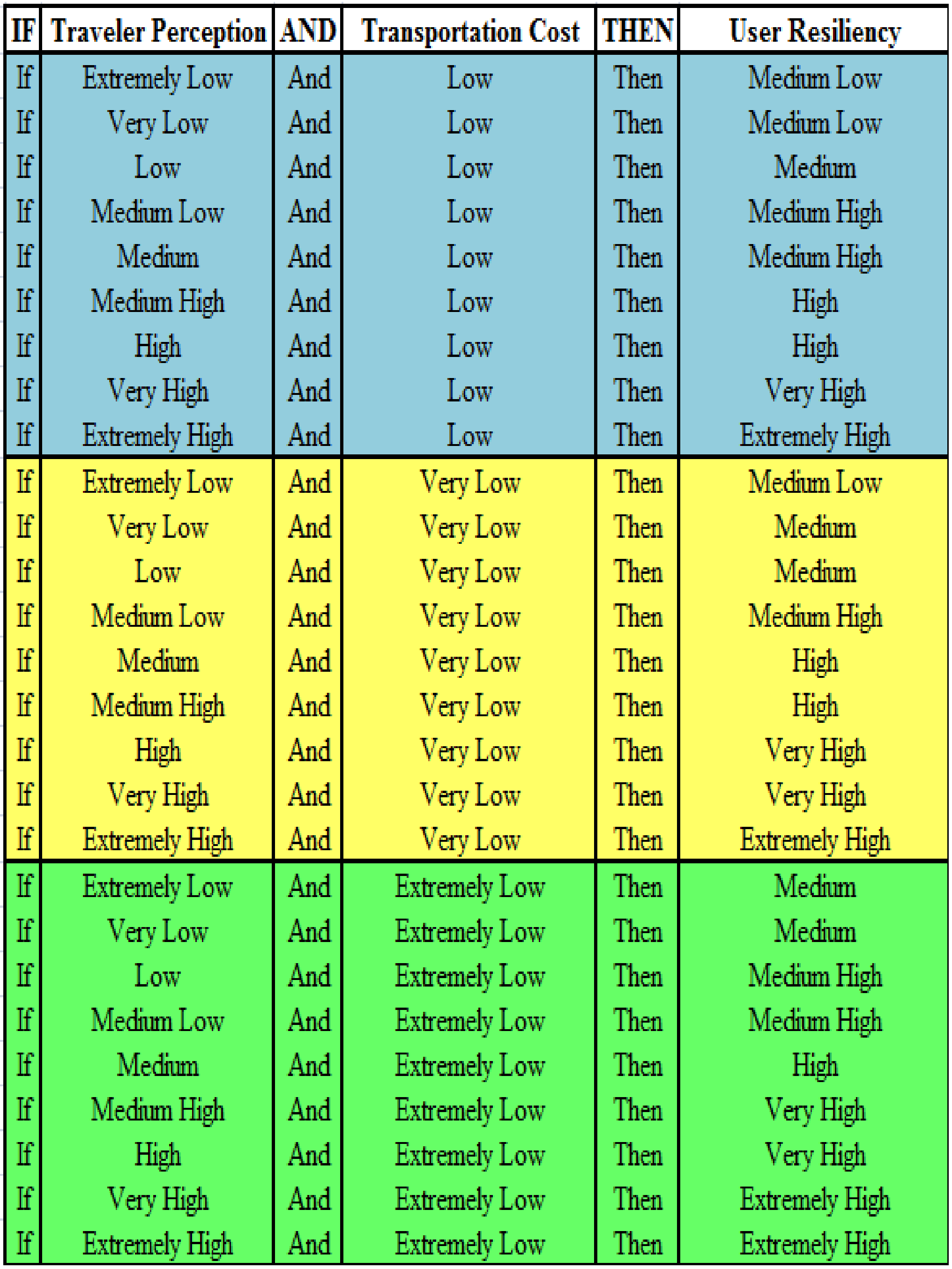
b) Medium Values



IF	Traveler Perception	AND	Transportation Cost	THEN	User Resiliency
If	Extremely Low	And	Medium High	Then	Low
If	Very Low	And	Medium High	Then	Low
If	Low	And	Medium High	Then	Medium Low
If	Medium Low	And	Medium High	Then	Medium Low
If	Medium	And	Medium High	Then	Medium
If	Medium High	And	Medium High	Then	Medium High
If	High	And	Medium High	Then	Medium High
If	Very High	And	Medium High	Then	High
If	Extremely High	And	Medium High	Then	High
If	Extremely Low	And	Medium	Then	Low
If	Very Low	And	Medium	Then	Medium Low
If	Low	And	Medium	Then	Medium Low
If	Medium Low	And	Medium	Then	Medium
If	Medium	And	Medium	Then	Medium
If	Medium High	And	Medium	Then	Medium High
If	High	And	Medium	Then	High
If	Very High	And	Medium	Then	High
If	Extremely High	And	Medium	Then	Very High
If	Extremely Low	And	Medium Low	Then	Low
If	Very Low	And	Medium Low	Then	Medium Low
If	Low	And	Medium Low	Then	Medium
If	Medium Low	And	Medium Low	Then	Medium
If	Medium	And	Medium Low	Then	Medium High
If	Medium High	And	Medium Low	Then	Medium High
If	High	And	Medium Low	Then	High
If	Very High	And	Medium Low	Then	Very High
If	Extremely High	And	Medium Low	Then	Very High

Table 4.7 Continued

c) High Values



IF	Traveler Perception	AND	Transportation Cost	THEN	User Resiliency
If	Extremely Low	And	Low	Then	Medium Low
If	Very Low	And	Low	Then	Medium Low
If	Low	And	Low	Then	Medium
If	Medium Low	And	Low	Then	Medium High
If	Medium	And	Low	Then	Medium High
If	Medium High	And	Low	Then	High
If	High	And	Low	Then	High
If	Very High	And	Low	Then	Very High
If	Extremely High	And	Low	Then	Extremely High
If	Extremely Low	And	Very Low	Then	Medium Low
If	Very Low	And	Very Low	Then	Medium
If	Low	And	Very Low	Then	Medium
If	Medium Low	And	Very Low	Then	Medium High
If	Medium	And	Very Low	Then	High
If	Medium High	And	Very Low	Then	High
If	High	And	Very Low	Then	Very High
If	Very High	And	Very Low	Then	Very High
If	Extremely High	And	Very Low	Then	Extremely High
If	Extremely Low	And	Extremely Low	Then	Medium
If	Very Low	And	Extremely Low	Then	Medium
If	Low	And	Extremely Low	Then	Medium High
If	Medium Low	And	Extremely Low	Then	Medium High
If	Medium	And	Extremely Low	Then	High
If	Medium High	And	Extremely Low	Then	Very High
If	High	And	Extremely Low	Then	Very High
If	Very High	And	Extremely Low	Then	Extremely High
If	Extremely High	And	Extremely Low	Then	Extremely High

4.3.6 Base Resiliency and Transportation Network Resiliency Index

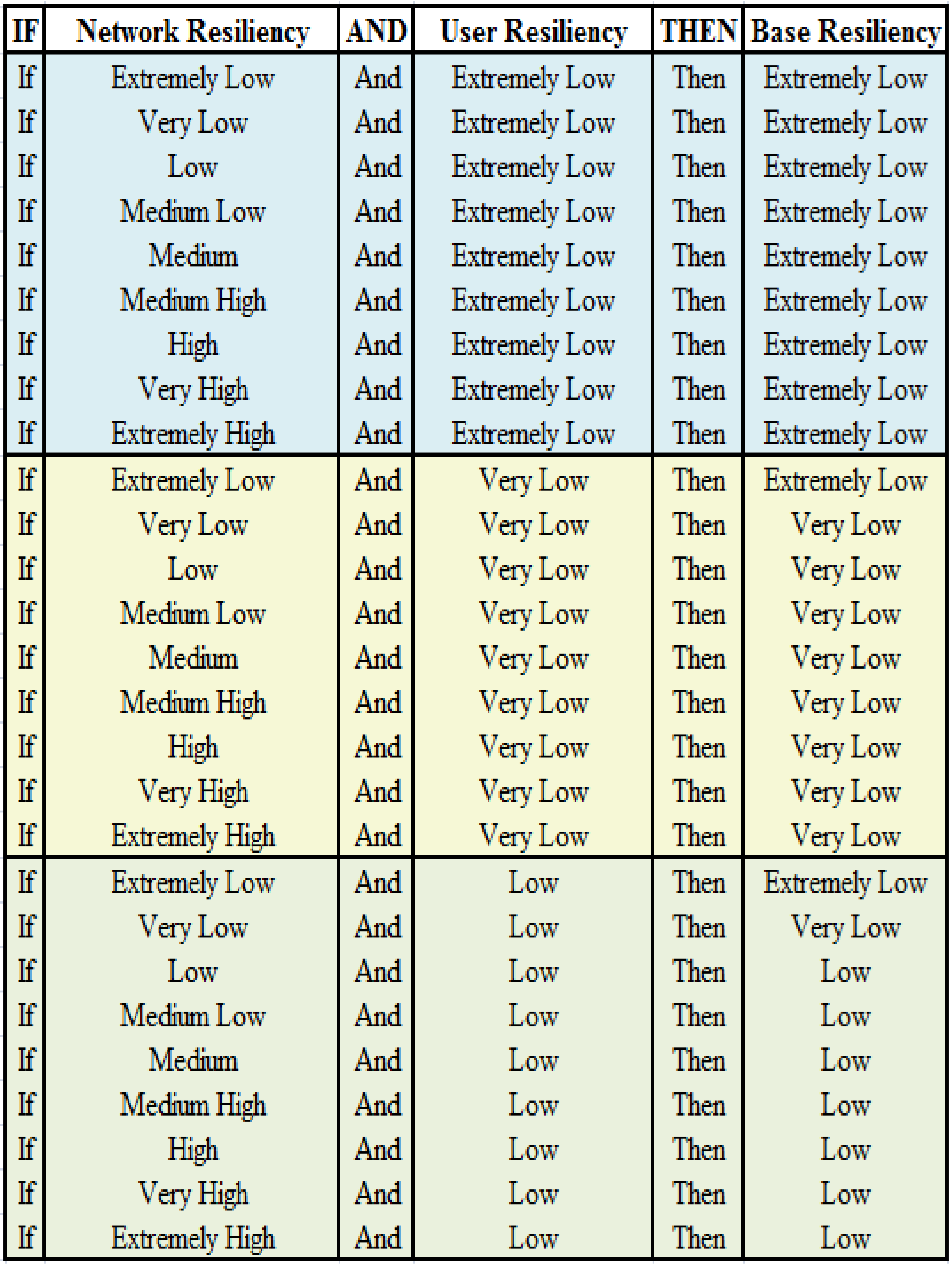
The final two steps of the model consist on combining Network and User Resiliency into a Base Resilience Index and subsequently merging it with the leveraging variable, Network Management, into the Transportation Network Resiliency Index (TNRI).

Base Resilience explains the level of resilience of the network based only on physical properties (e.g., capacity, cost, and alternative mode). For the purpose of this research, Network and User Resilience are considered as impacting equally the Base Resilience, since the user-network relation can be perceived as symbiotic (i.e., one's existence and efficiency depends on the other's). Hence, the final value of this tier would always be the lower of the two resiliencies. The resulting set of rules used to obtain Base Resiliency is presented in Table 4.8, (a) through (c).

Finally, Base Resiliency is fitted to reality using the leveraging variable, Network Management, which measures the level of technology (hardware and software) used by the region to manage their transportation network. As stated in Chapter 3, the Network Management variable effect over the TNRI grows weaker as Base Resilience increases in value. This assumption is based on the idea that as the network becomes more capable of handling demand, the lesser the need for management assistance from the regions DOT, or equivalent department. The set of rules that allows obtaining the final TNRI is presented in Table 4.9.

Table 4.8 Base Resiliency Set of Rules.

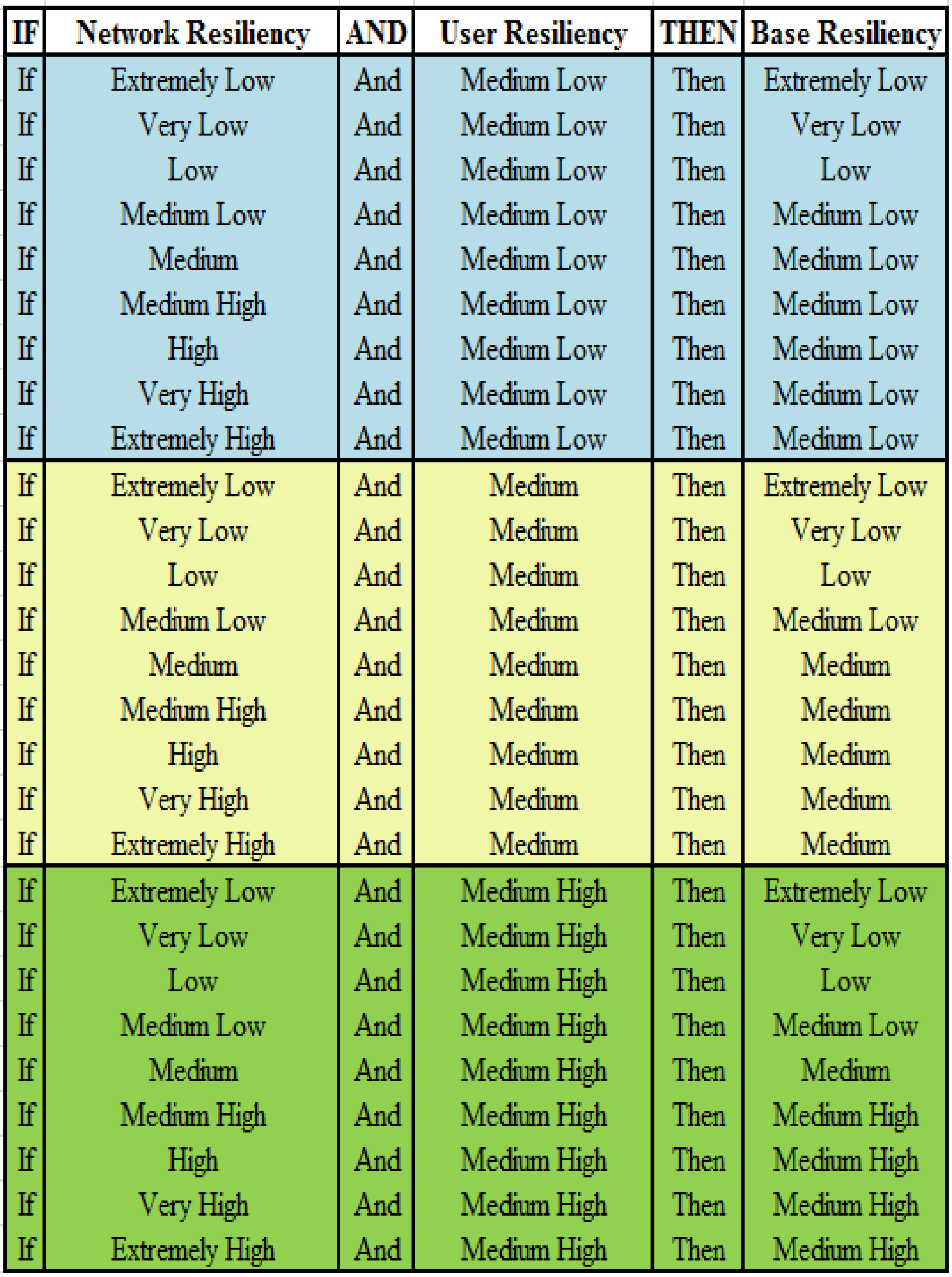
a) Low Values



IF	Network Resiliency	AND	User Resiliency	THEN	Base Resiliency
If	Extremely Low	And	Extremely Low	Then	Extremely Low
If	Very Low	And	Extremely Low	Then	Extremely Low
If	Low	And	Extremely Low	Then	Extremely Low
If	Medium Low	And	Extremely Low	Then	Extremely Low
If	Medium	And	Extremely Low	Then	Extremely Low
If	Medium High	And	Extremely Low	Then	Extremely Low
If	High	And	Extremely Low	Then	Extremely Low
If	Very High	And	Extremely Low	Then	Extremely Low
If	Extremely High	And	Extremely Low	Then	Extremely Low
If	Extremely Low	And	Very Low	Then	Extremely Low
If	Very Low	And	Very Low	Then	Very Low
If	Low	And	Very Low	Then	Very Low
If	Medium Low	And	Very Low	Then	Very Low
If	Medium	And	Very Low	Then	Very Low
If	Medium High	And	Very Low	Then	Very Low
If	High	And	Very Low	Then	Very Low
If	Very High	And	Very Low	Then	Very Low
If	Extremely High	And	Very Low	Then	Very Low
If	Extremely Low	And	Low	Then	Extremely Low
If	Very Low	And	Low	Then	Very Low
If	Low	And	Low	Then	Low
If	Medium Low	And	Low	Then	Low
If	Medium	And	Low	Then	Low
If	Medium High	And	Low	Then	Low
If	High	And	Low	Then	Low
If	Very High	And	Low	Then	Low
If	Extremely High	And	Low	Then	Low

Table 4.8 Continued

b) Medium Values



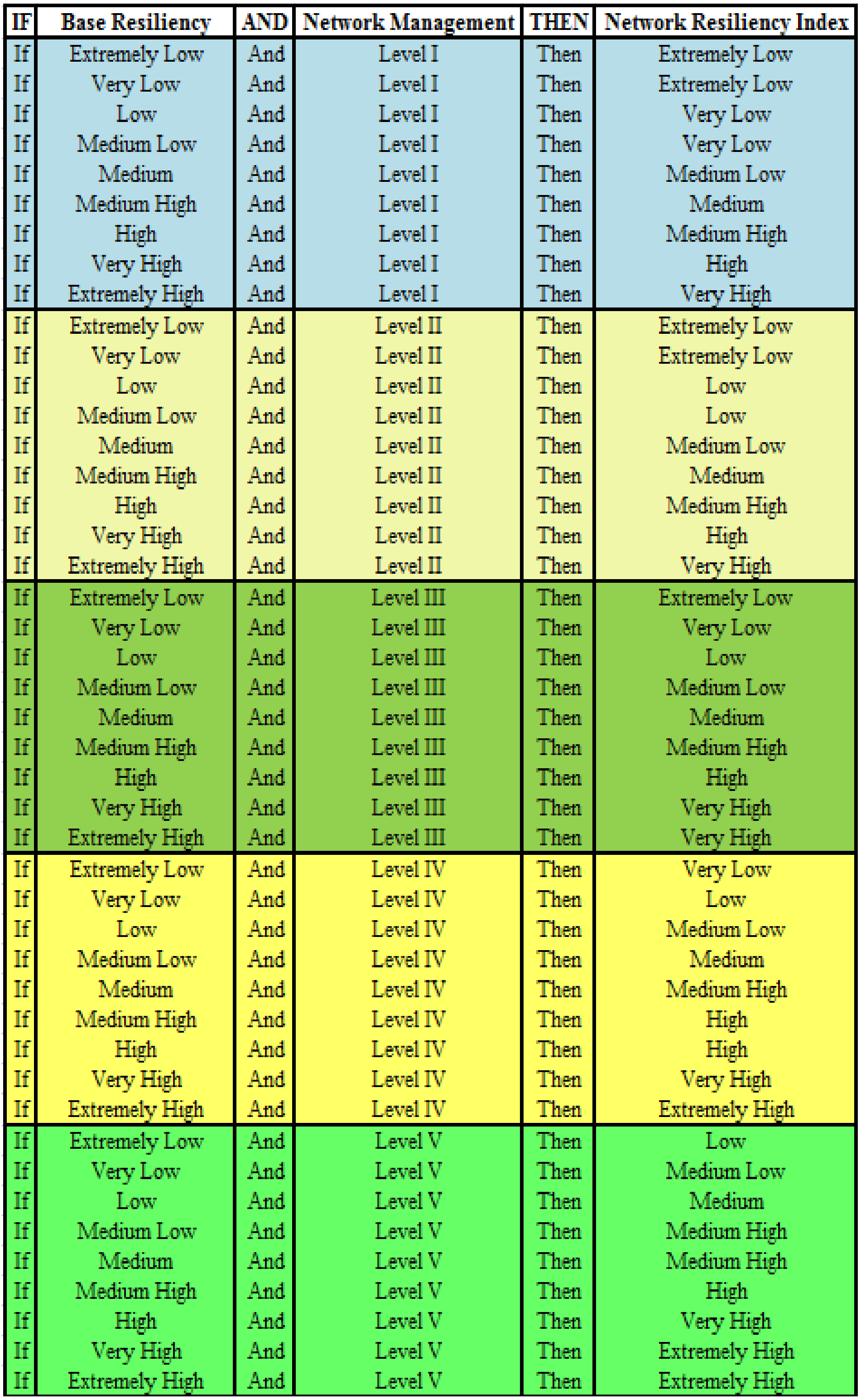
IF	Network Resiliency	AND	User Resiliency	THEN	Base Resiliency
If	Extremely Low	And	Medium Low	Then	Extremely Low
If	Very Low	And	Medium Low	Then	Very Low
If	Low	And	Medium Low	Then	Low
If	Medium Low	And	Medium Low	Then	Medium Low
If	Medium	And	Medium Low	Then	Medium Low
If	Medium High	And	Medium Low	Then	Medium Low
If	High	And	Medium Low	Then	Medium Low
If	Very High	And	Medium Low	Then	Medium Low
If	Extremely High	And	Medium Low	Then	Medium Low
If	Extremely Low	And	Medium	Then	Extremely Low
If	Very Low	And	Medium	Then	Very Low
If	Low	And	Medium	Then	Low
If	Medium Low	And	Medium	Then	Medium Low
If	Medium	And	Medium	Then	Medium
If	Medium High	And	Medium	Then	Medium
If	High	And	Medium	Then	Medium
If	Very High	And	Medium	Then	Medium
If	Extremely High	And	Medium	Then	Medium
If	Extremely Low	And	Medium High	Then	Extremely Low
If	Very Low	And	Medium High	Then	Very Low
If	Low	And	Medium High	Then	Low
If	Medium Low	And	Medium High	Then	Medium Low
If	Medium	And	Medium High	Then	Medium
If	Medium High	And	Medium High	Then	Medium High
If	High	And	Medium High	Then	Medium High
If	Very High	And	Medium High	Then	Medium High
If	Extremely High	And	Medium High	Then	Medium High

Table 4.8 Continued

c) High Values

IF	Network Resiliency	AND	User Resiliency	THEN	Base Resiliency
If	Extremely Low	And	High	Then	Extremely Low
If	Very Low	And	High	Then	Very Low
If	Low	And	High	Then	Low
If	Medium Low	And	High	Then	Medium Low
If	Medium	And	High	Then	Medium
If	Medium High	And	High	Then	Medium High
If	High	And	High	Then	High
If	Very High	And	High	Then	High
If	Extremely High	And	High	Then	High
If	Extremely Low	And	Very High	Then	Extremely Low
If	Very Low	And	Very High	Then	Very Low
If	Low	And	Very High	Then	Low
If	Medium Low	And	Very High	Then	Medium Low
If	Medium	And	Very High	Then	Medium
If	Medium High	And	Very High	Then	Medium High
If	High	And	Very High	Then	High
If	Very High	And	Very High	Then	Very High
If	Extremely High	And	Very High	Then	Very High
If	Extremely Low	And	Extremely High	Then	Extremely Low
If	Very Low	And	Extremely High	Then	Very Low
If	Low	And	Extremely High	Then	Low
If	Medium Low	And	Extremely High	Then	Medium Low
If	Medium	And	Extremely High	Then	Medium
If	Medium High	And	Extremely High	Then	Medium High
If	High	And	Extremely High	Then	High
If	Very High	And	Extremely High	Then	Very High
If	Extremely High	And	Extremely High	Then	Extremely High

Table 4.9 Network Resilience Index Set of Rules.



IF	Base Resiliency	AND	Network Management	THEN	Network Resiliency Index
If	Extremely Low	And	Level I	Then	Extremely Low
If	Very Low	And	Level I	Then	Extremely Low
If	Low	And	Level I	Then	Very Low
If	Medium Low	And	Level I	Then	Very Low
If	Medium	And	Level I	Then	Medium Low
If	Medium High	And	Level I	Then	Medium
If	High	And	Level I	Then	Medium High
If	Very High	And	Level I	Then	High
If	Extremely High	And	Level I	Then	Very High
If	Extremely Low	And	Level II	Then	Extremely Low
If	Very Low	And	Level II	Then	Extremely Low
If	Low	And	Level II	Then	Low
If	Medium Low	And	Level II	Then	Low
If	Medium	And	Level II	Then	Medium Low
If	Medium High	And	Level II	Then	Medium
If	High	And	Level II	Then	Medium High
If	Very High	And	Level II	Then	High
If	Extremely High	And	Level II	Then	Very High
If	Extremely Low	And	Level III	Then	Extremely Low
If	Very Low	And	Level III	Then	Very Low
If	Low	And	Level III	Then	Low
If	Medium Low	And	Level III	Then	Medium Low
If	Medium	And	Level III	Then	Medium
If	Medium High	And	Level III	Then	Medium High
If	High	And	Level III	Then	High
If	Very High	And	Level III	Then	Very High
If	Extremely High	And	Level III	Then	Very High
If	Extremely Low	And	Level IV	Then	Very Low
If	Very Low	And	Level IV	Then	Low
If	Low	And	Level IV	Then	Medium Low
If	Medium Low	And	Level IV	Then	Medium
If	Medium	And	Level IV	Then	Medium High
If	Medium High	And	Level IV	Then	High
If	High	And	Level IV	Then	High
If	Very High	And	Level IV	Then	Very High
If	Extremely High	And	Level IV	Then	Extremely High
If	Extremely Low	And	Level V	Then	Low
If	Very Low	And	Level V	Then	Medium Low
If	Low	And	Level V	Then	Medium
If	Medium Low	And	Level V	Then	Medium High
If	Medium	And	Level V	Then	Medium High
If	Medium High	And	Level V	Then	High
If	High	And	Level V	Then	Very High
If	Very High	And	Level V	Then	Extremely High
If	Extremely High	And	Level V	Then	Extremely High
]

4.4 Case Study in Santo Domingo

To illustrate the potential application of the proposed resiliency assessment framework, a case study in Santo Domingo, Dominican Republic was examined. Even though the methodology presented is not case-dependent, the consequences of a disaster event are. In addition, the degree of impact of the event can be linked to the network's pre-event level of resiliency. For this research, the scenario consists on the occurrence of a hurricane category 4+ in the Saffir-Simpson scale (S&S), which passes right over the city of Santo Domingo, capital of the Dominican Republic (see Figure 4.4 below), analyzing the possible repercussion based on the network's current characteristics. The case study considers the coastal region of Santo Domingo as data in that area was robust.

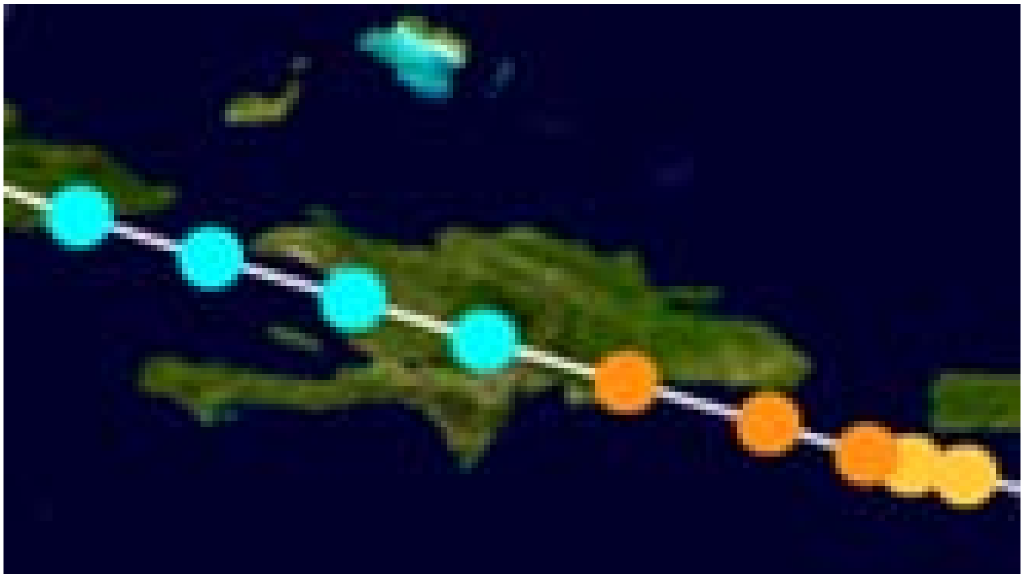


Figure 4.4 Dominican Republic's Hurricane X Scenario. Source: Wikimedia Commons (http://commons.wikimedia.org/wiki/File:1930_Dominican_Republic_hurricane_track.png).

4.4.1 The Case of the Dominican Republic

The Dominican Republic (DR) is a country that belongs to the Greater Antilles archipelago in the Caribbean region. The location of the DR lies in the middle of the hurricane belt and is vulnerable to severe storms from June to October (CIA, 2010).

When it comes to classifying this type of natural hazard, the Saffir-Simpson Hurricane Wind Scale is a 1 to 5 (HC1-HC5) categorization based on the hurricane's intensity at the indicated time. The scale generalizes the type and amount of damage as well as the expected consequences associated with winds of a given intensity (NHC, 2009). For a HC4+, impact can be generalized as:

- Massive damage to power lines and poles that would result in power outages that could last from a few weeks to possibly months.
- Long-term clean water shortages (i.e., shortages can last for several weeks or months).
- Collapse of all walls and loss of the roof structure in poorly constructed homes; severe damage with loss of most of the roof structure and/or some exterior walls in well-built homes.
- Widespread flooding in low-lying lands, riverbanks and lands adjacent to gullies, and possible failure of draining systems due to obstruction. As a consequence of the unstable ground conditions, caused by the excessive and long-term presence of water, the transportation infrastructure, potentially, could be damaged.

It is assumed that the whole country would be affected by the hurricane as category 4, or stronger, hurricanes have a wide radius which would encompass the area of the DR, which is 48,320 sq. km. (CIA, 2010). For the regions where the most intense portions of the storm directly effect, the transportation systems will become entirely interrupted.

The analysis of the impacts of Hurricane X is performed at two levels, first, its effects on the center of the metropolitan area of Santo Domingo (the National District) and second, its effects on the rest of the Santo Domingo Province (see Figure 4.5 to see some of the province's counties). Both levels are analyzed concurrently in order to account for: a) the correlation between the inter- and intra-city traffic, and b) the effects on the commuter population. Figure 4.5 illustrates the area of the Santo Domingo Province, the city, and other localities within its area.

Hurricane X's impacts on the transportation network would be, mainly, widespread flooding, obstruction of access to key arterial, and damages to key infrastructures. This would ultimately restrict the heavily traveled West-East and North-South Santo Domingo commuter corridors. Figure 4.6 shows the Santo Domingo network at the center of its metropolitan area from an altitude of 30,000 feet. Also, to accentuate the network's structure characteristics, the figure highlights the main arterials and secondary streets.

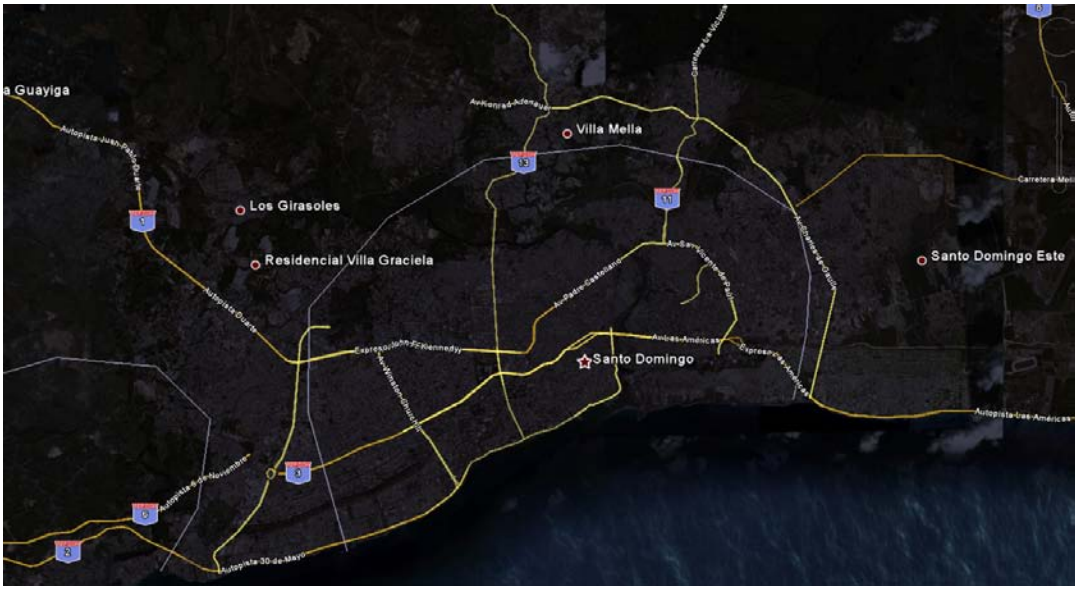


Figure 4.5 Santo Domingo and its Vicinity. Source: Google Earth.

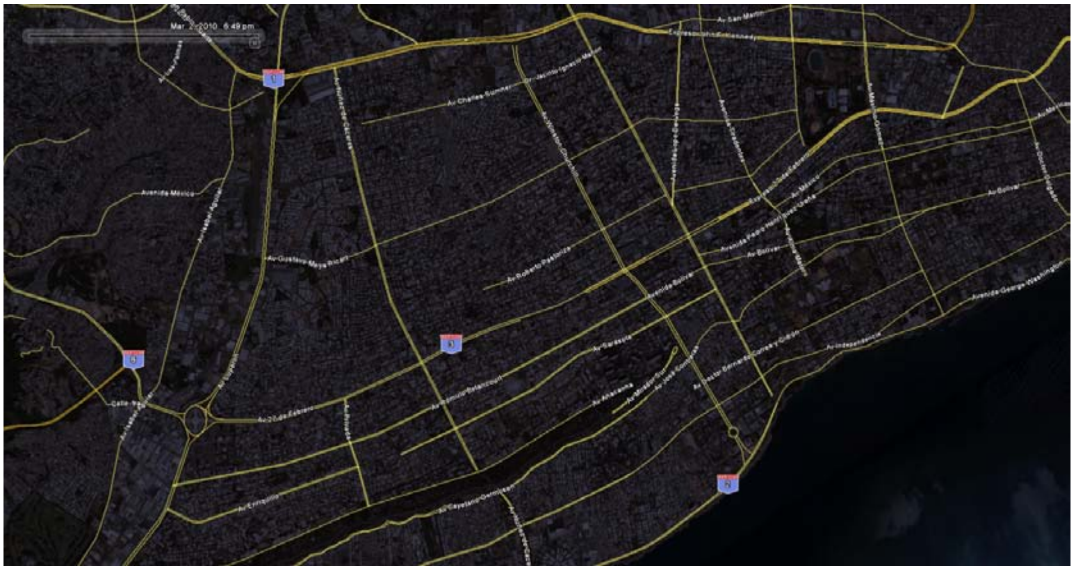


Figure 4.6 Santo Domingo's Transportation Network. Source: Google Earth.

Hurricane X would cause temporally blockage of access to the main arterials and secondary streets to the city of Santo Domingo; and in greater detail, the main causes for this to occur are:

Santo Domingo is characterized by a large amount of electricity and telecommunication cables, trees, and billboard advertising. These potential hazardous elements raise the probabilities of street access blockage. The strong winds of a HC4+ would likely cause these elements to fall, blocking the access to the streets. In the center of the metropolitan area, the most important arterials are the John F. Kennedy Avenue, 30 de Mayo Highway, and the 27 de Febrero Avenue (avenues 1, 2 and 3, respectively, in Figure 4.6). These links distribute the heavy West-East traffic flow as well as the one coming from the northern part of Santo Domingo into the city itself; hence the impeded access to these arterials due roadway obstructions could have severe impacts on the network.

Santo Domingo is located at the south coastal region of the Dominican Republic towards the center of the island, and it is sensitive to sea level rise. In addition, the metropolitan center’s topographic profile partially resembles a sinusoidal curve shape. That is, it has low altitude near the coast (below 60 ft. above sea level), higher altitude around the middle (ranging from 180-200 ft. above sea level near the 27 de Febrero Avenue), and it drops again near the John F. Kennedy Avenue (to 150-170 ft. above sea level). This makes the metropolitan area more likely to suffer from extensive flooding and foundations scouring. In addition, the drainage system has been deficient under extreme conditions, which, combined with the topography profile, causes a high reduction of network accessibility and availability, even at higher elevation levels. These geographical limitations can cause situations where temporary and/or permanent damage occurs in transportation infrastructure.

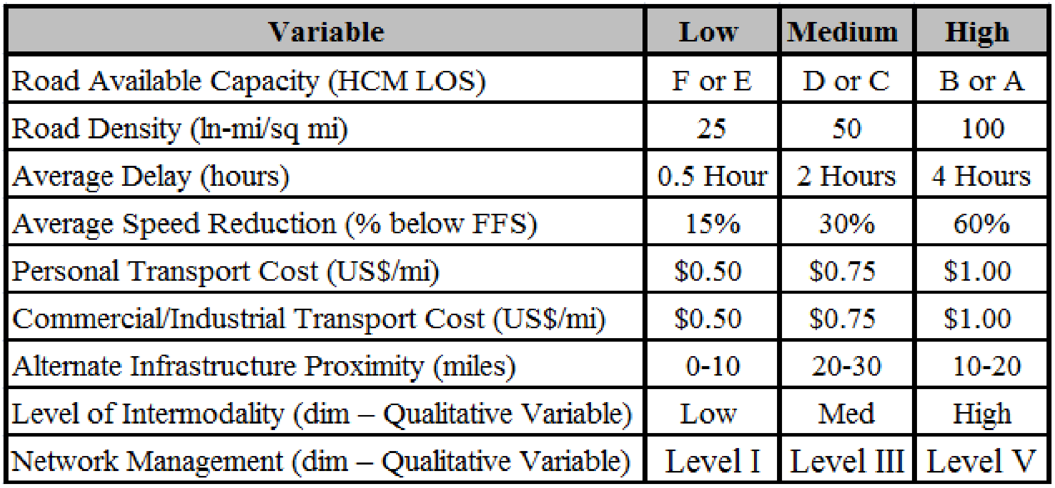
Finally, due to wind and water damage, electricity around the city could become limited. The transportation system would likely to experience severe losses in its components (e.g., signals and in-situ data collection equipment), complicating traffic management and the recovery process.

4.4.2 Santo Domingo Resiliency Model Inputs

The data used in this case study was compiled from public available data and private researches performed by the Autoridad Metropolitana de Santo Domingo (AMET, 2001) - which is the department equivalent to an MPO in the United States - and Jhael Isa (2010). This data set provides information of the Santo Domingo network at the link level, explaining the behavior of an extensive array of main and secondary arterials, providing sufficient information from which behavior at the network level can be inferred. It should be stated that this may not be the case in all regions; hence careful analysis should be performed before using link level data to identify network level behavior. The complete translated data sets are presented in the Appendix A. Expert judgment had to be used for some variable as the data were not available for the case study.

Table 4.10 illustrates the range of each variable used in this case study.

Table 4.10 Variables Ranges for Santo Domingo.



Variable	Low	Medium	High
Road Available Capacity (HCM LOS)	F or E	D or C	B or A
Road Density (ln-mi/sq mi)	25	50	100
Average Delay (hours)	0.5 Hour	2 Hours	4 Hours
Average Speed Reduction (% below FFS)	15%	30%	60%
Personal Transport Cost (US$/mi)	$0.50	$0.75	$1.00
Commercial/Industrial Transport Cost (US$/mi)	$0.50	$0.75	$1.00
Alternate Infrastructure Proximity (miles)	0-10	20-30	10-20
Level of Intermodality (dim – Qualitative Variable)	Low	Med	High
Network Management (dim – Qualitative Variable)	Level I	Level III	Level V

Prices of variables subject to exchange rate calculated using April 2010's exchange rate published by the Central Bank (CB) of the DR, which was U.S.$1.00 = R.D.$ 36.4 (CB, 2010). For this case study, the value of each variable was specified, as well as the respective membership function used in the process of *fuzzifying* the inputs. In detail:

Road available capacity. This variable was measured based on an average LOS index of the network. Isa (2010) conducted an emission analysis of the Santo Domingo network, focusing on the most important links, by using daily average speed and volume. Since resilience is crucial to overcome extreme conditions, peak-hour speed measurements are needed. Due to limitations on the availability of information, for this research the peak-hour speed is assumed to be 50% of the daily average speed obtained by Isa (2010). Classification of the different arterials was found using the HCM Arterial LOS table (1994), which indicates the level of service of an arterial based on its speed at a given time. Subsequently, each LOS was converted to a numerical value by assigning each letter from A to F with a number from 1 to 6, A being 6 and F, 1. This served as a capacity index for each letter-level (see Table 4.11). Finally, the average was calculated for the entire Santo Domingo network. This average was 2.29 and corresponded to a *LOS D*.

The value was then *fuzzified* by introducing it to its membership function (see Figure 4.7). As can be noticed in the plot bellow, any value lower than one is considered as an absolute member of the LOS F group.

Table 4.11 LOS Range Value.

LOS	Upper Limit
LOS A	6.00
LOS B	5.00
LOS C	4.00
LOS D	3.00
LOS E	2.00
LOS F	1.00

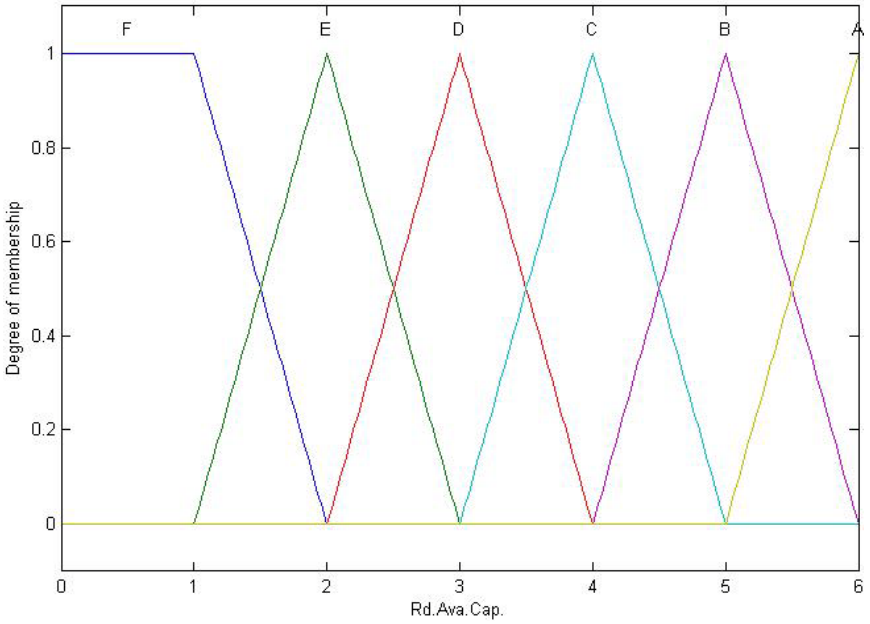


Figure 4.7 Road Available Capacity Membership Function.

Road density. This variable was measured as the density of lane miles per square mile. At the time of completion of this research, no study was found with the necessary information specifically for the Santo Domingo area. Based on the fact that Santo Domingo is a city, with a population of more than 3 million people, combined with empirical engineering judgment, this variable was located at the high section of the membership function. To confirm this assumption, a total lane-miles analysis was made for a busy residential/commercial area between two arterials (see Figure 4.8). The value of lane-mile per square-mile was obtained from a simple linear interpolation. The result was of approximately 90 ln-mi/sq-mi.

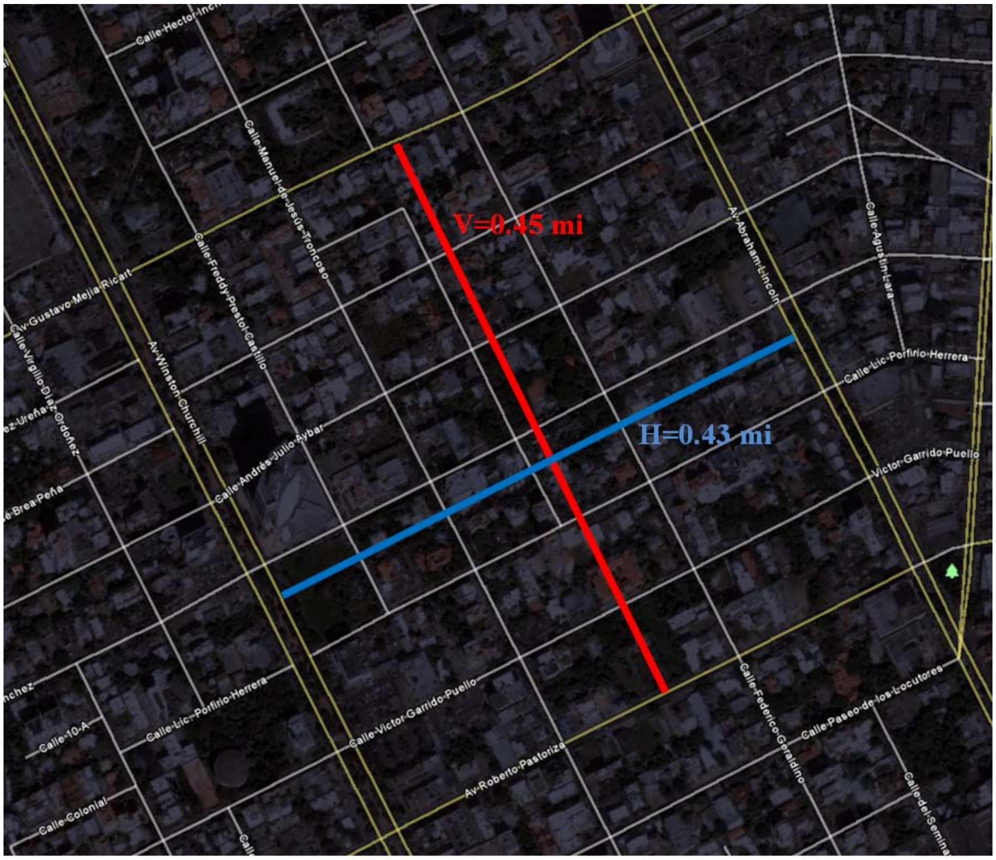


Figure 4.8 Road Density of Santo Domingo.

The approximate road density value obtained was then *fuzzified* using the membership function presented in Figure 4.9. For the purpose of this research, any value lower than 25 was considered as an absolute member of the 25 group (which is a low measure), and any value greater than 75 was considered as an absolute member of the 100 group (which is a high measure).

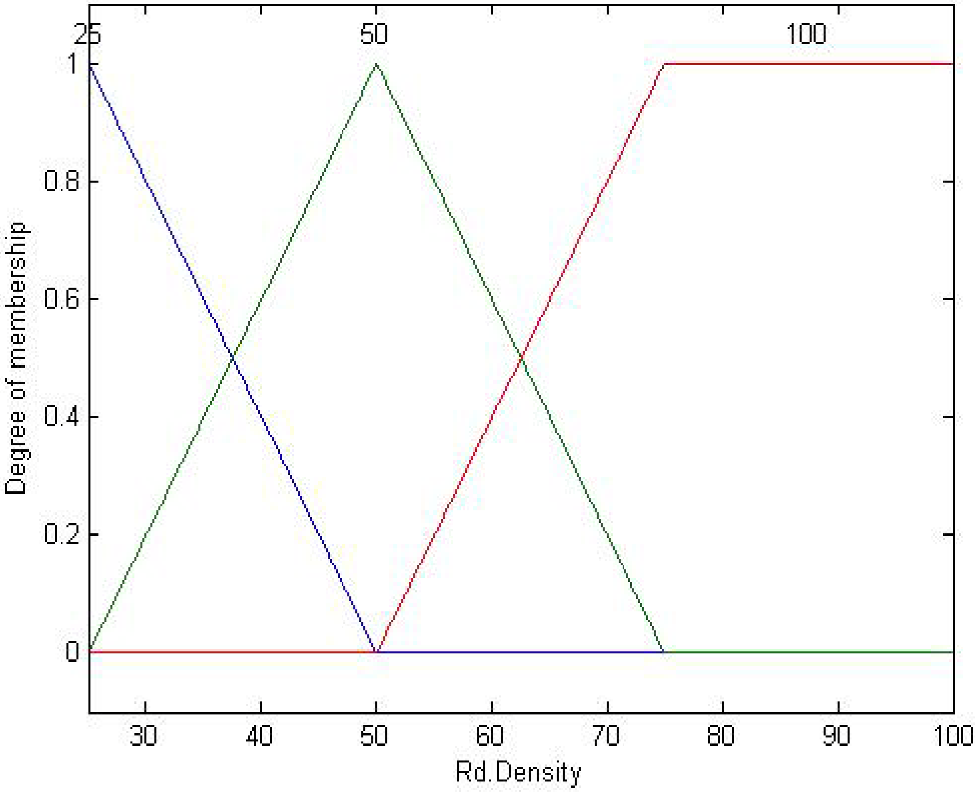


Figure 4.9 Road Density Membership Function.

Alternate infrastructure proximity. This variable was measured as the distance between primary infrastructures. As stated in Chapter 3, this variable works better when its value is around the middle range (10-20 miles) to avoid inclusion in the disaster area and exclusion as a viable alternative. An average North-South and East-West distance between infrastructures were obtained using the ruler tool of Google Earth, around 4 miles (from the Los Proceres Avenue to the 30 de Mayo Highway) and 7 miles (from the Luperon Avenue to the Fco. Del Rosario Sanchez Avenue), respectively. Therefore, this variable was located within the Low range. In this research, the distance was assumed to be on average 5 miles. This distance was then *fuzzified* using the membership function depicted in Figure 4.10. Any distance greater than 30 miles can be either disregarded or assumed to form part fully of the 20-30 miles group.

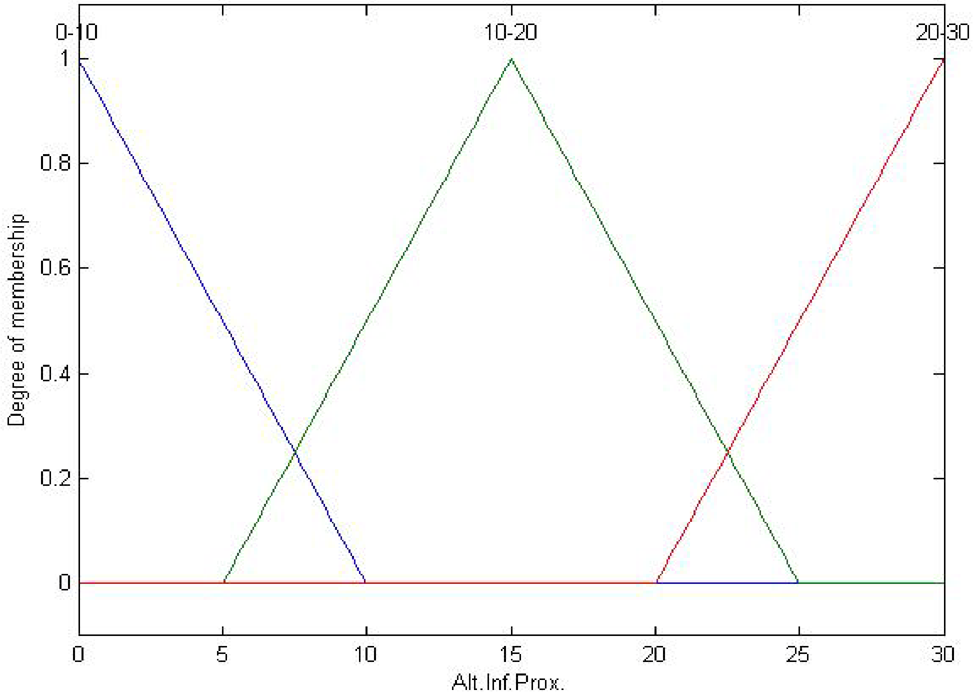


Figure 4.10 Alternate Infrastructure Proximity.

Level of intermodality. This variable was measured as the availability of modal transfer within the network. As stated previously, Santo Domingo lacks variety of modal choices, and the ones that exist have average interconnection. Santo Domingo has two airports within its vicinity, one international and one commercial, one metro line, and a second line under construction, and, even though not reliable time-wise, an extensive array of available car-transit routes. Based on the previous explanation, this variable was assumed to have a qualitative value of medium-low (2.5 in a 10-based scale). This qualitative value was then translated into a scale of 0 to 10, which facilitates the use of the membership function shown in Figure 4.11 to *fuzzify* the resulting value.

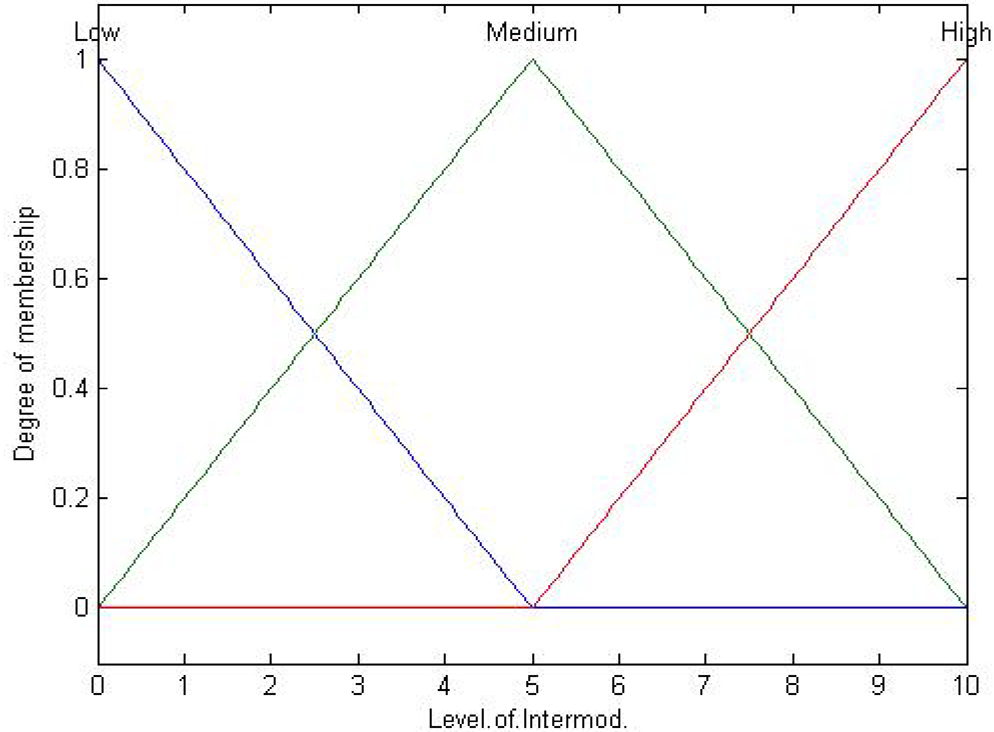


Figure 4.11 Level of Intermodality Membership Function.

Average delay. This variable was measured as the average delay of travel within the network. During peak hours the network becomes very congested, doubling and even tripling standard travel times. At the same time, Santo Domingo counts with a very redundant network, as was demonstrated with the high value obtained with the Road Density variable, which helps to ameliorate the high congestion. A percentage of delayed travel time was calculated from the data provided in Isa (2010), by differentiating the free-flow travel time and peak-hours travel time and dividing it by the free-flow travel time. The value obtained was approximately 320%, supporting the notion that during peak-hours travel time triples in Santo Domingo. Combining the information obtained from Isa with empirical observation, the average delay during peak-hours in the Santo Domingo network can be assumed to be around 1 hour. Figure 4.12 illustrates the membership function of this variable. As can be noticed, any delay greater than 4 hours is assumed to be in the 4 hour group.

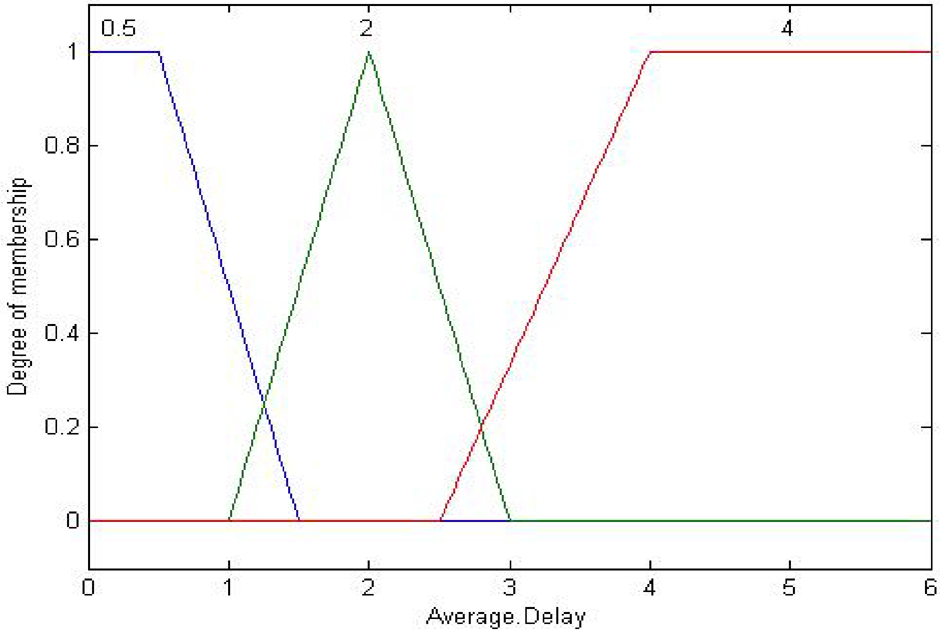


Figure 4.12 Average Delay Membership Function.

Average speed reduction. This variable was measured as a percentage of speed reduction. An average speed reduction was found from the data gathered by Isa (2010), and assuming that the average peak hour speed is 50% of the daily average speed. The percentage was calculated as the difference between peak-hours speed and free flow speed (speed limit) divided by the free flow speed. The value found was 66.29%, which is located in the high rage group shown in Figure 4.13.

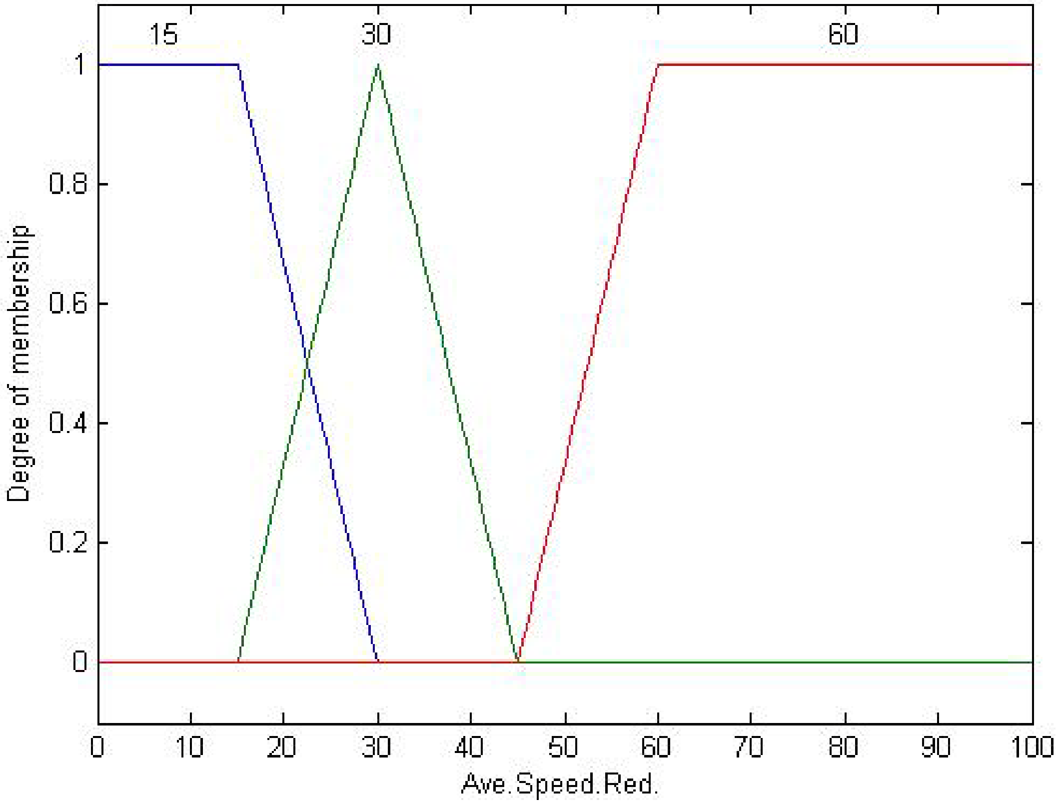
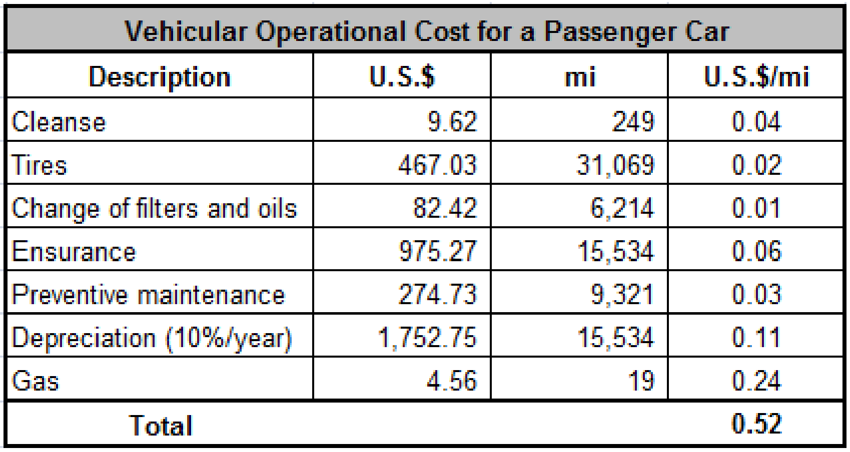


Figure 4.13 Average Seep Reduction Membership Function.

Personal transport cost. This variable was measured as the vehicular operation cost (VOC) of a passenger vehicle. Using Santo Domingo’s information about gas and maintenance services (as of 04/2010), a value of U.S.$0.52/mi was obtained (see Table 4.12). The membership function of this variable is presented in Figure 4.14, and since the Commercial/Industrial Transport Cost variable have equal logic and ranges, this figure can also illustrate its membership function.

Table 4.12 VOC for a Passenger Car in Santo Domingo.



Vehicular Operational Cost for a Passenger Car			
Description	**U.S.$**	**mi**	**U.S.$/mi**
Cleanse	9.62	249	0.04
Tires	467.03	31,069	0.02
Change of filters and oils	82.42	6,214	0.01
Ensurance	975.27	15,534	0.06
Preventive maintenance	274.73	9,321	0.03
Depreciation (10%/year)	1,752.75	15,534	0.11
Gas	4.56	19	0.24
Total			**0.52**

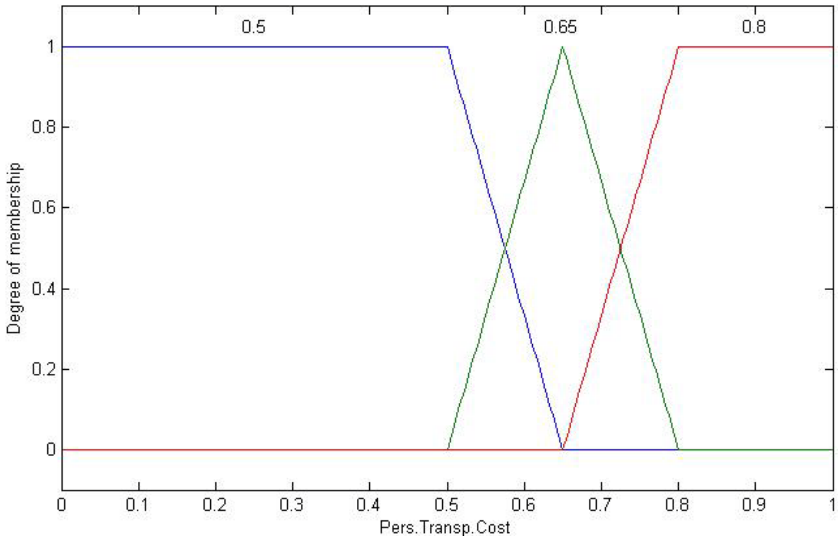


Figure 4.14 Personal and Commercial/Industrial Transport Cost Membership Function.

Commercial/industrial transport cost. This variable was measured as the vehicular operation cost of a common heavy vehicle (e.g., WB-50 and WB-100T). By empirical observation in the Santo Domingo area, the VOC of heavy vehicles is found to be nearly identical to the VOC of passenger cars. Hence, for the purpose of this research, this variable has the same value as the Personal Transport Cost variable, which, in this case is U.S.$0.52/mi (see Figure 4.14 for membership function).

Network management. This variable refers to the activities, methods, procedures, and tools that pertain to the operation, administration, maintenance, and provision of network systems (Clemm, 2006). Santo Domingo's network is characterized by a lack of sophisticated management hardware. Nonetheless, it has continuous development and acquirement of technologies that help the optimization of the network. In this manner, it was determined that the network management status of Santo Domingo is at Level IV. Its membership function is presented in Figure 4.15.

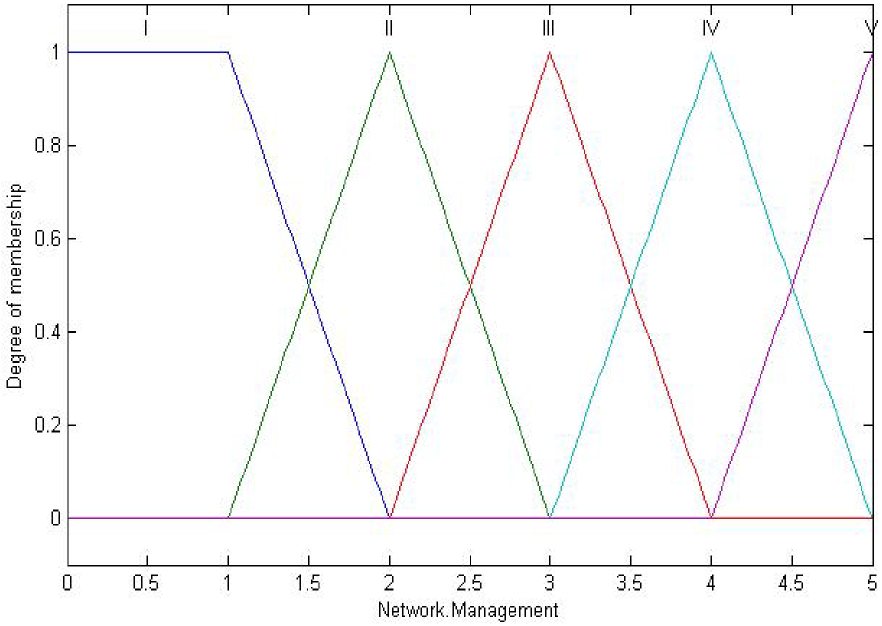


Figure 4.15 Network Management Membership Function.

4.4.3 FIS Model Results

The transportation network resilience index (TNRI) is a combination of FIS that follows a part-to-whole build methodology (see Figure 4.3). Each intersection of two or more variables is the result of a FIS that combines the respective variables. Next, the result of “fuzzifying” inputs and applying the “if-then” rules for each metric are explained for the case study.

All FIS have the same type of output, a 9 levels scale membership function; where 1 is “extremely low” and 9 is “extremely high” (see Figure 4.16).

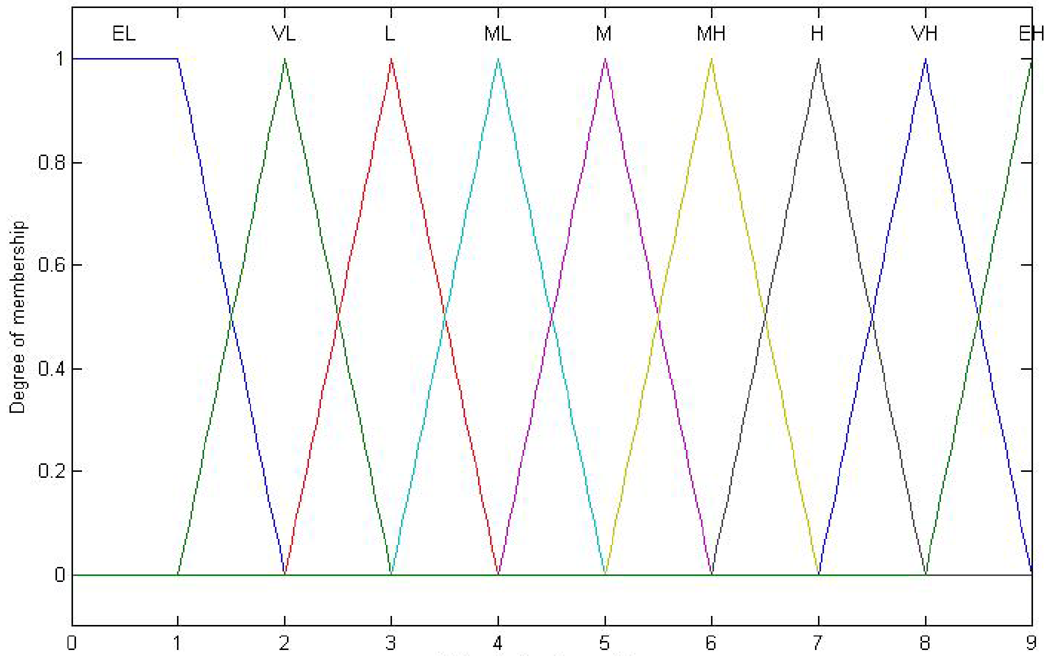


Figure 4.16 FIS Output.

In addition, each FIS produces a result-surface plot that provides a visual illustration of all possible combinations of inputs and their respective output. Moreover, the surface plot identifies the importance of each variable by illustrating their effect on the final result and their maximum achievable value. It also serves as an indicator for the decision-making process of funding allocation.

Also, the FIS produces a 2D plot that illustrates the behavior of the final output given the fluctuation of the selected input variable. They enhance the decision-making process by providing a more direct analysis. This analysis is performed calculating the slope of each relation within a given output range (e.g., from Low to Medium), which identifies the variable that can improve the output the most for that specific range, taking into consideration the cost associated with upgrading the variables. It should be stated that this analysis is better performed after the second tier since all variables are standardized (i.e., from “Extremely Low” to “Extremely High”), at that point a clearer comparison can be made. Furthermore, by indicating the range of its output, the 2D plots point out which variable has the most room for improvement. As expected, the variable with the wider range is the same variable that the result-surface shows as the most important.

These surfaces and 2D plots vary depending on the rule-set and membership function. Hence, the surfaces and 2D plots are specific for each scenario. In this matter, each result-surface and 2D plot for this study are explained next:

Network availability. This metric refers to the available capacity of the network. This metric depends on the Road Available Capacity and Road Density, ‘Rd.Ava.Cap.’ and ‘Rd.Density,’ respectively in Figure 4.17. As can be seen, the available capacity of the network has a great effect on the final outcome since this variable can help to achieve a maximum value of Network Availability of approximately 7, which is the equivalent of High, by its own (see Figure 4.16a). In contrast, Road Density cannot attain more than a network availability of approximately 3 (Low). In addition, ‘Rd.Ava.Cap.’ is more likely to enhance Network Availability since it has a wider effect range, from 2.5 to approximately 8 (from around Low to Very High); whereas ‘Rd.Density’ contributes a two level increment, from 4 to 6 (Medium Low to Medium High), see Figure 4.16b and Figure 4.16c.

Network accessibility. This metric refers to the ease of access to the different modes within a network. This metric is obtained by the combination of the variables Alternate Infrastructure Proximity and Level of Intermodality, ‘Alt.Inf.Prox.’ and ‘Level.of.Intermo.,’ respectively in Figure 4.18. It is evident the importance of having alternate infrastructure within a 10 to 20 miles range, since this alone secure a network accessibility of approximately 7 (High), which can be perceived in Figure 4.18a as Network Accessibility, counting only with Alternate Infrastructure Proximity, reaches this value. On the other hand, Level of Intermodality can push Network Accessibility up to a value of 3 (Low). In addition, Level of Intermodality only provides a two level increment for Network Accessibility, from 7 (High) to 9

(Extremely High), whereas Alternate Infrastructure Proximity has a wider effect range, from 2 (Very Low) to 8 (Very High), see Figure 4.18b and Figure 4.18c, respectively.

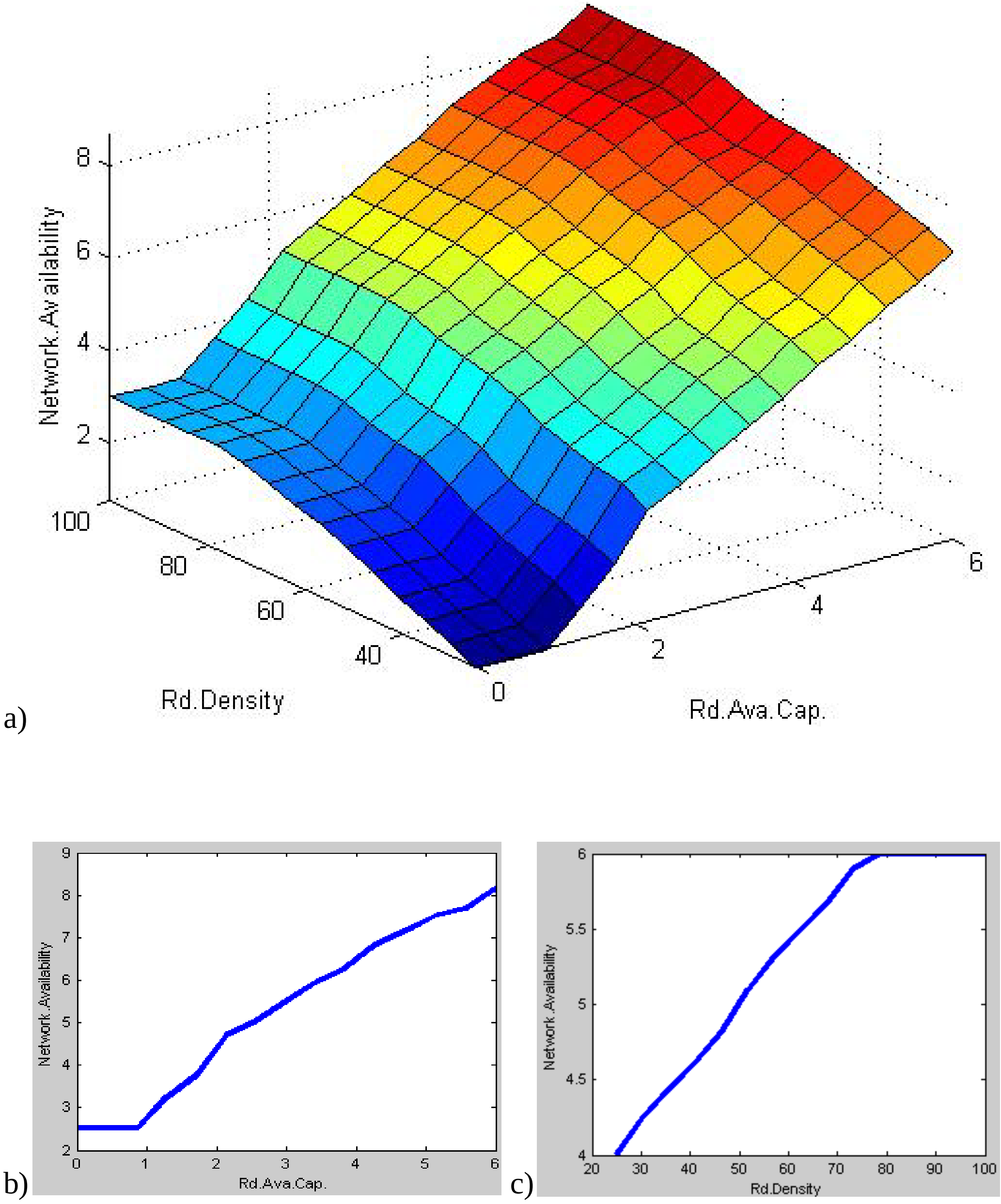


Figure 4.17 Network Availability's: a) Surface, b) Road Available Capacity plot, and c) Road Density plot.

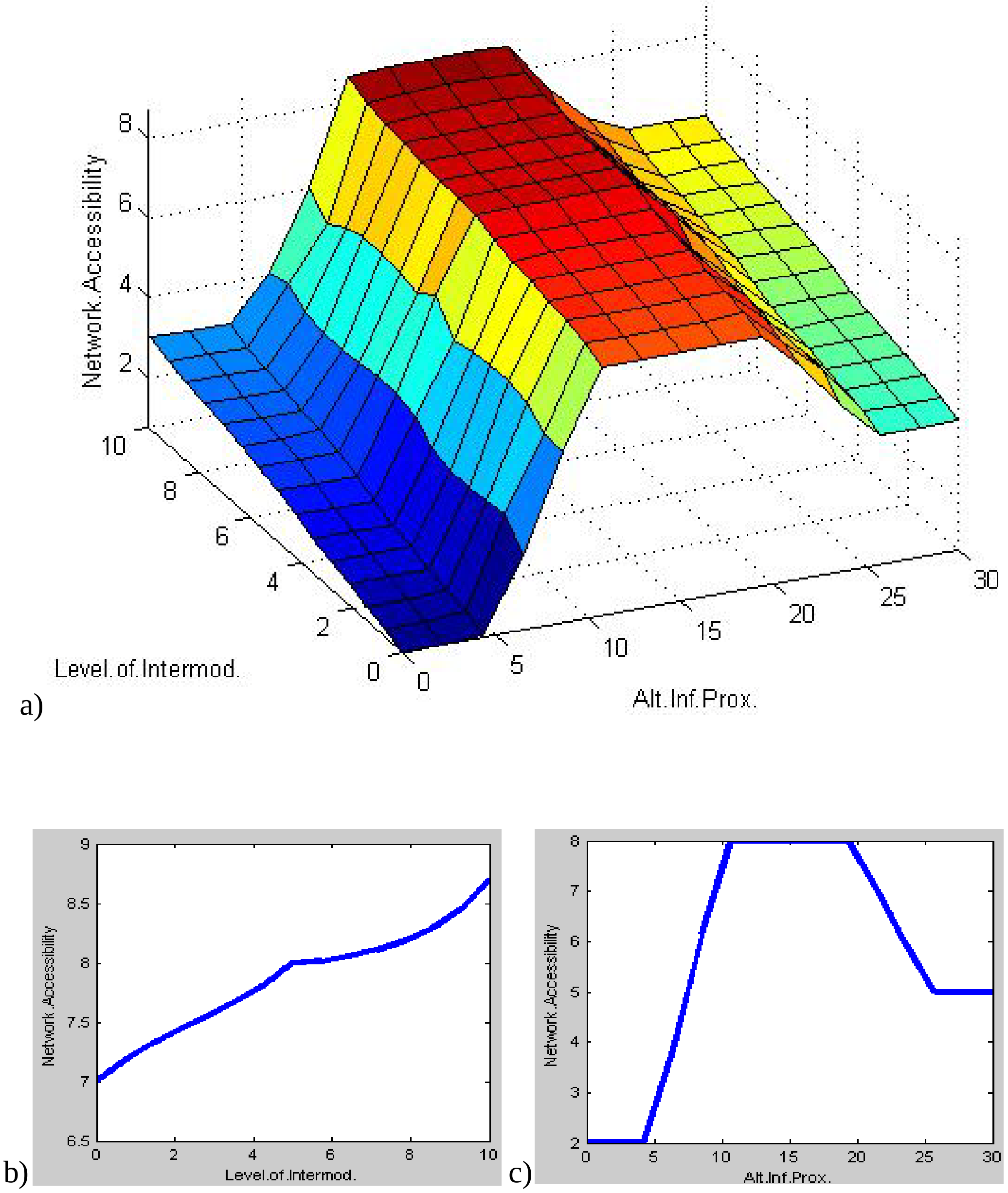


Figure 4.18 Network Accessibility's: a) Surface, b) Alternate Infrastructure Proximity plot, and c) Level of Intermodality plot.

Traveler perception. This metric refers to the level of satisfaction that a user may experience while voyaging through a network. It depends on the Average Speed Reduction and Average Delay variables, 'Ave.Speed.Red.' and 'Average.Delay' respectively in Figure 4.19. As can be seen, the delay experienced by the network's user has a greater effect on his perception, since it alone can give Traveler Perception value of 6 (Medium High), see Figure 4.19a. Also, both variables have a two-step decrease behavior, nevertheless, Average Speed Reduction presents less room for improvement, from approximately 1 (Extremely Low) to 3 (Low), in comparison with Average Delay, which ranges from approximately 1 (Extremely Low) to 6 (Medium High), see Figure 4.19b and Figure 4.19c, respectively.

Transportation cost. This metric refers to the monetary value associated with the user's interaction with the network, such as the use of private and public available modes of transport. The value is obtained by applying the commonly known "Vehicular Operation Cost" (VOC) calculation method to light and heavy vehicles, as explained in the previous section, to proxy personal and industrial/commercial transportation cost, 'Per.Transp.Cost' and 'Ind./Comm.Transp.Cost' respectively. The symmetry of Figure 4.20a can be explained by the assumption of equal effect of the variables over the transportation cost metric, which also produces identically shaped 2D plots.

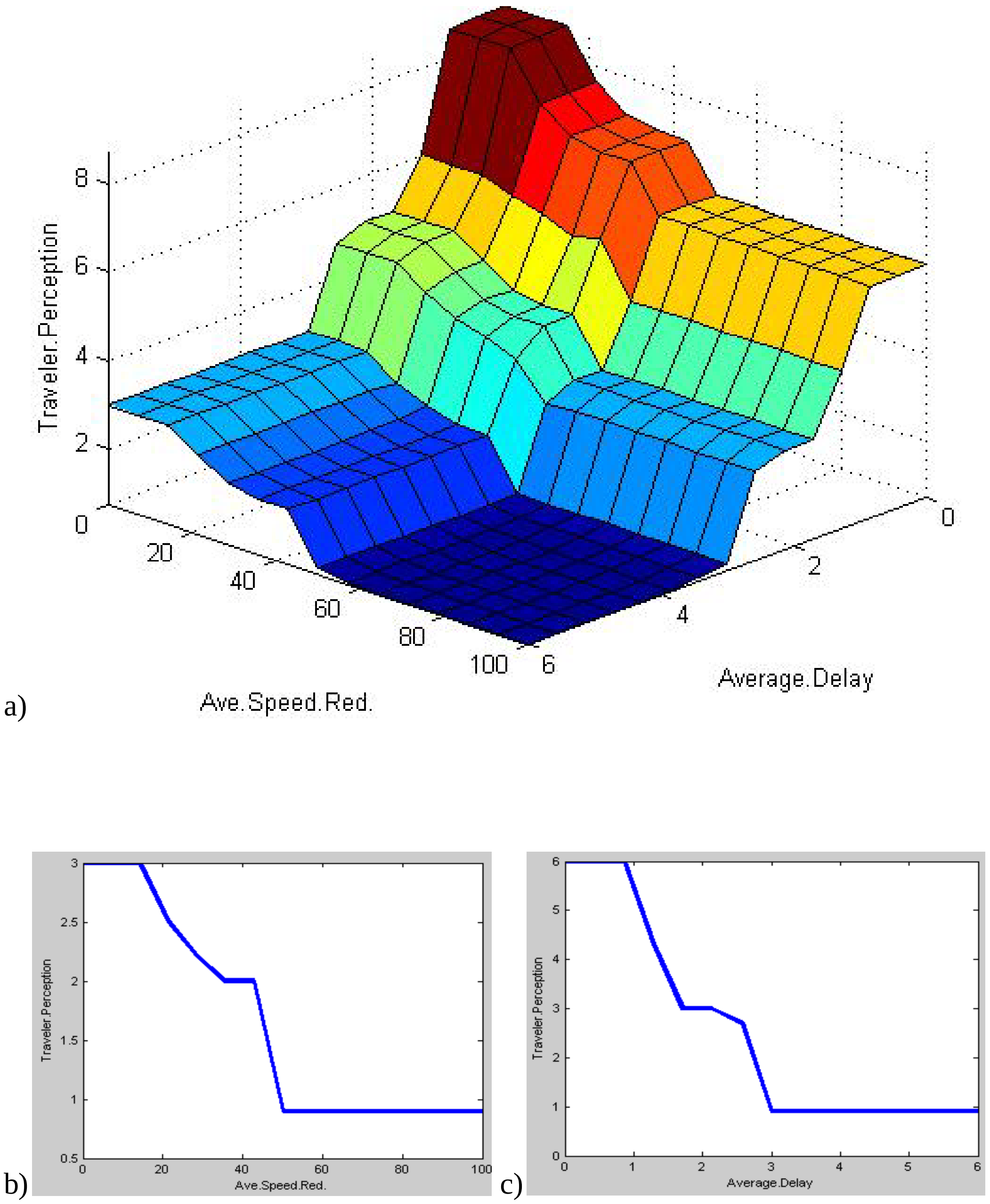


Figure 4.19 Traveler Perception's: a) Surface, b) Average speed Reduction plot, and c) Average Delay plot.

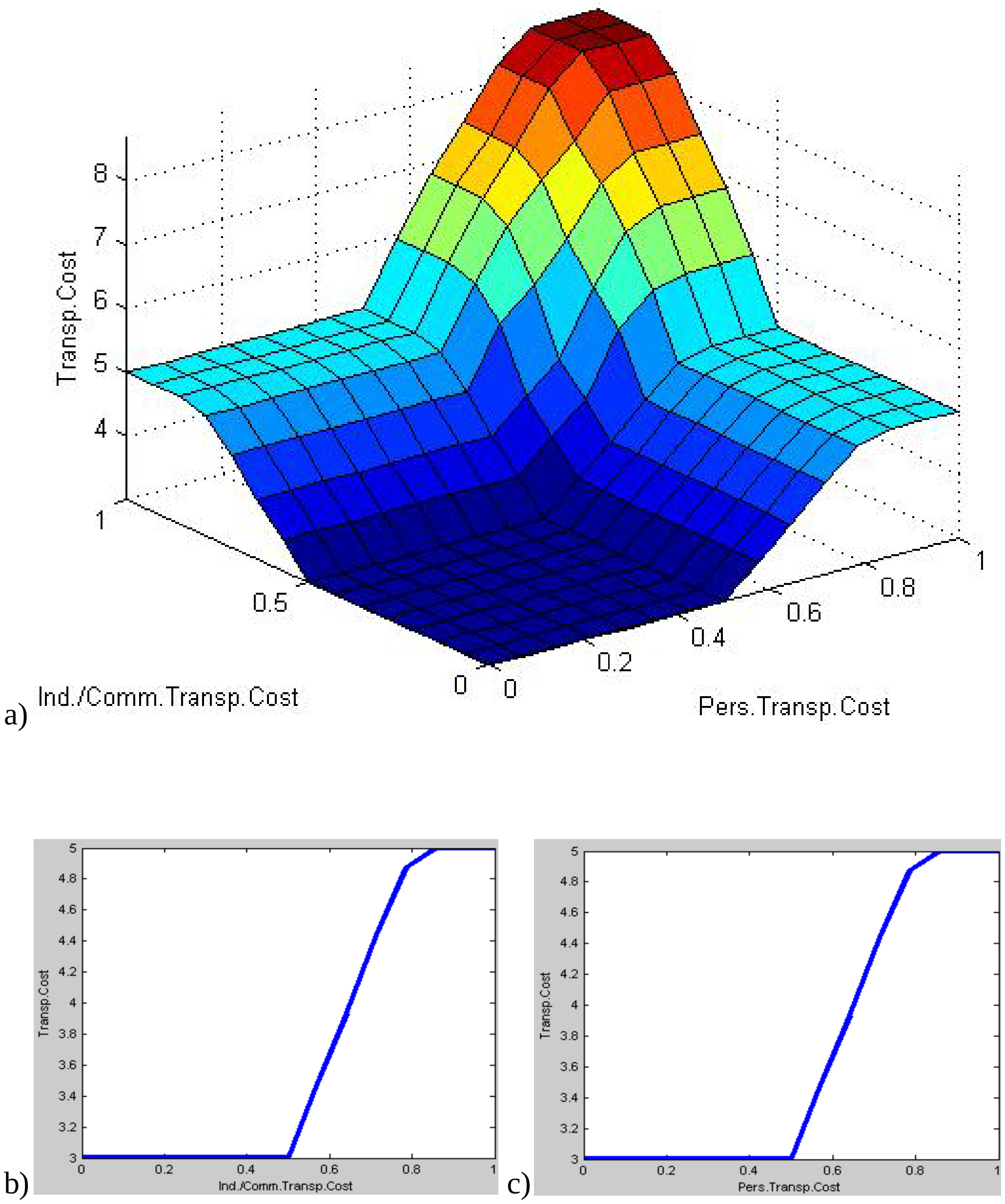


Figure 4.20 Transportation Cost's: a) Surface, b) Industrial and Commercial Transportation Cost plot, and c) Personal Transportation Cost plot.

Network resiliency. This metric explains how capable the network is, based on available and accessible capacity. Figure 4.21 illustrates the result-surface and the 2D plots for this metric. Consistent with the assumptions made in this research, Network Availability has greater influence on the final result than Network Accessibility.

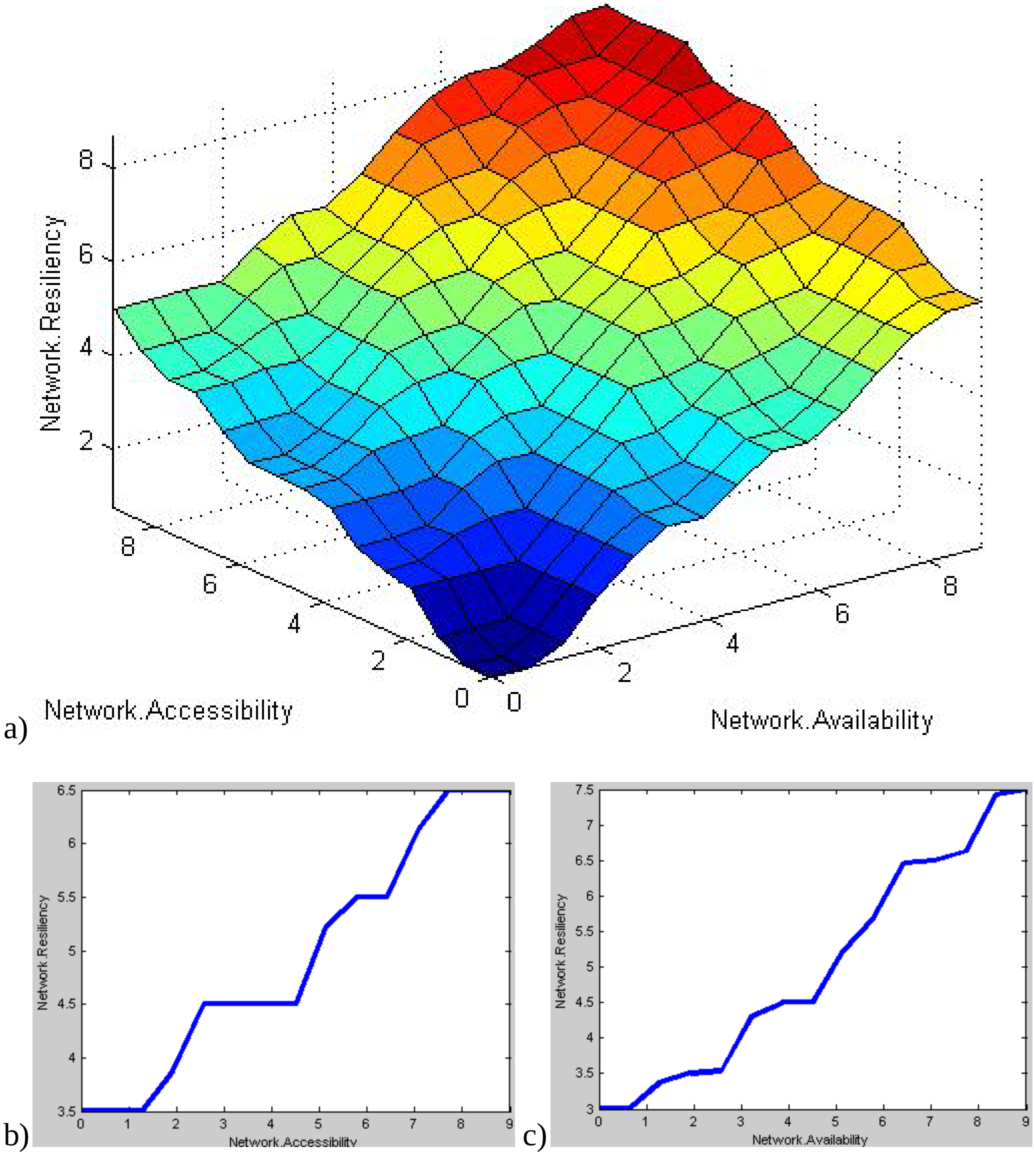


Figure 4.21 Network Resiliency's: a) Surface, b) Network Accessibility plot, and c) Network Availability plot.

<u>User resiliency.</u> This metric indicates the network's efficiency level and traveler's commodity, based on the traveler's perception and transport cost. Figure 4.22 shows the result-surface and variables plot for this metric. As expected, transportation cost has an inverse effect on the result.

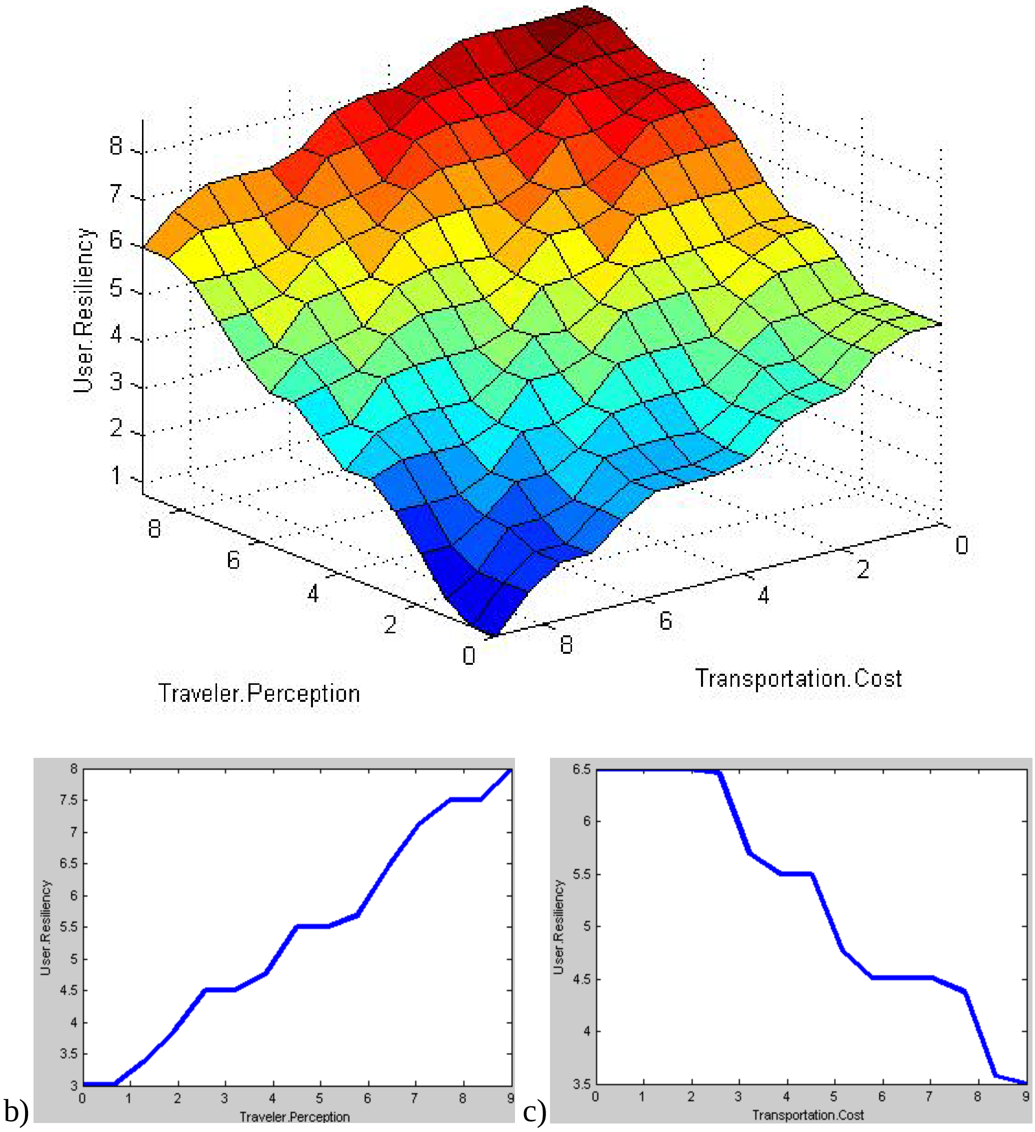


Figure 4.22 User Resiliency's: a) Surface, b) Traveler Perception Plot, and c) Transportation Cost Plot.

Base resilience. This index explains the level of resilience of the network based only on the networks functional properties located at the first tier, such as capacity, cost, and mode alternatives. In other words, the networks efficiency without any kind of management technique applied for optimization of resources. Figure 4.23 illustrates the result-surface and 2D plots related to this metric. The symmetry of the figures corresponds to the assumptions made in this research.

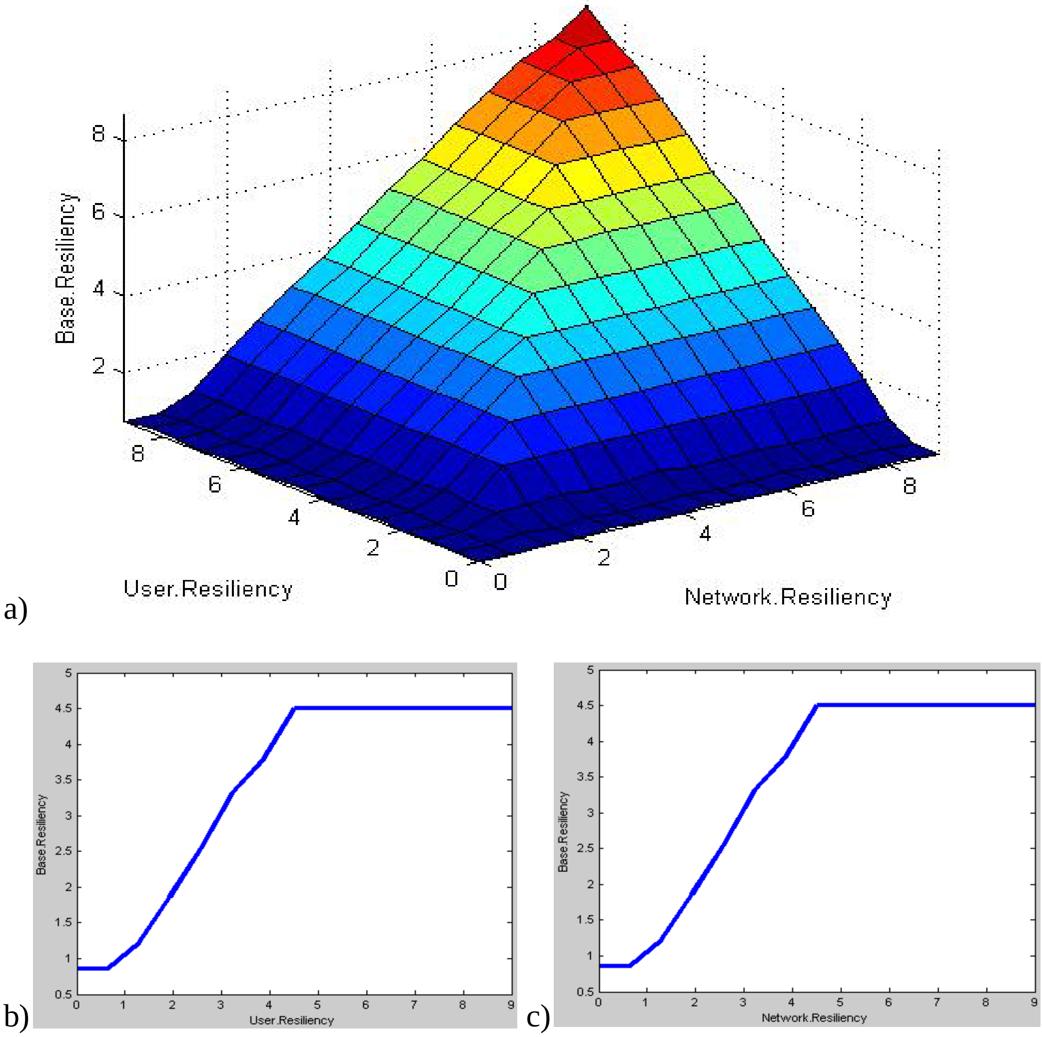


Figure 4.23 Base Resiliency's: a) Surface, b) User Resiliency Plot, and c) Network Resiliency Plot.

The TNRI result-surface is compose by Network Management and Base Resiliency, see Figure 4.24. As can be noticed in Figure 4.24a, Network Management start being effective after it reaches Level III.

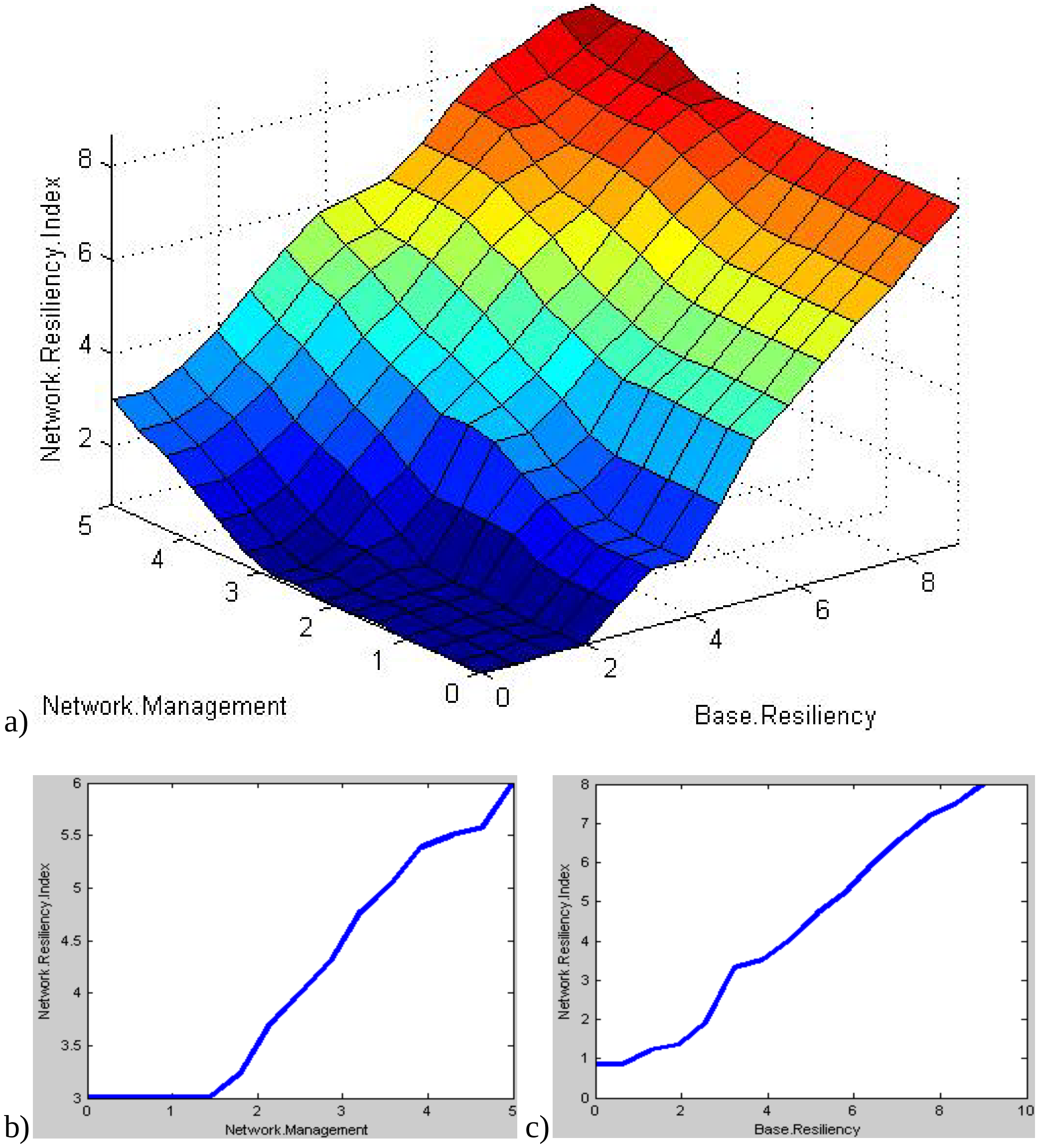


Figure 4.24 TNRI's: a) Surface, b) Network Management Plot, and c) Base Resiliency Plot.

4.4.4 Santo Domingo Transportation Resiliency Index: What should be done

After inputting all the information into the model, a final TNRI of 5.43 was obtained. This value is between Medium and Medium High, indicating that the city of Santo Domingo is somewhat prepared to overcome a disaster event, such as the scenario depicted previously. Figure 4.24 illustrates the result dependency diagram that summarizes the inputs and output of all the FISs applied.

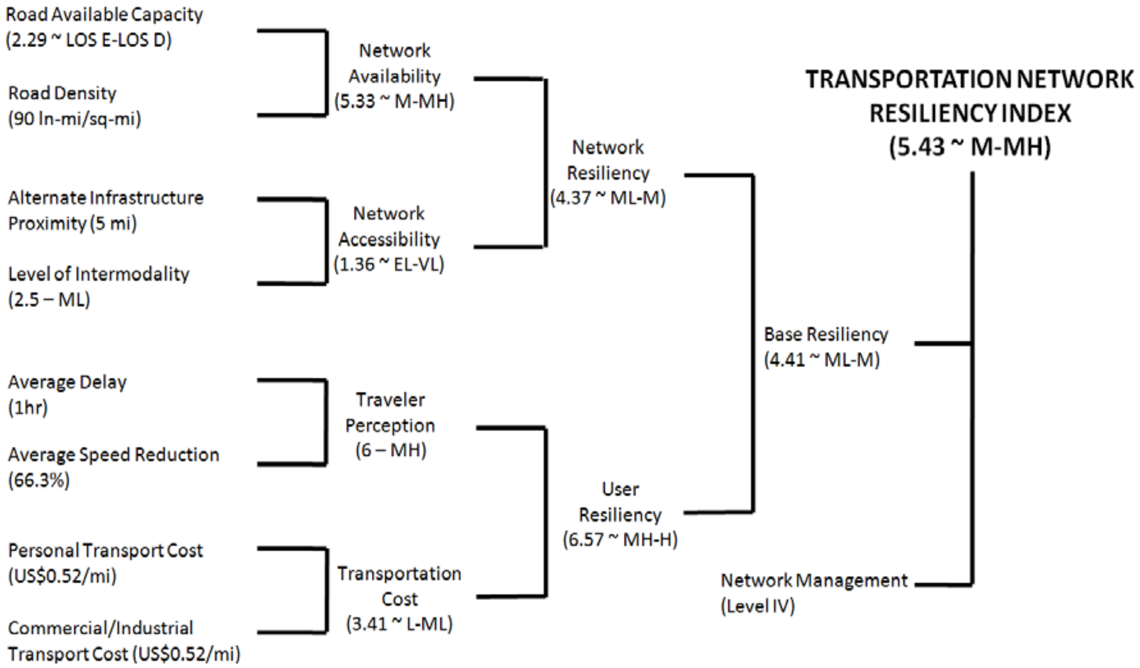


Figure 4.25 Santo Domingo’s Transportation Network Resiliency Index.

By analyzing the result dependency diagram, it is clear that the least contributing metric is Network Accessibility, with a value of 1.36, which is between ‘Extremely Low’ and ‘Very low’. This is the outcome of combining two low value variables. In addition, even though Network Availability is slightly above average, it is significantly and negatively affected by the low LOS in which Santo Domingo’s network operates. Because of the explanation above, Network Resiliency is limited to a value below average, therefore limiting the Base Resiliency to a similar level. On the other hand, Traveler Perception shows a value of ‘Medium High’, regardless the high percentage of speed reduction. Furthermore, the network presented an approximately ‘Low’ cost of transportation, that when combined with Traveler Perception, provides a User Resiliency value of 6.57, which is between ‘Medium High’ and ‘High’.

For Santo Domingo, having a TNRI of 5.43 means that:

- The network’s capacity will be diminished because of the obstruction to the infrastructure caused by the failure of the drainage system and the collapse of surrounding environment (e.g., trees, electricity poles). Nevertheless, the network could still manage considerable light-vehicle traffic volume thanks to its high micro-redundancy, explained by the Road Density variable.
- The network’s macro-redundancy will undergo great disturbance due to low distances between key infrastructures, which would be likely include them in the disaster diameter. This would force a shift on traffic movement, specially the heavy-vehicle traffic, from major arterials and

highways to secondary arterials and urban streets; as a consequence, this would saturate the network and lower the LOS.

- The network's users would be able to convey through the network at a reasonable cost and realistic travel timeframe. This would respond to the user's desire and/or need for travel, stimulating commerce and other economic activities.

Now that all of Santo Domingo's network characteristics have been evaluated, an analysis of possible solutions can be performed. This analysis should include cost/benefit studies, among other things, focusing on the alternatives that would improve the TNRI, and more specifically, Network Resilience. In this matter, the alternative analysis should center on Road Available Capacity, Alternate Infrastructure Proximity and Level of Intermodality, given that those variables presented more detrimental conditions. A general overview of possible solutions is presented next:

- Improve maintenance regulations of the infrastructure's environment and drainage system should be implemented in order to lower the possible street blockage.
- Add capacity to the network by adding lanes to key infrastructures, constructing new arterials that would increase mobility and route choices, and enhancing the intersections and arterials' performance by implementing more up-to-date ITS software and hardware.

- Enhance the transit system by making it more reliable, secure- and time-wise, and by creating mass-transit infrastructure. This will encourage a transfer of users from private vehicles to transit transportation for their home and non-home base trips. As a result, the amount of vehicles in the network will be lowered, which will contribute to its better performance.

CHAPTER 5

CONCLUSION AND FUTURE INVESTIGATIONS

5.1 Conclusion

There exists a potential for using resilience to supplement transportation performance indexes (e.g., travel time, travel speed, vehicle counts, LOS), as resilience can be considered as the collection of performance measurements. In this matter, if a standardized and uniformly agreed-on definition of resilience can be established, a resilience factor for measuring roadway performance may be useful as an organizing principle (Ta et al., 2009). This research was developed around and supports the following formal definition of transportation resiliency: “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., 2009).

In addition, this thesis provides evidence of the lack of quantitative approaches for measuring resilience by demonstrating how past research have been limited to a conceptual box. Therefore, as a way to fill the existing void in the academic literature of transportation network resilience, this research makes a contribution by providing a simple methodology for quantifying resiliency at pre-event conditions, which can be useful to researchers, practitioners and even decision-makers in the political arena.

The methodology recognizes the variability that exists in the transportation environment by using soft computing methods in the form of Fuzzy Sets Theory. As such, the methodology provides the starting point for decision makers to prioritize investments on a cost-benefit basis. The input variables were selected based on a review of prior research conducted by a wide array of individuals and institutions. The model is designed to recognize individual regional conditions, providing flexibility within its structure (i.e., set of rules).

Communities vulnerable to disasters often times count with strategies to respond to such events. However, the problem is that solutions are usually derived in an improvised, contingent and case to case manner. At the end, such a way of action (i.e., being corrective instead of preventive) represent higher costs, since authorities have to incur in solution costs every time an event hits, instead of making a one-time investment that permanently (or for a long period of time) increases the resilience of the system. Therefore, the `methodology presented in this thesis highlights the benefits of having a resilient network and of embracing policies that enhance it.

5.2 Future Investigations

The model proposed in this research is just in its initial stages; there is still room for improvement. The following are some ideas for future investigations in the area of transportation resiliency. Future research is needed to:

- Provide detail information about the relationship between resiliency and the resiliency cycle, especially with the self-annealing and recovery stages. Being able to clarify this relationship would pave the way for future research on how to quantify resilience at these stages.
- Provide evidence that the metrics suggested in this research offer enough information for the obtainment of an accurate value of resilience. The group of variables that were used need to be examined in greater detail so

as to improve their metrics and even to suggest more accurate and easily obtainable measurements at the network level.

- Link transportation resilience to a network performance index. Such index should not be considered in the set of variables so it could play a key control role. The relationship between the TNRI and this performance measurement needs to be identified, in order to acknowledge its sensitivity to change.
- Refine the shapes and softness (i.e., the overlap parameters) of the membership functions, as the calibration and verification and validation processes are carried out.
- Develop a new hierarchy that stratifies currently applied network management techniques. Such innovation should focus on assembling a more detailed hierarchy diagram. The result-surface and 2D plot of the FIS shows that levels bellow “Level III” do not contribute to the final outcome, likely because they are not commonly used. Hence, if such hierarchy is modified as proposed, then, users of the model would enjoy flexibility and accuracy when dealing with developed and developing regions.

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APPENDIX

Table A.1 Santo Domingo Data Set.

#	Arterial	Section	Average Travel Time (min)	Speed (mi/hr)			Variables		
				Average	Peak-Hr	Limit	RAC	AD	ASR
East - West Oriented Arterials									
1	Av. John F. Kennedy	Km 9 - Av. Núñez de Cáceres	1.6	21.4	10.7	40	LOS F	273.2%	73.21%
2		Av. Nuñez de Cáceres - Av. Winston Churchill	3.2	20.6	10.3	40	LOS F	288.0%	74.23%
3		Av. Winston Churchill - Av. Abraham Lincoln	0.8	32.6	16.3	40	LOS E	145.3%	59.23%
4		Av. Ortega y Gasset - Av. Máximo Gómez	2.3	11.0	5.5	40	LOS F	625.9%	86.22%
5	Av. V Centenario	Juan Pablo Duarte - Av. Maximo Gomez	2.4	33.1	16.5	30	LOS C	81.4%	44.86%
6	Av. Padre Castellanos	Av. V Centenario - Punte Fco. Rosario Sanchez	4.5	14.4	7.2	30	LOS E	316.3%	75.98%
7	Av. 27 de Febrero	Av. Luperon - Av. Isabel Aguiar	1.3	20.1	10.0	40	LOS F	298.6%	74.91%
8		Av. Luperon - Av. Núñez de Cáceres	6.1	12.6	6.3	40	LOS F	532.4%	84.19%
9		Av. Núñez de Cáceres - Av. W. Churchill	5.5	14.7	7.4	40	LOS F	444.0%	81.62%
10		Av. Abraham Lincoln - Av. Tiradentes	1.2	26.1	13.0	40	LOS E	206.6%	67.38%
11		Av. Ortega y Gasset - Av. Máximo Gómez	2.1	14.2	7.1	40	LOS F	463.4%	82.25%
12		Av. Máximo Gomez - Leopoldo Navarro	1	26.1	13.0	40	LOS E	206.6%	67.38%
13	Av. Independencia	Av. Nuñez de Cáceres - Av. Jiménez Moya	7	11.9	5.9	30	LOS F	405.3%	80.21%
14	Av. George Washington	Av. Máximo Gomez - Av. Del Puerto	6.5	33.0	16.5	30	LOS C	81.6%	44.95%
15	Av. Gustavo Mejía Ricart	Av. Núñez de Caceres - Ortega y Gasset	11	13.4	6.7	30	LOS F	349.4%	77.75%
16	Av. Paseo de los Reyes Católicos	Camino Chiquito - Av. Hermanas Mirabal	4	29.6	14.8	30	LOS C	102.5%	50.61%
17	Av. Los Próceres	Av. John F. Kennedy - Av. República de Colombia	12	10.6	5.3	30	LOS F	466.4%	82.35%
18	Av. José Contreras	Av. Tiradentes - Av. Maximo Gómez	2	19.2	9.6	25	LOS D	160.5%	61.61%
North - South Oriented Arterials									
19	Av. Winston Churchill	Av. Independencia - Av. John F. Kennedy	9.5	15.7	7.9	30	LOS E	281.3%	73.78%
20	Av. Tiradentes	Av John F. Kennedy - Av. Bolivar	13	6.9	3.4	30	LOS F	771.9%	88.53%
21	Av. Hermanas Mirabal	Estación Mamá Tingó - Av. John F. Kennedy	20	16.5	8.2	30	LOS E	264.2%	72.54%
22	Av. Máximo Gómez	Av. John F. Kennedy - Av. Bolivar	28	2.2	1.1	30	LOS F	2566.8%	96.25%
23	Av. Francisco del Rosario Sanchez	Av. Padre Billini - Av. Padre Castellanos	5	27.1	13.6	30	LOS C	121.1%	54.77%
24	Av. Ortega y Gasset	Av. 27 de Febrero - Av. John F. Kennedy	1.7	24.1	12.1	30	LOS D	148.8%	59.80%
25	Av. Nuñez de Cáceres	Av. John F. Kennedy - Av. Independencia	9	19.2	9.6	30	LOS D	212.2%	67.97%
Ring Arterials									
26	Autopista 30 de Mayo	Av. Luperon - Av. Núñez de Cáceres	4.1	44.6	22.3	40	LOS C	79.2%	44.20%
27		Av. Núñez de Cáceres - Av. Abraham Lincoln	3.7	29.5	14.8	40	LOS E	171.0%	63.10%
28	Av. Luperón	Av. John F. Kennedy- Autopista 30 de Mayo	12.5	20.3	10.2	40	LOS F	293.9%	74.61%
29	Av. Charles de Gaulle	Av. Hnas. Mirabal - Av. Restauración	4.1	40.5	20.2	30	LOS B	48.3%	32.57%
30		Av. Restauración - Carretera Mella	7.2	20.2	10.1	30	LOS D	197.2%	66.35%
31		Carretera Mella - Carretera de Mendoza	6	15.3	7.6	30	LOS E	292.6%	74.53%
32		Carretera de Mendoza - Punte Juan Carlos	4.2	30.2	15.1	30	LOS C	98.8%	49.71%
33	Av. República de Colombia	Av. Jacobo Majluta - Av. Monumental	11	14.8	7.4	30	LOS E	305.2%	75.32%
34	Prolongación 27 de Febrero	Aut. Duarte - Carretera a Manoguayabo	4.4	42.4	21.2	40	LOS D	88.9%	47.05%
35		Carretera Manoguayabo - Av. Las Palmas	3.7	20.1	10.1	40	LOS F	297.0%	74.81%
36	Av. Jacobo Majluta	Av. Hnas. Mirabal - Av. Mirador Norte	6.8	50.4	25.2	30	LOS A	19.0%	15.95%
37		Mirador Norte - Av. Rep. De Colombia	2	37.3	18.6	30	LOS C	61.0%	37.87%
38	Av. Abraham Lincoln	Av. John F. Kennedy - Autopista 30 de Mayo	13	11.8	5.9	30	LOS F	406.7%	80.26%
				Average			**LOS D**	**320.32%**	**66.29%**