A Simulation-Based Approach to the Characterisation of Urban Traffic Network Vulnerability

By

Naser Snobar

A thesis submitted to the Faculty of Graduate and Postdoctoral
Affairs in partial fulfillment of the requirements for the degree of

Master of Applied Science (M.A.Sc.)

In

Civil Engineering

Ottawa-Carleton Institute for
Civil Engineering

Department of Civil and Environmental Engineering
Carleton University
Ottawa, Ontario

© 2016

Naser Snobar

Abstract

This research employs modeling methodologies to obtain a better understanding of urban traffic network vulnerability. A methodological framework is presented, forming the basis for investigating critical dimensions affecting vulnerability. The focus is on the Central Business District (CBD) network type. The three dimensions; Centrality, Flowability, and Mobility are analyzed through the employment of traffic models. Mesoscopic and microscopic simulations are performed to obtain required data, then used for the construction of the Combined Vulnerability Index (CVI), representing the network friability. Next, the unique links making up the network are closed sequentially, and simulations are carried out for each scenario in order to obtain the link network influence for each of the links. The (% Effect) value is then obtained from the difference in traffic flow across the network, and multiplied by the CVI to obtain the adjusted vulnerability index (ACVI). The methodology is then applied to the Ottawa network.

Acknowledgements

I would first like to thank my thesis advisor Professor A.M. Khan of the Civil and Environmental Engineering Department at Carleton University. The door to Prof. Khan's office was always open whenever I ran into a trouble spot or had a question about my research or writing. He consistently allowed this paper to be my own work, but steered me in the right direction whenever he thought I needed it.

The completion of this research work wouldn't have been possible without the help of Jennifer Armstrong and Tim Wei from The City of Ottawa's Transportation Planning Branch. The data provided enabled the modeling and analysis of Ottawa's downtown core.

I must also express my very profound gratitude to my loving parents and siblings, my caring grandparents, and to my beautiful fiancée for providing me with unfailing support and continuous encouragement throughout my years of study and through the process of researching and writing this thesis. This accomplishment would not have been possible without them. Thank you.

Naser Snobar

Table of Contents

Abstract.....	ii
Acknowledgements	iii
List of Tables	ix
Acronyms	xiii
A Simulation-Based Approach to the Characterisation of Urban Traffic Network Vulnerability	1
1 Chapter: Introduction	1
1.1 Research Purpose	1
1.2 Problem Definition.....	1
1.3 Research Objectives	2
1.4 Research Goals.....	4
1.4.1 Vulnerability Index	4
1.4.2 Link Closure Network Effect.....	4
1.5 Research Framework.....	5
2 Chapter: Literature Review	8
2.1 Resilience	8
2.2 Vulnerability	10
2.3 Modeling of Infrastructure Systems	18
3 Chapter: Methodology and Design	21
3.1 Methodological Framework for Quantifying Vulnerabilities	21
3.1.1 Establishing an Idealized Network.....	23
3.1.2 Performing Traffic Flow Analysis	30
3.1.2.1 Mesoscopic Simulation	32
3.1.2.2 Microscopic Simulation	34

3.1.3	Obtaining Results.....	36
3.1.4	Varying the Network Properties	37
3.1.5	Sequential Link Closure	38
3.1.6	Determining Link Closure Effect.....	40
3.1.7	Producing the Vulnerability Index	42
3.1.7.1	Centrality.....	42
3.1.7.2	Flowability	45
3.1.7.2.1	Flow	46
3.1.7.2.2	Flowability Dimension.....	47
3.1.7.3	Mobility.....	48
3.1.7.3.1	Density	49
3.1.7.3.2	Mobility Dimension	49
3.1.7.4	Link Closure Network Effect	51
3.1.7.5	The Combined Vulnerability Index	51
3.2	Applying the Methodological Framework.....	53
3.2.1	VISUM.....	54
3.2.1.1	The Base Model.....	55
3.2.1.2	Simulation of Network Permutations.....	61
3.2.1.3	Sequential Link Closure Models	62
3.2.2	VISSIM	63
4	Chapter: Practical Application to the Ottawa Downtown Core	65
4.1	The City of Ottawa CBD Model; the Downtown Core	65
4.2	Ottawa Network VISUM Model Construction	66
4.3	Ottawa Network VISSIM Simulation	70
4.4	Ottawa Network CVI	71

5	Chapter: Findings.....	73
5.1	Statistical Analysis Methodology	73
5.2	The Base Network.....	75
5.3	Varying the Network Dimensions	75
5.3.1	Data.....	75
5.3.2	Correlation.....	77
5.3.3	Regression	78
5.4	Sequential Link Closure	81
5.4.1	Link Closure Network Effect.....	82
5.4.2	Data.....	83
5.4.3	Correlation.....	84
5.4.4	Regression	85
5.5	The Ottawa Network	87
5.5.1	Data.....	87
5.5.2	CVI.....	88
5.5.3	ACVI.....	88
5.5.3.1	Correlation	89
5.5.3.2	Regression.....	90
6	Chapter: Discussion	92
6.1	Varying the Network Dimensions: Vulnerability Dimensions	92
6.1.1	Centrality	92
6.1.2	Flowability.....	93
6.1.3	Mobility.....	93
6.2	Effect of Link Closures on the Network.....	94
6.3	The Ottawa Downtown Core Network	96
6.3.1	Vulnerability Dimensions (Base Model).....	96

6.3.2	Sequential Link Closures.....	96
7	Chapter: Research Implications, Conclusions and Recommendations	97
7.1	Research Implications	97
7.2	Conclusions	99
7.3	Recommendations	101
7.3.1	Centrality	101
7.3.2	Flowability.....	101
7.3.3	Mobility	102
7.3.4	Link Closures.....	102
7.3.5	The Ottawa Network	103
7.4	Research Limitations	103
7.5	Future Research	105
	References	107
	Appendices.....	112
	Appendix A City of Ottawa Data	112
	Appendix B Simulation Results: Varying Network Properties	114
B.1	Idealized Network.....	114
B.2	Centrality Generated Networks	115
B.3	Flowability Generated Networks	117
B.4	Mobility Generated Networks	119
	Appendix C Simulation Results: Sequential Link Closures.....	121
C.1	Sequential Link Closure Traffic Models	121
C.2	Model Version Comparisons	124
	Appendix D Simulation Results: City of Ottawa	127
D.1	Base Network	127

D.2	Sequential Link Closures: Ottawa Core Network	128
	Appendix E Simulation Results Summary	136
	Appendix F Graphs and Charts	139
	Appendix G Regression Results	141
G.1	Varying Network Properties: Centrality, Flowability, Mobility (CFM)	141
G.2	Sequential Link Closures (SLC)	149
G.3	City of Ottawa Network Model	155

List of Tables

Table 3.1: Variations in Idealized Network Parameters	38
Table 3.2: Traffic Volume Classification	61
Table 5.1: Summary Statistics for Network Permutation Variables	76
Table 5.2: Correlation Analysis Results for Network Permutations	78
Table 5.3: Single Regression Analyses Summary Results	79
Table 5.4: Beta Values for Regression Models.....	79
Table 5.5: Summary Results for VIF Analysis	80
Table 5.6: Values of Link Closure Networks	82
Table 5.7: Correlation Analysis of (% Effect)	83
Table 5.8: Summary Statistics for Sequential Link Closure Networks.....	84
Table 5.9: Correlation Analysis Results for ACVI	85
Table 5.10: Single Regression Analyses Summary Results	85
Table 5.11: Beta Values for Regression Models.....	86
Table 5.12: Summary Statistics for Ottawa Network Models	87

Table 5.13: Correlation Analysis Results for Ottawa ACVI	90
--	----

Table 5.14: Regression Analysis Summary Results for Ottawa ACVI.....	90
--	----

List of Figures

Figure 1.1: Adopted Research Framework	7
Figure 3.1: Conceptual Methodological Framework for Quantifying Network Vulnerabilities	22
Figure 3.2: HCM Exhibit 16-14 Generalized Daily Service Volumes (Highway Capacity Manual 2010)	25
Figure 3.3: HCM Exhibit 17-24 Default Values: Automobile Mode (Highway Capacity Manual 2010)	26
Figure 3.4: Arrangement of links in the idealized network along a typical 4x4 block arrangement.....	27
Figure 3.5: HCM Exhibit 16-3 Signal Spacing (Highway Capacity Manual 2010)	29
Figure 3.6: Vehicular arrival and departure flow (Canadian Capacity Guide for Signalized Intersections 2008)	31
Figure 3.7: Comparison of the three modelling levels (Marsico, et al. 2013)	36
Figure 3.8: Sequential Link Closure.....	39
Figure 3.9: Different Street Network Types Showing Varying Connectivity	43
Figure 3.10: Snapshot of the Ottawa CBD (City of Ottawa 2012)	44
Figure 3.11: Flow Density Relationship (Adeel 2009).....	46
Figure 3.12: CVI Ternary Plot	52
Figure 3.13: PTV Vision Suite Integration (WUS Group 2015)	54
Figure 3.14: Base Model Construction in VISUM.....	56
Figure 3.15: Example Demand Matrix in VISUM.....	57

Figure 3.16: Processing of ICA Assignment Procedure in VISUM.....	58
Figure 3.17: VISUM Network Check Function.....	60
Figure 3.18: VISUM (left) and VISSIM (right) Model Comparison	62
Figure 4.1: The City of Ottawa downtown core (City of Ottawa 2015)	65
Figure 4.2: Ottawa Central Area and Adjacent Gatineau Zones Model in VISUM	67
Figure 4.3: Ottawa Downtown Core Model in VISUM	68
Figure 4.4: Links Eliminated in the Link Closure Models	69
Figure 4.5: Ottawa Network Model in VISSIM.....	70
Figure 4.6: Calculation of the Ottawa CVI value from the ternary plot.....	72
Figure 7.1: Breakdown of Network Variation Properties.....	99

Acronyms

ACVI	Adjusted Combined Vulnerability Index
ANOVA	Analysis of Variance
CBD	Central Business District
CVI	Combined Vulnerability Index
DMCI	Dynamic functional Modeling of Critical Infrastructure
FFS	Free-Flow Speed
GIS	Geographic Information Systems
HCM	Highway Capacity Manual
LOS	Level of Service
OD	Origin-Destination
RC	Reserve Capacity
SOV	Single-Occupancy Vehicle
TDM	Transportation Demand Management
TRB	Transportation Research Board
VIF	Variance Inflation Factor

A Simulation-Based Approach to the Characterisation of Urban Traffic Network Vulnerability

1 Chapter: Introduction

1.1 Research Purpose

This research was undertaken as part of a greater research effort being carried out at Carleton University on infrastructure system resiliency. As such, this particular piece of work focuses on the characterization of system vulnerability, which plays a major role in the implementation and improvement of resiliency measures. This work is being carried out in conjunction with other research, which aims to develop intelligent technology-assisted methods for improving the resilience of adaptive capacity in urban road traffic networks. In addition to other work which intends to demonstrate the application of the developed methods as aids for operational-level traffic management decisions. It also intended to aid in the improvement of network planning at the strategic and tactical levels.

1.2 Problem Definition

This research aims to investigate vulnerabilities in road traffic networks in terms of risk of severe loss of capability to serve demand. Research products that integrate intelligent technology, predictive models, and decision aids for traffic management are needed for enhancing ‘resilience of adaptive capacity’. This leads towards the eventual goal of overcoming vulnerabilities of links, or entire routes in the network.

Most of the existing research is focused on the mathematical and conceptual aspects of the problem at hand. This research takes an alternative approach, and presents the characterization of traffic network vulnerability through a practical, model-based simulation procedure. This enables the comparison of traffic patterns. The approach also enhances the planning and design decisions, as well as the selection of urban traffic network components, parameters, and layouts. The aim is to develop such a methodology that can then be readily transferred and applied to a range of similar projects.

1.3 Research Objectives

The ultimate goal of the overall research is to obtain an understanding of the resilience of adaptive capacity in critical infrastructure. This is defined as ‘the ability to resist the loss of traffic-serving capability by dynamically activating capacity-enhancing measures’, which builds on the concepts of vulnerability. Resilience seems to have become a new focus for the short-term and long-term futures of city systems (Batty 2013). Taking the overall city as a combination of ecological, physical, and social systems, the resilient city movement is attracting attention of researchers around the world. But, in spite of its importance to the urban area, research in traffic network vulnerabilities and resilience has not received sufficient research attention. The National Research Council of the USA has called for approaches to mitigate vulnerability in transportation by modelling complex adaptive systems (Godschal 2013).

Advancements from research in sectors other than urban traffic networks also serve as a knowledge base for this research work. For instance, the freight transportation component of supply chains continues to be an area of research, as well as the soft systems (e.g. ITS

architecture) have been of research interest in recent years (Omer, Mostashari and Lindemann 2014). As such, the principles and findings from these undertakings can be employed to guide the work of interest, concerning urban traffic networks.

This document presents a methodology for the characterization of urban traffic network vulnerability, through the employment of specific vulnerability dimensions. In particular, the research focuses on a specific type of traffic network, the CBD, as it is arguably the most important part of the overall city-wide traffic network. It is often the most significant area, acting as the commercial and business center of the city. This area is usually typified by a concentration of retail and office buildings, and has an urban density higher than the surrounding districts of the city, and is often the location of the tallest buildings in the city as well (Rosenberg 2016). Due to these characteristics, this area of a city experiences the highest commuter volumes and rates of traffic flow, and consequently would be the part of the transportation network that is most under threat. As such, it has the highest risk of affecting the largest number of road users, as well as have impacts over the whole transportation network should critical incidents occur.

As seen in Section 2.2 of the literature review carried out, research has already been carried out on vulnerability aspects as they relate to network nodes (intersections) and their effect on traffic network functionality. As such, the focus of the research carried out herein is on network links (road segments) forming the overall infrastructure entity.

1.4 Research Goals

This work consists mainly of two exploratory areas, each of which is addressed through traffic modeling, as well as both: mesoscopic and microscopic simulations, in order to gain an understanding of the functionality of urban traffic networks. Firstly, through the vulnerability dimensions of the network, and secondly through the effect of link closures.

The main components are outlined below:

1.4.1 Vulnerability Index

- Define the critical dimensions affecting urban traffic network vulnerability
- Explore how the identified dimensions influence the network characteristics
- Construct a vulnerability index applicable to the defined network dimensions that provides a basis for the comparison of traffic network vulnerabilities

1.4.2 Link Closure Network Effect

- Perform a closure of each of the unique links along the traffic network to observe the link closure effects
- Conduct an analysis to determine the critical link attributes contributing to the greatest effects of link closure
- Employment of the results of link closure analyses in order to determine the relative importance of road segments along the traffic network based on the determined link attributes
- Application of the link closure effect value to the previously determined vulnerability index to obtain the adjusted vulnerability index

1.5 Research Framework

The research framework explained herein (narratively and graphically) outlines the main topics to be studied, including the key factors, concepts and variables, and the formed relationships between them. This study aims to characterize the vulnerability of urban traffic networks, and explore the main factors contributing to increased vulnerability by utilizing state-of-the-art modeling programs and simulation techniques. The research contributes knowledge towards achieving urban planning and network design decisions that reduce the vulnerability of urban traffic networks, and in turn, aid in developing more robust and resilient infrastructure.

The framework of this research requires the execution of two modeling phases. The first of which models an idealized urban network (representing a CBD), and then varying the network characteristics to explore how vulnerability is affected. The second phase involves the sequential elimination of links (road segments) to gain a better understanding of the effect of road closures in terms of overall network traffic flow disruptions. Figure 1.1 shows the overall conceptual framework for this research.

The overall conceptual framework is defined by five phases. First, the problem identification phase recognizes the source of the problem, the issues being faced, and the need for the research. A literature review of previous related research work and findings was also presented at this phase. The modeling and simulation phase outlines the

methodology used to produce the study models, and the mesoscopic and microscopic simulation procedures. It also shows how the CVI and ACVI were obtained.

The practical application phase presents the application of the previously discussed modeling procedures to the actual City of Ottawa CBD (the downtown core). The vulnerability dimensions are thus obtained, and an ACVI for Ottawa's CBD is constructed. The statistical analysis phase involves analyzing and culminating the collected data using appropriate modeling techniques to explore the underlying statistical relationships. Finally, the results obtained from the statistical analyses were interpreted and discussed in the discussion and findings phase. Research implications, conclusions, and recommendations were also presented in this phase.

Figure 1.1: Adopted Research Framework

2 Chapter: Literature Review

This chapter presents the reviewed literature from a variety of sources to provide a theoretical background to the work carried out in the research. The literature presented is in line with the objectives outlined in this work, and provides insight into the concepts related to urban traffic network modeling. It also presents network resiliency definitions and parameters, as well as urban traffic network (and CBD) vulnerability-determinant methodologies and concepts. Although not all the literature review carried out is presented here, the most relevant and most recent literature is included in the following sections.

2.1 Resilience

As this research in vulnerability is carried out in order to ultimately contribute to the development of traffic network resiliency, it is beneficial to carry out a review of the literature studying this area. In a report of a similar nature to what will be conducted in this document, Petrenj and Trucco presented a simulation-based characterization of critical infrastructure system resilience. The key attributes of system resilience presented constituted of three elements; absorptive, adaptive, and restorative. Here, system vulnerability and severity of the consequences due to loss of network performance were considered. Consequently, the resilience index was introduced, made up of three components: (1) Robustness, (2) Resourcefulness, and (3) Recovery (Petrenj and Trucco 2014).

The next section then went on to present the simulation-based resilience characterization. A simple disruption was defined as a disruption in a single node, and then the impact on

the system as a whole was investigated. Next, a complex disruption was defined as a disruption of several nodes, and the resulting global and local effects were explored. Two phases were then defined for the occurrence of events, with Phase 1 focusing on the analysis of vitality and agility of the nodes themselves, and Phase 2 exploring the variance in vitality and agility of the overall system over time, measured in hours. Lastly, the authors performed system resilience analysis, classified the nodes in terms of vitality and agility (with ‘high’ or ‘low’ attributed to each), and then after identifying the most promising nodes for action, compared the options available for system improvement.

Section 4 of the report presented the methodology implementation using the DMCI model to simulate the vulnerability and interoperability of critical system components. Among the model features are the specification of vulnerable nodes; those that are homogeneous, service self-providing, and vulnerable. They are connected to create intra- and inter-infrastructure interdependencies (Petrenj and Trucco 2014). Also, Specification of threat nodes characterized by time-variant intensity and specific impact potential on different vulnerable nodes. Another feature is the quantification of both functional and logic interdependencies due to the use of both service demand and service capacity for each node, as well as time-dependent specification of the main parameters of the model, i.e., node functional integrity, interoperability, service demand and loss. The final feature is the propagation of both inoperability and demand variations throughout the nodes of the same infrastructure and between interdependent network components. The model was then applied to the Lombardy region (Italy), and an event that took place was remodeled (a large snowfall event) in order to explore how the model reflects this occurrence, and explore infrastructure improvements. The analysis was then carried out for the two phases, with

Phase 1 simulating the behavior of the system by imposing a value of functional integrity equal to zero to a single node, and Phase 2 multiple nodes were varied in order to study the demand shift (Petrenj and Trucco 2014). Finally, the paper concluded that effective strategies for system resilience include identifying clusters of interdependent nodes on which to implement resilient measures concurrently. To maximize resilience, it is necessary to find the best combination of resilience options and node clusters, which is feasible through simulations. Another technique is prioritization, as it is not feasible to apply measures to the entire system, and therefore, it is necessary to prioritize activities, carefully target response efforts and act on selected nodes. Thirdly, it is proposed to allocate additional resources intelligently so that they can be utilized in the most efficient and beneficial manner (Petrenj and Trucco 2014).

2.2 Vulnerability

In a comprehensive culmination of a variety of documents, Katja Berdica produced a report outlining the research advancements in the vulnerability field thus far. It was presented that in order to implement suitable policies to attain various goals, there is a need for the characterization of road networks, in order to gain insight into their propensity to ‘malfunction’, and the extent of the resulting consequences and scope for possible mitigation measures (Berdica 2002). The author put forth a suggestion on how to define vulnerability, at five prescribed levels. The first concerns serviceability versus accessibility, where accessibility is defined as a function of mobility (traffic demand), and serviceability describes the possibility of using a certain link at a given time (traffic supply). Secondly, the author looked at vulnerability as it relates to incidents, specifically events of interest are the ones causing disturbances in traffic. An incident is defined as an

event resulting in reduction or interruption in the serviceability of links. The third level looks at the risk posed to the traffic network, in terms of a composite of probability of incident occurrence, and the resulting consequences of such an event. The fourth level looks at vulnerability itself, and defines it as the susceptibility to incidents that result in considerable reduction of serviceability (Berdica 2002). It is then proposed that reducing vulnerability can be regarded as reducing the risks involved in various incidents, which can be brought about in two ways: (1) by a fail-safe approach, through reducing the probability of infrastructure failure, or (2) by adopting a safe-fail perspective, implying a reduction of the resulting consequences should a failure occur. The fifth level presented concerns ‘neighboring terms’ related to the general subject of vulnerability, namely reliability, robustness, resilience, and redundancy.

Next, the author outlines how to approach vulnerability, through exploring six dimensions. First, reliability is introduced as the adequate serviceability under the operating conditions encountered during a given time period, and then the reliability indices are put forth, as there is a need to identify an acceptable LOS as it pertains to: (1) Reliability of connectivity, (2) Reliability of travel time, as well as (3) Capacity reliability. Next, the author presents network reliability in general terms, and the different approaches adopted in various research to tackle this issue. Following that, reliability and fluctuation of traffic flow is investigated, and then the concept of improvement of reliability under traffic management is explored, where the literature proposes new indicators of road network performance levels, instead of the conventional quantitative or static indicators of road network quality; (1) Terminal reliability and (2) Travel time reliability. The fifth dimension looked at is the “Degradable Transportation System” (DTS). As existing network reliability models are

lacking on a number of accounts, most noticeably as they assume fixed traffic demand, statistically independent component states, and they do not allow for components to have degradation levels between full and zero capacity. Sixth is a look how capacity is related to reliability, following up on the DTS concept. This starts with identifying the largest multiplier that can be applied to the OD-demand matrix allocated to a transportation network without exceeding a pre-specified LOS. Capacity is modeled as a random variable, and then the probability of network reserve capacity being greater than, or equal to, the required demand for different levels of degradation is estimated.

In the fourth section of this report, the author presents a methodology of studying vulnerability. A summary of what has been done so far is provided, namely the nature of work which is mostly isolated studies of the effects of individual emergency situations, or of separate vulnerability related issues. Next, the author took a look at what is being done actively to advance this field, with a highlight of vulnerability, exposure, and criticality in various infrastructure. Following that, perhaps the most important section of the report identifies what should be done in future research, as vulnerability analysis regards the road network as a whole and involves identifying a spectrum of incidents, data on probabilities, estimating different risks, setting acceptable levels of serviceability under unfavorable conditions, and identifying possible mitigations that can be incorporated to deal with the issue at hand. “Vulnerability analysis is not introduced as a downright measure but more as a way of characterizing a road network, basically as a means for being ‘wise after the event in advance’, and should be integrated into all the stages of the infrastructure planning and design process” (Berdica 2002). Further, the author suggests that macroscopic simulation is not suitable for event analysis, as essential vehicle interactions cannot be

adequately captured. The report then concludes with stating that vulnerability analysis is regarded as a framework using the different aspects of transport reliability studies as its foremost tools, which is an approach adopted in the research carried out herein.

The research carried out on road network vulnerability assessment based on fragile factor interdependencies in spatial-functional perspectives undertook the analysis of a prototype model to carry out the process. Vulnerability definitions were presented, such as “the elements involved in making a system susceptible to the damage incurred by a hazard” (Hsieh and Feng 2014). Next, the vulnerability factor determinations were discussed, with six vulnerability dimensions presented. The three main infrastructure-related factors presented were connectivity – calculated based on the Gamma index, reliability – the extent to which the network provides consistent outcomes and predictable LOS, and thirdly, mobility, which is concerned with the individual ease of movement and differences in travel time experienced across the network. The next three factors are exposure – the effect posed on road users, socioeconomic factors that determine what demographics are affected, and finally resilience, defined as the ability to resist incident impacts, and after event occurrence, the ability to recover (Hsieh and Feng 2014).

The authors then presented the proposed approach adopted, starting with data collection, then performing classification and factor weights, by assigning a rating from 0 to 4 (normal to failure) to the network, and Table 1 presented in the report presents standardized rates and weights of vulnerability factors, including Delay, LOS, number of alternatives, connectivity, residents, and dependency, among others. Next, an interdependency analysis was carried out, where the authors noted that the complex nature of vulnerability leads to

the development of a theoretical framework for a quantitative vulnerability assessment by using a composite index in a GIS environment (Hsieh and Feng 2014). In the fourth section, the authors then present the empirical results obtained, where vulnerability was calculated on the basis of the sum of the product score of each factor by standardizing the data using the values from the aforementioned Table 1. Finally, it was determined that all links converge to three vulnerability categories (A, B, and C) representing high, medium, and low levels of vulnerability in the network. It was concluded that the distance to hospital emergency centers, time delay in substitutions, and household income significantly influence the vulnerability of metropolitan road networks (Hsieh and Feng 2014).

In other research, Jenelius and Mattsson describe a process for road network vulnerability analysis, from (i) the conceptual definition of vulnerability measures, through (ii) the derivation of practical indicators and models adapted to available data and their implementation in computational procedures, to (iii) the application of the methodology in case studies (Jenelius and Mattsson 2015). The authors state that it's of interest to study the magnitude and distribution of impacts due to disruptions in different parts of the network, so that resources for prevention, mitigation and restoration can be suitably allocated. Disruptions are defined as either 'from within' or 'external' and have different impacts on the traffic network. Here, network vulnerability analysis is presented as "the study of potential degradations of the road transport system and their impacts on society", achieved through modeling the infrastructure (Jenelius and Mattsson 2015). It was recognized that quantitative methods for assessing the consequences of disruptions of the transport system were needed. And the aim of the work is to perform the vulnerability analysis, with respect to three key areas: (1) definition of measures, (2) derivation of

indicators and implementation, and (3) application in case studies. Here, vulnerability is regarded as the societal risk of infrastructure disruptions, particularly with regards to (a) how the road users are affected, and (b) how the network elements themselves are affected overall (Jenelius and Mattsson 2015).

The second section of the report presents the conceptualization: perspectives and formal vulnerability measures. Transport system vulnerability is here seen as society's risk of transport system disruptions and degradations. Road network vulnerability analysis, in particular, focuses on the road transport system and models the physical infrastructure as a network of links (road segments) and nodes (intersections). Risk is constituted of three elements; description, probability, and impact. The road network is considered, with a certain disruption scenario space, and having multiple dimensions representing a relevant aspect of a network disruption. With each scenario, a 'null' scenario is further associated, that represents the baseline, normal level of operations against which the impact of the disruption is assessed. Furthermore, the compensating variation is used here as a formal measure of the impact of a disruption for individuals. Vulnerability and exposure is looked at next, where the impact for a single user under a certain disruption scenario is referred to as the exposure of the user to that scenario. Combining the exposure with the probability of the scenario gives the vulnerability of the user to that scenario. Rather than focusing on single individuals, one may more often be interested in the exposure of aggregate groups of individuals. To formalize the worst-case exposure of groups, the dimensions of the scenario space are partitioned into two subspaces, the authors then consider the worst possible impacts along the dimensions in one of the subspaces, while the dimensions in the other are kept fixed at a certain point. Assuming that a maximum exists, the worst-case

user exposure can then be found, with respect to the considered subspace. Next, Importance and criticality are looked at, where the second perspective on vulnerability focuses on the technological side of the system. The main purpose behind the importance measure is to compare and rank different elements. This allows the identification of parts of the transport system where disruptions would be particularly severe. The combination of importance and disruption probability is called the criticality of the element; importance can thus be expressed as conditional criticality (Jenelius and Mattsson 2015).

The third section of the paper looks at the aspect of implementation: the derivation and computation of practical measures. Data and computational considerations are considered, as many different forms of practical vulnerability measures can be derived from the same formal framework. In this section a set of practical indicators and algorithms adapted for large-scale vulnerability analyses of the Swedish road network is considered, where disruption scenarios consist of complete closures of one or several links for a certain duration. The compensating variation for each trip related to the disruption is assumed to be proportional to the increase in travel time. The value of time is taken as a common proportionality constant for all trips and then omitted in relative analyses (Jenelius and Mattsson 2015). There are four main assumptions and approximations employed in this research: (1) Inelastic demand, as only changes in route choice are considered. (2) Static demand, as travel demand per unit time between OD pairs is constant. (3) No congestion effects, as link closure doesn't affect travel time on other links. (4) Perfect knowledge of the network; the users are assumed to know the shortest path and travel time available. Practical vulnerability measures are then outlined, wherein a disruption scenario can be described with only two parameters: the element (the link or group of links) being closed,

and the closure duration. A trip is also characterized by two factors: the OD pair, and the departure time relative to the duration of the disruption. The basic principle is that a user chooses the new shortest route if there are available routes during the closure, and assigned a value of infinity if there are no alternative routes (Jenelius and Mattsson 2015). The representation of disruption scenarios is then presented, where two kinds of scenarios are studied: single-link disruptions and area-covering network disruptions. For single-link disruptions, simultaneous closures of both directions of two-way road segments are considered, and for area-covering disruptions, a complete coverage of the study area is made using evenly displaced grids of uniformly shaped and sized cells. The computation of vulnerability measures is then performed, utilizing GIS software. The information is used to calculate measures of regional exposure, and the most straight forward way of computing impacts for all OD pairs and scenarios is used, where travel times are calculated in the null scenario, then elements are closed sequentially, and the disruption travel times are then computed. Consequently, delays are found from the difference in travel times. The process is then repeated for each element under study (Jenelius and Mattsson 2015).

Finally, the methodology is applied to perform a spatial vulnerability analysis of the Swedish transportation network. Data utilized included the number of OD nodes in relation to the total number of generated trips, which influences the quality of the results of a vulnerability analysis due to the effects of spatial bias. The study design is organized in such a way that each disruption scenario is associated with a normalized probability of occurrence, and Laplace's Principle of Indifference is used which says that all scenarios should be regarded as equally probable if there is no evidence to the contrary. The regional worst-case user exposure is then calculated, which yields a high value if a large share of

the regional trips normally use a link with poor alternatives, also named a cut link. Next, the regional expected user exposure is determined, where, for single link closures, expected exposure is high if trips are long on average, and if the network density is low. Finally, link and cell importance is found, where it is stipulated that a link is important if it is used by a large number of road users, typical characteristics are high traffic flow and poor alternatives (Jenelius and Mattsson 2015). All these results are presented on GIS maps of the Swedish transportation system.

The report then concludes, where the authors state that the intention of the paper is to help researchers on vulnerability analysis to identify areas for additions and improvements, and to see how areas are connected. A vulnerability analysis process such as outlined here provides the background and starting point for an evaluation of various measures to reduce vulnerability. There is a need for more normative approaches in model-based vulnerability analysis. Given certain spatial extents, durations and relative probabilities, the study found significant influences on regional variations in vulnerability from travel patterns, location patterns and the development of the road network. “In order to allocate resources for reducing vulnerability efficiently, it is necessary to combine the impact calculations with estimates of the frequencies with which different kinds of disruptive events will occur in different parts of the study area” (Jenelius and Mattsson 2015).

2.3 Modeling of Infrastructure Systems

In a detailed paper, Murray provides an overview of the evolution of modeling approaches to examine network vulnerability. Reviewed approaches are characterized in terms of how system performance is accounted for. Interdiction scenarios for each performance class are

discussed, illustrating the unique attributes of the various modeling approaches (Murray 2013). In this work, the author presents vulnerability as a reflection of the potential for disrupting or degrading network performance. Four types of disruption are presented: (1) component failure, (2) natural disaster, (3) unintended events, and (4) planned events. It is then discussed that vulnerability is addressed through network design, with queues inputted from system reliability assessment, which looks at the component failure likelihood. Maximal Flow is then looked at, in terms of single component performance, where the performance function leads to the identification of the worst case interdiction which results in the greatest decrease of traffic flow. The flow limiting components are identified as both: the link capacity, and the network topology (Murray 2013). Another dimension that looks at single-component effect is the Shortest Path analysis. This performance function aims to find the shortest path with respect to the minimum distance, travel time, and journey cost (Murray 2013).

On the other hand, the paper also looked at the dimensions affecting the whole network overall, the first of which is connectivity, measured through the impact of loss on the network diameter, characterized by the availability of connections between the different network elements (Murray 2013). The next dimension looked at was System Flow (also having influence over the performance of the whole network), where the level of interaction and flow between all node pairs in the network is paramount. Thirdly, Access Fortification is looked at, which is another class of vulnerability modeling approach which focuses on facilities that provide services. The facilities are distributed throughout a region and serve the nodes in a network (special generators). Previous researchers detail two measures of service access, median and coverage, then structure integer programming

models that can be solved optimally (Murray 2013). The last network characteristic investigated is actually the attributes of the components making up the network. That is, an interdiction effort might be interested in affecting the greatest amount or quantity of network component attributes, such as link capacity degradation (Murray 2013).

The paper then concludes, and it is stated that exploratory based systems are essential for any comprehensive assessment of network vulnerability. Optimization methods are important for identifying worst case scenarios, while there remains a gap in how best to address connectivity issues in the network. There is an increasing attention on coordinated interdiction by terrorist attacks through game theory, as infrastructure security is becoming an increasingly important global concern. Finally, there is a continued evolution in how vulnerability is considered, necessitating appropriate modeling advancements in order to better address spatial detail and specificity in network vulnerability assessment in addition to the recognition of different potential performance characteristics (Murray 2013).

3 Chapter: Methodology and Design

3.1 Methodological Framework for Quantifying Vulnerabilities

In order to obtain a valid strategy for developing the methodology by which the vulnerability index parameters are assessed, a conceptual methodological framework was developed. The purpose of the framework is the quantification of vulnerability factors that characterize the performance of traffic under a number of set conditions. These conditions influence the behavior of traffic flow patterns in the network, each according to the relative impact generated on the links making up the network. As such, the methodology outlined in Figure 3.1 was developed.

The first task involved establishing the idealized network upon which the analysis using traffic simulation software (PTV VISUM and VISSIM) was carried out. This is further detailed in Section 3.1.1, where the assumptions and steps are outlined. Next, the traffic flow analysis was performed in a two-step sequence utilizing PTV Vision's suite of traffic simulation software. First, mesoscopic-level simulations were carried out in order to obtain an overall functional network performance (this was carried out in VISUM). Then, a microscopic-level set of simulations were performed using VISSIM to further detail the modeled networks, and introduce stochasticity to the simulation procedure. This also allowed a greater level of detail to be obtained, whereby the interactions between the vehicles making up the traffic flow is modeled on to the resolution of individual road users. This yields outputs that better reflect the conditions encountered in real-life situations. The

process is further discussed in Section 3.1.2. Next, the outputs from the network analyses were obtained, and aggregated into four categories:

1. Travel Time (seconds)
2. Delay (seconds)
3. Flow Speed (km/h)
4. Distance Travelled (km)

The means by which this was carried out is detailed in Section 3.1.3 on page 36.

Figure 3.1: Conceptual Methodological Framework for Quantifying Network Vulnerabilities

After obtaining the baseline results by which the outputs of the other networks will be compared, the network variations were produced. These variations consisted of changes to the idealized network's three characteristic parameters:

1. Grid Layout (arrangement)
2. Block size (link lengths)
3. Traffic demand value

Each of these changes yields a set of comparison networks that are further discussed in Section 3.1.4 on page 37. Next, the previous steps of performing traffic flow simulation, obtaining, and analyzing the results are repeated for each of the network variations. Following that, the analyzed networks are reintroduced into the simulation software and links are sequentially eliminated (taken out of the network) in order to imitate road blocks. These occur in real-life situations due to any number of factors occurring, and consequently affecting the traffic flow. The previous simulation steps are repeated again for these network variations (this is detailed in Section 3.1.5 on page 38). Based on the obtained results, an analysis is carried out to determine the critical network factors, from which a set of criteria are adopted that quantify the effects of the varied network properties. Finally, the vulnerability index is constructed based on the output collected from the simulation results, taking into account the set of criteria adopted in the previous step, and combining them to come to the final form of the vulnerability index.

3.1.1 Establishing an Idealized Network

As can be seen from the flowchart in Figure 3.1, the first task in this framework was to establish the base traffic network upon which the analysis would eventually take place.

This network was designed to be of a simplified type in order to have a clear understanding of the interacting factors influencing the traffic flow patterns, and provide the capability of directly recognizing the relative impacts of each variable as it is introduced. This is referred to as the “idealized” network, as it adopts the standard typical characteristics of an urban central business district (CBD) as referenced from the TRB’s HCM 2010, Volume 1 Chapter 4 (Traffic Flow and Capacity Concepts), Volume 3 Chapter 16 (Urban Street Facilities), and Chapter 17 (Urban Street Segments).

As the goal is to model the behavior of traffic in urban city networks, the constituting links must be of the urban type. This type of street is ranked between local streets and multilane suburban and rural highways in the hierarchy of street transportation facilities, and the variations are primarily due to the street’s function, the control conditions found at the intersections (signalized, all-way stop, etc.), and the types and density of roadside developments. Arterial streets are roads that primarily serve longer through trips. However, providing access to abutting commercial and residential land uses is also an important function of arterials. Collector streets provide both land access and traffic circulation within residential, commercial, and industrial areas. Their access function is more important than that of arterials, and unlike arterials, their operation is not always dominated by traffic signals (Highway Capacity Manual 2010). As such, the links making up the CBD model adopt the collector street typology.

Downtown streets are signalized facilities that often resemble arterials. They not only move through traffic but also provide access to local businesses for passenger cars, transit buses, and trucks. Turning movements at downtown intersections are often greater than 20 percent

of total traffic volume because downtown flow typically involves a substantial amount of circulatory traffic (Highway Capacity Manual 2010). The dimensions for the links used in the network were adopted from the methodology given in the HCM 2010, where the degree of mobility was assessed in terms of travel speed for the through-traffic stream, and the level of access provided was taken into account for performance evaluation; where the factors favored levels of access, reflecting minimal mobility.

As per the manual, the design category “Urban” was chosen, and the functional category of “Minor Arterial” which corresponds to the street class IV. This is a lower class level, and was chosen in order to better approximate the operating conditions of a typical CBD, characterizing a city’s urban downtown traffic network.

K-Factor	D-Factor	Two-Lane Streets				Four-Lane Streets				Six-Lane Streets			
		LOS B	LOS C	LOS D	LOS E	LOS B	LOS C	LOS D	LOS E	LOS B	LOS C	LOS D	LOS E
Posted Speed = 30 mi/h													
0.09	0.55	NA	5.9	15.4	19.9	NA	11.3	31.4	37.9	NA	16.3	46.4	54.3
	0.60	NA	5.4	14.1	18.3	NA	10.3	28.8	34.8	NA	15.0	42.5	49.8
0.10	0.55	NA	5.3	13.8	17.9	NA	10.1	28.2	34.1	NA	14.7	41.8	48.9
	0.60	NA	4.8	12.7	16.4	NA	9.3	25.9	31.3	NA	13.5	38.3	44.8
0.11	0.55	NA	4.8	12.6	16.3	NA	9.2	25.7	31.0	NA	13.4	38.0	44.5
	0.60	NA	4.4	11.5	14.9	NA	8.4	23.5	28.4	NA	12.2	34.8	40.8
Posted Speed = 45 mi/h													
0.09	0.55	NA	10.3	18.6	19.9	NA	21.4	37.2	37.9	NA	31.9	54.0	54.3
	0.60	NA	9.4	17.1	18.3	NA	19.6	34.1	34.8	NA	29.2	49.5	49.8
0.10	0.55	NA	9.3	16.8	17.9	NA	19.3	33.5	34.1	NA	28.7	48.6	48.9
	0.60	NA	8.5	15.4	16.4	NA	17.7	30.7	31.3	NA	26.3	44.5	44.8
0.11	0.55	NA	8.4	15.3	16.3	NA	17.5	30.5	31.0	NA	26.1	44.2	44.4
	0.60	NA	7.7	14.0	14.9	NA	16.1	27.9	28.4	NA	23.9	40.5	40.7

Notes: NA = not applicable; LOS cannot be achieved with the stated assumptions.
 General assumptions include no roundabouts or all-way stop-controlled intersections along the facility; coordinated, semi-actuated traffic signals; arrival type 4; 120-s cycle time; protected left-turn phases; 0.45 weighted average g/C ratio; exclusive left-turn lanes with adequate queue storage provided at traffic signals; no exclusive right-turn lanes provided; no restrictive median; 2-mi facility length; 10% of traffic turns left and 10% turns right at each traffic signal; peak hour factor = 0.92; and base saturation flow rate = 1,900 pc/h/ln.
 Additional assumptions for 30-mi/h facilities: signal spacing = 1,050 ft and 20 access points/mi.
 Additional assumptions for 45-mi/h facilities: signal spacing = 1,500 ft and 10 access points/mi.

Figure 3.2: HCM Exhibit 16-14 Generalized Daily Service Volumes (Highway Capacity Manual 2010)

The chosen parameters correspond to a set of criteria from the manual. The mobility function is considered important, the access function is considered substantial, and it is assumed that the street points connect principal arterials. The type of predominant trips

served are those of moderate length within relatively small geographical areas, again, as would be expected in a city's CBD. On the other hand, the "Urban" design category corresponds to a high driveway/access density. Arterials may be undivided one-way, two-way, or multi-lane type (of which, a two-way, two lane typical street type was adopted, mirroring such actual roads like Bank Street in downtown Ottawa). The parking is considered to be significant (this affects the Flowability of the corridors), and although the exhibit refers to the provision for "some" separate left-turn lanes, these were not provided, in order to observe the constraints this would impose on the traffic network. There is often very limited right-of-way in city downtown cores, reducing the opportunities for adopting segregated left-turn auxiliary lanes. It is also stipulated that there are 4-8 signals/km and a speed limit ranging from 40 to 55 km/h, pedestrian activity is specified as "usual", and roadside development is regarded as being high density with commercial uses.

Data Category	Input Data Element	Default Values
Traffic characteristics	Access point flow rate	See discussion
	Midsegment flow rate	Estimate by using demand flow rate at the downstream boundary intersection approach
Geometric design	Number of lanes at access points	<u>Segment Approach</u> If median is present, one left-turn lane/approach. If no median is present, no left-turn lanes. No right-turn lanes. Through lanes are the same as N_{th} . <u>Access Point Approach</u> One left-turn lane and one right-turn lane.
	Turn bay length at access points	40% of the access point spacing, where spacing equals $2 (5,280) / D_{ap}$ in feet. Computed bay length should not exceed 300 ft or be less than 50 ft.
	Proportion of segment with curb	1.0 (curb present on both sides of segment)
	Number of access point approaches	Estimated for each segment side by multiplying default access point density by 1/2 segment length (i.e., $N_{ap,s} = 0.5 D_{ap} L / 5,280$) Urban arterial $D_{ap} = 34$ points/mi Suburban arterial $D_{ap} = 21$ points/mi Urban collector $D_{ap} = 61$ points/mi Suburban collector $D_{ap} = 48$ points/mi
Other	Analysis period duration	0.25 h
Performance measures	Midsegment delay	0.0 s/veh
	Midsegment stops	0.0 stops/veh

Note: D_{ap} = access point density on segment (points/mi); $N_{ap,s}$ = number of access point approaches on the right side in the subject direction of travel (points); L = segment length (ft); and N_{th} = number of through lanes on the segment in the subject direction of travel (in).

Figure 3.3: HCM Exhibit 17-24 Default Values: Automobile Mode (Highway Capacity Manual 2010)

It is understood that this is an idealized network, and practical applications will vary. However, this is meant to provide a basis, or a common denominator, by which variations will be compared and evaluated, each according to the applicable set of parameters. By varying the initial chosen parameters, permutations of the idealized network can be produced, resulting in a comparative baseline by which the resulting incremental values can be studied to determine the relative impact of each of the assigned dimensions.

The set dimensions of the idealized network (see Figure 3.4) are as follows:

1. A 4x4 block arrangement (each block consists of 2 consecutive links on each side in a square shape arrangement)
2. A unit demand of 1.0 trips per destination zone
3. 200 m uniform link lengths

Figure 3.4: Arrangement of links in the idealized network along a typical 4x4 block arrangement

The “Base Condition” is defined in the HCM as the best possible characteristic in terms of capacity for a given type of transportation facility. That is, further improvements would not increase capacity; a condition without hindrances or delays. The HCM 2010 further explains that in practice, there are sometimes ambiguities in determining the proper categories. The measurement or estimation of the free-flow speed is a great aid in this determination, because each urban street class has a characteristic range of free-flow speeds (Highway Capacity Manual 2010).

This arrangement was chosen based on the provisional thresholds from the HCM 2010. The manual stipulates that for the LOS speed criteria to be meaningful, the length of the urban street being analyzed should be at least 1.5 km long in a downtown area and 3.0 km long elsewhere, and study lengths shorter than 1.5 km should be analyzed as individual intersections and the LOS assessed according to individual intersection criteria (Highway Capacity Manual 2010). As such, the chosen link length of 200 m allows the developed network to have a total length of 1.8 km (four blocks, each with an edge consisting of two links). The length due to the blocks is:

$$200m \text{ link length} * 2 \text{ links} * 4 \text{ blocks} = 1.6 \text{ km}$$

In addition, the adjoining connectors of a 100 m length on each side yields a total network dimension of 1.8 km, which is 20% longer than the recommendation in HCM.

Free-flow speed, the theoretical speed of traffic (in km/h) when density is zero, that is, when no vehicles are present is a vital criterion that was also encoded into the network as part of the link characteristics. It is usually used to determine the urban street class and to estimate the segment running time. The analysis might rely on the posted speed limit (or

some value around that limit) or on default values in the manual (Highway Capacity Manual 2010). For the purposes of setting this baseline in the idealized network, the FFS value for the urban street class IV was chosen, and all the links and connectors in the network were assigned a default FFS value of 45 km/h. Signal density, the number of signalized intersections in the study portion of the urban street divided by its length, was also chosen as per the HCM recommendations. As such, for the urban street class IV, although a value of 6 signals/km is stipulated, the symmetrical geometry of the idealized network resulted in the corridors having a signal density of 5 signals/km (9 signals along the corridor length of 1.8 km). This is considered to be acceptable, as it is only a 20% variation, and although this might result in better Flowability of traffic along the network segments compared to a network with 6 signals/km (as per HCM 2010). This will still provide a valid baseline by which the network variations are assessed.

Figure 3.5: HCM Exhibit 16-3 Signal Spacing (Highway Capacity Manual 2010)

As per the HCM, the analytical procedures for estimating speed for urban streets depend on the estimation of delay at intersections, and are most accurate when the demand is less than capacity. Otherwise the intersection delay equations will not determine the effect of

excess demand. The length of the analysis period is typically given as 15 minutes (Highway Capacity Manual 2010), but should be extended to take into account the effects due to delay. Due to this, and to capture the peak effects due to traffic flow fluctuations, the created model has an analysis period of 60 minutes. It is understood that LOS criteria for urban streets, signalized intersections, and unsignalized intersections were developed for a 15-minute analysis period. Conditions that persist for longer periods (presumably with worse peak conditions within those periods) may no longer meet the 15-minute LOS criteria provided. This is addressed in the analysis of results in Section 3.1.3 accordingly. Finally, the service volume (the number of vehicles an urban street can carry at a given level of service and number of lanes, per direction) was determined as per the HCM manual, as the dimensions are similar to the default values assumed in the manual. All links were set to a capacity of 790 vehicles per hour, as this corresponds to LOS of E for single lane roadways of Class IV.

3.1.2 Performing Traffic Flow Analysis

The traffic flow analysis was done on the data output from the two-step simulation procedure. Here, traffic flow is defined as the number of vehicles, passenger car units, or pedestrians passing over a given cross-section of a roadway during a unit of time (Canadian Capacity Guide for Signalized Intersections 2008). The unit of time usually taken is one hour, and this is what has been adopted here, and almost steady traffic conditions are assumed to last over the whole analysis period. The set of procedures in the guide stipulates determination of all flow parameters on a lane-by-lane basis. “Arrival flow is the number of vehicles or pedestrians per unit of time approaching the intersection during the design or evaluation period. Typically, the vehicular arrival flow is counted upstream of the end

of an intersection approach queue. Only arrival flow should be used to represent travel demand at the intersection for the analysis, design, or evaluation” (Canadian Capacity Guide for Signalized Intersections 2008). This is in contrast to saturation flow (also called departure flow) where vehicles discharge from an accumulated queue (see Figure 3.6). In the constructed networks, the data collection points were set up at locations 50 meters upstream of the intersections to reflect this requirement.

Figure 3.6: Vehicular arrival and departure flow (Canadian Capacity Guide for Signalized Intersections 2008)

The vehicular traffic flows for all links in the network were expressed in terms of passenger car units, which is also equal to the number of vehicle flow. It was assumed that there are no heavy vehicles present in the network, which is typically the case for CBD applications, as such traffic is restricted during both morning and afternoon peak periods.

3.1.2.1 Mesoscopic Simulation

Seeing as VISUM is a GIS-based software, it is more applicable for use on a Macroscopic and Mesoscopic simulation scale, and hence was used for the high-level initial analysis of the transportation networks. Namely, macroscopic simulation is often applied to large networks (typically covering a whole city) and usually used to describe the evolution of traffic over time and space using a set of differential equations. Often analogues of physical phenomena are used in defining the differential equations, such as those describing traffic like flows in fluids or gases. The solution to these equations can be obtained analytically or using simulation (Burghout 2004). “Mesoscopic models normally describe the traffic entities at a high level of detail, but their behavior and interactions are described at a lower level of detail” (Burghout 2004). For the application in this analysis, mesoscopic-level simulation was used in order to model networks of a size comparative to that of a CBD, which is smaller than a city-wide application but larger than a single-road facility level (typical of microsimulation applications). This was deemed practical as a better approximation to the detail of microscopic simulation can be obtained, while not requiring as much resources.

The PTV Vision’s company website describes the software package “PTV VISUM is the world's leading software for traffic analyses, forecasts and GIS-based data management. It consistently models all road users and their interactions and has become a recognized standard in the field of transport planning. Transportation experts use PTV VISUM to model transport networks and travel demand, to analyze expected traffic flows, to plan public transport services and to develop advanced transport strategies and solutions” (PTV

Group 2016). The license for the PTV Suite of applications was provided by the thesis supervisor and consequently used for producing the simulations presented herein.

For the traffic assignment in the network, using VISUM all four stages of the classical traffic model (4-step model) can be calculated, including traffic assignment (choice and volume of the route to get from origin zone to destination zone), trip generation, trip distribution, and mode choice (the choice of means of transport by the road user). In the Classical model's first step – Trip Generation – the production and attraction (origin and destination traffic) of each zone is determined on the basis of socio-demographic data (for example, number of inhabitants and jobs), and was assumed to be uniform across all zones in the network as it is of homogeneous properties (all within the CBD). In the second step – Trip Distribution – the production and attraction values are used to define the totals of the total demand matrix, which is determined by means of relevant skim data (such as journey times, trip costs, etc.). For the third step – Mode Choice – the total demand matrix is distributed onto the different traffic modes on the basis of mode-specific skims (such as different types of private and public transport). But again, for the purposes of this analysis which focuses on vehicular traffic, all modes have been set to SOV; privately operated vehicle whose only occupant is the driver. The drivers of SOVs use their vehicles primarily for personal travel, daily commuting and for running errands (Mannering and Washburn 2013). This is typical of CBD vehicular commuter traffic. In the fourth step – traffic assignment – the resulting mode-dependent demand matrices can be assigned to the supply (VISUM network) by means of the assignment procedures in order to obtain link volumes and new skims. This skim data can again be used as input for trip distribution of a new demand calculation, this is done iteratively using VISUM functions, allowing the

calculations to be repeated until the convergence criteria (link volumes or matrix values) are satisfied (PTV AG 2014).

The method adopted for the traffic assignment step is the system optimum approach. This is based on the assumption that routes of all vehicles would be controlled by the system, and that rerouting would be based on maximum utilization of resources and minimum total system cost (cost can be interpreted as travel time). “Hence, in a System Optimum routing algorithm, all routes between a given OD pair have the same marginal cost. In traditional transportation economics, System Optimum is determined by equilibrium of demand function and marginal cost function. In this approach, marginal cost is roughly depicted as increasing function in traffic congestion. In traffic flow approach, the marginal cost of the trip can be expressed as sum of the cost (delay time, w) experienced by the driver and the externality (e) that a driver imposes on the rest of the users” (Muñoz and Laval 2006).

The system optimum assignment is based on Wardrop's second principle, which states that drivers cooperate with one another in order to minimize total system travel time. This assignment can be thought of as a model in which congestion is minimized when drivers are told which routes to use. Obviously, this is not a behaviorally realistic model, but it is useful to transport planners and engineers, trying to manage the traffic to minimize travel costs and therefore achieve an optimum social equilibrium (Mathew 2006).

3.1.2.2 Microscopic Simulation

Microscopic-level simulation is needed in order help understand the traffic system at a more detailed level. “It has been found that ‘details’ at the macroscopic level, such as the

length of an on-ramp or the settings of signal control, are often constraining when it comes to the maximum (capacity) and nominal flows through such sections. The study of the vehicular interactions is needed to discover and understand such constraining factors” (Burghout 2004). While the mesoscopic simulation models exhibit fewer details to favor more efficient calculations so that solutions can be found more quickly, the microscopic models include such details and favor the description of traffic entities more accurately at the expense of more cumbersome calculation procedures.

VISSIM is described by PTV Vision as allowing the user “to simulate traffic patterns exactly. Motorized private transport, goods transport, rail and road related public transport, pedestrians and cyclists – as the world's leading software for microscopic traffic simulation, PTV VISSIM displays all road users and their interactions in one model. Scientifically sound motion models provide a realistic modelling of all road users.” In addition, “The software offers flexibility in several respects: the concept of links and connectors allows users to model geometries with any level of complexity. Attributes for driver and vehicle characteristics enable individual parameterization. Furthermore, a large number of interfaces provide seamless integration with other systems for signal controllers, traffic management or emissions models” (PTV Group 2016). Hence, in order to obtain more detailed results, after the networks were set up and simulated using VISUM to get the preliminary results, they were then exported to VISSIM for further simulation and the aggregation of more detailed data. Figure 3.7 shows the different resolutions of simulation as presented in this section.

Figure 3.7: Comparison of the three modelling levels (Marsico, et al. 2013)

3.1.3 Obtaining Results

Data was collected from both software packages (VISUM and VISSIM), and exported into Microsoft Office Excel Spreadsheets for analysis. This was done in addition to the VISSIM comprehensive analysis options, which are a powerful tool for the evaluation and planning of urban and extra-urban transport infrastructure. For example, the simulation software was

used to create detailed computational results for the different scenarios; including data on links, nodes and turns. The four main result classes acquired were as follows:

1. Average Delay (seconds)
2. Average Flow Speed (km/h)
3. Total Distance travelled (km)
4. Total Travel Time (seconds)

These dimensions were specifically chosen as the values are needed in combination with the assumed defaults in the network properties in order to have the complete set of parameters needed to construct the vulnerability index. This is presented in Section 3.1.7, and further in Section 3.2 where the analysis is outlined in more detail.

3.1.4 Varying the Network Properties

In order to obtain an understanding of how the three network properties presented in Section 3.1.1 for the construction of the idealized network play a role in the functioning of the traffic network and its flow characteristics, each of the parameters was assigned a range of values. Subsequently, a number of networks were modeled adopting the chosen parameter values. These would naturally produce different results each time, and the obtained values helped shape an understanding of the relative effect of each of the characteristics in comparison to the base network. The variations were adopted as shown in Table 3.1. The shaded cells in the table represent the values from the idealized network that are held constant in the variation networks. Each modified network holds two of the three dimensions constant, and only one characteristic is varied at any time, in order to provide a valid comparison basis at which the dimensions can be equated.

Table 3.1: Variations in Idealized Network Parameters

Code	Number	Block Layout (arrangement)	Unit Demand (trips/destination)	Link Length (meters)
BASE	1	4 x 4	1.0	200
Centrality	2	1 x 16	1.0	200
Centrality	3	2 x 8	1.0	200
Centrality	4	3 x 5	1.0	200
Centrality	5	3 x 6	1.0	200
Flowability	6	4 x 4	1.5	200
Flowability	7	4 x 4	2.0	200
Flowability	8	4 x 4	2.5	200
Flowability	9	4 x 4	3.0	200
Mobility	10	4 x 4	1.0	250
Mobility	11	4 x 4	1.0	300
Mobility	12	4 x 4	1.0	350
Mobility	13	4 x 4	1.0	400

The traffic flow analysis was then done using the same methods described in Section 3.1.2 for all the 13 network variations produced from this technique. Each of the varied parameters aims at quantifying the effects of that characteristic on the traffic network in order to generate measurements of the respective dimensions, and lead to the piecing together of the vulnerability index. These three dimensions are as follows:

1. **Centrality** (due to varying **grid layouts**)
2. **Flowability** (due to fluctuating destination **node demands**)
3. **Mobility** (due to different **link lengths**)

3.1.5 Sequential Link Closure

The next phase of work undertaken was a process devised in order to provide the capability of identifying the relative importance of links *within* a network based on the relative

location and positioning in terms of network topology. That is, the previous process explored the factors affecting overall vulnerability of the network as a complete system. This procedure enables the identification of individual links between any two nodes and evaluate the relative vulnerability of each component (link) in order to aid in decision-making practices when it comes to the roadway level.

In the previous section (3.1.4), the studied networks represent pre-event conditions where there are no link closures and the traffic flow can utilize the whole network in the determination of route choice. The networks with link elimination mimic conditions during the occurrence of an event requiring road closure, hence forcing road users to seek alternate routes that result in an increase in individual journey travel times, and an overall increase in vehicle kilometers traveled over the whole network, and consequently increased trip costs.

Figure 3.8: Sequential Link Closure

The procedure undertaken was done in four steps. First, the links to be eliminated were identified. As can be seen from Figure 3.8, as the base network is symmetrical about the y and x axes, it was only necessary to produce six variations out of a total of forty (40) possible scenarios in order to represent all permutations of the network under single-link closure conditions. The second step was to then produce six networks for simulation in the third step, where the networks were modeled in VISUM and an initial Mesoscopic simulation was performed. The models were then exported to VISSIM, where a more detailed Microscopic simulation was performed. The fourth and final step was then carried out where the results were obtained from the software outputs, and evaluation was performed in order to study how the results differ from those obtained from the base network analysis.

3.1.6 Determining Link Closure Effect

In order to be able to construct the vulnerability index which describes urban traffic networks, the results obtained from the previously carried out model simulations were aggregated and imported into Microsoft Excel Spreadsheets for graphical analysis.

The raw data was also imported into the statistical analysis software Stata/MP for further analysis. “Stata/MP is a version of Stata/SE that runs on multiprocessor and multicore computers. Stata/MP provides the most extensive support for multiprocessor computers and multicore computers of any statistics and data-management package, allowing the user to analyze data in one-half to two-thirds of the time compared with Stata/SE on inexpensive dual-core desktops and laptops and in one-quarter to one-half the time on quad-core desktops” (StataCorp LP 2016). This program was used as experience already existed with

the use of this particular software package, and as it is a complete, integrated statistical software package that provides everything needed for data analysis, data management, and graphics. It is also compatible with Microsoft Excel.

The statistical analysis was carried out in several steps, where the first step involved identifying an appropriate dataset. The second step included formulating hypotheses and conducting preliminary data analysis, providing relevant descriptive statistics tables and figures on the data, and writing the corresponding results section. The third step included developing the methodology section, running various models of multiple regression analysis, producing related tables / figures and writing the results of the regression analysis. This was carried out for both sets of data obtained from the two analysis sets:

1. Varied Network Properties
2. Sequential Link Closure

These results are presented in Sections 5.3 and 5.4, then discussed in Section 6.1 in more detail. Values are obtained from the data aggregated from the models with sequential link closure, and a trend line is fitted that best describes the data. This variable – Link Closure Effect (% Effect) – is then determined from the volume of the closed link, and how this diverted traffic affects all other links in the network. Factors affecting this value include the number of alternate links available adjacent to the closed link that can have the traffic flow diverted to, as well as how far the closed link is from the central node (number of blocks).

3.1.7 Producing the Vulnerability Index

3.1.7.1 Centrality

Connectivity usually refers to the density of connections in path or road networks, and the directness of links. “A well-connected network has many short links, numerous intersections, and minimal dead-ends (cul-de-sacs). As connectivity increases, travel distances decrease and route options increase, allowing more direct travel between destinations, creating a more Accessible and Resilient system that reflects Complete Streets principles. Connectivity can apply both internally (streets within that area) and externally (connections with arterials and other neighborhoods)” (Victoria Transport Policy Institute 2015).

There is an established methodology of employing a “Connectivity Index” among municipal planners and planning and design professionals in a number of Canadian municipalities. For instance, the Region of Calgary applies this principle in its Greenfield Tool Box. Here, the connectivity index is most commonly determined by comparing the ratio of street segments to intersections. To quote, “the number of roadway ‘links’ divided by the number of roadway ‘nodes’ for a given study area. Cul-de-sacs are counted as a node. Index values typically fall between 1 and 2, with higher values indicating more connectivity” (02 Planning + Design Inc. 2012). As Figure 3.9 shows, different street network types have different levels of connectivity. The Connectivity Index allows for the effective comparison of each type (Marshall and Garrick 2010).

Figure 3.9: Different Street Network Types Showing Varying Connectivity

However, for the purposes of the CBD comparison, connectivity aims at establishing a comparison of the network topology, as the centrality of the blocks would act as a factor in the way vehicles traverse the road network. As such, it is proposed that the aforementioned Connectivity Index doesn't play a significant role in this analysis purpose, as all CBD networks are assumed to adopt a consistent street network type (in terms of neighborhood street network and citywide street network) of the type Grid-Grid (GG) as per Figure 3.9. A prime example of this is the Ottawa CBD which reflects the GG topology (see Figure 3.10).

Figure 3.10: Snapshot of the Ottawa CBD (City of Ottawa 2012)

The methodology presented herein is to be considered for the Centrality Index. When conducting the analysis, the selected layouts result in a comparison of an array of networks from a linear-type of arrangement (demonstrated by the 1 x 16 network layout), to the square network layout (as demonstrated by the 4 x 4 block layout). All the network layouts were chosen so as to have a total of sixteen blocks making up the grid, however this was not possible in two cases; the 3 x 5 network layout and the 3 x 6 network layout. These two networks have a total of 15 and 18 blocks respectively, and the results will reflect slightly varying measurements. However, the results can be interpolated appropriately, as further discussed in Section 5.3 (results). Centrality in this context is used to describe the

“connectivity” of the network. As will be demonstrated, the more square-shaped a network is the better it is connected, which by consequence results in a higher level of connectivity and mobility in the network.

Equation 1: Calculation of Centrality

$$Centrality = \frac{\# \text{ blocks (width)}}{\# \text{ blocks (length)}}$$

This directly relates to the ultimate goal of characterizing vulnerability; greater network centrality leads to less vulnerability as road users can more readily find an alternate route in case of the occurrence of an event. It is proposed that the calculation method for the centrality dimension be carried out by dividing the number of blocks making up the network width by the number of blocks along the network’s length. This results in values between 0 and 1, with values closer to 1 representing networks with higher centrality.

3.1.7.2 Flowability

In this transportation analysis, Flowability is an adapted concept of the traditional definition of transportation/traffic flow theory; where it is defined as the study of the movement of individual drivers and vehicles between two points and the interactions they make with one another. To better represent traffic flow, relationships have been established between the three main characteristics: (1) flow, (2) density, and (3) velocity. These relationships help in planning, design, and operations of roadway facilities (Daganzo 1997).

3.1.7.2.1 Flow

Flow (q) = the rate at which vehicles pass a fixed point (vehicles per hour) (Banks 1991);

$$q = \frac{3600 N}{t_{measured}}$$

Where:

q = equivalent hourly flow

N = number of vehicles occupying a highway segment of length L

$t_{measured}$ = Average measured time headway

Figure 3.11: Flow Density Relationship (Adeel 2009)

3.1.7.2.2 Flowability Dimension

For the construction of the vulnerability index, Flowability is introduced as the second dimension to be employed, this is defined as the characteristic of the network that relates the link capacities to the demand in the network (volumes on the links). Expressed in terms of residual capacity as a percentage of the total link capacity. This represents how easily vehicles can negotiate the network, as vehicle movement is more convenient (vehicles can attain higher speeds) when traffic density is low, and flow increases as density increases. More vehicles can utilize the network facilities, up to the critical density (k_c) at which the maximum flow (Q) occurs. After this point, the increase in density results in a deteriorated Flowability as headways become less, and interactions between vehicles at close proximity result in reduced flow across the network. Figure 3.11 represents this relationship in a graphical format, and as can be seen, flow is reduced up to the minimum value, at which jam density (k_j) occurs. Here, it is likely that the network has entered into a grid lock situation – representing the lowest Flowability conditions.

Equation 2: Calculation of Flowability

$$Flowability = \frac{Link\ Capacity\ (veh/hr) - Demand\ (veh/hr)}{Link\ Capacity\ (veh/hr)}$$

This dimension also contributes to the characterization of network vulnerability. Greater network Flowability leads to less vulnerability as vehicles traverse the network more quickly and can move away from incidents, as well as find capacity in alternate routes along the road network. It is proposed that the calculation method for the Flowability

dimension be carried out by finding the residual link capacity (total link capacity minus demand on the link) and then dividing by the total link capacity. This results in values between 0 and 1, with larger values (closer to 1) representing networks with a higher degree of Flowability. One performance function of a network is transmitting the maximum flow possible from an origin node to a destination node (Ford and Fulkerson 1962). As such, in order to identify the worst case interdiction scenario that has the greatest decrease in maximum flow possible, the range of increasing demands has been introduced. Each increase in demand results in an increase in density of traffic flow, and thus the vulnerability of the network at different flow levels can be studied.

3.1.7.3 Mobility

This dimension is employed to approximate the individual ease of movement for road users traveling in the network, indications for this include the difference in travel time for the vehicles traversing the network in varying operating conditions. The system flow over the whole network is thus considered, and the analysis is carried out on the level of interaction and flow between all nodes in the network. The maximal flow conditions exist when the flow limiting components become critical, including link capacities and the aforementioned network topology. As vulnerability reflects the potential for disrupting or degrading network infrastructure performance, addressing vulnerability must bring into focus the network design through reliability assessment; the likelihood of component failure (Murray 2013).

As such, when the link lengths are increased, paths taken by the road users increase in length as well, and the performance function evaluating the shortest paths with respect to

the minimum distance, travel time, and cost of trips increases. In addition, the longer the distance vehicles travel on a link, and the longer the travel time on the link, the greater the probability that an event will occur on the link when being traversed by a vehicle. As such the risk is increased and the network becomes subject to a greater degree of vulnerability.

3.1.7.3.1 Density

Density (Concentration) (k) = number of vehicles (N) over a stretch of roadway (L) in units of vehicles per kilometer (Banks 1991);

$$k = \frac{N}{L}$$

Where:

k = density

N = number of vehicles occupying a highway segment of length L

L = length of roadway

As can be seen from the above equation, when holding the variable (N) constant throughout the network, different values of density (k) will be obtained when the length (L) of the links is varied.

3.1.7.3.2 Mobility Dimension

This is the third and final dimension used for the construction of the vulnerability index. This characteristic of the network relates the vehicle kilometers traveled on the network to the length of the links themselves. This is also related to the network topology and depends on the number of blocks present in the network, as two networks of the same overall length

will have vastly different vulnerability characteristics depending on the link lengths and number of blocks making up the network. For example, consider two networks of the same overall dimension of 1 km by 1 km. If the first was made up of 4x4 blocks of 250 meter lengths, it will exhibit vastly different characteristics from a network made up of 5x5 blocks of 200 meter lengths, as the latter would have a higher Connectivity Index (refer to Section 3.1.7.1).

It is proposed that, in order to reflect the network density (in terms of roadway infrastructure, rather than traffic flow density), the mobility dimension be calculated as shown in Equation 3 below.

Equation 3: Calculation of Mobility

$$Mobility = \left[\frac{\left(\frac{\#Blocks\ width + \#Blocks\ length}{2} \right)}{Average\ Link\ Length\ (m)} \right] * 10$$

As was intended with the previous two dimensions, Mobility also has values ranging from 0 to 1. Smaller values indicate a more vulnerable overall network, as it indicates a smaller number of blocks in relation to the link lengths. This indicates that a greater number of vehicles must negotiate fewer links, thus subjecting a larger number of road users to risk if an event was to occur on that link. The reduced number of blocks also translates to a smaller of nodes where vehicles can make the change and adopt alternate links for the path being followed if a portion of the path cannot be traversed due to link closures.

3.1.7.4 Link Closure Network Effect

This analysis is meant to explore the effect of individual links on the network as a whole, exploring how the traffic flow patterns in the overall network are influenced when a certain link is closed. This could result, for example, due to an event occurring on the link under study. This then results in the rerouting of vehicles around the affected link, and onto the adjacent alternate links instead.

This dimension is presented in terms of the percentage increase or decrease of vehicle flow volumes over the whole network, obtained from the VISUM simulation models for each of the six networks with link closures. This is likely due to the effect of three vital variables; the residual link capacity (RC), which is the traffic volume on a link as a percentage of the link capacity. The next variable is the number of alternative links (A) available to accept the diverged traffic from the closed link. The third and final variable is the number of blocks (B), determined by the shortest route from the closed link to the central node of the network.

3.1.7.5 The Combined Vulnerability Index

The goal of the vulnerability index (CVI) developed herein is to provide a means by which existing CBD transportation networks can be evaluated for vulnerability assessment. It would also come into play for proposed networks during the development process of new transportation infrastructure (for example, expanding an existing network).

As was described from Sections 3.1.7.1 to 3.1.7.3, the lower values of each dimension reflect a higher degree of vulnerability for the network under study. Each dimension ranges

in value from zero to one (0-1). As such, a network with a greater CVI value will provide the best topology as per this methodology, and one which can best counteract the risks of vulnerability (relative to other networks, holding all other criteria constant). The CVI is thus represented on the ternary plot (simplex plot), as represented in Figure 3.12.

The ternary plot is constituted of the three dimensions employed for the characterization of vulnerability; Centrality, Flowability and Mobility. In order to determine the relative vulnerability of networks, the value of each dimension is to be calculated as previously described throughout this chapter, and then a triangle is to be plotted in the ternary plot area. The area of the triangle can then be calculated, which represents the network's vulnerability.

Figure 3.12: CVI Ternary Plot

The theoretical maximum triangle area that could be obtained occurs for a value of zero for each of the vulnerability dimensions. This area is equal to a value of (1.2991), calculated from the area of the triangle as shown below:

$$A = \frac{b * h}{2} = \frac{((2 \sin 120^\circ) * 1.5)}{2} = 1.2991$$

On the other hand, the smallest theoretical area of the triangle is zero. As such, the values of the individual dimensions range from (0-1), whereas the value of the CVI ranges from (0-1.2991). The networks exhibiting more vulnerable characteristics have a $CVI \approx 1.2991$. Finally, the link-network influence value obtained from the previous section is used to compute the influence of the closed link on the network vulnerability. The value of the obtained (% Effect) is then multiplied by the CVI, to obtain the ACVI value due to the effect of the closed link.

3.2 Applying the Methodological Framework

This section provides a description of the work done to apply the methodology under the framework described in Section 3.1, the models produced in VISUM are outlined and the export to, and additional simulation in VISSIM are also presented. These two programs have been chosen due to the suitability for their intended application, as well as interoperability and designed compatibility, as can be seen in Figure 3.13.

Figure 3.13: PTV Vision Suite Integration (WUS Group 2015)

PTV VISTRO was not adopted as it primarily focuses on signal optimization and related traffic impact analysis, which is not the focus of this research. While workflow is two-way between PTV VISUM and VISTRO, when data is exported to VISSIM, it is not valid for re-work in either. As such, data must be properly organized and formatted in VISUM before it is exported to VISSIM for detailed microscopic modeling. PTV VISWALK was not used either, as it is used for the simulation and modeling of pedestrian walking behavior, and in this research the focus is on motorized vehicle analysis.

3.2.1 VISUM

The first step involved constructing the base mesoscopic model in VISUM. This idealized network serves as the basis upon which all the other models are produced, each with its own specific changes to reflect the vulnerability dimension under study, respectively. The

reason the models were first produced in VISUM is due to the fact that macroscopic and mesoscopic models are easier to calibrate than microscopic models, due to their few and directly measurable parameters. But, their application is limited to cases where the interaction of vehicles is not crucial to the results of the simulation (Burghout 2004). As such, further analysis was conducted in VISSIM to model vehicle interactions.

3.2.1.1 The Base Model

The default parameters were used to produce the base network, as described in Section 3.1.1 on page 23. The nodes (intersections) were laid out as a grid with 200m spacing, then links (road segments) were inserted to connect between node pairs. The next step was to input zones (traffic cells) into the network, these model objects represent origins and destinations of movements within the transportation network, and one was placed at the center of each block to represent the traffic demand and supply of areas in the network. Zones were also placed at the edges of the network to represent the demand/supply to and from the study area originating from outside locations (such as residential areas outside the CBD). The zones were then connected to the link network via connectors, which represent the distance to be covered between a zone's center of gravity and the connector nodes. Turns were then set for every node, specifying which movements are permitted from one link to another.

Figure 3.14: Base Model Construction in VISUM

As a result of the creation of zones across the network, OD pairs are established between all zones. These are then in turn reflected in the rows and columns of skim matrices and demand matrices, with the values in the matrix each corresponding to a specific OD pair. Figure 3.15 shows part of the demand matrix created for the modeling of the network in VISUM, with a uniform demand value assigned across all OD pairs in order to observe the resulting traffic flow, before and after the sequential link closure. It was determined for the purposes of this research that when the initial flow is distributed evenly across the network, it is more suitable to observe changes in the flow patterns, as opposed to having the base network with already variable traffic flows. Next, for assignment calculation, paths are found between OD pairs, with appropriate traffic volumes allocated by the program, which has been based on a system-optimal assignment procedure. It is assumed that these described conditions take place on a typical weekday.

52 x 52		2	4	6	8	10	12	14	16	18	20	40	44	48	60	80	84	88	100	120	140	160	180	200	412	416	420	620	812	816	820	1020
	Name	Sum	127.50	127.50	127.50	127.50	127.50	127.50	127.50	127.50	127.50	127.50	127.50	127.50	127.50	127.50	127.50	127.50	127.50	127.50	127.50	127.50	127.50	127.50	127.50	127.50	127.50	127.50	127.50	127.50	127.50	127.50
2	127.50	0.000	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50
4	127.50	2.50	0.000	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50
6	127.50	2.50	2.50	0.000	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50
8	127.50	2.50	2.50	2.50	0.000	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50
10	127.50	2.50	2.50	2.50	2.50	0.000	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50
12	127.50	2.50	2.50	2.50	2.50	2.50	0.000	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50
14	127.50	2.50	2.50	2.50	2.50	2.50	2.50	0.000	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50
16	127.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	0.000	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50
18	127.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	0.000	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50
20	127.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	0.000	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50
40	127.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	0.000	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50
44	127.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	0.000	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50
48	127.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	0.000	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50
60	127.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	0.000	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50
80	127.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	0.000	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50
84	127.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	0.000	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50
88	127.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	0.000	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50
100	127.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	0.000	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50
120	127.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	0.000	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50
140	127.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	0.000	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50
160	127.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	0.000	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50
180	127.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	0.000	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50
200	127.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	0.000	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50
412	127.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	0.000	2.50	2.50	2.50	2.50	2.50	2.50	2.50
416	127.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	0.000	2.50	2.50	2.50	2.50	2.50	2.50
420	127.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	0.000	2.50	2.50	2.50	2.50	2.50
620	127.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	0.000	2.50	2.50	2.50	2.50
812	127.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	0.000	2.50	2.50	2.50
816	127.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	0.000	2.50	2.50
820	127.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	0.000	2.50
1020	127.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	0.000

Figure 3.15: Example Demand Matrix in VISUM

For the study network, all links, turns, and connections have been attributed to only the private transport system (passenger cars). The achieved travel times on the links depend on the permitted speed of the traversed link, which has been set to 50 km/h, as well as the capacity of the traversed link (refer to Section 3.1.1).

The demand matrix was then assigned to the demand segment (Private Transport) of the model, in passenger car units. As the occupancy was set to single-occupancy type, the calculation of person trips is done accordingly, where the assignment was carried out as an incremental system-optimal solution (designated as ICA in the program). This contrasts with user equilibrium, minimizing the overall travel costs of the traffic network (this is the fourth step of the standard 4-step model). The procedure was chosen as it is particularly suitable for urban areas where delays are mainly caused by junctions. The junctions are modeled in detail so that capacity and delay can be calculated based on HCM method, and the queue effects modeled. All assignments are path-based, that is, possible paths in the assignment are all calculated for every OD pair and then loaded with a demand share. All other results, such as the volumes on links and skim matrices, are then derived from these loaded paths; paths are the central result of the assignment procedure. The methodology

used in this model to handle the path objects is the “matrix distribution to paths” procedure. Based on the matrix and paths, the trips of the matrix are distributed to the paths. This enables the modification of the demand on the level of OD pairs, which can then be distributed to all existing paths of the OD pair, in proportion to the previous shares (PTV AG 2014).

Figure 3.16: Processing of ICA Assignment Procedure in VISUM

For the purposes of this analysis, each node (intersection) was allocated a signal control of the type signal – Group SCs, where signal groups were defined immediately in the model. All the signal groups were then set to undergo signal time optimization, with the program running an algorithm to determine the optimum signal phases and timing (Green time start, Green time end, as well as Amber and All-red times) required for efficient traffic flow for the conditions present. For more details on this lengthy function, please refer to the VISUM program user manual. The final step is to perform a network check. VISUM provides support for checking the consistency in the network model. For instance, if the network contains zones that are not connected to the rest of the network, a modeling error will be

indicated. Several test are employed by the program in order to identify such errors (PTV AG 2014), as seen in Figure 3.17, showing the check performed for this model.

Figure 3.17: VISUM Network Check Function

After the assignment was performed, and traffic volumes obtained for all the links in the network, the graphical display was modified in order to have the links display the volumes in a classified order. Classification was done based on the incremental traffic volumes, as can be seen from Table 3.2 below. The node display types was also modified in order to show the LOS of each intersection.

Table 3.2: Traffic Volume Classification

Draw	Class	Name	Preview
☒	<= 100	<= 100
☒	<= 150	<= 150
☒	<= 200	<= 200
☒	<= 250	<= 250
☒	<= 300	<= 300
☒	> 300	> 300

3.2.1.2 Simulation of Network Permutations

The base network was then used as a basis for the other models used in this research, with the necessary changes made for each model as required, as described in Section 3.1.4. The resulting traffic flow patterns are presented in Appendix A showing the network permutations and resulting traffic flow volumes, reflecting the three CVI dimensions; Centrality, Flowability, and Mobility. The results are presented in Section 5.3.

Finally, all the VISUM models were exported to ANM format files for conversion into VISSIM microsimulation models. The node geometry was first setup by using the “VISSIM Preview” function within VISUM, where junction editor was used to modify and make sure the intersections are translated correctly, including setting the correct turning movements at the node, stop bar locations, as well as lane widths and auxiliary lane lengths.

Figure 3.18: VISUM (left) and VISSIM (right) Model Comparison

3.2.1.3 Sequential Link Closure Models

The base model was also used to simulate the situations where a link in the network was eliminated, one at a time, for a total of six models. Each model was constructed in VISUM from the idealized network, and each having a unique link location closed in order to study the effects of link closures on the traffic flow patterns, and resulting volumes on the network, as well as intersection levels of service.

The results of the simulation procedures were analyzed using the “Version Comparison” function in VISUM. This entailed comparing the variants of the idealized network using the base case, set against the future case (networks with links taken out). A comparison of the link volumes resulting from the trip assignments was carried out, and the network changes were investigated to see how they affected the link volumes. The network variants

can be seen in Appendix C displaying the traffic flow patterns and the comparison models with the base network. The results are presented in Section 5.4.

3.2.2 VISSIM

All the previously presented traffic networks produced in VISUM were exported for further analysis in VISSIM using stochastic microsimulation (refer to Figure 3.18). The models are brought into the network editor, showing the precise position of the network objects. In this setting, the stochastic nature of traffic dictates the necessity to provide variability in VISSIM models. The program is based on Wiedemann's car-following model, which accounts for the variability via the implementation of parameters based on stochastic distributions. "The base data for simulation includes the settings for the entire network and all basic objects for modeling vehicle and pedestrian movement, e.g. distributions, functions, and behavior parameters. Base data further contains types and classes. These allow the grouping of properties that are the same for many network objects, so that it isn't necessary to set them for each individual object (PTV AG 2015).

Although the exported data from VISUM provides a network topology constructed in VISSIM, a number of settings must still be managed in order to ensure the model reflects the conditions intended. For running a simulation, the parameters must be set, wherein each model was assigned a number of simulation runs of ten to be performed. This was based on comparative research previously conducted, where three simulation runs were performed in the VISSIM model used to perform a safety assessment at freeway merge areas (Fan, et al. 2012). Another referenced example is the PhD dissertation for the modeling of freeway level-of-service based on travel time and travel time reliability, where

the researcher adopted ten simulation runs per modeling scenario (Imran 2015). The simulation parameters set included the simulation period (3600 seconds), in addition to an extra 300 seconds to account for lead times of the signal control. To represent the peak hour conditions, a simulation resolution of 10 time steps per simulation second (the rate at which the position of vehicles is recalculated), where values between 10 and 20 lead to smoother movements. This value range is suitable for high-quality simulation animations (PTV AG 2015).

A Random Seed initial value of 26 (this value initializes a random number generator. Two simulation runs using the same network file and random start number look the same, but if the random seed is varied, the stochastic functions in VISSIM are assigned a different value sequence and the traffic flow changes. This allows the simulation of stochastic variations of vehicle arrivals in the network. In order to produce meaningful results, the program must calculate the arithmetic mean of the results obtained for multiple simulation runs with different random seeds (PTV AG 2015)). Thus, for stochastic saving of results, the random seed increment was set to three, and the model was set to run at maximum simulation speed, utilizing all six processor cores of the simulation hardware. The simulation speed does not affect the simulation results, rather, this enabled the model simulation runs to be carried out at a faster rate, saving research time. The models took around three hours each to simulate. VISSIM then displays the results in a form of data lists, which are then imported into, and analyzed in Microsoft Excel.

4 Chapter: Practical Application to the Ottawa Downtown Core

This chapter demonstrates the practical application of the introduced methodology to the City of Ottawa's downtown core. This will aid in showing how this research can contribute to the analysis and design decisions taken when considering the functioning of urban traffic networks.

4.1 The City of Ottawa CBD Model; the Downtown Core

The constructed network model is based on the City of Ottawa's downtown core; the central area of the city's CBD. This is shown in Figure 4.1 below. The Core is confined by Sparks Street from the north, Gladstone Avenue from the south, Confederation Boulevard from the east, and Bronson Avenue from the west. The Core functions as the major focus of employment and economic activity within the Region (City of Ottawa 2015).

Figure 4.1: The City of Ottawa downtown core (City of Ottawa 2015)

The City of Ottawa’s website states: “In the future, the Core will remain as the vibrant center of economic activity, and as an important people-place destination which provides day/night, year-round activity. Its vitality will be based not only on its strong employment function, but equally on its rich diversity of uses and activities, and its significantly enhanced urban environment (City of Ottawa 2015).” As such, this area can be considered as the most vital to study, and explore options to ensure vulnerability is reduced in order to enable the continued functioning of the network.

4.2 Ottawa Network VISUM Model Construction

This area was incorporated into the model, in addition to the surrounding city zones, as obtained from the City of Ottawa’s Planning and Growth Management Department. The zones map can be seen in Appendix A . The model was constructed based on the City’s year 2011 data. Demand matrices were obtained for the PM peak hour for the year 2011, and incorporated accordingly into the VISUM model. The network topology was imported from the Open Street Maps database, as the map was imported into the model, and the links and nodes constructed based on the obtained data. The network was then double checked with Google Maps to make modifications to intersections, to make sure auxiliary and turning lanes were modeled accurately at all the nodes. The entire Ottawa Central Area (Inner City – see Official Plan Schedule F in Appendix A) was modeled in VISUM, in addition to the City of Gatineau zones adjacent to downtown Ottawa. Then, the area of interest (The Core) was extracted from the model. This ensures a more uniform model is obtained, as it takes into account the whole area of the city. In total, the resulting model

assigns the vehicles to the appropriate routes, according to the zone distribution in the network, taking into account the delays at all nodes along the assigned vehicle paths.

Figure 4.3: Ottawa Downtown Core Model in VISUM

Next, the obtained traffic counts from the City of Ottawa are inserted into the model, in order to compare the actual traffic counts (year 2011) to the results obtained from the traffic assignment procedure in VISUM. The function TFlowFuzzy is then utilized to calibrate the model's demand matrix. Matrix calibration is an important step in developing traffic models. The objective is to achieve a better match with traffic counts. In the parameter settings, the value for Alpha was set to 0.2 (this means that on every count site the tolerance value is $\pm 20\%$ compared to the count value). It is worth noting that first, a tolerance value

of 10% was attempted, but the model could not attain value convergence based on this criteria. This means that the solutions are less exact, and the mean deviation is worse. However, for the intended purpose, the achieved solutions are considered appropriate. A total of 40 links distributed across the network were set under this criteria to calibrate the model. This represents 5.5% of the total links, and is considered sufficient for calibration requirements. Next, the model was exported to ANM file formats to facilitate importing into VISSIM.

Figure 4.4: Links Eliminated in the Link Closure Models

All the described procedures in this section were repeated for each of the 16 models produced for sequential link closures. Each model has the same data as the base Ottawa network, except for the removal of a unique link in each model. The links eliminated are numbered 1 to 16 in Figure 4.4. Each model was then exported to ANM file formats for importing into VISSIM for further simulation. The simulation results can be seen in Appendix D .

4.3 Ottawa Network VISSIM Simulation

After the models are built in VISUM and mesoscopic simulation is performed to assign routes to vehicles in the network, they are imported into VISSIM. This is done to perform microscopic simulation, which gives the parameters needed for statistical analysis. These are the average delay, average speed, and total distance travelled by vehicles in the model.

Figure 4.5: Ottawa Network Model in VISSIM

4.4 Ottawa Network CVI

Based on the network characteristics, the values for the three vulnerability dimensions were calculated as per Equation 1 (Centrality), Equation 2 (Flowability), and Equation 3 (Mobility). These values were then plotted on the ternary graph to obtain the CVI value from the area of the triangle. See Figure 4.6. The obtained CVI value for the Ottawa downtown core is actually low ($0 < \text{CVI} < 0.1$). This indicates that the network is not highly vulnerable, and possesses characteristics that are favorable. The topology is arranged in an almost square shape (6 blocks by 7 blocks), giving a high Centrality value. The demand on the network's links isn't excessive (average of 116 veh/hr), yielding a high Flowability value. Thirdly, the network consists of short link lengths (66m on average), resulting in a high Mobility value.

$$\text{Centrality} = \frac{\# \text{ blocks (width)}}{\# \text{ blocks (length)}} = \frac{6}{7} = 0.8571$$

$$\begin{aligned} \text{Flowability} &= \frac{\text{Link Capacity} \left(\text{veh/hr} \right) - \text{Demand} \left(\text{veh/hr} \right)}{\text{Link Capacity} \left(\text{veh/hr} \right)} = \frac{790 - 116}{790} \\ &= 0.8532 \end{aligned}$$

$$\text{Mobility} = \left[\frac{\left(\frac{\# \text{Blocks width} + \# \text{Blocks length}}{2} \right)}{\text{Average Link Length (m)}} \right] * 10 = \frac{\left(\frac{6+7}{2} \right)}{80} * 10 = 0.8125$$

Figure 4.6: Calculation of the Ottawa CVI value from the ternary plot

$$\text{CVI} = \text{Area of the triangle} = 0.033$$

5 Chapter: Findings

This chapter presents the results obtained from the simulation models described in Chapters 3 and 4 of this report. Namely, the base network, the network variations, and the networks with link closures, for both VISUM and VISSIM applications. Here, the data set analyses are described, and the relationships among the chosen variables are outlined, as well as the presentation of correlation investigation, multiple regression analysis, and finally ANOVA analysis in order to analyze the differences among the data from the various simulations carried out.

5.1 Statistical Analysis Methodology

The analysis focuses on the dependent variable (Delay), which was chosen as the variable of interest as the research focuses on exploring how the traffic network characteristics exert influence on the delay experienced by the road users, increasing the risk of event occurrence, which in turn translates to increased network vulnerability. The variable is used to outline the analysis by demonstrating which network types, and corresponding dimensions, exhibit the highest levels of vulnerability – with linkages being done to the independent variables and any arising trends are observed.

It is also very interesting to see which network characteristics have the highest effect on vulnerability, as this will reflect on how the planning and design of urban traffic networks can be better implemented for new developments, and how existing infrastructure may benefit from the analysis by adopting some of the less costly improvement methods, where appropriate, or where at all possible to do so.

The main independent variables that will be used in order to conduct the analysis are outlined below (refer to Table 5.1 and Table 5.8 for descriptive statistics):

- a. Average vehicle travel speed (km/h): “Speed”
- b. Total vehicle kilometers travelled (km): “Distance”
- c. Total vehicle travel time (seconds): “Time”
- d. Network Centrality: “Centrality”
- e. Network Flowability: “Flowability”
- f. Network Mobility: “Mobility”

In order to reach the regression analysis required for exploring the main relationship of interest, all the original variables from the dataset were excluded except for the ones of interest. As such, the dependent variable (Delay) as well as the six independent variables (Speed, Distance, Time, Centrality, Flowability, and Mobility) were retained. An ANOVA test was consequently performed in order to determine how the mean vehicle delay experienced differs by network characteristics, and the STATA output can be seen in Appendix G . A number of analyses were also carried out on the data, as displayed throughout Appendix F in order to demonstrate the relationships and respective correlations between the travel delay and each of the independent variables.

In order to examine how the delay is related to, and explained by the network characteristics, a multiple regression analysis was carried out, whereby all the independent variables were included in a regression model, with the dependent variable (Delay) then regressed on the remaining six variables in the model. The first four variables (Delay, Speed, Distance, Time) are obtained from the VISSIM models, whereas the following three

variables (the vulnerability dimensions: Centrality, Flowability, Mobility) are obtained from the VISUM models.

5.2 The Base Network

The base model gives the set of results that will be used to assess the data obtained from both: the networks with vulnerability dimensions permutations, and the sequential link closure networks. The base network gives a delay value of approximately one minute (60.61 seconds), with an average travel speed value of 29.44, which is to be expected in a CBD setting with fairly high traffic volumes (typical of peak period traffic in downtown areas). The total distance travelled by all vehicles in the model is 3,673.78 km, and the total travel time for all vehicles in the model adds up to a total of 449,309.85 seconds (124.81 hours).

5.3 Varying the Network Dimensions

Based on the dimension variations presented in Table 3.1, the results due to the effect of different network characteristics can be explored. The variables used for this analysis are presented in Table 5.1.

5.3.1 Data

In this analysis, to maintain a uniform number of total blocks per network, the values for the (3x5) and (3x6) networks have been interpolated to better reflect values of a network with a total of sixteen blocks. While it is understood that this is not precise, it will nonetheless provide a good reference for comparison purposes. It can be clearly seen from the data that delay (Del) increases significantly for the (1x16) network, with all other

networks having delay values between 60 and 90 seconds, this network arrangement results in an average vehicle delay of 1,287.8 seconds (21.5 minutes), giving an idea of what a gridlock situation can look like in a similar network.

Table 5.1: Summary Statistics for Network Permutation Variables

Variable	Label	Range	Summary Statistics
CVI	Combined Vulnerability Index; calculated from Centrality, Flowability, and Mobility as in 3.1.7.5	0 – 1.2	Mean = 0.117 Std. Dev. = 0.146
Del	Delay; average delay experienced by vehicles on the network (seconds)	50 – 1,400	Mean = 200.12 Std. Dev. = 341.47
S	Speed; average speed of travel of vehicles along the network (km/h)	0 – 40	Mean = 25.78 Std. Dev. = 10.61
D	Distance; total distance travelled by all vehicles on the network (km)	3,000 – 9,000	Mean = 5,884.08 Std. Dev. = 1,623.16
T	Time; total travel time elapsed for all vehicles in the model (seconds)	400,000 – 6,000,000	Mean = 1,619,172.87 Std. Dev. = 2,346,655.47

As can be seen from the charts in Appendix F showing the summarized data, average speed (S) also drops significantly for the linear network topology (1 x 16), resulting in a mere average speed of 2.5 km/h, compared to 27 – 30 km/h for the networks exhibiting a higher degree of centrality. As for total distance traveled (D), it is not hugely different for the (1x16) network layout, while it does increase from the networks with higher centrality to the more linear network arrangements (values range from 3,500 km to 6,000 km). Finally, the extreme increase in travel time (T) for the (1x16) network can be seen, which is to be expected due to the very high delay and low travel speed experienced by vehicles on this network (approximately 2,400 hours compared to 124 – 206 hours for the other networks).

As represented from the trend line equations in the graphs included in Appendix F , Delay is best described via a polynomial function, with an R^2 value of (0.82); indicating a strong association with the data. As for Speed, it was found that this relationship with the vulnerability dimensions is best described by an exponential function, resulting in an R^2 value of (0.62). On the other hand, the relationship between CVI and total distance travelled on the network is not strong, with this factor seemingly being influenced by other activities taking place in the network, and when represented by a polynomial function, an R^2 value of only (0.03) is obtained. Finally, for total travel time, a good representation of the data is obtained via a polynomial function, with an R^2 value of (0.74).

5.3.2 Correlation

The correlation analysis shows that there is a strong correlation between delay and CVI, with a correlation coefficient of (0.87), which is to be expected, as a more vulnerable network is one that is less efficient, leading to road users experiencing an increase in trip times (causing the vehicles to spend a longer period of time traversing the network), thus resulting in increased delay. It also follows that total travel time of all vehicles in the model is highly correlated to delay, with a correlation coefficient of (0.83), as an increase in travel time for road users means that flow is hindered, and delay increases greatly. It is interesting, however, that total distance traveled by vehicles on the network does not correlate highly with CVI, with a correlation coefficient of only (-0.12). Speed also doesn't have a very high correlation with CVI, but is more conforming to the data than the previous variable, with a correlation coefficient of (-0.66), showing that vehicles travel at lower speeds in more vulnerable networks, as expected. These results are summarised in Table 5.2.

Table 5.2: Correlation Analysis Results for Network Permutations

	CVI	Del	S	D	T
CVI	1				
Del	0.872605	1			
S	-0.66474	-0.85053	1		
D	-0.11846	0.154051	-0.31719	1	
T	0.828706	0.993633	-0.88647	0.242509	1

As can be seen from Table 5.2 above, it is noticed that there is a high correlation between the variables (Del) and (T), with a correlation coefficient of (0.99). This requires attention, as collinearity and multicollinearity can be a problem in multiple regression. Multicollinearity happens when a combination of variables makes one or more of the variables largely or completely redundant. STATA can compute a variance inflation factor to assess the extent to which multicollinearity is a problem for each independent variable. This is computed by running the command (estat vif) after the regression. Refer to Section 5.3.3, page 79 for further details.

5.3.3 Regression

In order to examine how the network vulnerability is related to, and explained by the network characteristics, a multiple regression analysis was carried out, whereby all the independent variables were included in a regression model, and regressed against the variable (CVI).

Regression analyses were performed as can be seen in Appendix G . The first step was to run a regression of the dependent variable (CVI) on each of the four theoretical variables separately, and obtaining the Beta and R^2 values from each. Secondly, (CVI) was regressed

on all four theoretical variables at once. The single regression analyses for each variable yield the results shown below in Table 5.3:

Table 5.3: Single Regression Analyses Summary Results

Variable	F	R Square	Adjusted R Square	Root MSE
Del	376.63	0.761	0.759	0.072
S	93.43	0.442	0.437	0.109
D	1.68	0.014	0.006	0.145
T	258.70	0.687	0.684	0.082

Table 5.4: Beta Values for Regression Models

Variable	β value (Model 1)	β value (Model 2)	β value (Model 3)	β value (Model 4)	β value (Model 5)	β value (Model 6)	β value (Model 7)
Del	0.873				6.36	1.01	
S		-0.665			-0.48	0.12	0.17
D			-0.118		0.20	-0.24	-0.32
T				0.829	-5.96		1.06
R ²	0.761	0.442	0.014	0.687	0.903	0.831	0.801

In addition to the regression analyses performed in STATA, variance inflation factors (VIF) were also computed for three combinations of variables to check for multicollinearity. The three model combinations tested are as follows:

1. Model containing all **four** variables: Del, S, D, T (Model 5)
2. Model containing the **three** variables: Del, S, D (Model 6)
3. Model containing the **three** variables: S, D, T (Model 7)

A breakdown of the full analysis and coding can be found in Appendix G - Section G.1. It was found that the two variables under question (Del, T) were in fact exhibiting properties

of collinearity. The VIF values obtained for the three model combinations are summarized in Table 5.5 below.

Table 5.5: Summary Results for VIF Analysis

Model	VIF (Del)	VIF (T)
1 (Del, S, D, T)	395.88	487.53
2 (S, D, T)	-	4.71
3 (Del, S, D)	3.82	-

The results of the analyses indicate that a multicollinearity problem may exist, as the VIF values for (Del) and (T) are more than (10) in Model 5. As such, an adjustment should be done to the model. However, both values are significantly less than (10) when one of the variables is eliminated, as shown from the results obtained for Model 6 and Model 7. It was thus decided that to eliminate the issue with collinearity, a variable should be dropped from the model. This is not much of a problem, as a variable that has more than 90% of its variance confounded with the other predictors probably does not explain much uniquely. Furthermore, the regression analyses for Models 6 and 7 yield R^2 values of (0.80) and (0.83) respectively. Because the VIF for (Del) is lower, and the R^2 value for the model containing (Del) is higher, it was decided that the variable (T) is to be eliminated.

The multiple regression model gives the result summarized in Table 5.4. It can be seen that the variables generate results with: $F(3, 116) = 189.44$, $p < 0.0001$. There is a highly significant relationship between the CVI characterizing the traffic network and the set of three predictors. An R^2 value of (0.831) is obtained, indicating that a model containing the explanatory variables Delay, Speed, and Distance explains 83% of the variance in vulnerability for road users in CBD (urban city) downtown traffic networks, when

possessing characteristics and vulnerability dimensions comparable to those presented in this research.

The resulting regression model looks as follows:

$$\widehat{CVI} = 0.1073 + 0.0004 (Del) + 0.0016 (S) - 0.00002 (D)$$

Although this is a fairly exploratory analysis, the R^2 value obtained of 0.831 is relatively high ($0.8 \leq R^2 \leq 1.0$) according to the general rule of thumb. And, as the number of predictor variables is kept relatively low and a large sample size, the likelihood of getting a large R^2 by chance is reduced, as a result the Adjusted R^2 value obtained (0.826) is only 0.005 less than the R^2 value.

From the STATA results in Appendix G (G.1), it can be seen that all the variables included in the model are statistically significant ($p < 0.001$), however the variables (S) and (D) have a relatively weak effect ($\beta < 0.50$) on network vulnerability as characterized by the CVI, whereas the variable (Del) is more relevant, with an obtained value of $\beta = 1.01$, which is considered to have a significant influence on the network CVI value.

5.4 Sequential Link Closure

This section presents the results obtained from the models produced upon the application of sequential link closure, for each of the six unique links, as described in Section 3.1.5 on page 38.

5.4.1 Link Closure Network Effect

First, in order to calculate the ACVI needed for the analysis in Sections 5.4.3 and 5.4.4, the (% Effect) was obtained from the models under examination, the summarized data can be seen in Appendix D .

Table 5.6: Values of Link Closure Networks

Link #	Link Vol. (veh/h)	% Effect	Link RC	# Alternative Links	# Blocks Away
1	253.70	13	0.68	3	3.5
2	233.40	4	0.70	4	2.5
3	202.30	18	0.74	5	2.5
4	224.10	20	0.72	6	1.5
5	208.50	2	0.74	5	1.5
6	221.10	3	0.72	6	0.5

Table 5.6 shows the network model results, represented by the link number closed. The traffic volume that has to be diverted to alternate routes is shown, as well as the obtained (% Effect) from model simulation. This value is an average of the traffic volume increase of all the links in the network, which is representative of how the link closure affects the entire network.

The dimensions, link residual capacity (Link RC), number of alternative links available (# A), and the number of blocks the closed link is away from the central network node (# B) are also presented, and are correlated to the (% Effect) as shown in Table 5.7.

As can be seen, there are weak correlations between (% Effect) and both: Link Reserve Capacity and Number of Alternative Links, with correlation coefficients of only -0.006 and 0.064 respectively. The dimension that does seem to have an influence on the overall traffic

network vehicle flow pattern is the closed link's position. As the variable (Number of Blocks Away) has a correlation coefficient of 0.356, indicating a moderately significant statistical relationship.

Table 5.7: Correlation Analysis of (% Effect)

	% Effect	Link RC	# Alternatives	# Blocks
% Effect	1			
Link RC	-0.00596	1		
# Alternatives	0.063955	0.667695	1	
# Blocks	0.356436	-0.5233	-0.89715	1

5.4.2 Data

The variables employed in this analysis are presented in Table 5.8. All these models are based on the same base network with a 4 x 4 block arrangement, 1.0 unit demand, and 200 meter link lengths.

Table 5.8: Summary Statistics for Sequential Link Closure Networks

Variable	Label	Range	Summary Statistics
ACVI	Adjusted Combined Vulnerability Index ; the value of CVI multiplied by the link closure effect	0.0 – 0.1	Mean = 0.030 Std. Dev. = 0.002
Del	Delay ; average delay experienced by vehicles on the network (seconds)	50 – 70	Mean = 60.836 Std. Dev. = 0.404
S	Speed ; average speed of travel of vehicles along the network (km/h)	20 – 30	Mean = 29.424 Std. Dev. = 0.051
D	Distance ; total distance travelled by all vehicles on the network (km)	3,000 – 4,000	Mean = 3,642.299 Std. Dev. = 75.333
T	Time ; total travel time elapsed for all vehicles in the model (seconds)	400,000 – 500,000	Mean = 445,707.887 Std. Dev. = 9,922.768

5.4.3 Correlation

The correlation analysis shows that there isn't a strong correlation between ACVI and any of the included variables; delay, speed, distance travelled, and travel time, with correlation coefficients of (0.020, -0.042, -0.011, and -0.005) obtained, respectively. This is to be expected, as for this analysis the dimension being changed is the link closure, and as only one link is closed in each of the networks, all of which are otherwise identical, it can be seen why the results are very similar, and the variables have low values of standard deviation. These results are summarized in Table 5.9.

Table 5.9: Correlation Analysis Results for ACVI

	ACVI	Del	S	D	T
ACVI	1				
Del	0.019847	1			
S	-0.0416	-0.90502	1		
D	-0.0108	0.816019	-0.8771	1	
T	-0.00501	0.835479	-0.90083	0.998638	1

5.4.4 Regression

As in Section 5.3.3, a series of regression analyses are presented here. These were performed in order to explore how the network vulnerability is related to, and explained by the traffic network physiognomies.

Table 5.10: Single Regression Analyses Summary Results

Variable	F	R Square	Adjusted R Square	Root MSE
Del	0.03	0.0004	-0.0143	0.0022
S	0.12	0.0017	-0.0129	0.0022
D	0.01	0.0001	-0.0146	0.0022
T	0.00	0.0000	-0.0147	0.0022

The dependent variable (ACVI) was regressed on each of the independent variables individually, and then a model was constructed in STATA that included all the four independent variables, and the variable (ACVI) was then regressed on them all. These analyses can be seen in Appendix E Section E.2. The Beta and R^2 values were consequently obtained for each model. The single regression analyses for each variable yield the results shown in Table 5.10. In addition, the summarized Beta values for the individual regression models and the combined model are shown in Table 5.11.

Table 5.11: Beta Values for Regression Models

Variable	β value (Model 1)	β value (Model 2)	β value (Model 3)	β value (Model 4)	β value (Model 5)	β value (Model 6)
Del	0.0198				-0.0803	-0.0741
S		-0.0416			0.7291	-0.2822
D			-0.0108		-8.6994	-0.1979
T				-0.0050	9.4065	
R ²	0.0004	0.0017	0.0001	0.0000	0.0149	0.0124

In order to check for multicollinearity in this model, STATA was employed to perform VIF analyses. Model 5 containing all the variables yielded VIF values of (35,692.1), (29,159.79), and (420.65) for the variables T, D, and S, respectively. This is considered as a significant indicator that multicollinearity exists in the model. As such, the variable (T) was eliminated, similar to what was done for the CVI model (Section 5.3.3). As a result, Model 6 was constructed, yielding VIF values of (8.10), (5.59), and (4.39), for the variables S, Del, and D, respectively. All of the VIF values are less than 10, which indicates that it is not likely that multicollinearity exists. Refer to Appendix G Section G.2 for a detailed look at the STATA analysis.

The model obtained is characterized with $F(3, 66) = 0.28$, $p < 0.01$. Here, there is no highly significant relationship between the ACVI characterizing the traffic network and the set of three predictors. An R^2 value of (0.0124) is obtained, indicating that a model containing the explanatory variables Delay, Speed, Distance, and Time explain only 1.24% of the variance in vulnerability for road users in CBD (urban city) downtown traffic networks, when possessing similar characteristics to the base network, when explored on the basis of link closures and effects on the network as a whole. From the STATA output, it can be seen that the variable (Del) has a relatively weak effect, with a β value of (-0.074). On the

other hand, the variables (S) and (D) are more associative, with β values of (-0.28) and (-0.20) respectively. This indicates a slightly significant influence on ACVI. The resulting regression model looks as follows:

$$\widehat{ACVI} = -0.2085 - 0.0002(Del) - 0.0053(S) - 0.00004(D)$$

5.5 The Ottawa Network

This section presents the results obtained from the City of Ottawa downtown core network. The models were produced for the base case, and upon the application of sequential link closures for each of the sixteen unique links. This was described in Section 4.2 on page 66.

5.5.1 Data

The variables employed in this analysis are presented in Table 5.12. All these models are based on the same base network with a 6 x 7 block arrangement, demand values as obtained from City data, and the City's core network topology.

Table 5.12: Summary Statistics for Ottawa Network Models

Variable	Label	Range	Summary Statistics
ACVI	Adjusted Combined Vulnerability Index ; the value of CVI multiplied by (% Effect)	0.030 – 0.040	Mean = 0.034 Std. Dev. = 0.0004
Del	Delay ; average delay experienced by vehicles on the network (seconds)	70 - 150	Mean = 92.452 Std. Dev. = 14.262
S	Speed ; average speed of travel of vehicles along the network (km/h)	15 - 25	Mean = 18.269 Std. Dev. = 1.474
D	Distance ; total distance travelled by all vehicles on the network (km)	4,000 – 5,000	Mean = 4,525.765 Std. Dev. = 59.740

5.5.2 CVI

For the purposes of this analysis, the data obtained from the Ottawa core network for CVI was not suitable for statistical analysis. The outputs obtained from the models did not produce significantly different overall traffic flow volumes. As such, the value for the vulnerability dimension of Flowability was not noticeably different from one model to the next. This is primarily due to the fact that the models are all based on the exact same network. As the topology is constant across the produced models (with only eliminating one link), the values for the vulnerability dimensions of Centrality and Mobility are also almost the same in all seventeen models used for the analysis.

Due to the very similar vulnerability dimension values across all network models, the values obtained for CVI were very similar. As such, as can be seen from the obtained data for these models on page 138 in Appendix E all model variants have essentially the same value for CVI of (0.033).

5.5.3 ACVI

Due to the link closures, the traffic flow across the network undergoes some changes. When the chosen link is eliminated from the network, the volume of vehicles that originally utilized the closed link now have to find an alternative route. The new adopted path is comprised of links that don't include the closed link. As such, due to the different characteristics of the closed links, different values for (% Effect) are obtained. These values

are then multiplied by the network's CVI to give the ACVI of the networks with eliminated links. Again, this data can be found in the table on page 138 in Appendix E .

5.5.3.1 Correlation

The correlation analysis shows that there is a moderate correlation between ACVI and the variable (D) with a correlation coefficient of (0.223). On the other hand, there isn't a strong correlation between ACVI and the variables delay and speed, with correlation coefficients of (0.057) and (-0.028) obtained, respectively. This is to be expected, as for this analysis the dimension being changed is the link closure, and as only one link is closed in each of the networks, all of which are otherwise identical, it can be seen why the results are very similar, and the variables have low values of standard deviation. These results are summarized in Table 5.13.

Table 5.13: Correlation Analysis Results for Ottawa ACVI

	ACVI	Del	S	D
ACVI	1			
Del	0.056625	1		
S	-0.02755	-0.98439	1	
D	0.223097	-0.40813	0.362172	1

5.5.3.2 Regression

The multiple-regression analysis is presented here. This was performed in order to explore how the network vulnerability is related to, and explained by the traffic network variables when performing link closures.

Table 5.14: Regression Analysis Summary Results for Ottawa ACVI

Variable	F	R Square	Adjusted R Square	Root MSE	Beta
Del	0.54	0.0032	-0.0027	0.00043	1.5531
S	4.41	0.0289	0.0172	0.00042	1.3707
D	19.43	0.1306	0.1149	0.0004	0.3605

Four regression analyses were carried out in STATA. This included three models for each of the variables delay, speed, and distance. A fourth model was then constructed in STATA that included all the three independent variables. The dependent variable (ACVI) was then regressed on all three explanatory variables. This analysis can be seen in Appendix G Section G.3. The Beta and R^2 values were consequently obtained for the model. The summarized values for the regression model are shown in Table 5.14.

The model obtained gives $F(3, 166) = 8.31, p < 0.001$. Here, there is a low-moderately significant relationship between the ACVI characterizing the traffic network and the set of three predictors. An R^2 value of (0.131) is obtained, indicating that a model containing the explanatory variables Delay, Speed, and Distance explains only 13.1% of the variance in vulnerability for the Ottawa core network. This is obtained when the network is explored on the basis of link closures and effects on the network as a whole. From the STATA output, it can be seen that the variables (Del) and (S) have a strong effect on the model, with β values of (1.55) and (1.37) respectively. On the other hand, the variable (D) is less associative, with a β value of (0.36). This indicates a slightly significant influence on ACVI. The resulting regression model looks as follows:

$$\widehat{ACVI} = 0.01833 + 0.00003(Del) + 0.00025(S) + 0.00002(D)$$

6 Chapter: Discussion

This chapter goes over the findings obtained, and the implications of the results presented in Chapter 5. In addition, the information provided by the data, as well as the interpretation of what this information means for advancing this research area are discussed.

6.1 Varying the Network Dimensions: Vulnerability Dimensions

The results of the analyses suggest that urban traffic network vulnerability is influenced by the three dimensions: Centrality, Flowability, and Mobility. The resulting LOS diagrams for the various networks are presented in Appendix B (sections B.2 to B.4).

6.1.1 Centrality

The greatest effect is due to the network Centrality, with the lowest LOS values obtained for the nodes (intersections) among all the network variations. The most constrained conditions occur for the linear network of block arrangement of (1 x 16), with nodes experiencing LOS of “F” indicating a severe deterioration in operating conditions. As such, it is vital to try to achieve more squared-off network layouts in order to provide a multitude of route options for vehicles traversing the network, reducing the vulnerability of the network. That is, the more linear the network layout is, the less path options are available to road users, forcing vehicles to travel on already congested links, further worsening traffic conditions, and increasing the vulnerability of the network. This is reflected by the high delay values obtained from the multiple regression analysis, as well as the increased travel time experienced by the road users. The coefficient value of 0.003 for the variable (Del) means that the CVI increases by 0.003 units for every additional second of delay experienced across the traffic network.

6.1.2 Flowability

Secondly, another highly influential dimension is the network Flowability, as can be seen from the LOS diagrams in Appendix B showing that the network variations with increased traffic demand exhibit lower LOS values along the links and at the intersections. The network containing a demand value of 3.0 trips per destination node exhibits the lowest LOS, with an intersection LOS as low as “D”. This is logical, as the greater the demand experienced on the network, the more road users are under the risk of being negatively affected if an event occurs in the network, and the less residual capacity would exist along the other links to accept diverted traffic, and a greater number of road users are at risk in a more congested network. This is confirmed through the multiple regression analysis, showing the networks with a higher CVI (and higher demand) having an effect on the travel speed of vehicles in the network, and the negative notation means that with increased CVI, the travel speed decreases, subjecting the network to a higher vulnerability factor by extension. The coefficient value of -0.006 for the variable (S) means that the CVI decreases by 0.006 units for every additional 1 meter/second increase in average travel speed across the traffic network.

6.1.3 Mobility

The third vulnerability dimension, Mobility, appears not to have a largely significant influence on the LOS experienced across the network. An unchanged intersection LOS of “A” results from all network variations with 250, 300, 350, and 400 meter link lengths. However, this is likely due to the decreased traffic density, resulting in a low impact on LOS values. On the other hand, the increased link lengths result in higher total travel times for vehicles on the road network, as can be seen from the multiple regression analysis

results. This implies that the vulnerability of the network increases with longer road segments, even though the effect is low. The main influence of longer links is likely the risk they pose to the road users, as opposed to direct tangible effects on the CVI, as longer travel times mean that road users spend longer periods on the network, increasing the risk of being affected if an event occurs in a segment of the network.

6.2 Effect of Link Closures on the Network

After identifying how the network behaves under undisturbed conditions, via the three vulnerability dimensions, it is necessary to investigate how the network is affected when an event occurs (such as a major vehicle collision or accident, or road issues such as a sinkhole) that leads to the closure of a link. This means the affected link is essentially unusable, and as such, is no longer part of the traffic network, and no vehicles can utilize it as part of the intended trip. Different links in the network have varying overall effects on the traffic flow, mainly due to three link characteristics. These characteristics were presented in Section 5.4.1, and it was determined that the largest influence on the value of (% Effect) is due to the variable representing the distance from the closed link to the central network node (# Blocks). This is because the closer a link is to the center of the network, the greater the number of alternatives available to road users to choose from in order to replace the closed link with another as part of the OD trip. In addition, when the link is more centrally located, the diverted traffic can be distributed more evenly across the other parts of the traffic network, reducing the overall impact of the closure. This can be seen from the comparison diagrams presented in Appendix C Section C.2, where the number of links being used by the diverted traffic is significantly higher for links 4 and 6, compared to the ripple effects of the closure of links 1, 2, 3 and 5.

The factor (Link Residual Capacity) also contributes to the link closure effect, as the higher the initial volume on the link, the greater the number of vehicles that have to be accommodated on the alternate paths. In other words, if the link wasn't highly utilized in the first place, its closure would not have as high of an impact as a link that is used by a large proportion of the road users traversing the network. That said, this factor seems not to be as vital as the link's location in the network, as discussed beforehand.

This analysis needs to be expanded, by simulating the link closures on the other network types, including all the network permutations obtained from varying the vulnerability dimensions. Such an analysis would give a better understanding of the effect of link closure on the network, and how different network topologies are affected by the different link closures taking place.

The last part of this research involved increasing the value of the CVI of each network according to the link closure's resulting (% Effect) on the overall traffic flow. This value is multiplied by the CVI value to give the ACVI, which accounts for the effect of the diverted traffic. It is interesting to note that the β values obtained from the regression analysis for the total distance travelled and the total time spent on the network increase significantly when compared to the previous analysis. This confirms that due to traffic diversion, road users must now travel around the closed link, resulting in longer trips, and consequently higher kilometers travelled, as well as larger values resulting of travel time for vehicles traversing the network.

6.3 The Ottawa Downtown Core Network

6.3.1 Vulnerability Dimensions (Base Model)

The results of the analysis suggest that the Ottawa network vulnerability is influenced by the three dimensions: Centrality, Flowability, and Mobility. From the base network, it can be seen that the intersections experience LOS levels ranging from A to C. In addition, there is one intersection that experiences an LOS level of E. The average delay experienced by the road users is just under 2 minutes. This is to be expected, due to the high demand on the network during the peak hour. The resulting average speed is 18 km/h, which is reasonable for such conditions, as there is not much room for vehicles to attain higher speeds. Finally, the calculated total distance travelled by vehicles in the base network is 4,500 km.

6.3.2 Sequential Link Closures

The resulting variations in traffic flow for the various link closure networks are presented in Appendix D . The values for (% Effect) were obtained for the 16 modeled networks, and applied to the CVI value to get the ACVI for each. It can be seen that the greatest fluctuations in traffic flow occur in the vicinity of the link closure location. This is to be expected, as these areas have to absorb the traffic flow that was utilizing the closed link. The adjacent nodes also show a deteriorated LOS value, with the majority of nodes dropping from an LOS of B to D. Overall, the networks with link closures at the edge of the network (1, 2, and 4) or the middle of the network (8, 12, 14, and 15) experienced the highest effects. This is because these locations have the least number of alternative routes, and the highest traffic volumes, respectively.

7 Chapter: Research Implications, Conclusions and Recommendations

This chapter discusses the implications and contribution of the performed research on urban traffic network vulnerabilities. Limitations to the findings as well as other possible areas for future research on measures to consider for improving the planning and design of urban traffic networks with regard to vulnerability and resiliency are also outlined.

7.1 Research Implications

The research carried out in this document is intended to serve as a reference for the future refinement of urban traffic networks, especially those of the CBD type. The results obtained show that it is recommended to design a network with special consideration to the three vulnerability dimensions: Centrality, Flowability, and Mobility. As such, it was determined that the higher these vulnerability dimensions are, the more vulnerable the network is likely to be. These characteristics are deduced from the link attributes, and each has an influence on the performance of the links making up the network.

Centrality plays a vital role in determining the availability of alternate routes in order for road users to be able to negotiate the network more efficiently and avoid problematic areas on the network. This is similar to the concepts of accessibility and terminal reliability explored in the literature review (Chapter 2), and builds on the network property of redundancy, all of which are important factors that must be considered when determining the network topology.

The next vulnerability dimension explored was Flowability, which was determined upon completion of the model simulations, as the traffic demand on the network links is

determined based on the simulation results, and the assumptions of the paths that each road user selects for the completion of the respective journeys. Here, the component of Reserve Capacity was calculated, from the links' theoretical capacities and the traffic demand experienced as a result of the trip assignments. This dimension was found to have an influence on the traffic flow and the link LOS values, as increased traffic demand results in higher flow volumes, and consequently worsening values of LOS.

Thirdly, the dimension Mobility was presented, which is meant to reflect how dense a traffic network is arranged. The models consisting of longer links did not exhibit significantly reduced LOS values, but what resulted instead was longer vehicle travel times on the network, and increased total distance travelled for all road users. Although this did not contribute significantly to the variations in CVI values, this dimension is vital from another perspective, namely risk. In other words, the longer time spent on the network by the road users implies that there is an increased chance an event occurring on a link would be able to impact a greater proportion of vehicles traversing the network.

In the final part of the research, the impact of link closures was examined. This showed that some links in the network are more vital to the traffic flow than others. Primarily, this relationship relies on the location of the closed link in relation to the network's central node, and how far the link is from the network's center, measured by the number of blocks on the shortest route from the link to the central node. This is due to the fact that links closer to the outskirts of the network have a more important role to play in the network connectivity, as adjacent nodes would have less alternatives to divert traffic to. Furthermore, the closed link's residual capacity also plays a role in the vitality of the link

as part of the whole network. This is because the more heavily a link is relied on by the road users, the higher is its importance, and the traffic volume would also be larger, meaning that a greater number of vehicles have to be accommodated across the rest of the network if an event occurs on the link.

7.2 Conclusions

The chart shown in Figure 7.1 summarizes the variations applied to the base (idealized) network developed for the modeling of the traffic network, and the dimensions defining its vulnerability.

Figure 7.1: Breakdown of Network Variation Properties

As can be seen, the base network is a square-shaped 4 x 4 arrangement of blocks, consisting of 200 meter long links, and subject to 1.0 unit of demand per destination zone across the

model. The network variations were then applied to this model, according to the different values of “configuration”, “demand”, and “link length”.

It was demonstrated through a two-step simulation procedure (VISUM for mesoscopic simulation and then VISSIM for microsimulation), that networks with a more linear topology exhibit significantly higher vulnerability traits. That is also true for networks subjected to higher levels of demand from traffic, as well as networks consisting of blocks made up of links of longer lengths. While the Centrality and Flowability dimensions of the CVI cause an increase in the delay experienced by road users, as well as slower average travel speeds, the Mobility dimension plays a role in the risk factor experienced by the road users, as vehicles experience increased travel times and longer total travel distances across the network. Finally, the values of the three dimensions are plotted on a ternary diagram to obtain the CVI value from the area of the graph.

The closure of links due to event occurrence on the network (such as major collisions or infrastructure failure) further exacerbates the effects of worsening traffic conditions, as measured through link traffic volumes and node LOS values. Links with low residual capacity and are located closer to the edge of the network, with a fewer number of alternatives, exhibited the greatest influence on the traffic flow patterns across the network. The value (% Effect) obtained from the simulation models for each of the scenarios was multiplied by the CVI value to give the new ACVI value. This represents the increased overall vulnerability of the network after the adjustment made due to the impact of the closed link.

7.3 Recommendations

Here, recommendations are presented for the consideration of planners and engineers when planning and/or designing urban traffic networks, in order to take vulnerability into account. It is hoped that the adoption of these practices would help reduce network vulnerability, and in turn, improve network resiliency for the implementation of future urban traffic networks.

7.3.1 Centrality

It is recommended that there should always be a requirement for the use of square-shaped networks as much as possible. This means networks would have better connectivity, and a lower vulnerability dimension of Centrality, lowering the CVI value for the proposed network. In addition, modifications may be implemented in existing networks in the form of road restrictions or new road additions in order to achieve the desired network topology, leading to reduced vulnerability.

7.3.2 Flowability

Although already recognized by a majority of municipalities and governmental agencies through the publication of regional and local official plans, it is very important that the implementation of TDM measures takes place. This helps alleviate the pressure put on the traffic network, and may be achieved via any, or through a combination of any number of strategies, such as modal shift, trip elimination, time shifting, and increases in auto occupancy rates. Such measures are likely to play a vital role in the reduction of the dimension Flowability, and consequently, overall network vulnerability.

7.3.3 Mobility

It is important to strive to keep the dimension Mobility as high as possible in order to avoid subjecting the road users to undue risk, brought about by longer travel times on the network. This can be mainly achieved by implementing shorter links, with more blocks making up the network, via increasing signal density. This will provide road users with more chances of modifying the route being followed, as more intersections are encountered, as opposed to networks with fewer blocks and longer link lengths throughout, mandating the vehicles on the network to commit to single links for longer periods of time, increasing the risk of being exposed to an event.

7.3.4 Link Closures

Although a large array of link closure causes are not controlled, such as traffic incidents (major collisions) or infrastructure failure (such as sinkholes), it is worth knowing how possible link closures would affect the network as a whole. This aids in preparing emergency response plans, as well as evacuation (or similar) plans in the case of extreme events. Another potential application to this area is the scheduling of infrastructure maintenance operations (such as roadway repairs), where detour plans have to be prepared and traffic impact assessments carried out. Here, the presented analysis introduces the methodology by which an array of different scenarios and options may be compared, and the options with the least impact and lowest vulnerability factors would be chosen, in order to maintain more suitable traffic operation conditions for all road users.

7.3.5 The Ottawa Network

Although the vulnerability dimensions for the Ottawa network are favorable, there are possibilities for improvement. In order to ensure Centrality is kept at a high level, it is advisable to plan future expansions of the downtown core southward, as opposed to the east or west. This will ensure that the relatively square topology is maintained. Next, as the government is investing in alternative transportation mode projects, namely light rail transit, the Flowability dimension will likely improve. This is because public transit would become more appealing to commuters, prompting a modal shift and consequently decreasing traffic demand. In addition, a range of traffic demand management strategies could be introduced to further reduce private vehicle dependability. The Mobility dimension is unlikely to change, as improvements relevant to this dimension are usually only applicable to the planning stage of a network. As the Ottawa network already exists, with constrained conditions and property limitations, no changes can be made. However, on a positive note, the existing link lengths already give a high Mobility dimension.

7.4 Research Limitations

The results obtained from this research work were based on the data obtained from the simulation of hypothetical models of networks possessing specific characteristics. Although these factors were in accordance with the HCM 2010, every network has its own unique properties that must then be addressed appropriately, in accordance with the specific situation at hand. Furthermore, the models produced as a result of link closures are only hypothetical scenarios, and the effect of events taking place on a part of the network may be far more complex in real situations, where other considerations come into play, such as

safety concerns and emergency response, as well political and situational considerations that may play a role in the severity, or ramifications of such events.

In addition, the simulations presented herein are only applicable to networks possessing similar characteristics and comparable vulnerability dimensions. More model variations are needed in order to further explore the interactions between the different elements, and subsequent simulations carried out on these variations. The additional data can then be further analyzed to verify the results previously obtained, and build upon the accumulated knowledge base.

Another limitation of the presented research is the omission of any major generators, or special generators that would likely exist in a CBD type of urban traffic network. As CBDs are the main business and economic hub of almost every city, special generators such as tourist attractions, shopping centers, hospitals, and major education facilities (universities/colleges) often exist. Special generators are those land uses that do not generate or attract trips at the same rate as other land uses in the same land use category; hence they are assigned a unique trip rate (Lima & Associates 2006). Following on this point, all the networks modeled in this research were assumed to have uniform trip rates across all destination nodes, which is unlikely in a real-world scenario, as variations always exist along traffic networks.

Despite the above limitations, the findings of this research study are considered reasonable, and do reveal important information about the vulnerability of urban traffic networks, and the behavior of road users utilizing the central business district, as well as to the society at large. In addition, a better understanding of the effects of road closures is obtained.

7.5 Future Research

Aside from the contributions made by this research study to aid the advancement of network vulnerability knowledge and ultimately resilience concepts, there are other viable areas for future research to study and evaluate the factors contributing to the vulnerability dimensions of urban transportation networks. Some possible areas that future research could look into include the investigation of how access functions of different road classification types affect vulnerability, particularly as it pertains to the Mobility dimension. This is needed in order to present the effects of other activities taking place on the road segments, such as on-street parking and property accesses to and from the roadway, as opposed to uninterrupted traffic flow (except at intersections), which would be a better representation of CBD traffic operations. Furthermore, the definition of the dimension Mobility may be refined with the integration of a risk factor value into the concept. That is, the dimension can be related to the risk magnitude it poses to the network vulnerability, and addressed accordingly.

Another potential area for research advancement is the modeling of imbalances in demand across the traffic network. As opposed to the assumed uniform demand over the networks used in this research, an array of networks with varying trip rates in different parts of the model should be investigated, and the related effect on the vulnerability dimension of Flowability. Building on this point, it would also be fitting to consider the effects of special generators within the model on traffic flow patterns and the associated vulnerability effects, as outlined in Section 7.4.

Concerning the research area of link closure effects, a possible advancement to be undertaken is to develop a Link-Network Influence functions, which would better help in the identification of impacts of different link closures on the overall network. This requires the modeling and simulation of additional networks of varying types, but will likely be a significant contribution to the area of vulnerability research.

Additional work that can be carried out includes the application of the proposed methodology to additional city CBD networks as case studies (similar to what has been done for Ottawa). This will outline how the proposed concepts apply to the real world, increasing the benefits of the presented research. It is also proposed that considerations be made for the inclusion of fuel consumption and emissions evaluation in the proposed vulnerability assessments, as climate change issues take an increasingly vital role in today's society.

References

- 02 Planning + Design Inc. 2012. "Connectivity Index." *Greenfield Tool Box*. 11 5.
Accessed June 4, 2016.
http://greenfield.calgaryregion.ca/tools/greenfield_process_connectivityIndex.pdf.
- Adeel, Yusuf. 2009. *Flow Density Relationship*. December 16. Accessed June 5, 2016.
https://en.wikipedia.org/wiki/File:Flow_Density_Relationship.png.
- Banks, J. H. 1991. "Two Capacity Phenomenon at Freeway Bottlenecks: A Basis for Ramp Metering?" *Transportation Research Record* 1320 83-90.
- Batty, M. 2013. "Editorial: Resilient cities, networks, and disruption." *Environment and Planning B: Planning and Design* 40: 571-573.
- Berdica, Katja. 2002. "An Introduction to Road Vulnerability: What Has Been Done, Is Done and Should be Done." *Transport Policy* 9 117-127.
- Burghout, Wilco. 2004. *Hybrid microscopic-mesoscopic traffic simulation*. Doctoral Dissertation, Stockholm: Royal Institute of Technology.
- Canadian Capacity Guide for Signalized Intersections. 2008. *Canadian Institute of Transportation Engineers*. Canada: Institute of Transportation Engineers.
- City of Ottawa. 2012. "2013 Transportation Master Plan." *City of Ottawa Planning and Development*. April 19. Accessed August 9, 2015.

http://documents.ottawa.ca/sites/documents.ottawa.ca/files/documents/tmp_map_7_en.pdf.

—. 2015. *Official Plan - 1.3 - The Core*. Accessed February 6, 2016.
<http://ottawa.ca/en/official-plan-0/10-central-area/13-core>.

Daganzo, Carlos F. 1997. *Fundamentals of transportation and traffic operations*. Vol. 30. Berkeley: Oxford: Pergamon.

Fan, Rong, Hao Yu, Pan Liu, and Wei Wang. 2012. "Using VISSIM simulation model and Surrogate Safety Assessment Model for estimating field measured traffic conflicts at freeway merge areas." *IET Intelligent Transport Systems*.

Ford, L. R., and D. R. Fulkerson. 1962. *Flows in networks*. Princeton, New Jersey: Princeton University Press.

Godschalh, D.R. 2013. "Urban Hazard Mitigation: Creating Resilient Cities." *Natural Hazards Review* 4: 136-143.

Highway Capacity Manual. 2010. *National Research Council*. United States of America: Transportation Research Board.

Hsieh, Cheng-Hsien, and Cheng-Min Feng. 2014. "Road network vulnerability assessment based on fragile factor interdependencies in spatial-functional perspectives." *Environment and Planning A* 700-714.

- Imran, Shah. 2015. *MODELING FREEWAY LEVEL-OF-SERVICE BASED ON TRAVEL TIME AND TRAVEL TIME RELIABILITY*. Dissertation, Ann Arbor: ProQuest LLC.
- Jenelius, Erik, and Lars-Goran Mattsson. 2015. "Road network vulnerability analysis: Conceptualization, implementation and application." *Computers, Environment and Urban Systems* 49: 136-147.
- Lima & Associates. 2006. *Trip Generation - Lincoln MPO Travel Demand Model Report*. Model Development Documentation, Princeton: Princeton University.
- Mannering, Fred L, and Scott S Washburn. 2013. *Principles of highway engineering and traffic analysis*. 5th. Hoboken, New Jersey: Wiley.
- Marshall, Wesley E., and Norman W. Garrick. 2010. "The Effect of Street Network Design on Walking and Biking." *The 89th Annual Meeting of Transportation Research Board*. Washington, D.C.
- Marsico, Michael, Andrew Weeks, Keir Opie, and Murat Ayçin . 2013. *Bronx benefits from mesoscopic-microscopic modelling*. December. Accessed May 31, 2016. <http://www.itsinternational.com/categories/gis-mapping/features/bronx-benefits-from-mesoscopic-microscopic-modelling/>.
- Mathew, Tom V. 2006. "Transportation Network Design." *Princeton University - Transportation Program*. 10 2. Accessed June 5, 2016.

https://www.princeton.edu/~alaink/Orf467F08/TransportationNetworkDesign_Mathew.pdf.

Muñoz, Juan Carlos, and Jorge A. Laval. 2006. "System optimum dynamic traffic assignment graphical solution method for a congested freeway and one destination." *Transportation Research Part B : Methodological*.

Murray, Alan T. 2013. "An overview of network vulnerability modeling approaches." *Geojournal* 78 (Springer Science+Business Media B.V.) 209-221.

Omer, M., A. Mostashari, and U. Lindemann. 2014. "Resilience Analysis of Software Infrastructure Systems." *Procedia Computer Science* 28: 565-574.

Petrenj, Boris, and Paolo Trucco. 2014. "Simulation-based characterisation of critical infrastructure system resilience." *Int. J. Critical Infrastructures, Vol. 10, Nos. 3/4* 347-374.

PTV AG. 2015. *PTV VISSIM 7 USER MANUAL*. Karlsruhe, April 24.

PTV AG. 2014. *PTV VISUM 14 Manual*. Karlsruhe, October.

PTV Group. 2016. *PTV Vissim*. Accessed May 29, 2016. <http://vision-traffic.ptvgroup.com/en-us/products/ptv-vissim/>.

—. 2016. *PTV Visum*. Accessed 05 29, 2016. <http://vision-traffic.ptvgroup.com/en-us/products/ptv-visum/>.

Rosenberg, Matt. 2016. *CBD*. Accessed January 19, 2016.
<http://geography.about.com/od/urbaneconomicgeography/a/cbd.htm>.

StataCorp LP. 2016. *Stata/MP*. Accessed June 9, 2016. <http://www.stata.com/m/statamp/>.

Victoria Transport Policy Institute. 2015. "Roadway Connectivity." *TDM Encyclopedia*.
December 21. Accessed June 4, 2016. <http://www.vtpi.org/tdm/tdm116.htm>.

WUS Group. 2015. "PTV Vision Suite By WUS." *WUS TRAFFIC*. April 1. Accessed June
14, 2015. [http://www.wus-
group.com/page.php?menuid=117&submenuid=126&pageid=62](http://www.wus-group.com/page.php?menuid=117&submenuid=126&pageid=62).

Appendices

Appendix A City of Ottawa Data

Figure: City of Ottawa 2011 Traffic Zone Divisions in CBD

Figure: City of Ottawa Central Area – Official Plan Schedule F (City of Ottawa 2012)

Appendix B Simulation Results: Varying Network Properties

B.1 Idealized Network

Idealized Network: 4 x 4 grid, 1.0 demand value, and 200m link lengths.

B.2 Centrality Generated Networks

Figure: 1 x 16 Network

Figure: 2 x 8 Network

Figure: 3 x 5 Network

Figure: 3 x 6 Network

B.3 Flowability Generated Networks

Figure: 1.5 Demand Network

Figure: 2.0 Demand Network

Figure: 2.5 Demand Network

Figure: 3.0 Demand Network

B.4 Mobility Generated Networks

Figure: 250m Link Lengths

Figure: 300m Link Lengths

Figure: 350m Link Lengths

Figure: 400m Link Lengths

Appendix C Simulation Results: Sequential Link Closures

C.1 Sequential Link Closure Traffic Models

Figure: Link 1 Closure

Figure: Link 2 Closure

Figure: Link 5 Closure

Figure: Link 6 Closure

C.2 Model Version Comparisons

Figure: Link 1 Closure – Traffic Volume Comparison

Figure: Link 2 Closure – Traffic Volume Comparison

Figure: Link 3 Closure – Traffic Volume Comparison

Figure: Link 4 Closure – Traffic Volume Comparison

Figure: Link 5 Closure – Traffic Volume Comparison

Figure: Link 6 Closure – Traffic Volume Comparison

Appendix D Simulation Results: City of Ottawa

D.1 Base Network

Figure: City of Ottawa Downtown Core Base Network

D.2 Sequential Link Closures: Ottawa Core Network

Figure: Link 1 Closure – Traffic Volume Comparison

Figure: Link 2 Closure – Traffic Volume Comparison

Figure: Link 3 Closure – Traffic Volume Comparison

Figure: Link 4 Closure – Traffic Volume Comparison

Figure: Link 5 Closure – Traffic Volume Comparison

Figure: Link 6 Closure – Traffic Volume Comparison

Figure: Link 7 Closure – Traffic Volume Comparison

Figure: Link 8 Closure – Traffic Volume Comparison

Figure: Link 9 Closure – Traffic Volume Comparison

Figure: Link 10 Closure – Traffic Volume Comparison

Figure: Link 11 Closure – Traffic Volume Comparison

Figure: Link 12 Closure – Traffic Volume Comparison

Figure: Link 13 Closure – Traffic Volume Comparison

Figure: Link 14 Closure – Traffic Volume Comparison

Figure: Link 15 Closure – Traffic Volume Comparison

Figure: Link 16 Closure – Traffic Volume Comparison

Appendix E Simulation Results Summary

Table: Varying Network Properties – Average Simulation Results of 10 Runs

Model (Designation)	DELAYAVG (Avg.)	SPEEDAVG (Avg.)	DISTTOT (Avg.)	TRAVTMTOT (Avg.)	Centrality	Flowability	Mobility	CVI
Base	60.610	29.440	3673.780	449309.850	1.000	0.920	0.800	0.028
3x5	60.470	29.450	3527.220	431276.050	0.600	0.920	0.750	0.170
(3x5)*1.3	63.630	29.250	4016.350	495312.637	0.567	0.915	0.800	0.195
3x6	69.950	28.850	4994.610	623385.810	0.500	0.904	0.900	0.253
2x8	84.220	27.490	5664.990	741884.670	0.250	0.885	0.800	0.139
1x16	1287.760	2.470	5968.810	8718992.510	0.063	0.700	0.800	0.550
1.5	71.550	27.620	5507.060	717990.910	1.000	0.880	0.800	0.042
2	94.270	24.480	7300.240	1073965.050	1.000	0.839	0.800	0.056
2.5	203.050	15.480	8731.820	2036448.720	1.000	0.838	0.800	0.056
3	570.730	5.900	7837.920	4818453.820	1.000	0.759	0.800	0.083
250m	59.910	32.590	4828.790	533447.180	1.000	0.920	0.640	0.012
300m	58.790	34.590	5792.960	602929.060	1.000	0.920	0.530	0.016
350m	58.660	36.040	6788.000	678080.410	1.000	0.920	0.457	0.019
400m	58.100	37.330	7744.590	746943.530	1.000	0.920	0.400	0.021
Average	200.121	25.784	5884.081	1619172.872	0.784	0.874	0.720	0.117
Std. Dev.	341.472	10.611	1623.156	2346655.469	0.327	0.069	0.152	0.146

Table: Sequential Link Closure Networks – Average Simulation Results of 10 Runs

Model (Link Removal)	DELAYAVG (Avg.)	SPEEDAVG (Avg.)	DISTTOT (Avg.)	TRAVTMTOT (Avg.)	Centrality	Flowability	Mobility	% Effect	ACVI
Base	60.610	29.440	3673.780	449309.850	1.000	0.920	0.800	0.00	0.0280
1	60.020	29.520	3507.930	427816.750	1.000	0.920	0.800	13.00	0.0316
2	60.950	29.450	3561.800	435472.620	1.000	0.920	0.800	4.00	0.0291
3	61.210	29.370	3691.760	452631.030	1.000	0.920	0.800	18.00	0.0330
4	61.010	29.400	3685.850	451362.180	1.000	0.920	0.800	20.00	0.0336
5	61.090	29.390	3694.470	452596.230	1.000	0.920	0.800	2.00	0.0286
6	60.960	29.400	3680.500	450766.550	1.000	0.920	0.800	3.00	0.0288
Average	60.836	29.424	3642.299	445707.887	1.000	0.920	0.800	8.57	0.030
Std. Dev.	0.404	0.051	75.333	9922.768	0.000	0.000	0.000	8.24	0.002

Table: City of Ottawa Network Model – Average Simulation Results of 10 Runs

Model (Link Removal)	DELAYAVG (Avg.)	SPEEDAVG (Avg.)	DISTTOT (Avg.)	Centrality	Demand	Flowability	Mobility	CVI	%Effect	ACVI
Base	97.49	17.74	4500.25	0.8571	116.0000	0.8532	0.8125	0.0330		0.0330
1	82.258	19.468	4584.097	0.8571	120.0000	0.8481	0.8125	0.0330	4.00	0.0343
2	87.03	18.86	4509.45	0.8571	119.0000	0.8494	0.8125	0.0330	3.00	0.0340
3	91.02	18.22	4507.05	0.8571	118.0000	0.8506	0.8125	0.0330	2.00	0.0337
4	142.08	13.45	4363.34	0.8571	119.0000	0.8494	0.8125	0.0330	3.00	0.0340
5	94.16	17.84	4507.88	0.8571	118.0000	0.8506	0.8125	0.0330	2.00	0.0337
6	85.36	19	4552.87	0.8571	119.0000	0.8494	0.8125	0.0330	3.00	0.0340
7	95.01	17.84	4541.21	0.8571	118.0000	0.8506	0.8125	0.0330	2.00	0.0337
8	93.73	18.07	4545.72	0.8571	120.0000	0.8481	0.8125	0.0330	4.00	0.0343
9	86.28	18.77	4505.43	0.8571	116.0000	0.8532	0.8125	0.0330	0.00	0.0330
10	80.03	19.73	4576.89	0.8571	118.0000	0.8506	0.8125	0.0330	2.00	0.0337
11	101.96	17.06	4451.98	0.8571	117.0000	0.8519	0.8125	0.0330	1.00	0.0333
12	90.63	18.41	4563.67	0.8571	119.0000	0.8494	0.8125	0.0330	3.00	0.0340
13	89.35	18.35	4474.39	0.8571	115.0000	0.8544	0.8125	0.0330	0.00	0.0330
14	92.39	18.4	4608.43	0.8571	119.0000	0.8494	0.8125	0.0330	3.00	0.0340
15	85.43	19.12	4589.66	0.8571	119.0000	0.8494	0.8125	0.0330	3.00	0.0340
16	77.48	20.25	4555.69	0.8571	117.0000	0.8519	0.8125	0.0330	1.00	0.0333
Average	92.452	18.269	4525.765	0.857		0.851	0.813	0.033	2.250	0.034
Std. Dev.	14.262	1.474	59.740	0.000		0.002	0.000	0.000	1.238	0.0004

Appendix F Graphs and Charts

This section contains various graphs and charts that demonstrate the relationship between the dependent variable (CVI) and each of the independent variables.

Figure: Network CVI vs. Average Delay

Figure: Network CVI vs. Average Speed

Appendix G Regression Results

G.1 Varying Network Properties: Centrality, Flowability, Mobility (CFM)

. nestreg: regress cvi del, beta

Block 1: del

Source	SS	df	MS	Number of obs = 120		
Model	1.92897852	1	1.92897852	F(1, 118) = 376.63		
Residual	.60435074	118	.005121616	Prob > F = 0.0000		
				R-squared = 0.7614		
				Adj R-squared = 0.7594		
Total	2.53332926	119	.021288481	Root MSE = .07157		

cvi	Coef.	Std. Err.	t	P> t	Beta
del	.0003611	.0000186	19.41	0.000	.8726054
_cons	.0210323	.0077354	2.72	0.008	.

Block	Block F	Residual df	Residual df	Pr > F	R2	Change in R2
1	376.63	1	118	0.0000	0.7614	

. nestreg: regress cvi s, beta

Block 1: s

Source	SS	df	MS	Number of obs = 120		
Model	1.11943973	1	1.11943973	F(1, 118) = 93.43		
Residual	1.41388953	118	.011982115	Prob > F = 0.0000		
				R-squared = 0.4419		
				Adj R-squared = 0.4372		
Total	2.53332926	119	.021288481	Root MSE = .10946		

cvi	Coef.	Std. Err.	t	P> t	Beta
s	-.0088227	.0009128	-9.67	0.000	-.6647442
_cons	.3239445	.0250975	12.91	0.000	.

Block	Block F	Residual df	Residual df	Pr > F	R2	Change in R2
1	93.43	1	118	0.0000	0.4419	

. nestreg: regress cvi d, beta

Block 1: d

Source	SS	df	MS	Number of obs = 120	
Model	.035549944	1	.035549944	F(1, 118) =	1.68
Residual	2.49777931	118	.021167621	Prob > F =	0.1975
				R-squared =	0.0140
				Adj R-squared =	0.0057
Total	2.53332926	119	.021288481	Root MSE =	.14549

cvi	Coef.	Std. Err.	t	P> t	Beta
d	-.0000114	8.79e-06	-1.30	0.198	-.1184605
_cons	.1715559	.0557282	3.08	0.003	.

Block	Block F	Residual df	Pr > F	R2	Change in R2
1	1.68	118	0.1975	0.0140	

. nestreg: regress cvi t, beta

Block 1: t

Source	SS	df	MS	Number of obs = 120	
Model	1.73977164	1	1.73977164	F(1, 118) =	258.70
Residual	.793557621	118	.006725065	Prob > F =	0.0000
				R-squared =	0.6868
				Adj R-squared =	0.6841
Total	2.53332926	119	.021288481	Root MSE =	.08201

cvi	Coef.	Std. Err.	t	P> t	Beta
t	5.02e-08	3.12e-09	16.08	0.000	.8287057
_cons	.0109716	.0093629	1.17	0.244	.

Block	Block F	Residual df	Pr > F	R2	Change in R2
1	258.70	118	0.0000	0.6868	

. nestreg: regress cvi del s d t, beta

Block 1: del

Source	SS	df	MS	Number of obs = 120	
Model	1.92897852	1	1.92897852	F(1, 118) =	376.63
Residual	.60435074	118	.005121616	Prob > F =	0.0000
				R-squared =	0.7614
				Adj R-squared =	0.7594
Total	2.53332926	119	.021288481	Root MSE =	.07157

cvi	Coef.	Std. Err.	t	P> t	Beta
del	.0003611	.0000186	19.41	0.000	.8726054
_cons	.0210323	.0077354	2.72	0.008	.

Block 2: s

Source	SS	df	MS	Number of obs = 120	
Model	1.98390147	2	.991950734	F(2, 117) =	211.23
Residual	.549427789	117	.004695964	Prob > F =	0.0000
				R-squared =	0.7831
				Adj R-squared =	0.7794
Total	2.53332926	119	.021288481	Root MSE =	.06853

cvi	Coef.	Std. Err.	t	P> t	Beta
del	.0004596	.0000339	13.57	0.000	1.11073
s	.0037159	.0010865	3.42	0.001	.2799707
_cons	-.094626	.0346207	-2.73	0.007	.

Block 3: d

Source	SS	df	MS	Number of obs = 120		
Model	2.103895	3	.701298333	F(3, 116) = 189.44		
Residual	.429434258	116	.003702019	Prob > F = 0.0000		
Total	2.53332926	119	.021288481	R-squared = 0.8305		
				Adj R-squared = 0.8261		
				Root MSE = .06084		

cvi	Coef.	Std. Err.	t	P> t	Beta
del	.0004188	.0000309	13.54	0.000	1.012016
s	.0016083	.0010333	1.56	0.122	.1211774
d	-.0000227	3.99e-06	-5.69	0.000	-.2359262
_cons	.1073142	.0469365	2.29	0.024	.

Block 4: t

Source	SS	df	MS	Number of obs = 120		
Model	2.28866765	4	.572166911	F(4, 115) = 268.94		
Residual	.244661611	115	.002127492	Prob > F = 0.0000		
Total	2.53332926	119	.021288481	R-squared = 0.9034		
				Adj R-squared = 0.9001		
				Root MSE = .04612		

cvi	Coef.	Std. Err.	t	P> t	Beta
del	.0026317	.0002386	11.03	0.000	6.3595
s	-.0063687	.0011603	-5.49	0.000	-.479848
d	.0000188	5.38e-06	3.50	0.001	.1957695
t	-3.61e-07	3.88e-08	-9.32	0.000	-5.96315
_cons	.211118	.0372843	5.66	0.000	.

Block	Block F	Residual df	Pr > F	R2	Change in R2
1	376.63	118	0.0000	0.7614	
2	11.70	117	0.0009	0.7831	0.0217
3	32.41	116	0.0000	0.8305	0.0474
4	86.85	115	0.0000	0.9034	0.0729

. estat vif

Variable	VIF	1/VIF
t	487.53	0.002051
del	395.88	0.002526
s	9.10	0.109884
d	3.73	0.268079
Mean VIF	224.06	

. nestreg: regress cvi s d t, beta

Block 1: s

Source	SS	df	MS	Number of obs =	120
Model	1.11943973	1	1.11943973	F(1, 118) =	93.43
Residual	1.41388953	118	.011982115	Prob > F =	0.0000
Total	2.53332926	119	.021288481	R-squared =	0.4419
				Adj R-squared =	0.4372
				Root MSE =	.10946

cvi	Coef.	Std. Err.	t	P> t	Beta
s	-.0088227	.0009128	-9.67	0.000	-.6647442
_cons	.3239445	.0250975	12.91	0.000	.

Block 2: d

Source	SS	df	MS	Number of obs =	120
Model	1.42489793	2	.712448966	F(2, 117) =	75.20
Residual	1.10843133	117	.009473772	Prob > F =	0.0000
Total	2.53332926	119	.021288481	R-squared =	0.5625
				Adj R-squared =	0.5550
				Root MSE =	.09733

cvi	Coef.	Std. Err.	t	P> t	Beta
s	-.0103641	.0008558	-12.11	0.000	-.7808818
d	-.0000352	6.20e-06	-5.68	0.000	-.3661472
_cons	.5796142	.0502531	11.53	0.000	.

Block 3: t

Source	SS	df	MS	Number of obs =	120
Model	2.02986289	3	.676620963	F(3, 116) =	155.90
Residual	.503466368	116	.004340227	Prob > F =	0.0000
				R-squared =	0.8013
				Adj R-squared =	0.7961
Total	2.53332926	119	.021288481	Root MSE =	.06588

cvi	Coef.	Std. Err.	t	P> t	Beta
s	.0023002	.0012191	1.89	0.062	.1733081
d	-.0000308	4.22e-06	-7.32	0.000	-.3205681
t	6.42e-08	5.44e-09	11.81	0.000	1.060079
_cons	.1175082	.0518553	2.27	0.025	.

Block	Block F	Block df	Residual df	Pr > F	R2	Change in R2
1	93.43	1	118	0.0000	0.4419	
2	32.24	1	117	0.0000	0.5625	0.1206
3	139.39	1	116	0.0000	0.8013	0.2388

. estat vif

Variable	VIF	1/VIF
s	4.92	0.203064
t	4.71	0.212501
d	1.12	0.892409
Mean VIF	3.58	

. nestreg: regress cvi del s d, beta

Block 1: del

Source	SS	df	MS	Number of obs = 120		
Model	1.92897852	1	1.92897852	F(1, 118) = 376.63		
Residual	.60435074	118	.005121616	Prob > F = 0.0000		
Total	2.53332926	119	.021288481	R-squared = 0.7614		
				Adj R-squared = 0.7594		
				Root MSE = .07157		

cvi	Coef.	Std. Err.	t	P> t	Beta
del	.0003611	.0000186	19.41	0.000	.8726054
_cons	.0210323	.0077354	2.72	0.008	.

Block 2: s

Source	SS	df	MS	Number of obs = 120		
Model	1.98390147	2	.991950734	F(2, 117) = 211.23		
Residual	.549427789	117	.004695964	Prob > F = 0.0000		
Total	2.53332926	119	.021288481	R-squared = 0.7831		
				Adj R-squared = 0.7794		
				Root MSE = .06853		

cvi	Coef.	Std. Err.	t	P> t	Beta
del	.0004596	.0000339	13.57	0.000	1.11073
s	.0037159	.0010865	3.42	0.001	.2799707
_cons	-.094626	.0346207	-2.73	0.007	.

Block 3: d

Source	SS	df	MS	Number of obs =	120
Model	2.103895	3	.701298333	F(3, 116) =	189.44
Residual	.429434258	116	.003702019	Prob > F =	0.0000
				R-squared =	0.8305
				Adj R-squared =	0.8261
Total	2.53332926	119	.021288481	Root MSE =	.06084

cvi	Coef.	Std. Err.	t	P> t	Beta
del	.0004188	.0000309	13.54	0.000	1.012016
s	.0016083	.0010333	1.56	0.122	.1211774
d	-.0000227	3.99e-06	-5.69	0.000	-.2359262
_cons	.1073142	.0469365	2.29	0.024	.

Block	Block F	Block df	Residual df	Pr > F	R2	Change in R2
1	376.63	1	118	0.0000	0.7614	
2	11.70	1	117	0.0009	0.7831	0.0217
3	32.41	1	116	0.0000	0.8305	0.0474

. estat vif

Variable	VIF	1/VIF
s	4.15	0.241091
del	3.82	0.261699
d	1.18	0.850969
Mean VIF	3.05	

G.2 Sequential Link Closures (SLC)

```
. nestreg: regress acvi del, beta
```

Block 1: del

Source	SS	df	MS	Number of obs =	70
Model	1.2482e-07	1	1.2482e-07	F(1, 68) =	0.03
Residual	.000316761	68	4.6582e-06	Prob > F =	0.8705
				R-squared =	0.0004
				Adj R-squared =	-0.0143
Total	.000316886	69	4.5925e-06	Root MSE =	.00216

acvi	Coef.	Std. Err.	t	P> t	Beta
del	.0000416	.0002539	0.16	0.870	.0198471
_cons	.0278568	.0154511	1.80	0.076	.

Block	Block F	Residual df	Residual df	Pr > F	R2	Change in R2
1	0.03	1	68	0.8705	0.0004	

```
. nestreg: regress acvi s, beta
```

Block 1: s

Source	SS	df	MS	Number of obs =	70
Model	5.4847e-07	1	5.4847e-07	F(1, 68) =	0.12
Residual	.000316337	68	4.6520e-06	Prob > F =	0.7324
				R-squared =	0.0017
				Adj R-squared =	-0.0129
Total	.000316886	69	4.5925e-06	Root MSE =	.00216

acvi	Coef.	Std. Err.	t	P> t	Beta
s	-.0007808	.0022741	-0.34	0.732	-.041603
_cons	.0533603	.0669106	0.80	0.428	.

Block	Block F	Residual df	Residual df	Pr > F	R2	Change in R2
1	0.12	1	68	0.7324	0.0017	

. nestreg: regress acvi d, beta

Block 1: d

Source	SS	df	MS	Number of obs = 70	
Model	3.6986e-08	1	3.6986e-08	F(1, 68) =	0.01
Residual	.000316849	68	4.6595e-06	Prob > F =	0.9293
				R-squared =	0.0001
				Adj R-squared =	-0.0146
Total	.000316886	69	4.5925e-06	Root MSE =	.00216

acvi	Coef.	Std. Err.	t	P> t	Beta
d	-1.92e-07	2.16e-06	-0.09	0.929	-.0108036
_cons	.0310866	.0078713	3.95	0.000	.

Block	Block F	Residual df	Pr > F	R2	Change in R2
1	0.01	1	68	0.9293	0.0001

. nestreg: regress acvi t, beta

Block 1: t

Source	SS	df	MS	Number of obs = 70	
Model	7.9694e-09	1	7.9694e-09	F(1, 68) =	0.00
Residual	.000316878	68	4.6600e-06	Prob > F =	0.9671
				R-squared =	0.0000
				Adj R-squared =	-0.0147
Total	.000316886	69	4.5925e-06	Root MSE =	.00216

acvi	Coef.	Std. Err.	t	P> t	Beta
t	-6.60e-10	1.60e-08	-0.04	0.967	-.0050149
_cons	.03068	.0071198	4.31	0.000	.

Block	Block F	Residual df	Pr > F	R2	Change in R2
1	0.00	1	68	0.9671	0.0000

. nestreg: regress acvi del s d t, beta

Block 1: del

Source	SS	df	MS	Number of obs = 70		
Model	1.2482e-07	1	1.2482e-07	F(1, 68) = 0.03		
Residual	.000316761	68	4.6582e-06	Prob > F = 0.8705		
Total	.000316886	69	4.5925e-06	R-squared = 0.0004		
				Adj R-squared = -0.0143		
				Root MSE = .00216		

acvi	Coef.	Std. Err.	t	P> t	Beta
del	.0000416	.0002539	0.16	0.870	.0198471
_cons	.0278568	.0154511	1.80	0.076	.

Block 2: s

Source	SS	df	MS	Number of obs = 70		
Model	1.1036e-06	2	5.5182e-07	F(2, 67) = 0.12		
Residual	.000315782	67	4.7132e-06	Prob > F = 0.8897		
Total	.000316886	69	4.5925e-06	R-squared = 0.0035		
				Adj R-squared = -0.0263		
				Root MSE = .00217		

acvi	Coef.	Std. Err.	t	P> t	Beta
del	-.0002061	.0006005	-0.34	0.733	-.0983991
s	-.0024523	.0053812	-0.46	0.650	-.1306561
_cons	.1150764	.1920208	0.60	0.551	.

Block 3: d

Source	SS	df	MS	Number of obs =	70
Model	3.9318e-06	3	1.3106e-06	F(3, 66) =	0.28
Residual	.000312954	66	4.7417e-06	Prob > F =	0.8422
				R-squared =	0.0124
				Adj R-squared =	-0.0325
Total	.000316886	69	4.5925e-06	Root MSE =	.00218

acvi	Coef.	Std. Err.	t	P> t	Beta
del	-.0001552	.0006059	-0.26	0.799	-.0740919
s	-.0052967	.0065343	-0.81	0.421	-.2822027
d	-3.52e-06	4.56e-06	-0.77	0.443	-.1978627
_cons	.208505	.2274432	0.92	0.363	.

Block 4: t

Source	SS	df	MS	Number of obs =	70
Model	4.7174e-06	4	1.1793e-06	F(4, 65) =	0.25
Residual	.000312168	65	4.8026e-06	Prob > F =	0.9113
				R-squared =	0.0149
				Adj R-squared =	-0.0457
Total	.000316886	69	4.5925e-06	Root MSE =	.00219

acvi	Coef.	Std. Err.	t	P> t	Beta
del	-.0001682	.0006106	-0.28	0.784	-.0803052
s	.0136843	.0473899	0.29	0.774	.7290885
d	-.000155	.0003745	-0.41	0.680	-8.699448
t	1.24e-06	3.06e-06	0.40	0.687	9.406466
_cons	-.3495232	1.398613	-0.25	0.803	.

Block	Block F	Residual df	Pr > F	R2	Change in R2
1	0.03	1	0.8705	0.0004	
2	0.21	1	0.6501	0.0035	0.0031
3	0.60	1	0.4427	0.0124	0.0089
4	0.16	1	0.6872	0.0149	0.0025

. estat vif

Variable	VIF	1/VIF
t	35692.11	0.000028
d	29159.79	0.000034
s	420.65	0.002377
del	5.61	0.178303
Mean VIF	16319.54	

. nestreg: regress acvi del s d, beta

Block 1: del

Source	SS	df	MS	Number of obs =	70
Model	1.2482e-07	1	1.2482e-07	F(1, 68) =	0.03
Residual	.000316761	68	4.6582e-06	Prob > F =	0.8705
Total	.000316886	69	4.5925e-06	R-squared =	0.0004
				Adj R-squared =	-0.0143
				Root MSE =	.00216

acvi	Coef.	Std. Err.	t	P> t	Beta
del	.0000416	.0002539	0.16	0.870	.0198471
_cons	.0278568	.0154511	1.80	0.076	.

Block 2: s

Source	SS	df	MS	Number of obs =	70
Model	1.1036e-06	2	5.5182e-07	F(2, 67) =	0.12
Residual	.000315782	67	4.7132e-06	Prob > F =	0.8897
Total	.000316886	69	4.5925e-06	R-squared =	0.0035
				Adj R-squared =	-0.0263
				Root MSE =	.00217

acvi	Coef.	Std. Err.	t	P> t	Beta
del	-.0002061	.0006005	-0.34	0.733	-.0983991
s	-.0024523	.0053812	-0.46	0.650	-.1306561
_cons	.1150764	.1920208	0.60	0.551	.

Block 3: d

Source	SS	df	MS	Number of obs =	70
Model	3.9318e-06	3	1.3106e-06	F(3, 66) =	0.28
Residual	.000312954	66	4.7417e-06	Prob > F =	0.8422
Total	.000316886	69	4.5925e-06	R-squared =	0.0124
				Adj R-squared =	-0.0325
				Root MSE =	.00218

acvi	Coef.	Std. Err.	t	P> t	Beta
del	-.0001552	.0006059	-0.26	0.799	-.0740919
s	-.0052967	.0065343	-0.81	0.421	-.2822027
d	-3.52e-06	4.56e-06	-0.77	0.443	-.1978627
_cons	.208505	.2274432	0.92	0.363	.

Block	Block F	Block df	Residual df	Pr > F	R2	Change in R2
1	0.03	1	68	0.8705	0.0004	
2	0.21	1	67	0.6501	0.0035	0.0031
3	0.60	1	66	0.4427	0.0124	0.0089

. estat vif

Variable	VIF	1/VIF
s	8.10	0.123457
del	5.59	0.178799
d	4.39	0.227967
Mean VIF	6.03	

G.3 City of Ottawa Network Model

```
. nestreg: regress acvi del, beta
```

Block 1: del

Source	SS	df	MS	Number of obs =	170
Model	9.7777e-08	1	9.7777e-08	F(1, 168) =	0.54
Residual	.000030396	168	1.8093e-07	Prob > F =	0.4633
				R-squared =	0.0032
				Adj R-squared =	-0.0027
Total	.000030494	169	1.8044e-07	Root MSE =	.00043

acvi	Coef.	Std. Err.	t	P> t	Beta
del	1.18e-06	1.61e-06	0.74	0.463	.0566253
_cons	.0335965	.0001523	220.54	0.000	.

Block	Block F	Residual df	Pr > F	R2	Change in R2
1	0.54	1	168	0.4633	0.0032

```
. nestreg: regress acvi s, beta
```

Block 1: s

Source	SS	df	MS	Number of obs =	170
Model	2.3146e-08	1	2.3146e-08	F(1, 168) =	0.13
Residual	.000030471	168	1.8138e-07	Prob > F =	0.7214
				R-squared =	0.0008
				Adj R-squared =	-0.0052
Total	.000030494	169	1.8044e-07	Root MSE =	.00043

acvi	Coef.	Std. Err.	t	P> t	Beta
s	-5.04e-06	.0000141	-0.36	0.721	-.0275506
_cons	.033798	.00026	130.01	0.000	.

Block	Block F	Residual df	Pr > F	R2	Change in R2
1	0.13	1	168	0.7214	0.0008

```
. nestreg: regress acvi d, beta
```

Block 1: d

Source	SS	df	MS	Number of obs = 170	
Model	1.5178e-06	1	1.5178e-06	F(1, 168) =	8.80
Residual	.000028976	168	1.7248e-07	Prob > F =	0.0035
				R-squared =	0.0498
				Adj R-squared =	0.0441
Total	.000030494	169	1.8044e-07	Root MSE =	.00042

acvi	Coef.	Std. Err.	t	P> t	Beta
d	1.07e-06	3.59e-07	2.97	0.003	.2230964
_cons	.0288828	.0016262	17.76	0.000	.

Block	Block F	Residual df	Pr > F	R2	Change in R2
1	8.80	1	0.0035	0.0498	

```
. nestreg: regress acvi del s d, beta
```

Block 1: del

Source	SS	df	MS	Number of obs = 170	
Model	9.7777e-08	1	9.7777e-08	F(1, 168) =	0.54
Residual	.000030396	168	1.8093e-07	Prob > F =	0.4633
				R-squared =	0.0032
				Adj R-squared =	-0.0027
Total	.000030494	169	1.8044e-07	Root MSE =	.00043

acvi	Coef.	Std. Err.	t	P> t	Beta
del	1.18e-06	1.61e-06	0.74	0.463	.0566253
_cons	.0335965	.0001523	220.54	0.000	.

Block 2: s

Source	SS	df	MS	Number of obs = 170	
Model	8.8008e-07	2	4.4004e-07	F(2, 167) =	2.48
Residual	.000029614	167	1.7733e-07	Prob > F =	0.0867
				R-squared =	0.0289
				Adj R-squared =	0.0172
Total	.000030494	169	1.8044e-07	Root MSE =	.00042

acvi	Coef.	Std. Err.	t	P> t	Beta
del	.0000199	9.05e-06	2.20	0.029	.9524398
s	.0001666	.0000793	2.10	0.037	.9100207
_cons	.0288228	.0022778	12.65	0.000	.

Block 3: d

Source	SS	df	MS	Number of obs =	170
Model	3.9829e-06	3	1.3276e-06	F(3, 166) =	8.31
Residual	.000026511	166	1.5971e-07	Prob > F =	0.0000
				R-squared =	0.1306
				Adj R-squared =	0.1149
Total	.000030494	169	1.8044e-07	Root MSE =	.0004

acvi	Coef.	Std. Err.	t	P> t	Beta
del	.0000325	9.05e-06	3.59	0.000	1.553102
s	.0002509	.0000777	3.23	0.001	1.370735
d	1.72e-06	3.91e-07	4.41	0.000	.3605229
_cons	.0183277	.0032159	5.70	0.000	.

Block	Block F	Block df	Residual df	Pr > F	R2	Change in R2
1	0.54	1	168	0.4633	0.0032	
2	4.41	1	167	0.0372	0.0289	0.0257
3	19.43	1	166	0.0000	0.1306	0.1018

. estat vif

Variable	VIF	1/VIF
del	35.83	0.027912
s	34.37	0.029098
d	1.28	0.782841
Mean VIF	23.82	