Contemporary Network Theory: Concepts and Implications for Transportation Asset Management

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ABSTRACT

This thesis proposes a novel working paradigm for transportation infrastructure asset management by viewing the transportation networks as key components (or nodes) of a broader network of resources, which includes infrastructure linked with society's ecological, social, and economic systems. An extensive review of network science literature suggested that to understand the behavior of a complex network is imperative to characterize its topology. Consequently, this thesis focused on developing a framework to characterize the topology of the transportation infrastructure systems, and understanding how the unveiling topology can be used for supporting transportation asset management decisions.

The proposed methodology determines whether the transportation infrastructure networks can be modeled as scale-free or exponential networks, using a framework for characterizing the agents of the network, their direct and indirect interactions among each other, and their importance as elements of a complex network, and utilizes these data to support transportation asset management. The methodology consist of seven steps: (1) define the networks of interest; (2) identify their intrinsic components; (3) visualize the identified networks using GIS maps; (4) identify direct and indirect interactions through superposition of the networks; (5) represent the relationship between the nodes and their linkages by frequency diagrams in order to determine the intrinsic topology of the network; (6) illustrate (graphically) the overall transportation infrastructure with the help of GIS; and (7) analyze the TINs from the decision-maker point of view, identifying the elements that are more relevant or need more attention on the network.

The procedure is then implemented in a small network in a localized area (Town of Blacksburg, Virginia) to show its practicality, and recommendations for further development and mathematical modeling in order to allow its implementation in larger networks are provided. Based on frequency analysis of the nodes and their connectivity, it was concluded that the transportation infrastructure networks in the case study behave as exponential networks. The study showed that the links determine how the infrastructure network grows and that problems like congestion can be addressed by analyzing other factors related with topology, such as speed, unit size, and lane width. The proposed methodology was found to be useful as an asset management tool. Finally, a list of findings and recommendations for further research are presented as opportunities to enhance the management of transportation infrastructure networks.

DEDICATION

To the One whose love, glory and power have brought me here. Dear Lord, I found the strength, discipline and inspiration for this thesis in You. I truly believe that every word on these pages exist because of your power. I am beyond thankful to everyone who prayed for me and encouraged me to pursue this endeavor. To my parents, Yolanda and Guillermo, whom I love, and are always proud of me. Last but not least, to the love of my life, Aaron, who never stops believing in me.

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Attribution

The members on my committee aided in the writing, research and conclusions behind the chapters of this thesis. A brief description of their background and their contributions are includes here.

Dr. Gerardo W. Flintsch, Associate Professor, The Via Department of Civil and Environmental Engineering. Director, Center for Safe and Sustainable Infrastructure, Virginia Tech Transportation Institute. Dr Flintsch is the primary Advisor and Committee Chair. He provided the research direction for all the work during the author's graduate study. Furthermore, Dr. Flintsch also directed the composition of the chapters, extensively edited each chapter as well and provided major contributions to the conclusions for the overall document.

Chapter 2: Contemporary Network Theory: Concepts and Implications for Transportation Infrastructure Management.

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Chapter 2: Methodology for Using Network Topology to Support Infrastructure Asset Management: A Case Study

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CHAPTER 1 - INTRODUCTION

Background

The Transportation Equity Act for the 21st Century (TEA-21) impacted the way to approach the mobility needs of Americans. TEA-21 required district and state transportation plans to be "fiscally constrained" conforming with air quality standards and to consider other transportation modes in making transportation investment decisions. As a result of the implementation of TEA-21, the federal investment in connectivity grew more than 20 percent between 1996 and 2001. However, the investment still appears to be insufficient to cover the large demands for mobility and transportation services. Consequently, SAFETEA-LU (Safe, Accountable, Flexible, Efficient Transportation Equity Act: A legacy for Users); designated $244 Billion to promote a more efficient, effective and safe transportation system, while considering the upfront problems and needs of the communities. Although, regulations like SAFETEA-LU, have created the umbrella for more investment and improvement in the transportation networks, decision makers and planners still face the challenge of determining how to invest these funds to maximize the benefits to the society, its economy, and its environment. This process is increasing being supported by the use of asset management, principles, procedures and tools.

At the same time, preservation, mobility and safety are not the only issues related to transportation infrastructure systems. Recent devastating events, such as Hurricane Katrina and the terrorist attacks of September 11, 2001, have exposed the vulnerability of the systems and prompted the initiation of research aimed at enhancing security, protection, and integrity (accessibility) of transportation assets and systems. Recent studies in network infrastructure, have shown that the identification of the characteristics of a particular infrastructure can help understand and manage the network [1].

Moreover, in other disciplines, such as biology, communications, information technologies, and social sciences, the characterization of the network topology has provided better and more systematic ways to address issues and improvements. Although, in terms of transportation systems it is relatively easy to visualize the physical structure of the network and the various modes interacting in this network (e.g., roadways, train routes, aviation routes, etc), the interaction of the various modes among each other and how social, economic and environmental networks interact with these modes is still not fully understood. This thesis proposes a methodology for visualizing these interactions in order to determine the topology of the network and analyzing transportation infrastructure network under the rules of complex networks recently found by Barábasi [2], This topology will ultimately allow asset management decision-makers paying more attention to those nodes or links that are more critical to the system, and to make more efficient investment decisions towards a better management and preservation of the transportation systems.

Problem Statement

Transportation infrastructure systems and all its coexisting networks are essential for the society wellbeing and maintaining our quality of life. Changes in facilities or services have immediate and permanent impact on the users, society, environment and the development and productivity of the economy. Moreover, costs of building, operating, and regulating transportation networks keep rising due to increase on demand and the risks that they represent. These changes represent difficult challenges to decision-makers in charge of designing and managing the transportation infrastructures networks and facilities, who need better ways to efficiently managing the networks. This thesis proposes an innovative approach that takes the networks to its basic nature, finding out its topology with intermodal visualization, in order to apply concepts from complex network science to support the asset management decisions.

Objective

This thesis proposes a novel paradigm for modeling multimodal transportation infrastructure network in order to support consistent and cost-efficient decisions for the management of transportation assets. The incorporation of contemporary network theory, its basic concepts, and their implications for transportation infrastructure management in the decision-making process can enhance the management, preservation, protection, and expansion of the transportation infrastructure systems. The first step in accomplishing this objective was to define a methodology to model the transportation infrastructure network (TIN) and determine whether the network can be seen as a scale-free or an exponential network. Subsequently, the methodology is implemented in a case study and examples of applications for asset management are presented.

Thesis Overview

The thesis is composed by two research papers. The first paper, "Contemporary Network Theory: Concepts and Implications for Transportation Infrastructure Management" [3] presents a summary of the recent advances and findings in complex network's theory and explores how these new theories can be applied to enhance transportation infrastructure management. In particular, the work of professor Laszo Barabási and his research group [1] provide the foundation for the theoretical development of this thesis. Their insights on how intrinsic properties of complex networks play an important role in how the networks grow and react to failures or attacks are very valuable for transportation infrastructure, which currently struggles with issues such as unsatisfied demand and vulnerability. The paper proposes that understanding the topology of transportation infrastructure networks can help develop new procedures to improve the efficiency of the decisions and methods used for managing these networks. This paper was presented at the 86th Annual Meeting in Washington DC.

Subsequently, the second paper, "Methodology for Using Network Topology to Support Infrastructure Asset Management: A Case Study" presents the first steps towards the development of the methodology to enhance the transportation asset management decision-making process proposed in the first paper. This second paper answers the question of whether the transportation infrastructure is or is not a scale-free network and provides recommendations on how to use network topology to enhance transportation asset management. The proposed methodology consist of seven steps: (1) define the networks of interest; (2) identify their intrinsic components; (3) visualize the identified networks using GIS-maps; (4) identify direct and indirect interactions through superposition of the networks; (5) represent the relationship between the nodes and their linkages by frequency diagrams in order to determine the intrinsic topology of the network; (6) illustrate (graphically) the overall transportation infrastructure with the help of GIS; and (7) analyze the TINs from the decision-maker point of view, identifying the elements that are more relevant or need more attention on the network. The procedure is then implemented in a small network in a localized area (Town of Blacksburg, Virginia) to show its practicality, and recommendations for further development and mathematical modeling in order to allow its implementation in larger networks are provided.

Significance

Networks are not only a set of nodes and links connected, but also, they interact dynamically with other networks. In particular, the transportation system consists of a complex interaction of facilities, vehicles (modes), users, providers, investors and the environment. The complexity of the system makes it difficult to understand how the various components and sub-systems interact among each other, to characterize the interactions, and to identify synergies (if any). The significance of envisioning this architecture relies on the possibility of managing infrastructure networks more efficiently and improving their performance. The effects of understanding network topology on reliability, robustness and vulnerability of the system can have a tremendous impact in the success of asset management programs, improving the procedures to determine the most effective investments strategies for the transportation infrastructure network.

References

1. van der Mandele, M., *Policy Development for Infrastructure Networks: Concepts and Ideas.* Journal of Infrastructure Systems, ASCE, 2006. **12**(2): p. 69-76.
2. Barabási, A., *Linked: The New Science of Networks* 2002, Cambridge, MS: Pesseus Publishing.
3. Fonseca A.; Flintsch G.; Garving M., S.E., and Reza B, *Contemporary Network Theory: Concepts and Implications for Transportation Infrastructure Management.* 86th Annual Meeting of the Transportation Research Board **January 2006 Meeting (CD-ROM)**.

CHAPTER 2 - CONTEMPORARY NETWORK THEORY: CONCEPTS AND IMPLICATIONS FOR TRANSPORTATION INFRASTRUCTURE MANAGEMENT

Andrea Fonseca, Gerardo W. Flintsch, Michael Garvin, Elisa Sotelino and Reza Barkhi

Paper 07-3224
Presented at the 86th Annual Meeting of the Transportation Research Board

Abstract

Efficient and well-maintained infrastructure (roads, bridges, water, pipelines, etc.) systems are essential for societal stability, economic growth, sustainable competitiveness, and resilient response to natural and man-made disasters. This paper proposes a novel working paradigm for the infrastructure asset management by viewing it as a key component of a broader network of resources, which includes infrastructure linked with society's ecological, social, and economic systems. The model attempts to use the knowledge gained from studying different types of networks and their synergies and interdependencies to enhance the asset management process. The proposed paradigm requires (1) to understand the topology of the transportation infrastructure network, and (2) to find new procedures to improve the efficiency of the decisions and methods used for managing these networks.

Recent work in the area of transportation infrastructure suggests that more research is needed to determine the topology of the transportation infrastructure network in order to more accurately identify its vulnerability. Concepts such as robustness, modularity, hierarchy and imitation seem promising as mechanisms to identify procedures to make transportation networks more efficient, robust, and reliable especially when dealing with internal errors and possible attacks.

The investigation conducted suggest that understanding a transportation network's topology may help enhance the beneficial attributes and minimize the detrimental qualities of the identified topology in terms of economic, social and political costs. The incorporation of contemporary network theory, its basic concepts, and their implications for transportation infrastructure management may help enhance the management, preservation, protection, and expansion of the transportation infrastructure systems.

Introduction

Efficient and well-maintained infrastructure (roads, bridges, water, pipelines, etc.) systems are essential for societal stability, economic growth, sustainable competitiveness, and resilient response to natural and man-made disasters. Unfortunately, many existing networks do not provide the level of service that society demands since they have deteriorated due to use, misuse and environmental action or they have become obsolete due to technological or regulatory change. Moreover, recent events, such as the aftermath of Hurricane Katrina, have dramatically illustrated the vulnerability of existing infrastructure networks. This decline in the service or protection that infrastructure systems can provide represents an urgent problem and rectifying it is rather complex because existing infrastructure systems cannot simply be replaced; the monetary cost and the disruption to daily life would be astronomical. Therefore, a paradigm shift that emphasizes the intelligent management, preservation, protection, and renewal of our infrastructure is essential for our society's welfare.

Objective

The paper proposes a working paradigm for the management of infrastructure by viewing it as a key component (or node) of a broader network of resources, which includes infrastructure linked with society's ecological, social, and economic systems. It explores various types of networks and their synergies and interdependencies and investigates how these concepts can be used to enhance infrastructure asset management. The paper focuses on transportation infrastructure but the same concepts and principles could be easily extrapolated to other types of physical assets. It also emphasizes the importance and significance of efficiently managing infrastructure networks for improving quality of life, promoting economic growth, and ensuring resilience to emergencies.

Society's Networks

Society is supported by a broad network of interdependent systems: (a) physical systems such as civil infrastructure, ecological and cyber networks, (b) social systems and (c) financial systems (see Figure 1). Each of these systems affects and relies upon the others to provide society with the services that it demands.

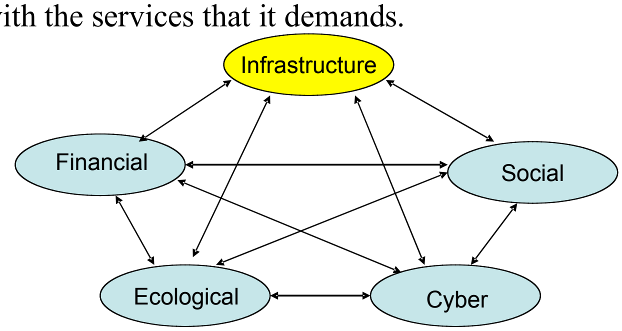


Figure 1. Network of Interdependent Systems

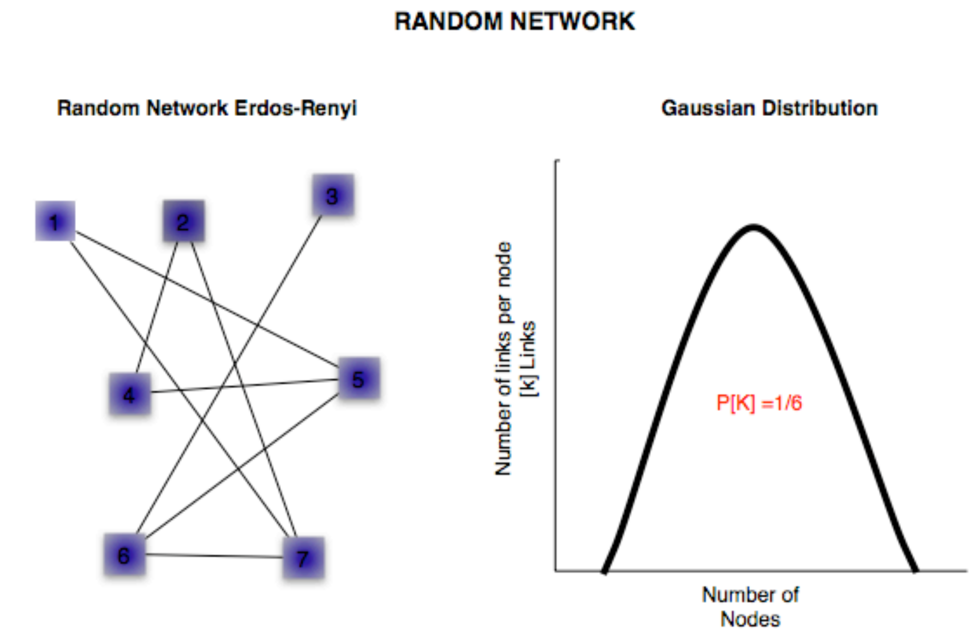
Argentinean novelist J. Luis Borges once said: "Everything touches everything", a vision that is becoming very relevant in the twenty-first century. For over four decades scientists viewed networks as a set of nodes (points or vertices) connected by links (lines or edges) that are weighted to represent the strength of the connection. However, today, networks can no longer be interpreted that way, they are more than simple nodes and links, furthermore, they are a group of agents, both nodes and links that interplay dynamically among each others, building relationships that at the end convey in strict architecture ruled by fundamental rules. Interconnectivity is behind any complex system in the universe. The discovery of complex networks has brought us into a world where everything seems to be connected. Our biology, sociology, language, economy and traditions are intermingled. The universe of networks has evolved from random to structured and from static to dynamic, uncovering shocking topological similarities between many very different systems. The science of networks has progressed remarkably in the last few decades and its mains principles and concepts are finding their way into the asset management field.

By mapping networks researchers have discovered that there are universal rules that govern the world of complex networks. The introduction of *scale-free networks* by Barabási *[1]*, has helped researchers understand many pieces of a network's structure, such as: how properties among nodes and links govern their interaction and evolution as a network and how networks have very different capacities to resist failures and attacks. The importance of these findings for the field of infrastructure management has to do precisely with network reliability, predictability and vulnerability to deterioration, failures and attacks. The asset preservation and protection resources will have a greater impact on the overall performance of the system if focused on the critical links. For example, modeling the transportation infrastructure as a scale-free network, may allow taking advantage of the intrinsic robustness of this network structure against internal errors. On the other hand, this structure also makes them more vulnerable to intentional or organized attacks.

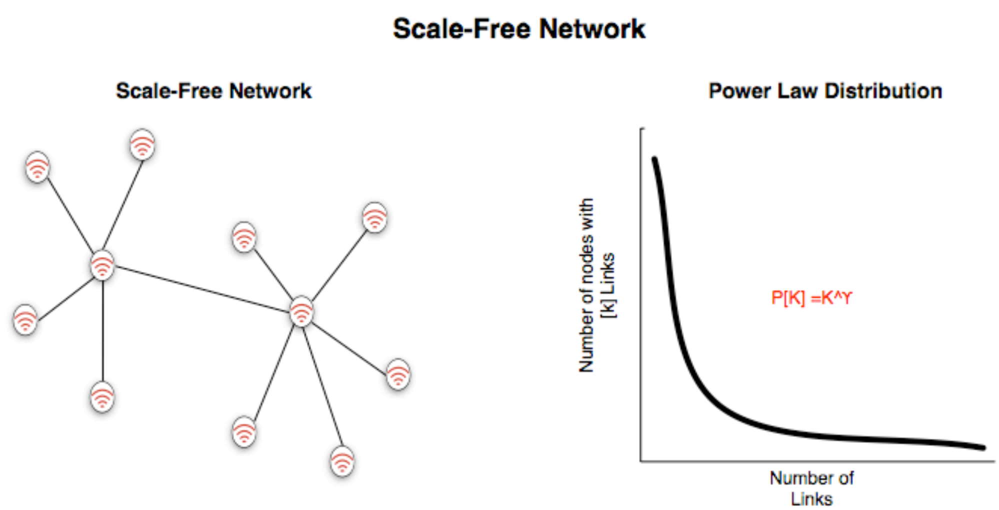
Evolution of Network Theory

In the 1960s, Erdos and Renyi, two Hungarian mathematicians, attempted to answer the question "what do networks look like?" Their assumption was laid on the grounds of the Random Universe, where basically there are a group of nodes whose possibilities to be connected with each other are random as if throwing a dice. For example, we could select two nodes and roll the dice. If the number is six, there is a link between them, otherwise, do not connect the nodes and choose a different set of nodes. The result is that in a selected network, every node has a probability of 1/6 to be connected with any other node. Each node has equal possibilities to be connected to any other one. The histogram of the relationship between the number of nodes and the number of links per node shows a Gaussian distribution, where the most nodes have an average number of links and most nodes have a number of links close to the average, as shown in Figure (a).

Important debates were created around this theory, especially by sociologists who were already studying social networks, bringing important findings such as, the *Six Degrees of Separation* of Stanley Milgram (1967) and, *The Strength of Weak Ties* of Mark Granovetter (1973) [1, 2]. These studies suggested that societal networks do not show random behavior. Similar findings had been observed in other disciplines. Researchers in many fields were discovering that networks worked differently than what Erdos-Renyi had predicted; however, there were no good models for representing the observed behaviors. In the late 1990s, Barabási *[1]* investigated complex networks, trying to determine if networks were actually random. His research group decided that instead of assuming certain behaviors within networks, they should first find the real structure of one existing network. They chose the World Wide Web (WWW); a network large enough to be considered complex, but also with somewhat easy access to its components. Considering that the nodes are the *documents* in the web, and the links are *"URL links",* they created a digital robot that surfed the web starting on one web page, collected all the URLs found there, and then, went to those and collected the other ones recursively.



(a)



(b)

Figure 2. Complex Networks' Structures: (a) Random, and (b) Scale-free

The researchers discovered that the topology of complex network was far from what Erdos-Renyi had predicted, and that the histogram of the number of nodes for each number of links followed a power law distribution instead of the Gaussian distribution discussed earlier. As seen in Figure (b) the power law distribution indicates that most nodes have very few links, and very few nodes, considered hubs, have a large number of links. The group also proved that the power law distribution[1] was behind any complex network. Different studies showed that the topology of many different complex networks follows this pattern, that few large nodes carried most of the action. Examples of complex networks include: the WWW (documents connected by URLs), the Internet (routers and domains), the cellular network (molecules connected by biochemical reactions), the air traffic system, and the surface transportation networks, among others.

<u>*Scale-free networks*</u>

One important question that remained unanswered was: how did the random universe of Erdos-Renyi miss the existence of hubs? It was found that networks are not static as the random theory had implied, but that networks are constantly growing. They begin with one or two nodes that likely will connect together, and new nodes appear in time steps and link to the existing nodes. In the example of the WWW, back in 1989 when Tim Berners-Lee invented it, it only had one document. In less than 20 years, it has grown to the size of 8 billion.

It was also found that there is nothing random in the way nodes link with each other. There is a bias behavior, ruled by the popularity of the nodes within the network. In other words, a new node will prefer to connect to the most connected node available. Therefore, the most connected node will grow faster than the less connected ones. So the mechanism for the evolution of the hub is the proverbial *rich gets richer or fit gets fitter* mechanism. The researchers found that there are two laws that govern complex networks *[1]*:

- *Growth*: every time step a new node is added to the network. In other words, networks are assembled one node at the time, and
- *Preferential Attachment*: the probability that a new node connects to an existing node is proportional to the number of links to the existing node.

The discovery of these rules provided a first attempt to explain the scale-free Network, where: "the scale-free topology is a natural consequence of the ever-expanding nature of real networks" [1]. Networks expand freely and nodes have the autonomy to choose which node to link to. It is important to understand that not all existing network systems obey the scale-free topology. The characteristics of redundant systems found by Erdós-Renyí are still considered valid for exponential networks, in which the connectivity distribution P(k) is characterized by a normal distribution. A typical behavior in the nodes is always expected in this type of networks. In other words, if a random node is selected, it can be expected that any other node will have similar characteristics. On the other hand, in scale-free networks P(k) decays following a power law, denoted by $P(k) \approx k^{-\gamma}$. No typical behavior can be seen in this type of network. As explained above, this

[1] Power Law is basically the mathematical interpretation of the 80/20 rule of Pareto. [1]

type of architecture is compounded by a few nodes with very large number of connections and many other nodes with very few connections.

Robustness and Vulnerability

One of the most important consequences of the discovery of scale–free networks is the understanding of robustness and vulnerability in interconnected systems. Réka *[3]* demonstrated that the two types of networks, random and scale-free, have very different capabilities to resist errors or failures and attacks. An error is a random malfunction that is almost unpredictable. Réka and her research group simulated the event of an error by removing random nodes from a network and measuring the changes of the average length of the shortest paths between any two nodes.

In the case of exponential networks, the researchers found that this path increased continuously as nodes were removed, and the connectivity of the network was highly compromised. Because every node is almost equally connected, they contribute in the same way to the integrity of the system. On the other hand, in scale-free networks, the shortest path remains unchanged after several nodes are removed. For instance, in the case of the internet, as many as 80% of the routers can be removed without noticing any communication problems between the remaining components. This advantage is attributed to the inhomogeneous topology of these networks that typify the robust characteristic of scale-free networks. Since the majority of the nodes have small connectivity, they also have higher probabilities of failing. In other words, very complex systems are able to maintain their basic functions even if many of their components break down.

The effect of an attack is completely different, however, because attacks do not happen randomly. They are linkage actions, thus, their targets are the most connected agents. For exponential networks, the effect is not any different than the effect of failures. Because nodes are not remarkably distinctive from each other, there is no big difference whether the nodes are removed randomly or in order of connectivity. In contrast, the hubs in scale-free network are the main targets of attacks and the shortest path between nodes increases rapidly as each hub is removed, creating an extremely high vulnerability in inhomogeneous networks under attack circumstances. In general, the findings of Réka *[3]*, suggests that the simultaneous elimination of as few as 5 to 15% of all hubs can crash the system.

Finally, another important concept in complex networks is their fragmentation. Part of the architecture of scale-free networks is formed by modules or clusters of nodes, where nodes interact between each other in a particular way. For instance, society is fragmented into clusters of individuals having similar interests. The advantage of modularity in networks is that it allows fragmentation, and one can look at a small module of a particular system and understand the relationship inherent in the entire system.

The network topology and its associated characteristics have a significant impact on the network behavior and performance. Thus, an understanding the topology of infrastructure systems management may enhance the procedures and practices used for managing these systems.

Recent Research of Networks

Flake et al. [4] studied the fragmentation of the world wide web into communities in which members have high similarities and applied this theory to optimize web filtering and search engines in general. Réka et al. [3] describes the differences between exponential and scale-free networks in responding to internal errors or organized attacks. Watts [5], deals with the influence of social networks in economics through individual agents. Such agents interact with each other, creating an aggregate level of behavior that is very different from that of the one individual. Satorras and Vázquez [6] address the dynamic regimes of the internet recalled in the interaction between its nodes. Barabási [1] models various different physical systems as networks and explains how everything is connected to everything else and what it means to business, science and everyday life.

Birk [7] demonstrates that the popular saying "build it and they will come" was true when they enhanced the quantity and quality of the bicycle network in Portland. This case study addresses the correlation between the power of context of an infrastructure network and social behavior. Lambert and Sarda [8] analyze the risk of terrorism attacks to any vulnerable nation's networks and how an emergency could be managed by allowing superposition of the infrastructure networks and having a detailed mapping and frequency analysis of the potential risks previously modeled against these networks.

Zimmermann and Eguíluz [9] describe how networks evolve in an environment where players (agents/nodes) imitate the behavior of their best neighbors. Carrasco [10] studies the role of social networks in activity-travel generation processes, how trips are biased in regard to the social behavior of the individual. Whether it is to visit friends or go shopping, it is all driven by the social status and number of acquaintances. Lin [11] presents a methodology to generalize the hub-and-spoke network design that integrates all different types of networks identified in transportation and communication industries. Van der Mandele et al. [12] seeks to demonstrate that by having a more systematic and comparative view of networks, the decision-making process in infrastructure policy development can be more efficient.

Implications of Current Theory and Research

The new science of networks has opened the window to a complete new vision of the redundant systems in the universe. We can now understand and measure the behavior of possibly any network, as long as we can visualize its topology; however, recent work in the area of transportation infrastructure suggests that a need exists for more research to determine the topology of the transportation infrastructure network (TIN) in order to more accurately identify its vulnerability against errors (deterioration and natural disasters) and attacks (premeditated). Moreover, it is necessary to determine if the TIN could be considered a scale-free network and if so, to define its components (nodes and links) and how they interact with each other.

Accordingly, our research effort is designed to first, understand the topology of the transportation infrastructure network, and then aspire to find new procedures to improve the efficiency of the decisions and methods used for managing these networks. The remainder of the paper explores the topology of TIN to determine the applicability of recent findings in complex networks to the management, preservation, protection, and expansion of the TIN. Concepts such as robustness, modularity, hierarchy and imitation seem promising as mechanisms to identify procedures to make transportation networks more efficient, robust, and reliable especially when dealing with internal errors and possible attacks.

Transportation Infrastructure Networks

The transportation infrastructure system in America is a worldwide example of high mobility and access to goods and services, considering the vast size of the territory. In general, the U.S *Transportation Infrastructure Network* is compounded by different systems, such as: streets, roads, highways, bridges, rail, navigable channels, ports, and airports. Each one of these networks is unique and has an internal structure. However, there must be links between these systems to guarantee the integrity and connectivity of the entire system or network.

The recent developments in network theory can have deep implications upon the understanding of transportation infrastructure systems. They may help with finding more efficient systematic ways to manage the transportation infrastructure. Yet, it is understandable that networks are not only a set of nodes and links connected, but also, they interact dynamically within other networks. Van der Mandele et. al. [12], provides a good review of the most relevant characteristics of infrastructure networks. First, nodes and links interact with each other in order to provide a service. In addition, generally any infrastructure network requires a large capital investment that often affects the service it is to provide. Furthermore, most networks involve many stakeholders that are directly involved with the performance of the system; these include users, operators, service providers, investors, owners, and the general public. On the other hand, all of these different systems that comprise the TIN have different types of link infrastructures (e.g., roads or airline routes) and node infrastructures (e.g., terminals or intermodal facilities). These links have great influence on travel. For instance, while public transport is regulated by the operators, auto users have the autonomy to choose their routes. The efficiency and safety of most of the networks depends greatly upon the "right" interaction between the infrastructure design and the users/modes. For example, the facilities of a train station should be in accordance with the type of trains, the number of users, the access, etc. According to van der Mandele [12], the ownership of the infrastructure also contributes to the level of efficiency of the decision-making process for optimization of the services. Conventionally, the infrastructure is owned by the government, like in the case of highways and roadways. It can also be semiprivate or privately owned, such as rail transportation.

Van der Mandele [12] suggest that the efficiency of complex systems goes further than blueprints. Policy-makers, and federal and state allocation of budgets, play an important role in the interaction between the components of transportation infrastructure network.

The paradigm proposed in this paper will provide a more systematic way to understand the interactions between, not only the components of this system, but also between it and the social, economic and environmental agents that are directly affected by the performance of the studied network.

Proposed Paradigm

Characterization

The literature on transportation infrastructure systems appears to lack a detailed description of the network topology. New complex network science has proved that, by sketching the architecture of a network, one can understand its intrinsic characteristics such as growth and connectivity relationships between entities as well as to identify the "*Achilles' heel*" that makes such a system vulnerable. therefore, topology is very important to network behavior. Barabási's [1] used the National Highway System (NHS) and the Air Traffic System (ATS) to illustrate the difference between the exponential topology, NHS, and the scale-free topology, ATS (Figure 3). However, this may not be the correct portrayal of the TIN. The answer to the question of whether the TIN could be modeled as a scale-free network, an exponential network, or as a "hybrid" that combines characteristics of both can help discover a more systematic and universal way to manage the infrastructure network more efficiently, and also, make it less vulnerable.

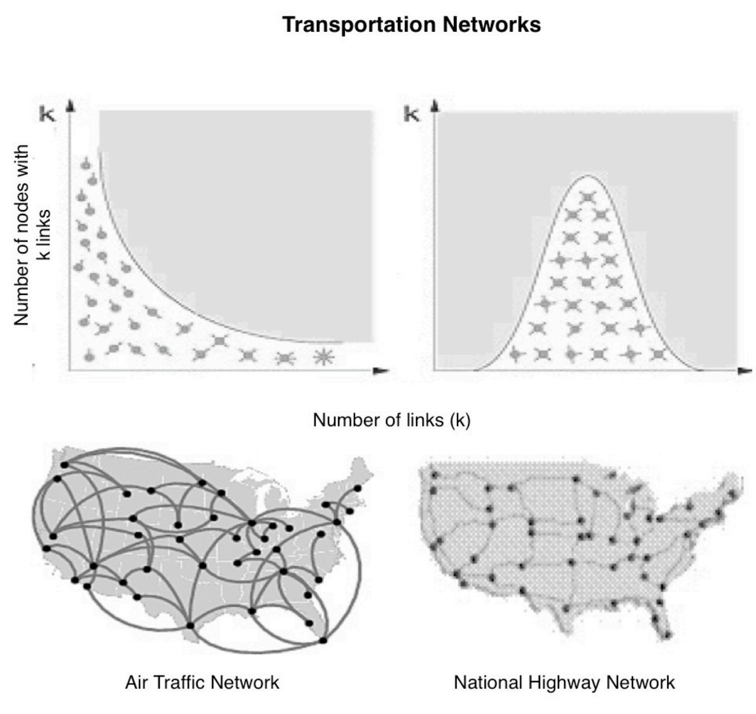


Figure 3. Random and Scale-Free Network

Analytical Framework

The asset management (AM) paradigm has gained a strong foothold within the transportation community. As a systematic, integrated approach for managing the transportation infrastructure that emphasizes service to the user or client, this form of management relies on accurate asset inventory, condition, and system performance information; considers the entire life-cycle cost of the asset; and combines engineering principles with economic methods, thus seeking economic efficiency and cost-effectiveness. In this context, AM aims to find the most effective investment strategies to maximize agency objectives as reflected in its performance measures. These strategies should consider a portfolio of investments, or work program, that balances system preservation, modernization, expansion, and protection. An understanding of the topology of the networks being managed, with its consequent effect on the reliability, robustness and vulnerability of the system, can have a significant impact in the effectiveness of AM business processes by supporting a more holistic, and informed, view of the investment possibilities for the TIN. More simply, we as researchers can try to answer the question: given the topology of the TIN, what can managers do to improve its performance?

Once the character of the localized infrastructure networks is determined, the implications of their intrinsic topology upon transportation infrastructure management have to be determined using a set of performance measures. As defined in the NCHRP Report 551 [13], "*performance measurement is a way of monitoring progress toward a result or goal, more specifically it helps to keep track and forecast the impacts within and outside the system.*" These performance measures can help to: (1) evaluate the condition of the localized networks and (2) determine the effect of their intrinsic topologies on these measures. The following are examples of categories of performance that can be used for this purpose:

- *Security:* Involves the protection of goods and users of the system from natural disasters and intentional attack. Clearly, security has become a major issue in transportation because of changes in the world's geo-political balance and increased global mobility.
- *Safety:* Measures the quality of the infrastructure facilities and services in terms of number of fatalities, crashes and injuries annually reported by the National Highway Safety Administration. In particular, safety is a concern for road users, such as drivers, pedestrians and cyclists.
- *Congestion:* Evaluates the efficiency of the transportation system to move people and goods from place to place. There are many ways to measure the level of congestion in infrastructure facilities, such as: level of service, real travel time vs. free flow travel time, and volume capacity ratios, among others. This is important to consider because congestion can be seen as a common internal error that could compromise the connectivity of the system, specifically in relationship with its topology.
- *Operations and Maintenance:* Measures how effective the system is in terms of travel costs, age and maintenance need of the infrastructure, customer satisfaction and revenues.
- *Accessibility and Mobility:* According to NCHRP Report 551 [13], accessibility should be measured in terms of the ability of a facility/mode to serve a particular user group, and mobility can be measured in terms of the travel time and travel cost of making a trip.

- *Social Impacts:* Deals with the influence of transportation on the users and their quality of life. Equity is the major issue within this category since in America 25% of the average household income is spent on transportation. Having an automobile has become almost indispensable for the average citizen; however, low-income families that cannot afford vehicles' expenses face critical disadvantages on a daily basis.

Implementation

As the research progresses, we expect to examine a variety of questions and to encounter various challenges as we attempt to determine the topology of the TIN and subsequently the implications of this topology upon its management.

One of the more interesting aspects of the TIN characterization process is the significance that defining the nodes and the links has upon the resulting topology. In the case of the world-wide web, the nodes and the links are homogeneous. Within a transportation system, this can not be applied. How to define the nodes is not categorically clear. This is primarily an issue of scale or granularity – is the node a city or an intersection or a neighborhood? Moreover, the links have a heightened significance in a transportation system since interstate highways are not necessarily compatible or seamless with county roads. More than likely, the scale and the compatibility presumed will affect the resulting topology.

Once the characterization effort is complete, the more practical issues for transportation infrastructure management may be evaluated. One of the intriguing differences between exponential and scale-free networks is their sensitivity to failures versus attacks. The exponential is better suited to withstand attacks while the scale-free is better suited against failures. Presumably, a scale-free topology would be more advantageous for the TIN since failures are more frequent and probable within it while the existence of transportation hubs would allow focused efforts to enhance security against attacks. But, perhaps a "tipping point" exists. Could we define a "hybrid" network that combines the attractive features of both?

Clearly, the differing topologies' behaviors present interesting issues for system design and management, and the real issue for infrastructure managers is how they can obtain the desired behaviors (performance) at the least cost and impact to the system, and more importantly, its users and stakeholders. In others words, given a transportation network's topology, is it feasible to enhance the beneficial attributes and to minimize the detrimental qualities of the identified topology in terms of economic, social and political costs? This and other critical questions may be answered by understanding contemporary network theory, its basic concepts and their implications for transportation infrastructure management.

Conclusion

This paper proposes a novel working paradigm for the infrastructure asset management by viewing it as a key component (or node) of a broader network of resources, which includes infrastructure linked with society's ecological, social, and economic systems.

The model takes advantage of the new science of networks and attempts to use the knowledge gained from studying different types of networks and their synergies and interdependencies to enhance the asset management process. The proposed paradigm requires (1) to understand the topology of the transportation infrastructure network, and (2) to find new procedures to improve the efficiency of the decisions and methods used for managing these networks.

Differing network topologies' behaviors present interesting issues for system planning, design and management, and the real issue for infrastructure managers is how they can obtain the desired behaviors (performance) at the least cost and impact to the system, and more importantly, its users and stakeholders. Recent work in the area of transportation infrastructure suggests that more research is needed to determine the topology of the transportation infrastructure network in order to more accurately identify its vulnerability. Concepts such as robustness, modularity, hierarchy and imitation seem promising as mechanisms to identify procedures to make transportation networks more efficient, robust, and reliable especially when dealing with internal errors and possible attacks.

The research suggest that understating a transportation network's topology may help enhance the beneficial attributes and minimize the detrimental qualities of the identified topology in terms of economic, social and political costs. Understanding contemporary network theory, its basic concepts, and their implications for transportation infrastructure management, may help enhance the management, preservation, protection, and expansion of the transportation infrastructure systems.

References

1. Barabási, A., Linked: The New Science of Networks 2002, Cambridge, MS: Pesseus Publishing.
2. Gladwell, M., The Tipping Point. 2002, New York: Back Bay Books.
3. Réka, A., Hawoong Jeong, Albert-László Barabási, Error and attack tolerance of complex networks. 2000, Department of Physics, University of Notre Dame: Notre Dame, IN. p. 14.
4. Flake, G.w., Steve Lawrence, C. Lee Giles, Efficient Identification of Web Communities. 2000, ACM Press New York, NY, USA: Proceedings of the sixth ACM SIGKDD international conference on Knowledge discovery and data mining. Boston, MS.
5. Watts, D.J., A Simple Model of Fads and Cascading Failure on Sparse Switching Networks. 2001, Jean-Benoit Zimmermann: Economics with Heterogeneous Interacting Agents. p. 13-25.
6. Satorras, R.P., Alexei Vázquez, Alessandro Vespignani, Dynamical and Correlation Properties of the Internet. APS physics, 2001. **Review Letters 87**(25): p. 4.
7. Birk, M., Roger Geller, Bridging the Gaps: How the Quality of a Connected Bikeway Network Correlates with Increasing Bicycle Use. TRB 2006 Annual Meeting, 2005: p. 26.
8. Lambert, J.H., Priya Sarde, Terrorisim Scenario Identification by Superposition of Infrastructure Networks. Journal of Infrastructure Systems, ASCE, 2005. **11**(4): p. 211-220.
9. Zimmeramann, M.G., Víctor M. Eguíluz, Cooperation, social networks, and the emergence of leadership in a prisoner's dilemma with adaptive local interactions. APS physics, 2005. **Review E** (72): p. 15.
10. Carrasco, J.A., Eric J. Miller, Exploring the Propensity to Prefom Social Activities: A Social Networks Approach. TRB 2006 Annual Meeting, 2006: p. 20.

11. Chang Lin, C., A Link-Based Approach for The Generalized Hub-and-Spoke Network Design Problem. TRB 2006 Annual Meeting, 2006: p. 24.

12. van der Mandele, M., Policy Development for Infrastructure Networks: Concepts and Ideas. Journal of Infrastructure Systems, ASCE, 2006. **12**(2): p. 69-76.

13. NCHRP, Report 551: Performance Measures and Targets for Transportation Asset Management, T.R. Board, Editor. 2006, National Cooperative Highway Research Program: Washington, DC.

CHAPTER 3 - METHODOLOGY FOR USING NETWORK TOPOLOGY TO SUPPORT INFRASTRUCTURE ASSET MANAGEMENT: A CASE STUDY

Andrea Fonseca, Gerardo W. Flintsch, Michael Garvin, and Elisa Sotelino

Abstract

This paper proposes a framework for modeling the transportation infrastructure network topology, characterizing the components of the network and the direct and indirect interactions among these components, investigating their importance as elements of a complex network, and using these data to support transportation asset management. The proposed methodology consist of seven steps: (1) define the networks of interest; (2) identify their intrinsic components; (3) visualize the identified networks using GIS-maps; (4) identify direct and indirect interactions through superposition of the networks; (5) represent the relationship between the nodes and their linkages by frequency diagrams in order to determine the intrinsic topology of the network; (6) illustrate (graphically) the overall transportation infrastructure with the help of GIS; and (7) analyze the TINs from the decision-maker point of view, identifying the elements that are more relevant or need more attention on the network.

The procedure is then implemented in a small network in a localized area (Town of Blacksburg, Virginia) to show its practicality, and recommendations for further development and mathematical modeling in order to allow its implementation in larger networks are provided. Based on frequency analysis of the nodes and their connectivity, it was concluded that the transportation infrastructure networks in the case study behave as exponential networks. The study showed that the links determine how the infrastructure network grows and that problems like congestion can be addressed by analyzing other factors related with topology, such as speed, unit size, and lane width. The proposed methodology was found to be useful as an asset management tool.

Introduction

The aging of transportation infrastructure is causing a decrement in the level of service that is provided to the users. Unfortunately, rectifying or changing the problems of the past is not an easy task since infrastructure system cannot simply be replaced. The challenge then is to learn how to manage and preserve the existing resources while incorporating technology and contemporary ideas. Fonseca et al. [1]concluded that by looking at the transportation infrastructure system as a key component of a broader network of resources and understanding their interdependencies and synergies, the asset management process can be enhanced. The first step in this process is to visualize and characterize the topology of the transportation infrastructure network.

In the last decade, the study of the properties of complex networks has been a major topic of research. Scientists have directed their interests towards defining the architecture of different complex networks. One interesting result has been that many of these networks display similar topology. In a variety of fields, many networks, from the Internet to the brain, are dominated by few number of nodes, known as hubs, which have very large connections in contrast to the rest of the nodes in the system. The discovery of these particular property led to the birth of what is called Scale-Free Networks [2].

Today, networks are defined by their topology (see Figure 1). Networks where almost every node has the same number of connections or display homogenous structures are called Random Networks. These networks consist of nodes with randomly placed connections. The study of random networks is covered by the graph theory. After characterizing a random network, it is determined that, the system will be deeply democratic: most nodes will have approximately the same number of links. Later, random networks have also been called exponential, because in terms of the degree of connectivity *'k'*, the probability that a node is liked to *'k'* other nodes decreases exponentially as *k* gets larger [2]. On the other hand, the most recent discovered scale-free topology, is everything but homogenous. The existence of few "very connected" nodes, creates a hierarchy effect in the nodes, where the importance of a node is determined by its own connections and the most vital nodes in a system will have the most connections [3].

The important factor in determining the topology of a particular network is to understand the system's behavior. Also, it is necessary to determine intrinsic properties such as, degree of connectivity and resilience. The resilience of the network is the capacity to know what would happen if one (or many) particular node is (are) removed from the system. Scale-free networks are extremely resilient. The robustness of their structures allows them to lose as many as 80% of their nodes and still remain with an intact connectivity, due to the existence of the hubs that hold the majority of the connections in the system. However, such massive presence in single location, converts it into a potential target for coordinated attacks.

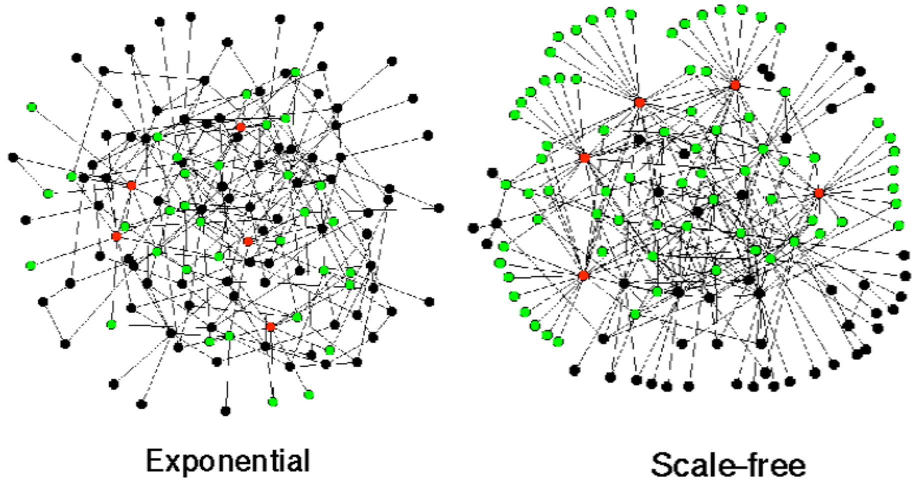


Figure 1. Exponential and scale- free networks

Vulnerability issues in large-scale systems have also been a matter of study for a long time in military logistics or complex technical systems. However, recent catastrophic events such as Hurricane Katrina in 2005 and the terrorism attacks of September 11, 2001, have encouraged researchers to investigate about the vulnerability and reliability of the transportation network. In general, the transportation network can also be seen as a complex system composed of different elements (facilities, modes, vehicles, and infrastructure) with constant interaction and interdependences between its members.

The reviewed literature suggests that: (1) a complex system can be modeled or sketched, and (2) once the topology is uncovered, not only it is possible to measure intrinsic properties is possible, but it is also easier to identify the possible targets and create strategies to confront an emergency and protect the rest of the system. Given the importance of the transportation infrastructure systems, it is relevant to characterize the topology of the system as a whole, identifying the components that interact within each network and measuring the properties that define its nature. For the purpose of asset management, for instance, the unveiling of the topology will allow decision-makers to pay more attention to those nodes or links that are more critical to the system and to develop efficient methodologies to enhance the management, preservation, protection, and expansion of the transportation infrastructure systems.

Objective

This paper attempts to be the first step in the process of finding more systematic approaches for managing the infrastructure networks by seeing them as components (nodes) of a much complex network. The paper evaluates whether the transportation infrastructure for a particular case study behaves as an exponential or a scale-free network. Based on the results, the paper presents a framework using network topology for supporting decision-makers and helping them in making consistent and cost–efficient decisions for the management of transportation assets. The next sections present key concepts of complex network science and describe the stages of the algorithm developed to identify the topology of the network and its application in a practical case study.

Definition of Key Concepts

<u>Transportation Networks</u>

Transportation networks are the spatial structure and organization of linear infrastructures and terminals [4]. The nodes are often identified as locations or facilities, they serve as access points to some sort of distribution system (links), and they are also where flows originate, end, or are transferred. The interactions between facilities (nodes) and links are very important when defining the topology of the system.

In Scale-Free Networks, Barabási [2] references transportation networks to describe the different topologies of networks. He describes the U.S. highway system as a random network, considering that the cities are the nodes and the links are the highways going through these cities. At the same time, he compares scale-free networks with the air transportation network, where, one can find nodes with very a large number of connections, known as airport hubs. These comparisons have been the motivation to attempt to determine the topology of the transportation infrastructure network as a whole and its subsequently implications upon transportation asset management.

<u>Nodes</u>

By definition, a node is a connection point, either a redistribution point or an end point for traveling data transmissions. In a complex network there are special nodes with extraordinary large number of links, defined as ***the hubs***. These hubs partly dominate the networks as they keep them together. For example, in the World Wide Web, the majority of documents are linked to global search engines, such as Google or Yahoo. The number of links and the size of the hub are fundamentally determined by the network's size, and they are responsible for the integrity and spread of data. For example, in the Internet, highly connected routers are responsible for turning viruses into a complete network breakout.

According to Barabási [5], the formation of a hub-based network could be determined by a "rich gets richer" growth rule, where new nodes would automatically prefer the most popular (bigger) node. However, Barabási also supports the theory that hub-based networks can be formed on the basis of "fitness." In this case, every node has a different value of fitness. The new nodes added to the network will preferentially attach to the nodes with higher fitness. This theory helps explain the domination of newcomers in some existing networks. For example, in the 1990's the World Wide Web was being dominated by the AltaVista search engine. A few years later the Google search engine was introduced to the web. Google had the disadvantage of being a new node added to a widely complex network with already powerful and dominating hubs. However, Google was superior (more fit) in technology and user interface. As a result, Google became a dominant hub despite being a new comer. This example also suggests that complex networks are dynamic. In this picture, AltaVista did not disappear because the superiority of Google, it only became a minor node (less fit).

The measure of the fitness of nodes in complex networks is still under research. In the case of transportation infrastructure networks (TIN), the measure is complex. With the Internet, or the World Wide Web the nodes are somewhat homogeneous, but for TIN the way to see and analyze the nodes/hubs can vary with perspectives. For example, the nodes can be intersections, destinations, neighborhoods, or facilities, depending on the degree of granularity and aggregation used for modeling the network. For the present study, nodes represent intersections in a road network or bus stops.

Links

Links can be defined as connectors of two nodes or vertices. Literature about the importance of the links in complex networks mostly focuses on the characteristics that determine their strength. For example, the strength of links has been a major topic of research in social sciences. The foundation of most common theories about link strength comes from one of the most influential contemporary sociologists, Mark Granovetter.

Granovetter's theory about the spread of information in a community is known as "The Strength of Weak Ties" [6]. This theory suggests that when it comes to finding out about new jobs, new information, or new ideas, "weak ties are always more important than strong ties." "Weak ties" refer to those personal connections or acquaintances that are outside of our personal circle of friends, which represent the "strong ties." For example, when looking for a new job, most people will refer to professors or classmates. This is because a person's closest friends' (strong ties) may be limited to the same environment in which the job seeker is already established.

Likewise, in complex networks, we can compare the weak ties of Granovetter to those links between small nodes that may seem insignificant. Because these networks have a large number of small nodes, the majority of the links will be weak. These weak links are important because they guarantee the integrity and robustness of the network. In a random event, these weak links are most likely to be targeted because they are more abundant, but the breakage of one or many may not compromise the integrity of the network. However, it will be critical for the nodes directly connected through these links, since they may be the only path between them, and when being broken, these nodes may disappear from the network.

On the other hand, the strong links are very important as well. Although they are the minority, they are the ones that guarantee the interconnection of the network. They connect the hubs and carry the most significant flows. Hence, they are also the most vulnerable links, and will be targets that truly affect the network.

In this research, we will analyze the importance of the links and nodes in the TIN since they are a fundamental part of its topology and consider them as physical assets that need to be managed, as the public demand requires.

<u>Degree of Distribution</u>

The degree of distribution (*k*) in any node of a particular network is the number of links connected to such node. Since not all nodes have the same number of links or same degree *k*, in order to characterize the spread in the nodes degree, it is suggested to use a distribution function *P(k),* equivalent to the probability that a random node has a degree *k*. In the random graph, since the majority of nodes have approximately the same number of connections, close to the average degree <k>, the degree of connectivity is described by a Poisson distribution with a peak at <k>. When the size of the network increases, complex random networks development follows an exponential distribution that has a large tail that decays exponentially, according to equation (1):

$$P(k) \approx e^{-k_i/\langle k \rangle} \qquad (1)$$

At the same time, the most recent findings in complex-network science have found that for some larger networks (e.g. the World Wide Web or the brain), the connectivity distribution tail of the graph decays with a power law showing a distribution of the type:

$$P(k) \approx k^{-\gamma} \qquad (2)$$

This discovery has led to the construction of scale-free models of networks that are more dynamic (they are allowed to grow) than static ([7], [8]).

Overall Approach

Figure 2, shows the systematic approach proposed for incorporating network topology in the transportation asset management decision-making. This algorithm is based on the "scenario identification algorithm for detecting and responding to knowledge about infrastructure risk" proposed by Lambert and Sarda [9], which has been adjusted to fit the purpose of this research. The steps of this algorithm are described as follows

- *Define the systems of interest:* The transportation networks of interest are selected from the entire infrastructure transportation systems in a selected area. The considered networks can include both physical infrastructure and transportation modal systems, such as highway system, road network, public transit, rail, and air transportation networks.
-
- *Identify the intrinsic components for each network*: This stage represents the systems as networks --in terms of its nodes and connecting links and their respective attributes. It is necessary to define each one of these elements and to characterize them by attributes that latter will be subject to analysis. The attributes or weights can be developed based on (1) usage volumes; (2) important intersections and through volumes; and (3) location of stops, transfer points and time checks.

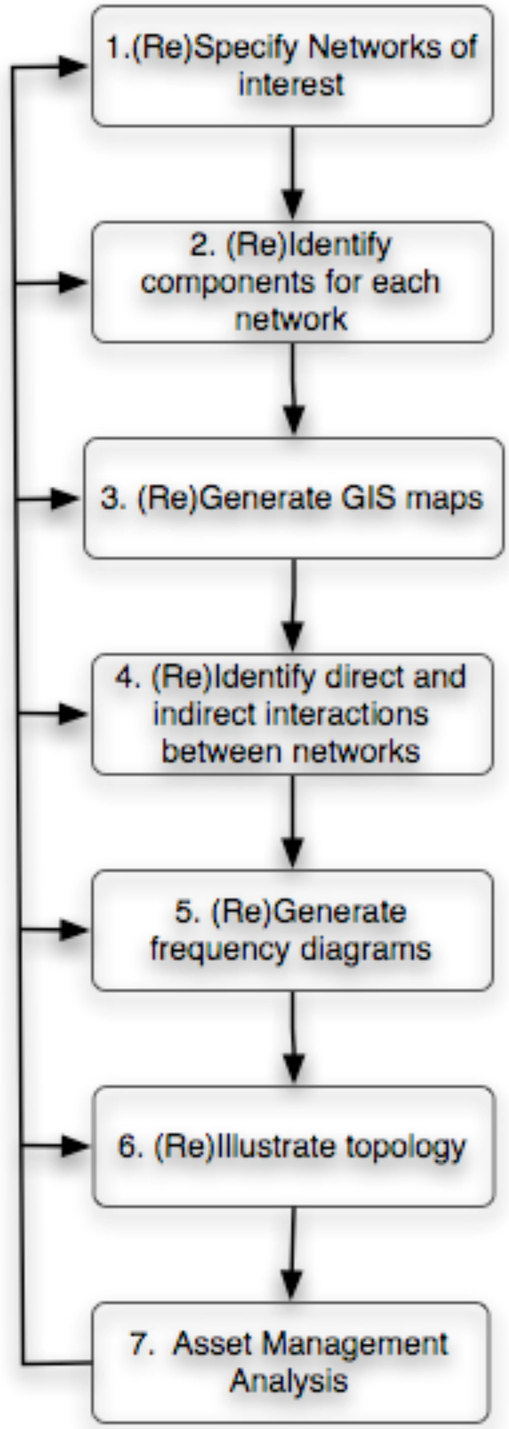


Figure 2. Scenario identification algorithm for network topology identification and decision-making.

- *Visualize the identified Networks*: This phase generates geographic information systems (GIS) maps of the networks identified in Stage 1 and their components from Stage 2. The purpose is to visualize the complexity of the network based on the attributes assigned to its components. For further research and implementation of this algorithm in transportation network analysis, the attributes assigned to links and nodes can vary depending upon the scope of the analysis.

- *Identify direct and indirect interactions:* In this step the analyst identifies system components that have direct interactions with all the systems, as well as those indirect relationships that can be seen as interdependencies between infrastructure systems and characterize the linkage across the networks [9]. The components are identified according to the following criteria: (1) component(s) which are vital to the network and therefore, more vulnerable due to the high connectivity; (2) adjacent element(s) that would be affected in case of a failure in the particular component; (3) indirect interaction(s) at the nodes where two or more networks conflict; (4) and indirect missing interactions, or points of interest in which the absence of network interdependencies contribute to lack of efficiency in the system.

- *Generate frequency diagrams:* In a simple and systematic way the analyst develops frequency diagrams or histograms of the interactions between nodes and links. The purpose of this stage is to find out the type of node linkage distribution to classify the topology of the network. The histograms are generated by plotting the count of connections (k) on the horizontal axis versus probability of any node having k connections $P(k)$ on the vertical axes.

- *Examine the topology of the network:* This step simplifies the graphical representations with the help of illustrations on GIS and diagrams of the architecture of the TIN. ArcGIS Desktop 9.0 provides the ideal interface to illustrate the characteristics of the network. For example, it is possible to not only see all the components and their interactions among each other, but also their intrinsic properties –e.g., the different weights or important spatial locations.

- *Asset Management Analysis:* The TIN is analyzed from the decision-maker point of view by identifying the elements that are more relevant or need particular attention on the network for better management. This stage will use the learned network topology to support decisions regarding the allocation of resources for preservation, renewal, and/or expansion based on their impact on specific performance measurements.

Case Study

This section presents the description of a case study for implementing the proposed algorithm. It applies the methodology and illustrates the results of implementation the proposed process using the transportation systems of the Town of Blacksburg, Virginia.

Geographic Context

The Town of Blacksburg is located in the northwest part of Montgomery County, and is close to the City of Radford and Town of Christiansburg. The population is diverse on an international level, and highly educated thanks to Virginia Tech University and Research Institute. The estimated population of Blacksburg is 40,000 residents, 60% of which are college students. An illustration of the population density distribution of the town is shown in Figure 3.

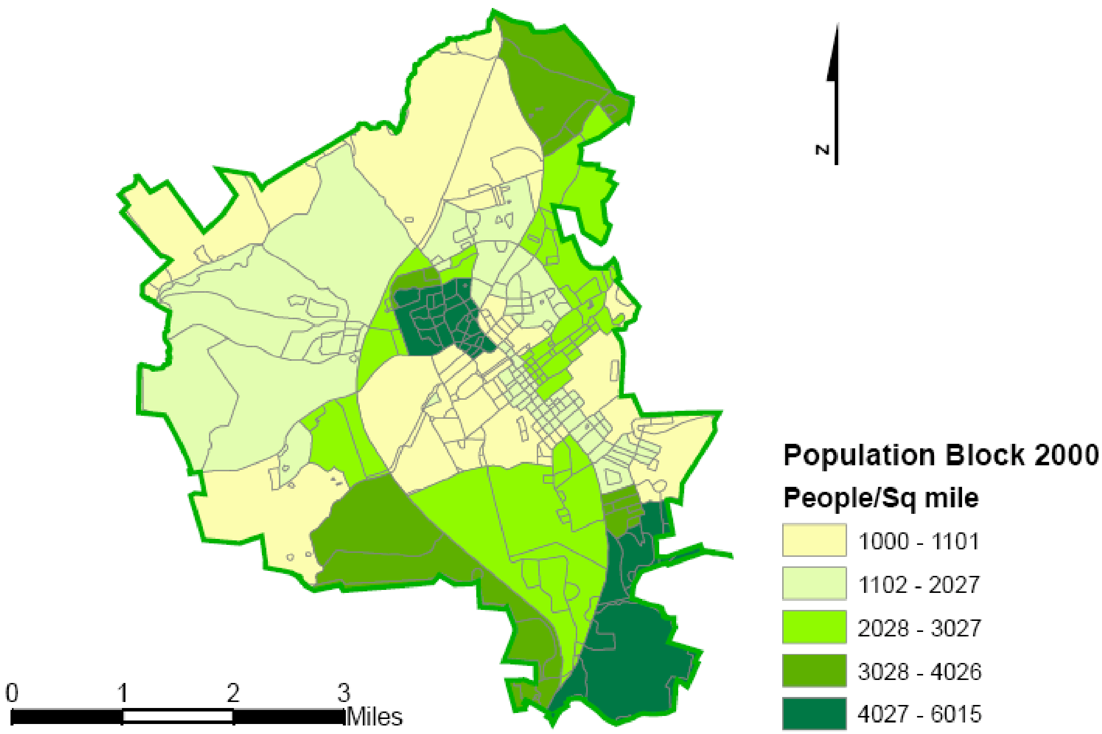


Figure 3. Population density of Blacksburg VA[2]*.*

Transportation Networks of Interest

The only major road that constitutes an economic development link in Blacksburg is U.S. Route 460. This highway crosses through Blacksburg in the north-south direction, carrying approximately 52,000 vehicles per day. It connects the town with Interstate 81 and the Town of Christiansburg, as well as, Interstate 77 in West Virginia[3] [10]. The most important transportation networks in Blacksburg are the road system, comprised of local streets, collectors and arterials, and the public transportation system. Of minor significance, the transportation system also includes bicycle/recreational paths, and public/general air transportation.

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[2] Extacted from the USA Census Bureau, Tiger Data, 2000.

[3] Statistics and demographic data for Town of Blacksburg has been taken form the Blacksburg 2046 Comprehensive Plan.

The visualization of the intrinsic transportation network topology provides a relevant cluster to set a precedent of how more complex cities the country's transportation infrastructure structure can be perceived. The transportation network is rtelatively simple, and the traffic characteristics that affect the town's daily mobility offer interesting patterns, e.g., great displacement of vehicles towards the college campus throughout the day and large commuting patterns between the New River Valley and Roanoke.

Road and Street Network

Table 1 includes the classifications of the arterials and collector streets in Blacksburg according to Virginia Department of Transportation (VDOT). Figure 4 illustrates Blacksburg's road network distribution.

Table 1. Arterial and Collector Streets Classification of Blacksburg according to VDOT

Arterial Streets				
Street	From	To	Miles	Speed (mph)
North Main Street	College Ave	US 460 Bypass	3.27	35
South Main Street	College Ave	US 460, ECL Blacksburg	3.06	35
Prices Fork Road	WCL Blacksburg	North Main St	3.03	40
Tom's Creek Road	US 460 Bypass	Prices Fork Rd.	0.95	35
Clay Street	South Main St	Allegany Street	1.36	25
Harding Avenue	Owens St.	ECL Blacksburg	0.84	25
Owens Street	Roanoke St.	Harding Ave.	0.10	25
Roanoke St.	South Main St	Owens St.	0.42	25
Patrick Henry Drive	Harding Ave.	Tom's Creek Rd	1.46	35
University City Blvd.	Prices Fork Rd.	Tom's Creek Rd	1.11	25
Progress St.	Jackson St	Cherokee Rd	1.54	25
Collectors Streets				
Street	From	To	Miles	Speed (mph)
Airport Rd.	Country Club Dr.	South Main St.	0.88	25
Country Club Dr.	Airport Rd	Palmet Dr.	0.43	25
Ellett Rd.	South Main St.	ECL Blacksburg	0.84	25
Glade Rd.	WCL Town Limit	Prices Fork Rd.	2.42	25
Suthgate Dr.	U.S.460 Bypass	Spring Rd.	0.71	25
Mount Tabor Rd.	ECL Blacksburg	North Main St	0.97	25

Public Transportation System

The mass transportation provider is Blacksburg Transit (BT) serving the communities of Blacksburg and Christiansburg, with its 44 buses and 8 routes. In general, it can be said that the BT provides a satisfactory service in the area. According to the data provided by BT's main office, the buses carried 2,482,523 customers in Fiscal Year 2006. The ridership distribution is 90% Virginia Tech Students 5% Virginia Tech faculty, and 5% other riders.

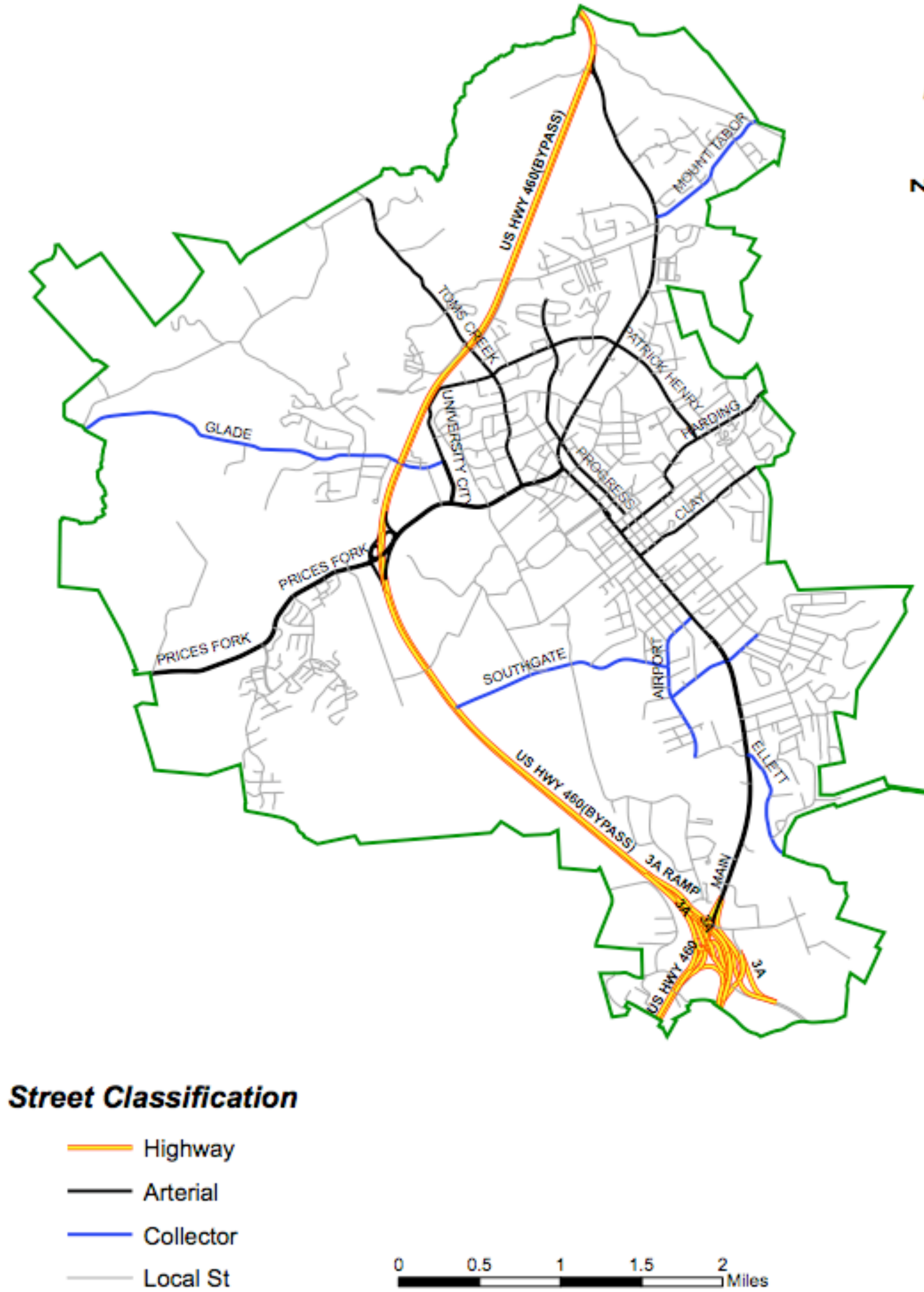


Figure 4. Street Classification - Map of Blacksburg [11]

The eight BT fixed campus routes are listed in detail as follows:

- Ramble Road: 2 buses used, 30-minute route, 30 -minute frequency. Operates year-round on weekdays only.
- Hokie Express: 2 bus used, 15- minute route, 15 minute frequency, and operates seven days a week during the fall and spring semesters only.
- Hethwood/Windsor Hills: 1 to 4 buses used, 60 -minute route, 15-minute frequency during regular operations and 60-minute frequency on weekends and break service. Operates seven days a week.
- Tom's Creek A: 1 to 4 buses used, 30-minute route, 10- to 30-minute frequency. Operates seven days a week.
- Tom's Creek B: 1 to 4 buses used, 30-minute route, 10- to 30-minute frequency. Operates seven days a week.
- Two Town Trolley: 1 bus used, 60-minute route, 60-minute frequency, operates year-round seven days a week, starting at noon.
- University Mall Shuttle: 1 to 2 buses used, 30-minute route, 15- to 30-minute frequency, and operates seven days a week during the fall and spring semesters only.
- Main Street: 1 to 2 buses, 60-minute route, 15- to 60- minute frequency, and operates seven days a week.

Tom's Creek loop (Routes A and B), carries an average of 30 to 70 passengers per hour, generating an approximation of 11.77 pass-miles per trip. These two routes consistently carry the most passengers (up to 30% of total system ridership). During summer session the system's frequency drops to hourly instead of every 15 min on the regular service. Also, on football days (every fall session) the service not only provides special and more frequent service for fans, but also at no charge.

Algorithm Application and Results

1. Define the Networks of Interest

For the purpose of this case study, the transportation infrastructure model in Blacksburg is dived into two subnetworks, the road network and the public transit network. The Blacksburg road network was used as an example of physical transportation infrastructure. This network is represented by 1166 junctions and 1469 edges. The network's data was obtained from Blacksburg GIS Website [11], this data contains the length, feature name, type (highway, arterial, collector, local road), traffic volumes[4], and speed limits for each link. The data was imported into ArcInfo GIS, in order to facilitate visualization and spatial analysis. It is important to state that links whose data were not acquired were assigned with zero traffic values, however, this does not indicate that they are not taken into consideration as part of the network. The most current data available was VDOT 2005 counts. However, not all the important intersections were accounted on the 2005 data, therefore it was necessary to project previous year's data using growth

[4] The traffic volumes are limited to those provided by VDOT data and The Town of Blacksburg Planning and Engineering. No field data was collected for this study, due to time limitations and also because the scope of the research is rather pragmatic than empirical.

factors. These factors were found using a sample of volumes from past years and comparing these values with those in the VDOT 2005 sample.

The public transit network was selected as an example of a transportation modal system that uses the road infrastructure to provide a service. The network includes 214 nodes or bus stops and 202 links out of eight bus routes. The GIS shape file's data was downloaded from Blacksburg GIS website as well, and modified for analysis purposes to include the following fields: route name, total route passengers, stops name, number of connections (possible transfers).

2. Identify the intrinsic components of each network

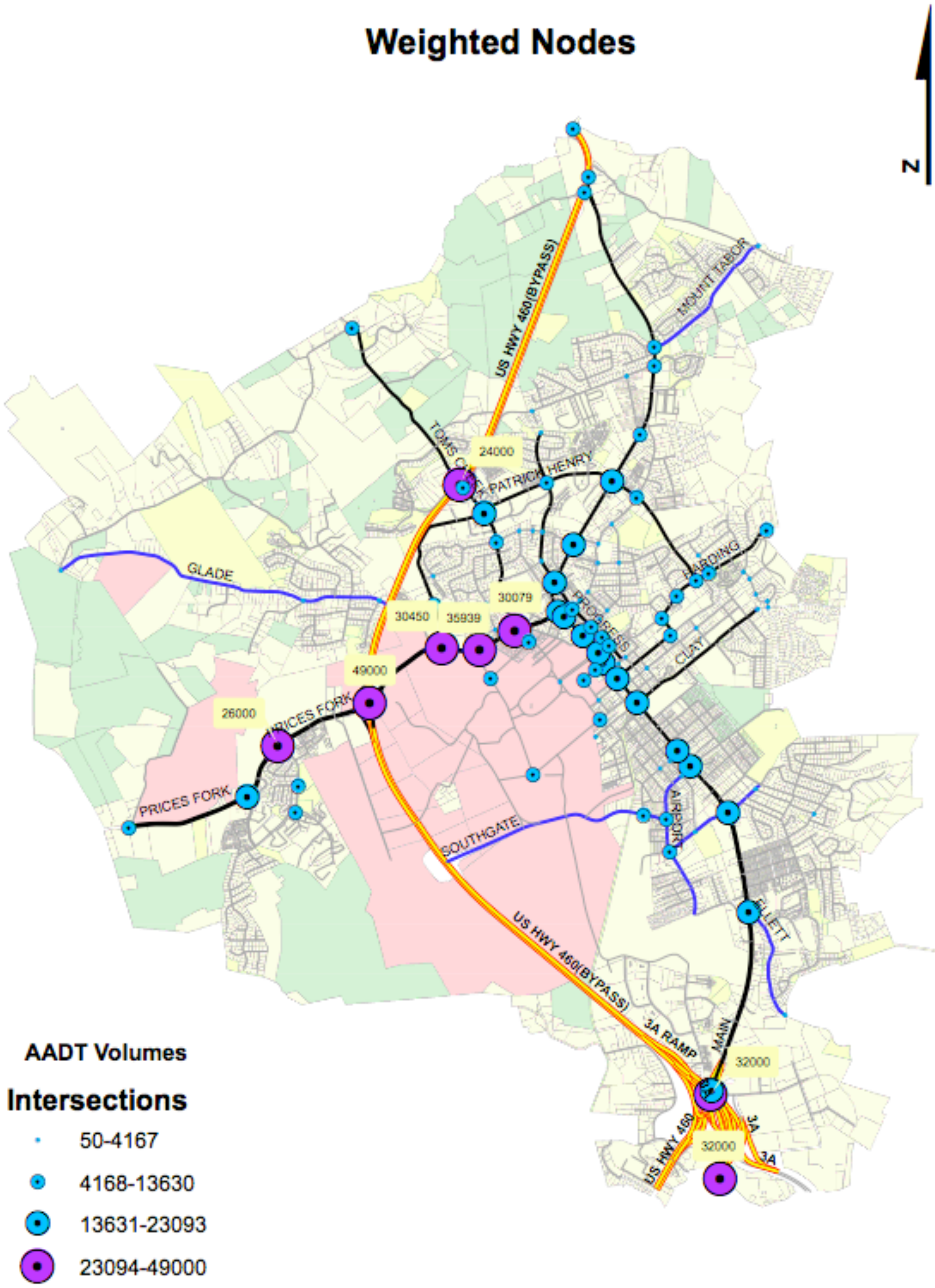
This stage identified and characterized the components of each one of the networks of interest, as summarized in Table 2. When deciding how the complexity of the infrastructure network should be characterized, the first step is to give dynamic attributes to its components such as traffic volumes and ridership, in order to allow potential growth. In addition, it necessary to indicate the components of the networks that are dynamic and those that are static, based on the attributes assign to each component. For example, the graphic representation of the road network is a grid where the majority of nodes have one to four links, however, by assigning weights to nodes (traffic volumes in this case study), we can see more dramatic differences in the connectivity of such nodes. This representation allowed showing the existence of intrinsic topology in the transportation infrastructure network based on the dynamics between its components, despite the very simple nature of the network.

Table 2. Description of the Components for the Considered TIN

Network	Structural Characteristics	Nodes	Links	Dummy Nodes	'Weak Links'	Node's Weight	Links' Weight
Road	Grid Network	Main intersections	Streets connecting two nodes	Dead Ends	Local and Residential streets	Converging AADT Volumes	Annual Average Daily Traffic Volumes
Bus	Linear Network	In lane and Off Lane Stops	Network routes	-	-	Average Daily Ridership counts at stops	Annual Average Ridership

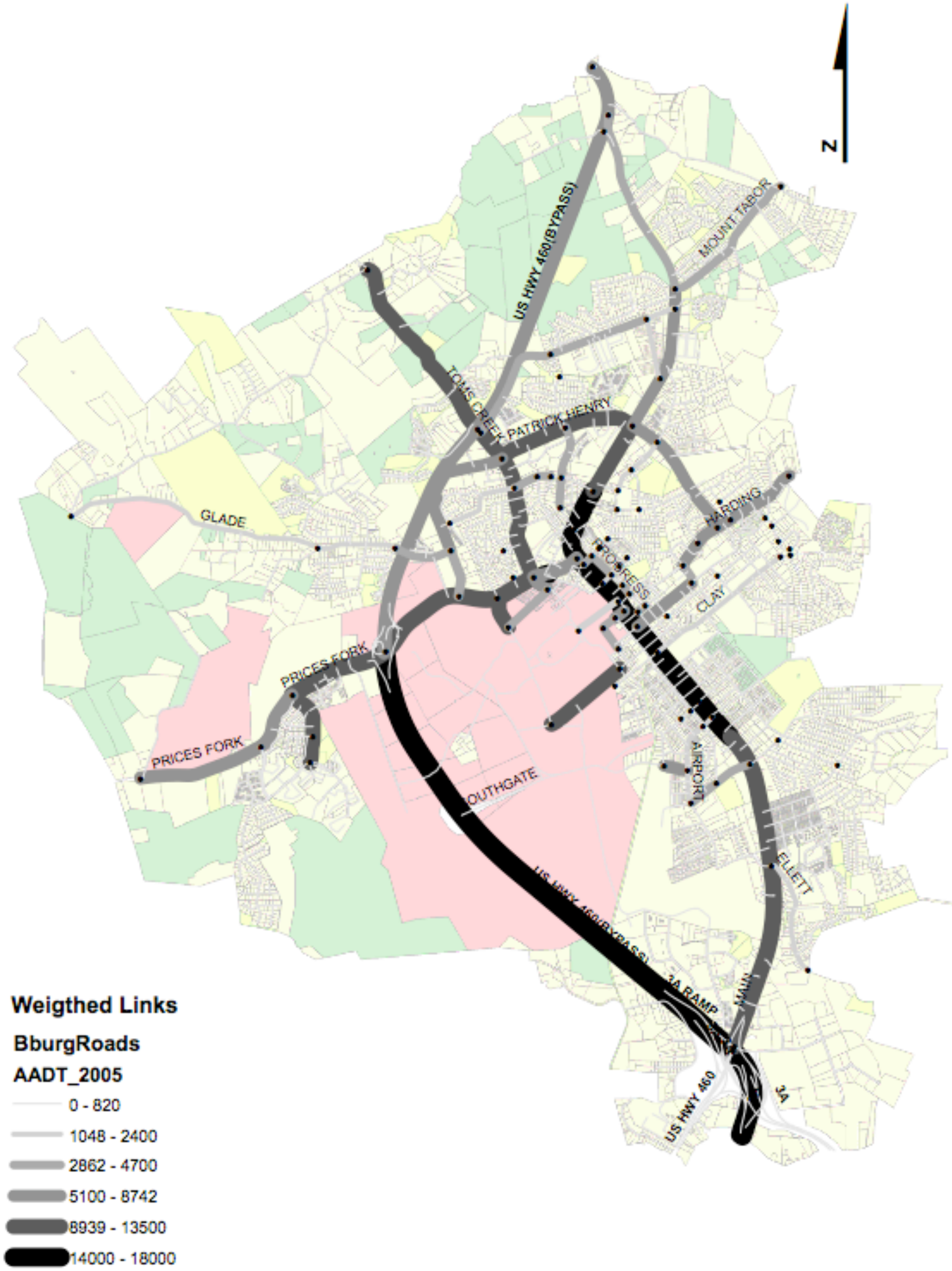
3. GIS descriptive maps

The visualization of the network components after having assigned the weight values is displayed in GIS maps for both networks of interest, road and public transit. These are presented graphically in Figures 5 (a and b) and 6, respectively.



(a) Nodes

Figure 5. Weighted components of Blacksburg road network



(b) Links

Figure 6. Weighted components of Blacksburg road network

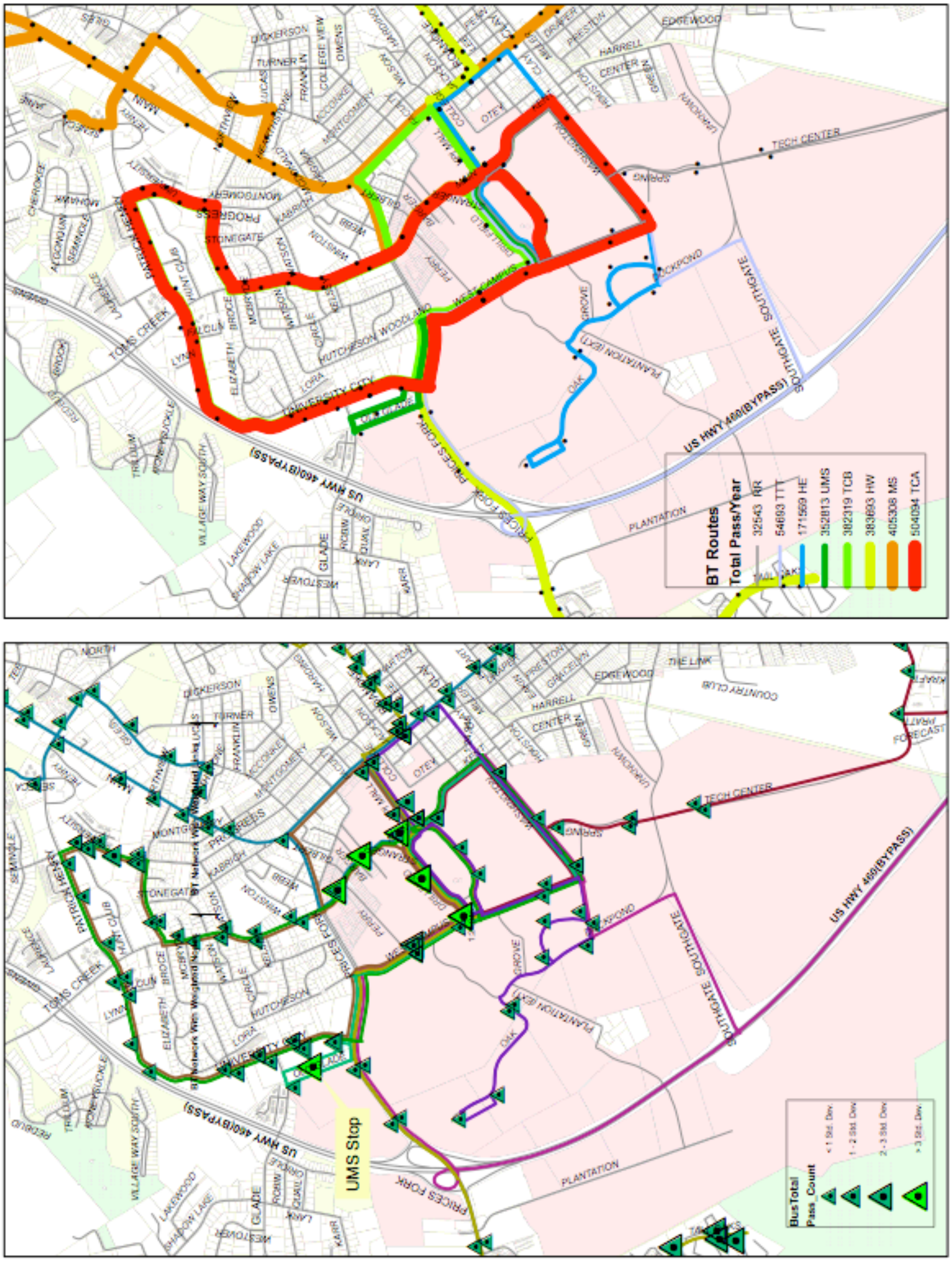


Figure 7. Weighted components of Blacksburg transit network

4. Identify direct and indirect interactions

The purpose of this step is to identify: (1) the key components of each network, and (2) the direct and indirect interactions present between the two subnetworks. First, the critical components of the road and bus networks were classified based on the standard deviation classification method of ArcGIS Desktop, where class breaks are placed above and below the mean value of the sample at intervals of 1 standard deviation. This method allows us to easily identify the elements that are distinctively above the mean and are therefore more relevant to the network integrity. Table 3 show the threshold values for the classification of the nodes.

Table 3. Threshold Values for Node Classification

Road Network		
St Dev	Volume thresholds	Feature per class
< 1	50-4167	43
1	4168-13630	34
1 - 2	13631-23093	17
> 2	23094-49000	8

Total Sample= 103
Mean= 8898 St. dev. = 9509

Bus Network		
St Dev	Ridership thresholds	Feature per class
< 1	1-162	138
1-2	163-356	6
2-3	357-549	8
> 3	550-1793	8

Sample Size= 160
Mean= 1106 St. dev. = 236

It is important to clarify that for the GIS classification of the road network's volumes, the entire road network (1116 nodes and 1469 links) was not considered. Instead, a sample based on the traffic data obtained was used for the "dynamic" network analysis. This sample was rather small with only 103 nodes, representing the most important intersections. For the purpose of this research it is more relevant to know the characteristics of the most relevant component such as, the arterials and collector streets. The remaining 1063 nodes (local and residential streets) were included in the topology map ("static" network analysis) but no traffic was assigned.

According to Table 3 the vital nodes are those whose standard deviations surpass the mean most significantly, (last row of each table). The concept of vital nodes is explained by Grubesic and Murray [3], and basically is the denotation for the most significant elements of the system and whose failure would significantly compromise the connectivity of the network. The vital nodes of the networks based on direct interactions for both networks are shown in Table 4.

Indirect interactions were identified allowing spatial superposition of the two networks on ArcGIS. First, a buffer (500-foot radius, 0.2-mile approx diameter that equals the length of a block) for each road intersection. Indirect interactions are counted as any bus-stop/intersection relationship encounter in each of the buffers (see Figure 7). A total of 40 indirect interactions were found for this study. Such locations were then replaced by a node 'S' for 'sharing points.'

Table 4. Critical Nodes for TIN

Road Network				
Id	Name (nodes)	AADT (links)	Direct interactions	
			Nodes connected (ID)	AADT (Total Links)
4	Heather Dr	26000	2, 3, 5, 6, 9	97430
9	PricesFork/460	49000	4,13,14	80450
13	Prices Fork/UCB	30450	9,12,16	95189
14	460/Tom's Creek	24000	8,9,15,17,43	134413
16	PricesFork/WestCampus	35939	13,19,22	69468
22	PricesFork/Tom's Creek	30079	16, 20, 21,24,33	73297
88	460/BUS460_South	32000	9, 69, 88, 90	119248
90	460/SCL_Bburg	32000	88, 89	51000

Transit Network		
Name (nodes)	Direct interactions	
	No. Bus lines connected	Total Pass_ Count (links)
Burruss Hall	6	1793
Torgersen Hall	2	1208
Stanger	2	1208
Old Security	2	1208
Davidson Hall	4	1495
West Campus	4	1495
University Mall	1	565

Finally, the missing indirect interactions of the infrastructure network were identified. For this case study, they correspond to those points in which the absence of bus network make the overall network somehow inefficient, because the mode split will be the result of the user’s choices made based on the alternatives provided by the network rather than by individual preferences. The results were obtained by performing a raster spatial analysis on ArcGIS, classifying a distance raster of 0.25 mi (the distance that an average individual would walk to access to the bus) for every bus stop.

The results can be seen in Figure 8, where the shaded area is the bus coverage for the town. The question mark nodes represent the road intersections from the sample that do not fall into the raster. Therefore, we conclude that those are key missing interactions. Another way to see the significance of these missing interactions is by classifying them by sector and population. Some areas such as Southwest and Midtown South have a low population density. This factor can justify the reason for not having transit service. On the contrary, it can be seen that other more populated areas such as northwest have insufficient public transit.

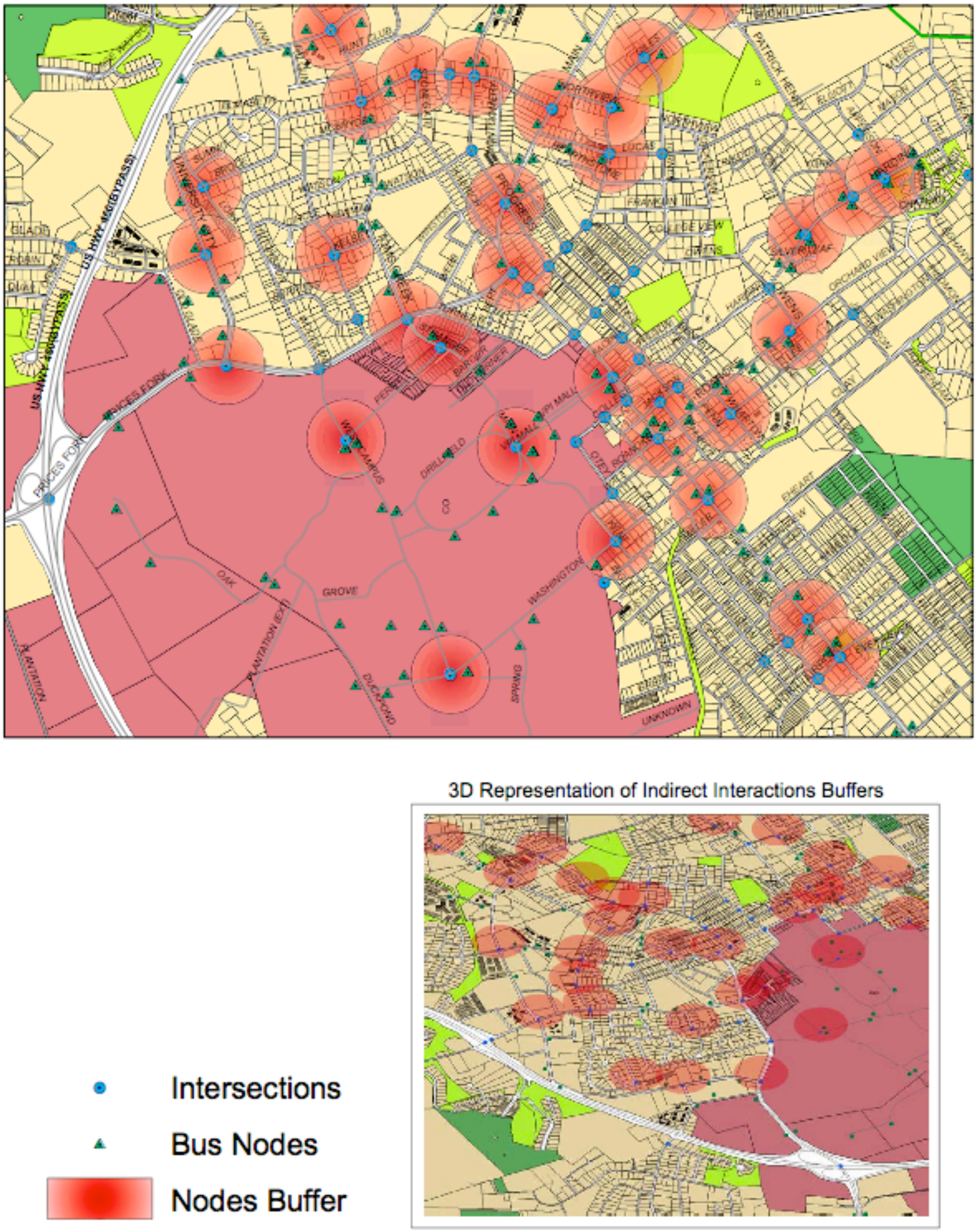


Figure 8. Allocation of buffers to identify indirect interactions between nodes

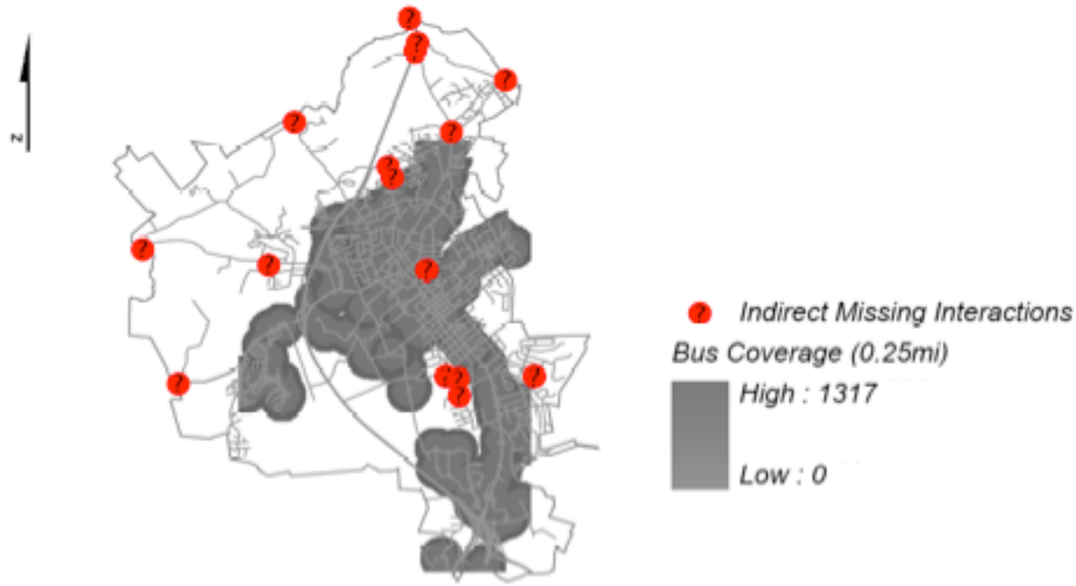
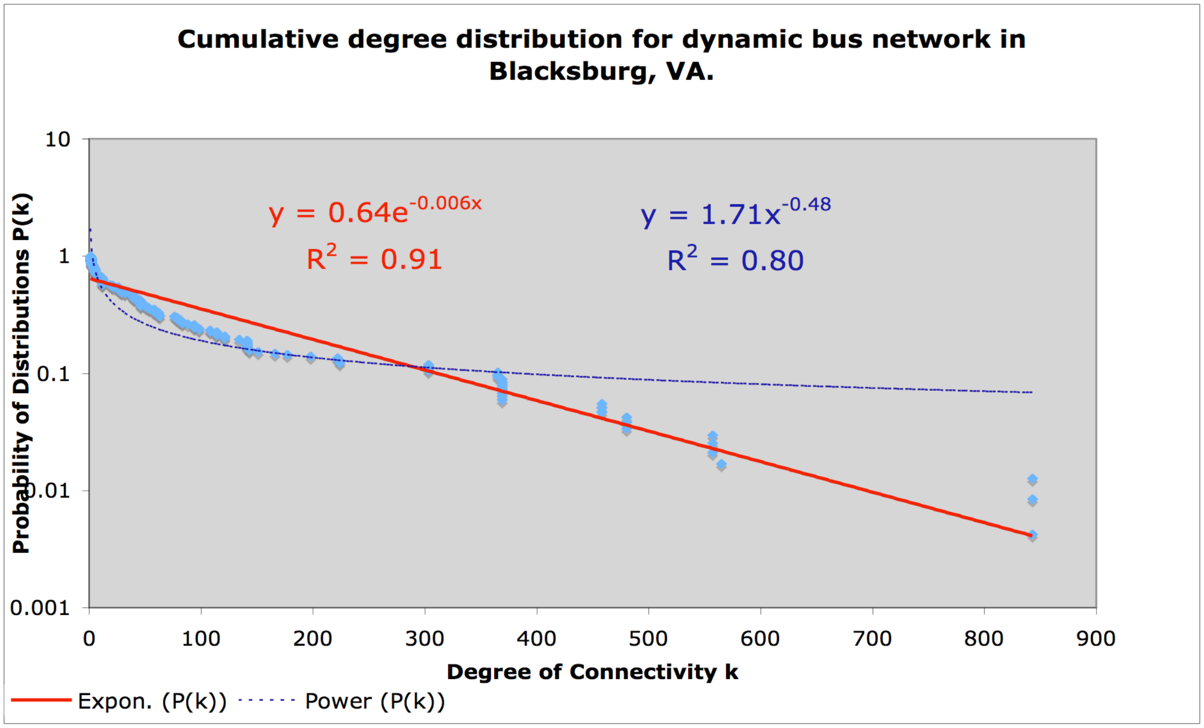


Figure 9. TIN missing interactions

5. Generate Frequency Diagrams

Up this point each element of the case study's transportation network has been characterized by giving attributes to its nodes and links and recording visually the nature of the components in a spatial environment. However, to characterize the network topology, it is imperative to find the degree of distribution *(k)* in the network, represented by a histogram of the connectivity degree of each node in the entire network and the probability of its occurrence $p(k_i)$ [7].

The cumulative frequency diagram for $p(k_i)$ were prepared for both dynamic networks. The values on the x-axis represent k_i (connectivity of node *i*), and $p(k_i)$ on the y-axis represent the percentage of nodes that have connectivity between k_i and k_{i+1} the network. The results show for the dynamic network that the distributions had a long tail of values far from the mean. Although, in most complex network this result implies the existence of a scale-free network topology, it was not the case for the TIN in Blacksburg, whose frequency distribution follows am exponential distribution. This is probably due to the physical constraints that stop the network from a scale-free growth. Figure 9, shows the best-fit power and exponential regressions (Equations (1) and (2)) for distribution of $p(k)$ in a semi-logarithmic scale. By analyzing the regression goodness-of-fit statistics, one can conclude that the distribution is closer to exponential behavior in both cases. The average degree of distribution found for the dynamic road network was 8898 vpd (vehicle per day) and 91 passengers per day, for the transit network. This indicates that the significant difference between transit users versus vehicle users reflected in the connectivity of each node makes a big impact. Probably, in other cities, where the transit service exceeds vehicle usage, e.g., New York or London, the networks are more likely to have higher connectivity values.



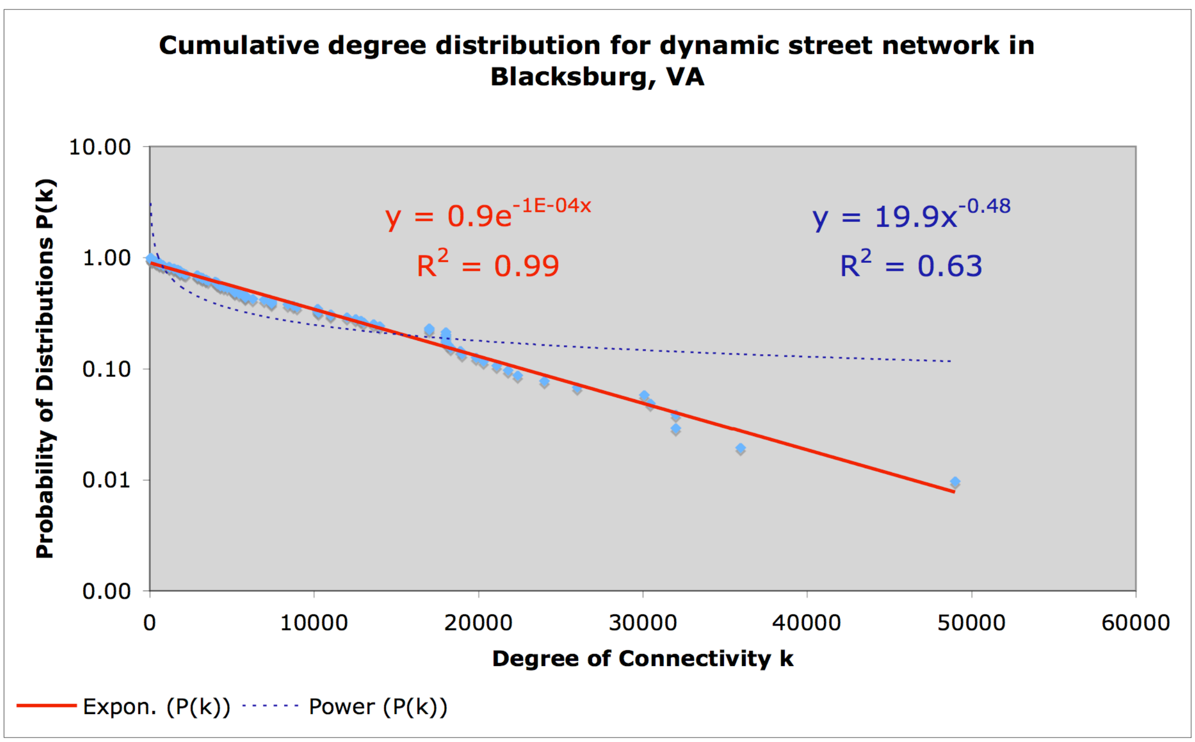


Figure 10. Cumulative degree distributions for the dynamic transit and road networks.

6. Examine the Topology of the Networks

The characteristics of the unveiling topology for the Blacksburg infrastructure transportation network lead the following observations:

- If the network is seen as static (considering the physical infrastructure), obviously the topological features show a random topology similar to the random graph theory of Erdos and Renyi. Nevertheless, by adding dynamic attributes to the nodes and links and by combining different modes of transportation, we are adding complexity to the network. Based on this premise, it is logical to think that the topology of the network could be perceived in a different way. However, the results indicate that regardless of the complexity of the attributes added to the agents, both networks in fact still behave more as an exponential network than as a scale-free network. For exponential networks, the performance is controlled by the capacity on the links. For instance, for the case of the transportation infrastructure, or at least for the road networks, it is simply not feasible to build a direct route between any two desired points.

- The two considered networks are displayed in Figure 10. The red nodes (starts) represent the locations in which indirect interactions between two modes of transportation are taking place, representing the level of intermodal connectivity of the network. For instance, it can be said for Blacksburg that the intermodal interactions is high along Main Street and really significant as well as in the main intersections along Prices Fork Road. This realization in the case of bigger and more ambiguous networks can help with the decision-making process in issues like scheduling and routing for public services. However, the fact that public transit networks share the spatial network (links) with road networks constrains this study from a more striking visualization of where other types of links can be incorporated to the scene. Nodes in green (triangles) and blue (circles) represent the vertices of transit and road networks, respectively that are not sharing indirect interactions between each other, but still are interconnected through the sharing points.

- Another repercussion of representing the topology of the network is the possibility to identify some critical points that may not show up as important as the hub-like ones, due to their apparent size. For example, this is the case for the bus stop at math emporium of the University Mall Shuttle bus route. Although this particular stop was not included in the group of critical nodes, this stop is definitely a ”high priority” node since is one of the overall heaviest routes, carrying approximately 70% of bus capacity in every trip. (approximately 55 passengers). This is an example of how it is possible to compare the attributes of the elements in relationship with its interactions in the network.

Finally, an important consequence of finding out that the sub-networks behave as exponential is the existence of intrinsic properties ruling their nature. In particular, it is possible to apply the findings of Reka et al [12], on how the exponential networks respond to failures and coordinated attacks. Some of the most interesting implications are discussed following:

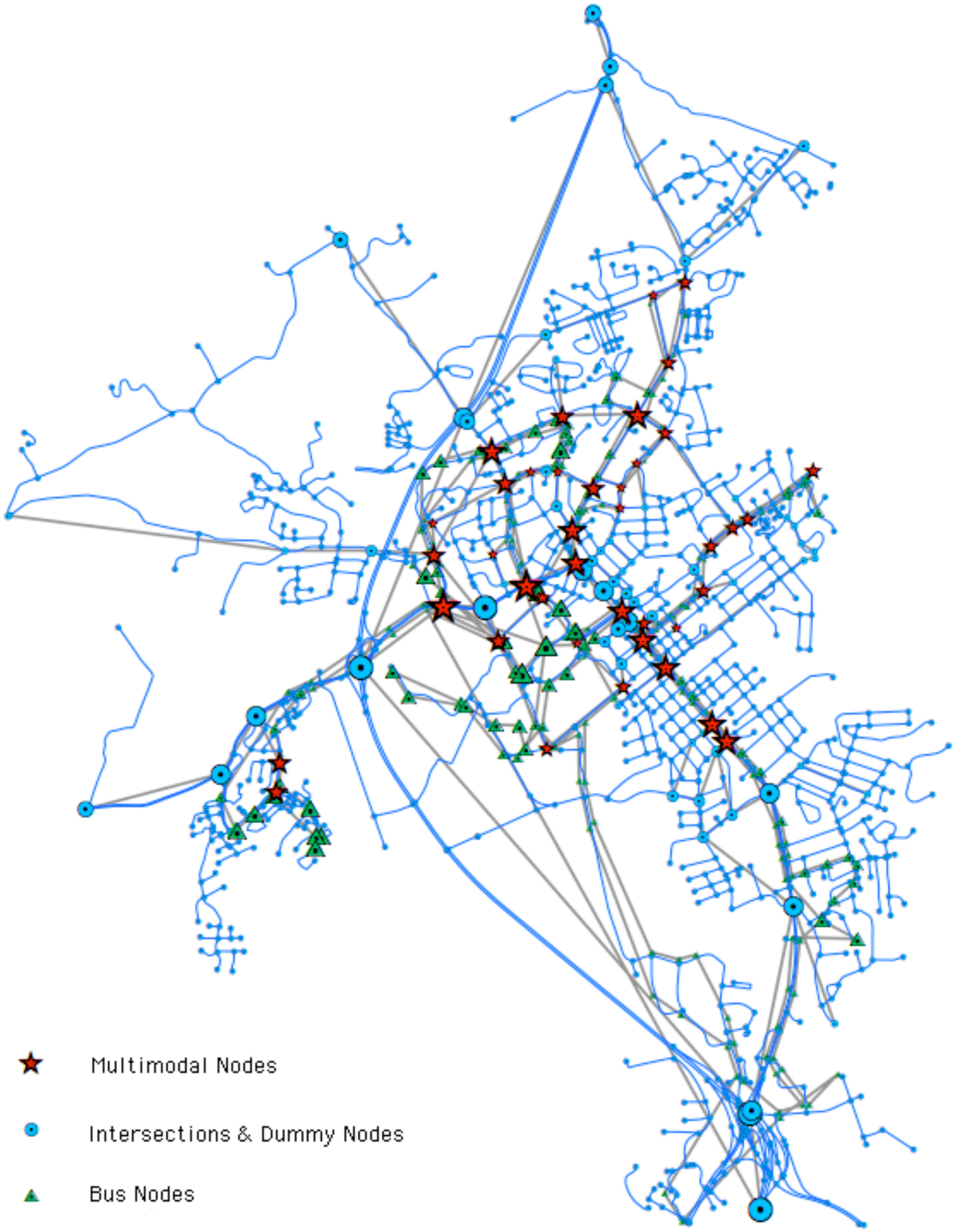


Figure 11. Topology of Blacksburg TIN Case Study

- The diameter of network *d*, defined as the average length of the shortest paths between any two nodes in the network, is directly affected when a small fraction of the nodes are removed. In the case of exponential networks, it was found that due to the homogeneity in the connectivity degrees for the nodes, the effects on the diameter are the same regardless of the importance of the nodes that were removed. The diameter increases significantly as nodes are removed, making more difficult for the remaining nodes to communicate with each other. This point suggest the fact that neglecting some elements of the infrastructure would result in discontinuities in the networks, followed by lack of accessibility and decrement on the level of service.
-
- Exponential networks have less resilience against internal error, but in contrast are much less vulnerable to coordinated attacks. This particular point can constitute and advantage to the TIN, by allowing more control over incident management and foreseen more alternatives to contingency plans.

- Despite the fact that exponential networks are not subjected to dramatic growth as the scale-free counterparts, these types of networks are also dynamic and constantly growing. The difference is that exponential networks present more restrictions to the addition of new nodes or links. In most cases these restrictions are due to external factors such as capital investment, policies, ownership, etc.

7. Asset management Analysis

The final step in the process is to demonstrate how the unveiling topology of the infrastructure network can contribute to asset management decisions and resource allocation. Following is a list of some typical challenges that decision makers usually face along with suggestions of how the topology and properties behind the network can contribute to the enhancement of this decision-making process and the system performance measures that are considered most relevant studying each case:

- **Economic Development**: *Finding the most efficient investment strategies to maximize the agency and government objectives*. The importance of presenting a graphic representation for planners and decision makers lies in the fact that nodes and links can be analyzed by their spatial location simultaneously with their significance for the network. In other words, it not only helps demonstrate how the failure of any node or link will impact the network structure and functionality, but also highlights those components that require more particular attention.

  For example, the importance of each link for the whole network is measured based on the density of volumes that it carries. It can be seen in Figure 5 that the most important links are the U.S . Route 460, and the sections of the main arterials Prices Fork Road, Main Street, and Tom's Creek Road that intersect with the highway. This is to be expected since the road is a bypass that allows higher speeds and accommodates both local and regional traffic, and the arterials are connected with the denser population zones in Blacksburg. At the same time, for transit network, the lines with more significant impact in the system are Tom's Creek A and Main Street; this fact is attributed to the high concentration of student housing along these lines.

- **Mobility**: *Evaluation of alternatives to increase capacity.* One particular advantage of integrating the topologies of different transportation networks is the opportunity to maximize its efficiency by adjusting some variables that have the most impact on the performance of the system, such as width of the links, unit size, and speed. For instance, the number of lanes in a roadway determines the capacity; thus, in order to add more capacity, more lanes could be added. However, this alternative is not always feasible due to environmental and economical constrains. In these cases, there are other options to improve overall capacity of the network [13]. For example, an option is to increase unit size by adding bus lines or car-pooling (instead of simple occupation cars). This concept of increasing the unit size has a long tradition in the transportation industry where the size of trucks, ships, and airplanes have steadily increased throughout the last half-century. The second option is to increase the speed of the network. For example, in the air transportation industry, increasing the speed of airplanes has increased capacity dramatically.

- **Safety and Security**: *To reduce vulnerability of the networks*, or in other words to maintain and improve their reliability, form the standpoint of the most common random interruptions (accidents) and/or targeted attacks. Hence, the next step is to know how the closure of a particular link will affect the network. The demand-weighted importance of the nodes (see Figure 5) is attributed to the volumes on the links that converge into the intersection at a given time. Nevertheless, if the capacity of the intersection is surpassed or an accident occurs, it creates a block on the junction. Therefore, the impact of removing a node in the TIN is equivalent to a blockage in the intersection that impedes traffic from moving. The most affected elements from this event will be the direct interaction associated with the particular nodes, as well with the links that converge to it. Special attention should be devoted to these critical points to control the safety of passenger under incidents.

- **Accessibility**: *Identify and preserve 'weaker links'*. Understanding the topology and interactions of the transportation infrastructure networks can help policy-makers realize the significance of weaker links, or streets that carry smaller volumes. In the case of a particular obstruction in a link or a node, these weaker links will allow the users of the network detour though the alternative routes available. As a result, weak links could serve as bridges to keep the network connected and functioning. Similarly, the links that cause the largest conflict on demand when closed are the ones isolated from weak links. For instance, if a disruption occurs on Route 460 between the Southgate intersection and Main Street, the link will be completely shut down until the incident clears. Whereas, if the blockage occurs along Main Street, the existence of many local roads will alleviate the congestion and help clear the road.

- **Preservation**: *Identify critical assets*. Once researchers are able to identify indirect interactions between modes, nodes can be characterized by the number of facilities interacting at the given point, and determine what type of actions are to be taken for preserving such assets, giving good repair and improving the actual conditions. For example, if a given intersection has heavy traffic, but at the same time is a major bus stop, it could be considered to improve its conditions by including pedestrian bridges or controls. Or vice versa, other vital nodes where concentration of assets already are taking place, such as airport terminals, may need special attention due to high vulnerability.

In retrospect, it could be argued that the conclusions of the case study are somehow predictable for the case of a small network, such as the one in the town of Blacksburg. However, the proposed methodology can help identify and visualize the topology of more complex networks and apply the conclusions to benefit asset management. The Town of Blacksburg was chosen as a first alternative due to the easy access to data and small size. Further research efforts are recommended to implement the proposed methodology on a larger level, possibly with the help of computer simulation and utility programs to facilitate the automatic entry and analysis of data.

Conclusions

This paper proposes a framework for modeling the TIN topology, characterizing the components of the networks and the direct and indirect interactions among these components, investigating their importance as elements of a complex network, and using these data to support transportation asset management. As a first step to validate the methodology, it was implemented on the transportation network in the Town of Blacksburg, Virginia. Based on frequency analysis of the nodes and their connectivity, it was concluded that the TINs in the case study behave as exponential networks.

The case study helped understand the main components of the transportation infrastructure network, the principles governing the network behavior, and the multiple possible interactions with other systems. The study showed that the links determine how the infrastructure network grows and that problems like congestion can be addressed by analyzing other factors related with topology, such as speed, unit size, and lane width.

For the case of the TIN in Blacksburg, the application of the proposed methodology was found to be useful as a planning tool. All the attributes of the chosen networks (road and transit) were imported into a GIS for visualization at various desired levels of detail. For example, it is possible to identify the most important nodes per demographic zone and to determine alternative routes in case of a disruption in a particular link.

In addition, the application also showed that the nodes with greater usage volume values are considered more ‘vital’ for the networks and can be assumed to have hub-like capabilities that are important to take into consideration for condition, safety, and vulnerability studies. More importantly, thanks to the visualization, it is possible to localize highly connected nodes with small link representation (e.g. University Mall Shuttle, only one route but very high percentage of volume usage).

Finally, the fact that the TINs are not scale-free is advantageous in term of assessing their vulnerability. Infrastructure networks are in general vulnerable. However, the vulnerability of exponential networks is less than that of the scale-free networks due to their inherit topology. For example, the network can be easily divided into loosely connected independent networks, which provide some degree of redundancy. In addition, understanding the importance of weak links as backup facilities can contribute to easing the consequences of breakdowns or congestion.

References

1. Fonseca A.; Flintsch G.; Garving M., S.E., and Reza B, *Contemporary Network Theory: Concepts and Implications for Transportation Infrastructure Management.* 86th Annual Meeting of the Transportation Research Board January 2006 Meeting (CD-ROM).
2. Barabási, A., *Scale-Free Networks.* Scientific American, 2003(288): p. 60-69.
3. Grubesic, T.a.M., Alan T., *Vital Nodes, Interconnected Infrastructures, and the Geographies of Network Survivability.* Annals of the Association of American Geographers, 2006. **96**(1): p. 64-83.
4. Rodrigue, J.-P.C.C.a.S.B., *The Geography of Transport Systems*. 1998, New York: Routledge. 248.
5. Barabási, A., *Linked: The New Science of Networks* 2002, Cambridge, MS: Pesseus Publishing.
6. Granovetter, M., *The Strength of Weak Ties: A Network Theory Revisted.* Sociological Theory, 1983. **1**: p. 201-233.
7. Newman, M.E.J., *The Structure and Function of Complex Networks.* Society for Industrial and Applied Mathematics, 2003. **45**(No. 2): p. 167-256.
8. Barabási, A.-L.a.R.A., *Statistical mechanics of complex networks.* Reviews of modern physics, 2002. **74**.
9. Lambert, J.H., Priya Sarde, *Terrorisim Scenario Identification by Superposition of Infrastructure Networks.* Journal of Infrastructure Systems, ASCE, 2005. **11**(4): p. 211-220.
10. Blacksburg, Blacksburg 2046 Comprehensive Plan. 2001.
11. Town of Blacksburg Maps and GIS, http://www.blacksburg.gov/maps/. [cited.
12. Réka, A., Hawoong Jeong, Albert-László Barabási, *Error and attack tolerance of complex networks*. 2000, Department of Physics, University of Notre Dame: Notre Dame, IN. p. 14.
13. van der Mandele, M., *Policy Development for Infrastructure Networks: Concepts and Ideas.* Journal of Infrastructure Systems, ASCE, 2006. **12**(2): p. 69-76.

CHAPTER 4 - FINDINGS, CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

The thesis introduced the utilization of the transportation infrastructure network topology for supporting transportation asset management, and proposed a framework for characterizing the various components of the network, their direct and indirect interactions among each other, and their importance as elements of a complex network. The practicality of the methodology was demonstrated through its implementation to the transportation network in the Town of Blacksburg, Virginia.

Findings

The thesis proposed a novel working paradigm for transportation infrastructure asset management by viewing the various networks as a key components (or nodes) of a broader network of resources, which includes infrastructure links with society's ecological, social, and economic systems. The proposed paradigm requires: (1) to understand the topology of the transportation infrastructure network, and (2) to find new procedures to use the gained knowledge to improve the efficiency of the decisions and methods used for managing these networks. This thesis focused on developing a framework to answer the first question and providing some examples of how it can be used for supporting the asset management decision process. The most relevant findings for the research effort are listed following:

- Differing network topologies' behaviors present interesting issues for system design and management, and could help infrastructure managers reach desired behaviors (performance) at the least cost and impact to the system, and more importantly, its users and stakeholders. Concepts such as robustness, modularity, hierarchy and imitation seem promising as mechanisms to identify procedures to make transportation networks more efficient, robust, and reliable, especially when dealing with internal errors and possible attacks.

- The literature review suggested that understating a transportation network's topology can help maximize the beneficial attributes and minimize the detrimental impacts of the identified topology in terms of economic, social and political costs and effects. Understanding contemporary network theory, its basic concepts, and their implications for transportation infrastructure management, can enhance the management, preservation, protection, and expansion of transportation infrastructure systems.

- The implementation of the proposed paradigm in a simple case study helped understand the characteristics of the various components of the infrastructure networks, in order to get a better knowledge of the organized principles governing the behavior of the network and the possible multiple interactions with other systems. A frequency analysis of the nodes and connectivity degree for the street and transit networks in the Town of Blacksburg showed that both transportation infrastructure networks behave as exponential networks.

- The fact that the TINs are not scale-free is advantageous in term of assessing their vulnerability. Infrastructure networks are in general vulnerable. However, the vulnerability of exponential networks is less than that of the scale-free networks due to their inherit topology. For example, the network can be easily divided into loosely connected independent networks, which provide some degree of redundancy. In addition, understanding the importance of weak links as backup facilities can contribute to easing the consequences of breakdowns or congestion.

Conclusions

This thesis utilized complex network theory to propose a novel working paradigm to determine and visualize the topology of transportation infrastructure network as a key component (node) of a broader network of resources, including, society, environment and finances. By analyzing the intrinsic topology of a particular transportation network, it has been possible to suggest more systematic ways to improve the performance of the system, starting by emphasizing the importance of the links and nodes of the network in accordance with their dynamic attributes. This research proposes a method to determine the topology of the transportation infrastructure network. The structure of the methodology build on the framework proposed in a previous study of risk scenario identification by superposition of infrastructure networks [1].

The practicality of the methodology was demonstrated through its implementation on the transportation network in the Town of Blacksburg, Virginia. The analysis indicated that the TIN behave as exponential networks; this was expected because the considered TINs are constrained from uncontrolled growth (scale-free type) even when the nodes and links are dynamically weighted. Although the results of the case study are somewhat predictable for the relatively small Blacksburg transportation infrastructure network, they illustrate the type of benefits that can be obtained by incorporating network topology for managing larger and more complex transportation infrastructure networks.

Recommendations for Future Research

This thesis provides a first attempt to develop a methodology for incorporating network topology in the management of transportation infrastructure systems. The following paragraphs suggest some research questions that may help continue enhancing this field.

- *Can the TIN be modeled as a key component of a broader network?* This thesis suggests that the transportation infrastructure can be seen as a node of a broader network of resources, including the environment, economy and society systems. This research has first attempted to visualize the topology of a localized transportation infrastructure network based on weighted values assigned to its components. However, the analysis of how the physical infrastructure interacts with the other networks and systems could provide additional insight and understanding of the complex interaction and synergies among the various systems.

- *Can the proposed methodology be practically implemented on a bigger network?* The seven-step methodology introduced in this thesis could be implemented in a semi-manual way for a small network such as the one in the Town of Blacksburg. However, it would probably need to be incorporated into a mathematical simulation model to improve the input and processing of information if it were to be used in larger network, e.g., a large metropolitan area. This would also allow to add other modes. For instance, other transportation networks such as air transportation or rail are more likely to represent a more complex behavior. The challenge though, will be to incorporate those in further studies and examine the changes among nodes and links interactions.

- *How to practically apply network topology for supporting asset management decisions?* This thesis only provides some simple examples on how this can be done. In further research, it may be worthwhile to apply these recommendations, followed by conducting the respective performance measurements and determining if the challenges were overcome. For example, the traditional approach to handle congestion is to increase the network capacity by increasing the number of lanes. However, this approach not only requires large capital investments but also, impacts the environment and society very significantly, and ultimately, it does not solve the problem because simply more vehicles will end up occupying the road (the traditional *'build it, they will come'* effect). Therefore, it may be more effective to focus on increasing the capacity of the links, which are designed to hold specific number of units traveling a certain speed. If new technologies and research were dedicated to find better ways to control the traffic up to the link's capacity, not only the network could run more efficiently, but also, it would be easier to schedule programs for rehabilitation and maintenance of the assets.

- *Which are the adequate weight measurements to characterize the TIN?* For many complex networks researchers, it is clear that this science is still in its first phase. We are just beginning to understand some of the rules governing the behavior of the complex networks. A true understanding of these rules is necessary to start answering more practical questions about behavior, vulnerability, growth and optimization. In the case study developed in this thesis, for instance, assumptions were necessary for assigning volume weights to the nodes and links. Likewise, assumptions are made in social networks, where, it is common to assign a value to each acquaintance indicating how well two individuals know each other [2]. However, there are many significant ways in which a transportation network can be weighted and there are related with the performance measures used to evaluate the network, e.g., travel time from origin to destinations, congestion, and accident rate. Therefore, it would be worthwhile to develop mechanisms to determine the adequate weights for the TIN and to what degree they affect the network topology.

- *Is redundancy important and if so, how can it be achieved more efficiently?* In this thesis we have seen how some network properties, such as degree distributions, affects the behavior of the network. However, there are some other concepts yet to be developed and studied within transportation networks, such as, redundancy, hierarchy and fragmentation. Clearly, these properties will affect the behavior of TIN substantially. In a recent study, Waters [3] presented an important insight about redundancy that is worth mentioning. In networks like the Internet, redundancy plays a crucial role in it intrinsic behavior and unveiling properties. Since it was designed to allow messages and information sent over the network to be rerouted when necessary because servers are busy, the creation of redundant paths is an everyday task to maintain the efficiency of the system. In contrasts, the lack of redundancy in transportation network may contribute to make it inefficient. The redundancy in TINs could be achieved through multimodal facilities, or by using the exiting infrastructure to carry more passengers. The monetary, environmental and society costs of building infrastructure, often make unfeasible for example to have two parallel highways connecting the same points (although this theory may be refuted by those who consider that adding one more lane creates link redundancy). However, the interconnection of modes actually improves the efficiency of the networks, and the capacity on the links can be increased by increasing the vehicle size (cheaper) as opposed to increase the link size (expansive and damaging).

References

1. Lambert, J.H., Priya Sarde, *Terrorisim Scenario Identification by Superposition of Infrastructure Networks.* Journal of Infrastructure Systems, ASCE, 2005. **11**(4): p. 211-220.
2. Barabási and Réka, A., *Statistical mechanics of complex networks.* Reviews of modern physics, 2002. **74**.
3. Waters, N., *Network and nodal indices: measures of complexity and redundancy: a review.* Presented at the Regional Science Association International (RSAI) World Conference 2004.

APPENDICES

Appendix A: Traffic Volumes Annual Average Traffic Volume Estimates by Section of Route, VDOT 2005

Source	Route Prefix	Route Number	Route Label	Route Alias	Link Length	Start Label	End Label	AADT	AADT 2005
VDOT 2005	SR	00412	VA 412	Prices Fork Rd	1.07	US 460	Toms Creek Rd	27000	27000
					0.28	Toms Creek Rd	Main St	17000	17000
VDOT 2005	US	00460	US 460	US 460	0.40	NCL Blacksburg	Bus US 460	12000	12000
					3.30	Bus US 460	SR 412 Prices Fork Rd	13000	13000
					2.97	SR 412 Prices Fork Rd	Bus US 460	32000	32000
					0.72	BUS US 460	SCL Blacksburg	32000	32000
VDOT 2005	C8US	00460	Bus US 460	Main St	1.01	US 460	Mount Tabor Rd	4200	4200
					0.87	Mount Tabor Rd	Patrick Henry Dr	7400	7400
					0.44	Patrick Henry Dr	Broce Dr	12000	12000
					0.26	Broce Dr	Progress St	14000	14000
					0.17	Progress St	Prices Fork Rd	17000	17000
					0.53	Prices Fork Rd	Roanoke St	18000	18000
					0.19	Roanoke St	Clay St	16000	16000
					0.53	Clay St	Upland Rd	18000	18000
					1.00	Upland Rd	Ellet Rd	18000	18000
					1.33	Ellet Rd	US 460, ECL Blacksburg	19000	19000
VDOT 2005	150	00002	150-2	University City Blvd	1.11	Prices Fork Rd	Toms Creek Rd	7900	7900
VDOT 2005	150	03150	150-3150	Country Club Dr	0.23	Southgate Dr	Country Club Dr	450	450
VDOT 2005	150	03150	150-3150	Country Club Dr	0.40	Airport Rd	Main St	3800	3800
VDOT 2005	150	03151	150-3151	Ellett Rd	0.71	SCL Blacksburg	S Main St	2100	2100

Source	Route Prefix	Route Number	Route Label	Route Alias	Link Length	Start Label	End Label	AADT	AADT 2005
VDOT 2005	150	03152	150-3152	Prices Fork Rd	0.75	WCL Blacksburg	Hethwood Blvd	11000	11000
					0.36	Hethwood Blvd	Heather Dr	17000	17000
					0.58	Heather Dr	US 460	26000	26000
VDOT 2005	150	03153	150-3153	Airport Rd	0.37	Southgate Dr	Main Street	2300	2300
VDOT 2005	150	03154	150-3154	Glade Rd	1.55	WCL Blacksburg	Boxwood Dr	1200	1200
					0.46	Boxwood Dr	Oriole Dr	2400	2400
					0.33	Oriole Dr	University City Blvd	4700	4700
VDOT 2005	150	03156	150-3156	Roanoke St	0.49	Main St	Owen St	5700	5700
VDOT 2005	150	03156	150-3156	Owen St	0.11	Roanoke St	Harding Ave	4500	4500
VDOT 2005	150	03156	150-3156	Harding Ave	0.11	Owen St	Cork Dr	5600	5600
					0.66	Cork Dr	ECL Blacksburg	5100	5100
VDOT 2005	150	03159	150-3159	Tom's Creek Rd	0.96	Prices Fork Rd	US 460 Bypass	11000	11000
VDOT 2005	150	03164	150-3164	Mt Tabor Rd	0.92	US 460	NCL Blacksburg	3100	3100
VDOT 2005	150	03165	150-3165	E Clay St	0.61	C8US 460	Dead End Gap Terminus	1800	1800
VDOT 2005	150	03165	150-3165	Patrick Henry Drive	0.79	Roanoke St	C8US 460	5900	5900
					0.83	C8US 460	Toms Creek Rd	11000	11000
VDOT 2005	150	00000	150-0	Apperson Drive		Mason Drive	Harding Avenue	190	190
VDOT 2005	150	00000	150-0	Draper Rd		Country Club Dr	Airport Rd	570	570
VDOT 2005	150	00000	150-0	Edgewood Lane		Preston Ave	S Draper Rd	290	290
VDOT 2005	150	00000	150-0	Hillcrest Dr		Country Club Dr	Sunrise Dr	100	100
VDOT 2005	150	00000	150-0	Jackson Street		Church St	Penn St	4100	4100
VDOT 2005	150	00000	150-0	Lucas Drive		Giles Road	Turner Street	380	380
VDOT 2005	150	00000	150-0	McBride Dr		Kelsey Dr	Burrus Dr	590	590

Source	Route Prefix	Route Number	Route Label	Route Alias	Link Length	Start Label	End Label	AADT	AADT 2005
VDOT 2005	150	00000	150-0	Progress St		Broce Dr	Watson Ave	3400	3400
TOB 2003						Faculty St	Wilson St	3342	4291
TOB 2004						Patrick Henry Dr	Broce Dr	2932	2873
TOB 2003						Turner St.	Giles Rd	3410	4378
TOB 2004						Patrick Henry Dr	Cherokee	780	764
TOB 2003	150	00000	150-0	Fincastle Dr.		Kam Dr	Ridgeview Dr	551	590
						East Roanoke	Kam Dr	307	329
TOB 2003	150	00000	150-0	Floyd St		Ridgeview Dr	Northbound	193	207
TOB 2003	150	00000	150-0	Giles Rd		Northview St	McCorney St.	623	800
						Turner St	Northview St	1320	1695
						Turner St	Patrick Henrry St.	816	1048
						Progress st	Montgomery St	1701	2184
						Main St	Progress St	2229	2862
						Montgomery St	McCorney St.	1282	1647
VDOT 2001	150	00000	150-0	Lucas Dr.		Giles Rd	Turner st	423	403
TOB 2002	150	00000	150-0	Turner St		Main St	Montgomery St	1324	1417
TOB 2003						Montgomery St	McConkey St	1358	1453
TOB 2003	150	00000	150-0	Clay St		Main St	Dead End West Main St	757	810
TOB 2002	150	00000	150-0	College Av		Otey/ St	Draper Rd.	4213	4508
						Draper Rd	Main St.	8170	8742
VDOT 2001	150	00000	150-0	Otey St		College Av	Wall St.	4171	3972
TOB 2001	150	00000	150-0	Lee St		Wharton St.	Jefferson St	861	820
VDOT 2001	150	00000	150-0	Heather Dr.		Tall Oaks Dr.	Plymouth St.	10727	10215
TOB 2003	150	00000	150-0	Broce Dr.		Tom's Creek Rd	Lora St.	1892	2024
						Stonegate	Scott Alan	2987	3196
TOB 2001	150	03159	150-3159	Tom's Creek Rd		Meadowbrook	Prices Fork	14808	11000
TOB 2002	150	00000	150-0	Southgate Dr.		Airport Rd	Edgewood	5839	6248
TOB 2003	150	00000	150-0	Whipple Dr		Givens Ln	Main St.	1361	1759
TOB 2003	150	00000	150-0	Givens Ln		Tom's Creek	Winslow St	2356	3025
						Winslow St	Whipple Dr.	2268	2912
						Whipple Dr	Main St.	889	1141

Source	Route Prefix	Route Number	Route Label	Route Alias	Link Length	Start Label	End Label	AADT	AADT 2005
VDOT 2001	150	00000	150-0	Perry St		West Campus Dr	Stanger St	4839	4608
VDOT 2001	150	00000	150-0	Stanger St		Perry St	Prices Fork Rd	5416	5158
VDOT 2001	150	00000	150-0	VIP Alumni Mall		Main St	Drillfield	1234	1175
VDOT 2001	150	00000	150-0	Washington St.		West Campus Dr	Kent Dr	10678	10169
VDOT 2001	150	00000	150-0	West Campus Dr.		Prices Fork Rd	Perry St	9387	8939

Appendix B: Total Ride Passengers for Blacksburg Transit

	Fall	Football	Spring	Summer	Break	Year
Main	202460	7824	170608	28211	13540	422643
Hwd/WH	191364	7306	171335	23526	11023	404554
TCA	237209	11958	204476	43113	20208	516964
TCB	216457	8301	183214			407972
UMS	198834	2003	140263	8942	3660	353702
TTTBB	23973	1547	17316	7002	4923	54761
TTTCB	2785	167	2877	1906	1362	9097
Hokie Exp	85465	1965	82255	3110		172795
Ramble	13389	176	12818	4300	1861	32544
Service	1171936	41247	985162	120110	56577	

Appendix C: Blacksburg Road Network with dynamic nodes

Id	Node Name	No. Links AADT	Id	Node Name	No. Links AADT	Id	Node Name	No. Links AADT
1	Glade/WCL_Bburg	1200	36	Progress/Giles	4722	71	Main/Givens	7400
2	WCL Blacksburg	11000	37	NCL_Bburg/460	12000	72	Main/Mt_Tabor	7400
3	Hethwood Blvd	17000	38	Main/Broce	14000	73	Edgewood/Preston	145
4	Heather Dr	26000	39	Giles/Montgomery	2184	74	Owen St/Harding	5800
5	Heather/Tall Oaks	10215	40	Giles/Montgomery	1847	75	Southgate-Airport	5424
6	Heather/Plymouth	10215	41	Main/Turner	18000	76	Draper/Edgewood	145
7	Glade/Boxwood	1800	42	College/Otey	4508	77	ContryClub/Airport	4200
8	TomsCreek/Meadowbrook	11000	43	460/BUS460_North	13000	78	Roanoke/Owen St	5700
9	PricesFork/460	49000	44	Giles/McConkey	1847	79	Harding/Cork	5800
10	Glade/Oriole	3550	45	Main/460_North	10200	80	Main/Upland	18000
11	Broce/Lora	2024	46	Progress/Turner	5795	81	Draper/Airport	2870
12	Glade/UCB	10250	47	Clay_West MainSt	810	82	Main/Airport	20300
13	PricesFork/UCB	30450	48	College/Draper	8742	83	Draper/CountryClub	4085
14	460/TomsCreek	24000	49	Giles/Lucas	1180	84	Lee/Jefferson	410
15	TomsCreek/Givens	12513	50	Giles/Northview	1695	85	Harding/PatrickHenry	8400
16	PricesFork_WestCampus	35939	51	Otey/Wall	3972	86	Apperson/Mason	80
17	TomsCreek/UCB	18900	52	Main/VIP_Mall	18000	87	Harding/Apperson	5180
18	McBryde/Kelsey	590	53	Turner/Montgomery	1453	88	460/BUS460_South	32000
19	Perry/West Campus	8939	54	Washington/Kent	5085	89	Main/460_South	19000
20	McBryde/Burrus	590	55	Progress/Faculty	4291	90	460/SCL_Bburg	32000
21	TomsCreek/Broce	13610	56	Main/College	22371	91	Main/CountryClub	21800
22	TomsCreek/PricesFork	30079	57	Turner/McConkey	1453	92	E.Roanoke/Fincastle	329
23	Broce/Stonegate	3196	58	Progress/Wilson	4291	93	Main/Ellett	21100
24	Perry/Stranger	5158	59	Giles/Turner	1685	94	Fincastle/Kam	590
25	Givens/Winslow	2912	60	Main/Patrick_Henry	18150	95	CountryClub/Hillcrest	50
26	Broce/Scott Alan	3196	61	Main/Roanoke	19850	96	Fincastle/Ridgeview	590
27	Washington/WestCampus	5085	62	Jackson/Church	4100	97	Clay_End_BCL	1800
28	Progress_NorthEnd	784	63	Turner/Lucas	380	98	Mt_Tabor_NCLBburg	3100
29	Progress/Watson	3400	64	Jackson/Penn	4100	99	Harding_ECLBburg	5100
30	Progress/Broce	3400	65	Givens/Whipple	2912	100	Floyd/Ridegeview	104
31	Progress/PatrickHenrry	12829	66	Giles/PatrickHenry	6948	101	Floyd_BCL	104
32	Main/Progress	17000	67	Main/Clay	18305	102	Ellet/ECL_Bburg	2100
33	PricesFork/Main	18000	68	Main/Whipple	7400	103	Sunrise/Hillcrest	50
34	Drillfield/VIP_Mall	1175	69	Southgate-Edgewood	6248			
35	Main/Giles	18000	70	Lee/Wharton	820	Data Provided by Town of Blacksburg and VDOT		

Appendix D: Road Intersections correlated with bus stops for the Transportation Infrastructure Network of Blacksburg

ID	Road Intersection	AADT	Indirect Interactions: Nodes: Route ID-Stop ID	Indirect Interactions: Nodes: Name	Indirect Interactions: Links: Pass_Count	Total No of Pass
11	Broce/Lora	2024	1-180	Sturbridge	6	
			1-181	UCB Post Office	98	2128
23	Broce/Stonegate	3196	1-157, 1-158	Broce	45	3241
34	Drillfield/VIP_Mall	1175	3-102, 5-228, 6-230, 7-237	Newman Library	340	
			1-103, 8-250	Torgesen Hall	1208	
			4-215, 8-248	Squires West	61	
			1-104	Drillfield	12	2796
49	Giles/Lucas	1180	8-69	Lucas	3	1183
50	Giles/Northview	1695	8-70	Northview	1	1696
66	Giles/PatrickHenry	6948	8-81	Giles	4	
			8-82	Rutherford	5	6957
59	Giles/Turner	1685	8-80	Giles	4	1689
65	Givens/Whipple	2912	8-114	Whipple Dr.	51	2963
12	Glade/UCB	10250	1-175	UCB Mall	222	
			2-176	Math Emporium	46	
			1-182	Sturbridge	98	
			2-189	Macados	46	10662
87	Harding/Apperson	5180	4-14, 4-15, 4-16, 4-17	Harding In/Out	84	5264
79	Harding/Cork	5800	4-20, 4-62, 4-63, 4-136	Harding In/Out	84	5884
85	Harding/PatrickHenry	8400	4-18, 4-19	Harding Out	42	8442
99	Harding_ECLBburg	5100	4-9, 4-10	Windsor Hills	156	5256
6	Heather/Plymouth	10215	4-201	Heather Drive	45	10260
5	Heather/Tall Oaks	10215	4-203, 4-205	FoxRidge	738	10953
62	Jackson/Church	4100	4-73	Roanoke In	6	4106
70	Lee/Wharton	820	4-68, 4-71	Roanoke In/Out	8	828
82	Main/Airport	20300	8-40	Country In	46	
			8-41	School Out	12	20358
38	Main/Broce	14000	8-60, 8-76	North Main In	124	14124
67	Main/Clay	18305	8-51	Post Office	5	
			8-52	Downtown Out	27	18337

			Indirect Interactions			
			Nodes		Links	
ID	Road Intersection	AADT	Route ID-Stop ID	Name	Pass_Count	Total No of Pass
71	Main/Givens	7400	8-135	Givens	51	7451
60	Main/Patrick_Henry	18150	8-83	Rutherford	5	
			8-84	Patrick Henry Place	63	18218
32	Main/Progress	17000	8-57	Wades	6	17006
61	Main/Roanoke	19850	8-(54,75,244,245) 4-(55,72,74,79)	All stops in downtown	89	19939
80	Main/Upland	18000	8-42	School Out	12	
			8-43	Country In	46	18058
52	Main/VIP_Mall	18000	4-(78,216) 8-(246,247)	Stops at VIP Mall entrance	428	18428
68	Main/Whipple	7400	8-112	Food Lion	37	
			8-115	Maple Ridge	26	7463
18	McBryde/Kelsey	590	1-256	Tom's Creek	21	611
24	Perry/Stranger	5158	1-106, 8-252	Stanger	843	6001
19	Perry/West Campus	8939	1-174, 2-172 4-(220,221) 7-(241,242)	Stops at West Campus	1649	10588
33	PricesFork/Main	18000	8-56	North Main In	62	18062
13	PricesFork/UCB	30450	1-177	UCB Mall	222	
			4-184	Campus In	12	30684
30	Progress/Broce	3400	1-94	Progress	83	
			2-95	Terrace View	303	3786
31	Progress/PatrickHenrry	12829	2-89, 2-91	Terrace View	606	
			1-96	Progress	83	13518
78	Roanoke/Owen St	5700	4-64, 4-66	Roanoke Out	42	5742
21	TomsCreek/Broce	13610	1-159, 2-254	Tom's Creek	24	13634
22	TomsCreek/PricesFork	30079	2-257	Tom's Creek	21	30100
17	TomsCreek/UCB	18900	2-155	Patrick H. Timecheck	198	
			2-163	Chasewood	8	
			1-167	UCB Timecheck	177	19283
54	Washington/Kent	5085	3-133, 7-236	YMCA	125	5210
27	Washington/W.Campus	5085	3-130, 7-234	McComas Hall	126	5211