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FRAMEWORK FOR INCORPORATING NETWORK CONNECTIVITY IN TRANSPORTATION SYSTEMS EVALUATION

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FRAMEWORK FOR INCORPORATING NETWORK CONNECTIVITY IN TRANSPORTATION SYSTEMS EVALUATION

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of

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To my late parents

Belayneh Woldemariam and Bekelech Woldemeskel

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LIST OF ABBREVIATIONS

AvgBC	Average Betweenness Centrality
AvgCC	Average Closeness Centrality
AvgLBC	Average Link Betweenness Centrality
AvgND	Average Nodal Degree
AvgSPL	Average Shortest Path Length
BC	Betweenness Centrality
BN	Base Network
BPR	Bureau of Public Roads function
CC	Closeness Centrality
CityBus	Greater Lafayette Public Transportation Corporation
CPP	Chinese Postman Problem
Diam	Diameter
DN	Degree of a Node
EMS	Emergency Medical Service
LBC	Link Betweenness Centrality
MCA	Multi-Criteria Analysis
MRS	Marginal Rate of Substitution
MST	Minimum Spanning Tree
NCI	Network Connectivity Index
NCL	Nodal Connectivity Level
ND	Nodal Degree
NFIRS	National Fire Incident Reporting System
NIndPath	Number of Independent Paths
NP1	Network with Project 1
NP2	Network with Project 2
NTPM	Network Topology Performance Measure
O-D	Origin-Destination
PCI	Pavement Condition Index
PM	Performance Measure
PMTC	Performance Measure Tradeoff Curve
RN	Random Network
SEMCOG	The Southeast Michigan Council of Governments
SNCL	Sparse Network Connectivity Level
SPL	Shortest Path Length
TPPP	Transportation Project Programming Process
TSP	Traveling Salesman Path (Problem)

VMT	Vehicle Miles Traveled
VOC	Vehicle Operating Cost
WL	West Lafayette
WLED	West Lafayette Engineering Department
WLFD	West Lafayette Fire Department

ABSTRACT

Woldemariam, Wubeshet Belayneh. Ph.D., Purdue University, December 2015. Framework for Incorporating Network Connectivity in Transportation Systems Evaluation. Major Professor: Samuel Labi.

In transportation investment evaluation, agencies often do not consider the impact of proposed projects in terms of the increased connectivity of the parent network. Thus, agencies may be inadvertently omitting a key and critical goal of transportation investment evaluation and decision making, particularly in regions and countries with sparse networks. This dissertation develops a framework for measuring network connectivity performance for use as an input for the evaluation process and is applicable to existing or proposed networks in any mode of transportation. The steps for the framework include selection of network performance measures (PMs), scaling the PMs, determining the level of topological performance for a given network, establishing the levels of node and link importance, and calculating the overall network connectivity performance. Another framework is used to quantify the overall connectivity level of the sparse networks with due consideration of the contribution of individual nodes in terms of economic, social, or political importance to the entire network. This dissertation also proposes a methodology to investigate the effect of prospective projects on sparse network connectivity to develop PM tradeoff curves (PMTC) that could be used to investigate the tradeoffs between the different measures of network topological performance. Application of the network connectivity framework using a case study network is also presented in this dissertation to demonstrate the usefulness of the framework in developing vital information of interest to transportation decision makers.

The developed PM tradeoff curves were found to be useful for scenario analysis and investigating the relationships between PMs. The case study also demonstrated that the overall topological performance impact of a number of projects can be significantly different from the sum of their individual topological performance impacts. In other words, the effect of the sum of the stimuli is superior to the sum of the individual effects of the stimuli, which is consistent with holism, a basic concept in systems engineering. More importantly, this finding suggests that inter-project interdependencies, a phenomenon whose characterization has been largely elusive in the literature, can be demonstrated and measured in terms of network topological performance.

CHAPTER 1. INTRODUCTION

1.1 Overview

The first section of this chapter presents the background for the work of this dissertation and the problem statement. The second section outlines the dissertation motivation. The third section describes the research objectives. The fourth and final section describes how the remaining chapters are organized.

1.2 Background and Problem Statement

Sinha and Labi (2007) recommended that transportation project decisions should maximize the mobility of system users and the connectivity and connectivity of the transportation network. A 2008 World Bank report suggested that project selection processes should consider the impacts of projects at the local level (The World Bank, 2008).

However, in transportation investment evaluation, analysts rarely consider the impact of proposed projects on the entire network connectivity as a criterion for evaluation. Thus, analysts may be inadvertently excluding a key and critical factor in transportation investment evaluation and decision making, particularly in regions and countries with sparse networks. The existing literature indicates that transportation infrastructure investment decisions often do not consider the impacts of projects on the topological performance of a network and its elements (An and Casper, 2011; Gurganus and Gharaibeh, 2012; Gokey et al., 2009).

A number of network connectivity measures exist in the literature (Bon, 1979; Gattuso and Miriello, 2005; Derrible, 2009; Derrible, 2012). However, these measures are not comprehensive (i.e., each network PM deals with only a single aspect of network topology). Also, these measures do not allow decision makers to assign their degrees of preferences to the relevant network PMs based on their appropriateness with respect to the policies of the transportation agency; rather, they focus on the total trip on the network (Sullivan et al., 2010). There is no widely-used network PM that enables decision makers to incorporate network connectivity performance during their tasks of investment evaluation; and existing network PMs have their specific areas of application as well. In addition, during project selection, it is difficult to satisfy all possible connectivity considerations because the outcomes for a given project may conflict with each other.

A need therefore exists to develop a comprehensive measure of network connectivity that utilizes, as its input, multiple network PMs and provides a quantified output that could be used by decision makers to compare different investment alternatives and to make investment choices that, as much as possible, maximize the network topological performance among other performance considerations.

1.3 Research Motivation

As discussed in Section 1.2, network topological measures are typically not considered during transportation infrastructure investment decisions even though transportation projects can and do affect the topological performance of a network. In addition, the existing measures are not comprehensive (i.e., they measure only a single aspect of the network topology). When these measures are applied during project evaluation, they may provide complex and often conflicting results that could complicate the decision making process. Existing measures often do not allow decision makers to incorporate stakeholders' preferences among the element-level PMs (e.g., nodal degree, node and link betweenness centralities (LBCs), closeness centrality (CC), shortest path length) or among network-level PMs, e.g., network diameter, gamma index, pi index. Furthermore, network stakeholders may have special interest in particular elements (nodes and links) of the network with the objective of minimizing their operating costs when routing the network. In this regard, they may want to prioritize each network element with respect to each network topological PM. Therefore, there is a need to develop a network connectivity framework that permits decision makers to incorporate any topological PMs and stakeholders' preferences into these topological measures in investment decisions.

In transportation decision making, the travel times in transportation links are often determined by using the Bureau of Public Roads (BPR) function, which relates the traffic flow on the link with the capacity of the link (*v*/c ratio), the free-flow speed on the links (Sinha and Labi, 2007). For sparse networks such as rural roads and low-volume urban roads where traffic congestion is not of great concern, project selection processes may not be ruled completely by the level of congestion on the individual links. Therefore, consideration of the topological performance of the network may not necessarily be in conflict with the congestion criteria but may constitute rather a separate measure that assists in making more comprehensive investment decisions. Therefore, in any task involving evaluation of projects (and hence prioritization, ranking, and optimization), it is essential to consider the topological performance of the entire network and its elements (nodes and links) in addition to congestion and other impacts on the network.

1.4 Organization of the Dissertation

This dissertation is organized into eight chapters. The dissertation overview, background and problem statement and motivation are discussed in Chapter 1. Chapter 2 presents a case study to demonstrate the dissertation motivation. Chapter 3 is a summary of the literature pertaining to evaluation of transportation projects and network PMs. Chapter 4 analyzes an existing highway network in Ethiopia to demonstrate how the implementation of different projects can have different impacts on the topological performance of the entire network as well as its constituent elements (nodes and links). Recognizing that some measures of network performance are achieved at the expense of others, Chapter 5 investigates the existence and extent of such tradeoffs using PMTCs. The PMTCs were developed using thousands of hypothetical networks that were generated using computer simulation. Chapter 6 proposes a framework for agencies that seek to quantify network connectivity performance as a single number and for use as an input in multiple criteria project evaluation along with traditional criteria. Chapter 7 presents a case study for the proposed framework developed in Chapter 6. Multi-criteria evaluation of potential projects on the basis of network connectivity is demonstrated, using data from the West Lafayette, Indiana road network and preference information from various stakeholder organizations and businesses in the city whose operations are impacted by the efficiency level of the city's road network system. Also, for sparse networks, Chapter 7 presents and demonstrates a framework for characterizing the connectivity levels for individual nodes as well as for the entire network. Finally, Chapter 8 presents the conclusions, itemizes the research contributions, and makes recommendations for further research on this vital but nascent aspect of transportation evaluation and decision making.

CHAPTER 2. DISSERTATION MOTIVATION, SCOPE, AND OBJECTIVES

In this chapter, the research motivation is demonstrated using a case study network and the research scope and objectives are presented.

In the existing transportation systems evaluation literature, the assessment of a project's feasibility or the ranking of multiple projects are carried out on the basis of their impacts in terms of a traditional set of PMs that include travel time, vehicle operating cost, safety, and economic efficiency. Other traditional criteria are related to the impacts on land use, the social and biological environment, economic development, aesthetics, air quality, and noise. Rarely is the impact of a project on network connectivity considered directly.

It may be argued that travel time is a proxy for topology because an efficient network topology generally translates into lower travel times between the different O-D pairs. However, it is worth considering that (i) in certain cases, such as sparse networks, travel time is not the primary concern but rather the mere availability of connections and access to certain nodal points; and (ii) even where travel time is of paramount concern, the network topology can be represented not only in terms of distance but also in terms of travel time (where the "cost" of each link is the travel time and not the distance). Therefore, topological performance, in terms of network connectivity, could be enhanced even on the basis of travel time. Based on this gap in the literature, this chapter uses a case study involving a real network using a number of common measures of network topological performance to demonstrate the motivation of this dissertation. In a discussion of the results of this case study, justification is presented for the supposition that including network topological performance in the suite of criteria considered can further enhance the evaluation of transportation systems.

2.1 Demonstration of Research Motivation

The implementation of a transportation project may affect the topological performance of either the parent transportation network or its elements (nodes or links). As discussed in Section 1.3, the primary motivation of this dissertation is to enable transportation planners and decision makers to consider network connectivity in their evaluation of projects, policies, and programs.

The network PMs shown in Table 2.1 were used to evaluate the impacts of alternative scenarios (do nothing, project 1, and project 2) on network topological performance. The resulting impacts of different projects on the network topological performance, computed using the Python programming language, are shown in Table 2.2. For comparison purposes, only the average values of certain PMs are presented.

To demonstrate the dissertation motivation, a case network (Figure 2.1) was used. Appendix A presents a computer program that was written using Python programming language (van Rossum, 2012) to generate the network and to compute the topological performance of the network. The topological performance of a network is the performance or level of the network in terms of topological PMs, for example, the topological performance of a network in terms of a BC PM, which measures the fraction of the shortest paths that pass through a node in the network. The case network consists of 25 nodes and 40 links, and the "costs" of each link is represented by the link length.Figure 2.1 also shows two candidate projects, project 1 and project 2. Project 1 is a 3.61-mile link between nodes *J* and *N*; project 2 is a 2.24-mile link. Assume that a transportation agency seeks to implement only one of the two candidate projects on the basis of their contribution to the network connectivity; and another assumption is that all other impacts are the same for these two projects (travel time reduction, safety enhancement, economic efficiency, etc.). We use only connectivity as a criterion in this dissertation for evaluation in order to make the argument that the different projects will have different impacts in terms of network topology; therefore, one of these projects could be superior to the other from the perspective of the contribution to network connectivity.

Table 2.1 Network topology PMs considered in the case network

Network PM	Definition and References
Degree of a node (DN)	The number of nodes directly attached to a node in a network (Rodrigue et al., 2006; Costa et al., 2010).
Cyclomatic number	The maximum number of independent cycles of a network (Kansky, 1963; Bon, 1979; Gattuso and Miriello, 2005), which measures the extent to which a network is developed, compared to other networks (Kansky, 1963).
Alpha index	The ratio between the actual number of circuits in the network and the maximum number of circuits (Kansky, 1963; Gatusso and Miriello, 2005). Therefore, a higher alpha index indicates a level of higher network connectivity.
Diameter	The length of the longest path between an origin and destination pair (Kansky, 1963; Gatusso and Miriello, 2005). Network diameter is an indication of the extent (spreadout) of the network.
Beta index	The ratio between the number of links and the number of nodes in a network (Kansky, 1963; Gatusso and Miriello, 2005). A higher beta index indicates a more connected network.
Gamma index	The ratio between the actual number of links and the maximum number of links in the network (Kansky, 1963; Sullivan et al., 2010; Bon, 1979; Gattuso, 2005; Taaffe, 1996). A completely connected network has a gamma value of 1.
CC	A measure of the inverse of the average shortest path from a given node to all other nodes in the network (Erath et al., 2009).
Center of network	A node or a set of nodes whose greatest shortest distance to any other nodes in the network is the smallest in the network (Diestel, 2000).
Node BC	The number of shortest paths in a network that pass through the node (Erath et al., 2009).
Link BC	The number of shortest paths in a network that pass through a link (Erath et al., 2009).

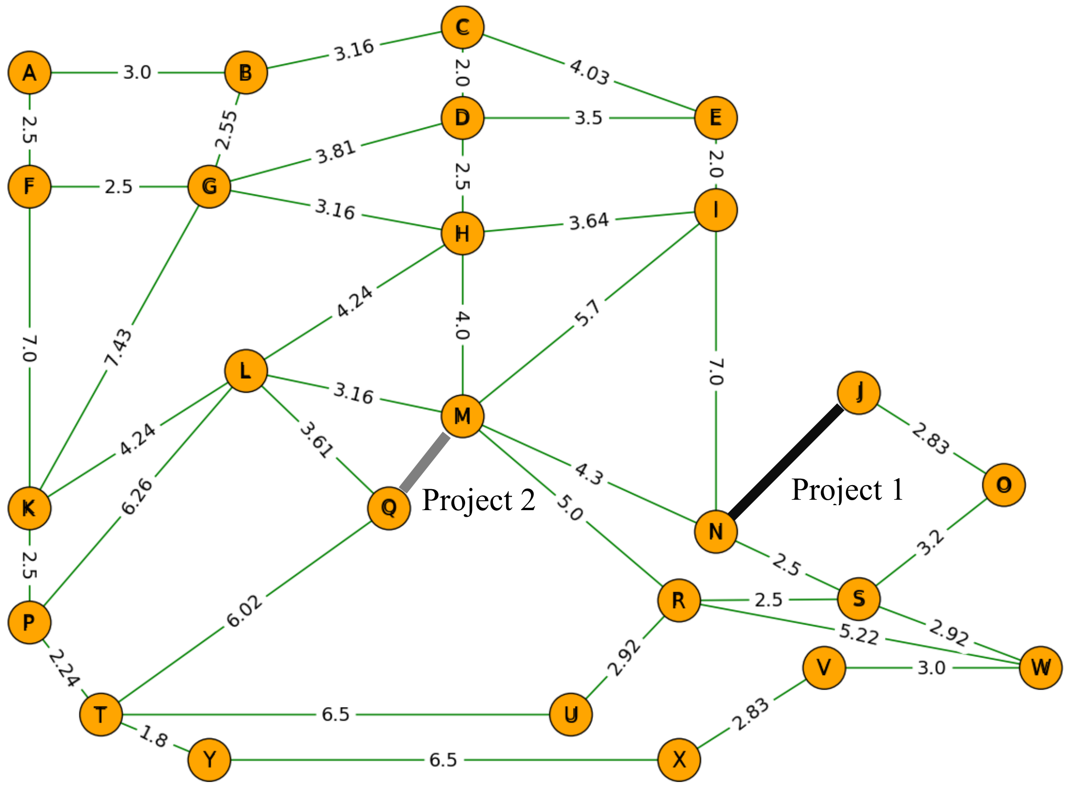


Figure 2.1 Case network with two project alternatives

First, the topological impact of each project at the network level was analyzed in three scenarios: network without implementing any project (the base network (*BN*)); network with project 1 (*NP1*); and network with project 2 (*NP2*).

Table 2.2 Impacts of projects 1 and 2 on the topological performance of the case network

Network PM	Base Network (Do Nothing)	Percent Change in PM Value	
		Network with Project 1	Network with Project 2
Maximum degree in the network	5	0	+20
Node with maximum degree	Node *G*	Node *G*	Node *M*
Diameter (miles)	8.0	-12.5	0
Center of network	Node*M*	Nodes *M* and *L*	Node *M*
Average node BC	0.103	-3.88	-1.94
Average link BC	0.081	-6.17	-4.94
Average CC	0.319	+2.82	+2.51

Generally, a network with a higher average nodal degree or higher maximum nodal degree is preferable to one with a lower average or maximum nodal degree because the former is indicative of the number of direct node-to-node connections in the network. The maximum degree of the network remains unchanged if project 1 is implemented while project 2 increases the maximum degree by 20 percent. Also, in the base network, the node with the maximum degree is G; and the node with the maximum degree remains as G if project 1 is implemented but changes to M is project 2 is implemented. The degree of a node (DN) is the number of direct links that the node has in the network (Rodriguez et al., 2006; Costa et al., 2010).

The diameter of a transportation network is an indirect indicator of its degree of network connectivity because a network with a higher degree of connectivity is generally associated with a lower diameter (Kansky, 1963). Therefore, in the case network, project 1 is preferred to project 2 from the perspective of the network diameter PM because it reduces the diameter of the base network by 12.5 percent compared to project 2 (which does not change in the diameter of the base network).

The center of a network is a node or a set of nodes whose max-min distance (maximum of the shortest distances to all other nodes in the network) is the smallest compared to other nodes in the network (Diestel, 2000). In other words, the center of a network is a node or a set of nodes whose maximum shortest distance to other nodes in the network is the minimum. This minimum distance is taken as the radius of the network (Diestel, 2000). A transportation project also may influence which node becomes the network center after the project implementation. In the case network, nodes M and L become network centers if project 1 is implemented while the network center remains the same (node M) as in the base case if project 2 is implemented (see Table 2.2).

A node or link that has a high BC is a reflection of the importance of the node or the link because that node or link plays a major role in achieving the shortest distance for most origin-destination (O-D) pairs. For the case network, the average node BC decreased by 3.88 percent if project 1 was implemented and decreased by 1.94 percent if project 2 was implemented. Higher values of BC are desirable; therefore, project 2 is preferred from the perspective of the node BC PM. With respect to the average link BC

(LBC) PM, project 2 is preferred to project 1 because its effect on the percent reduction of the average LBC (i.e., -4.94 percent) is lower than that of project 1 (i.e., -6.17 percent). From the perspective of CC, project 1 is preferred compared to project 2 because the former improved this PM by 2.82 percent while project 2 improved it by about 2.51 percent.

In general, transportation projects can have an important effect on the transportation topological structure and hence on the network topological performance with respect to different PMs. Some network-level measures may remain unaffected by projects, particularly projects at corridors in densely-linked networks. However, as will be described in the following sections, the measures can change greatly at the level of individual nodes or links. It is therefore recommended to consider both the local and global (entire network) effects during project evaluation.

Thus far, using the case network, it can be seen that different projects can have different effects on the overall topological performance of a network. It is also of interest to ascertain whether different projects have different effects on individual elements (nodes and links) of the network.

Figures 2.2 through 2.4 depict graphically the impact of the different projects on the degrees of nodes in the network. Nodes with an equal nodal degree are represented by the same color or size.

Project 1 changed the degree of nodes *J* and *N* (Figures 1.2 and 1.3): the degree of node *J* increased from 1 (in the base case) to 2 and that of node *N* increased from 3 to 4. Project 2 did not affect the degrees of nodes *J* and *N* but did affect the degrees of nodes *Q* and *M* (Figures 2.2 and 2.4). In the base network, the degrees of nodes *Q* and *M* are 2 and 5, respectively. If project 2 is implemented, the degrees of nodes *Q* and *M* will increase to 3 and 6, respectively .Clearly, the different projects have a very significant local effect on nodal degrees as seen in Figure 2.2 through 2.4.

Different projects may also affect the proportion of shortest paths that pass through a node differently, which is represented by the BC network PM. Figure 2.5 through 2.7 show how the BCs of nodes change due to each of the two projects compared to the BC of the base network.

Figure 2.5 through 2.7 present the BCs of nodes classified on the basis of their BC values, which was done to acquire insights of how different projects can affect the network topological importance of each node in terms of the BC measure.

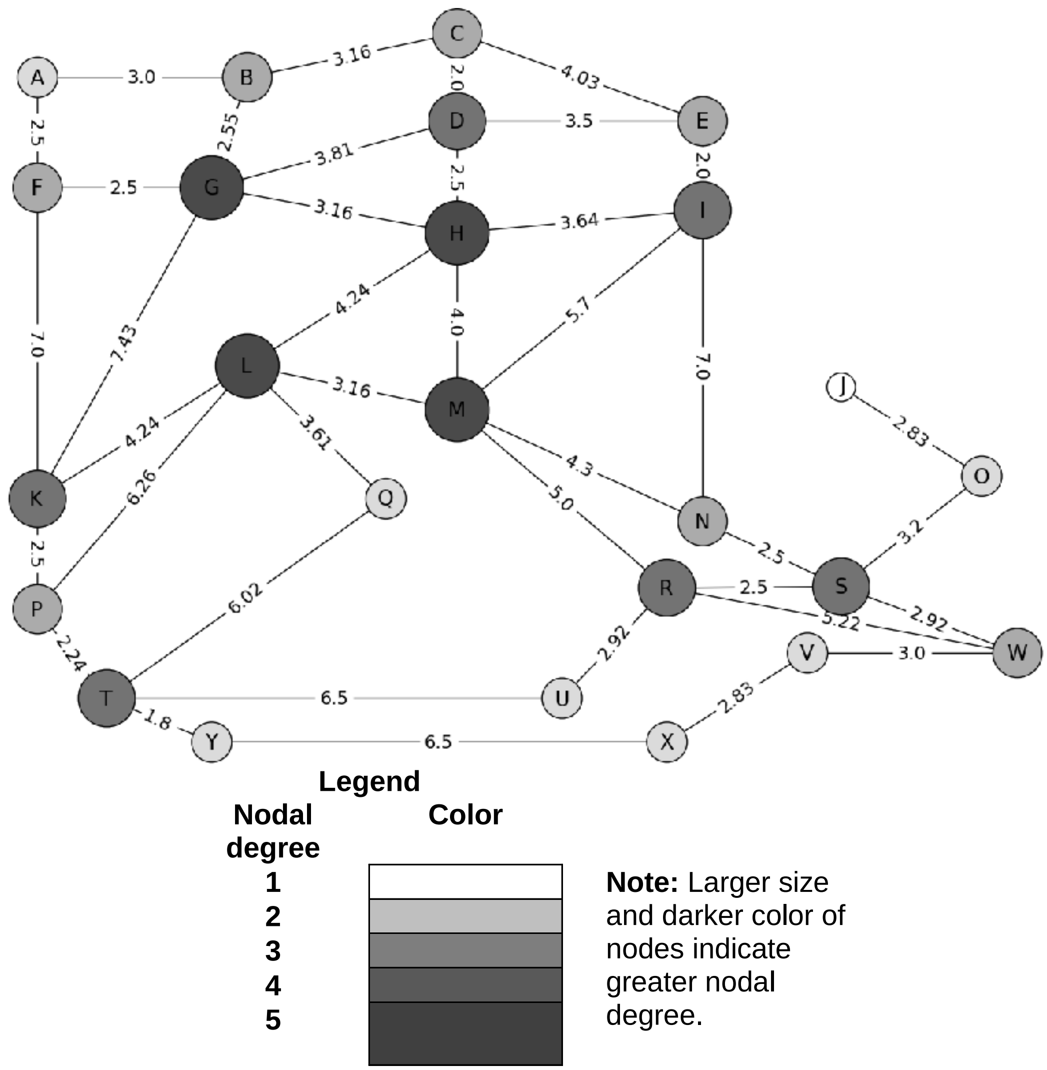


Figure 2.2 Degree of nodes (base network)

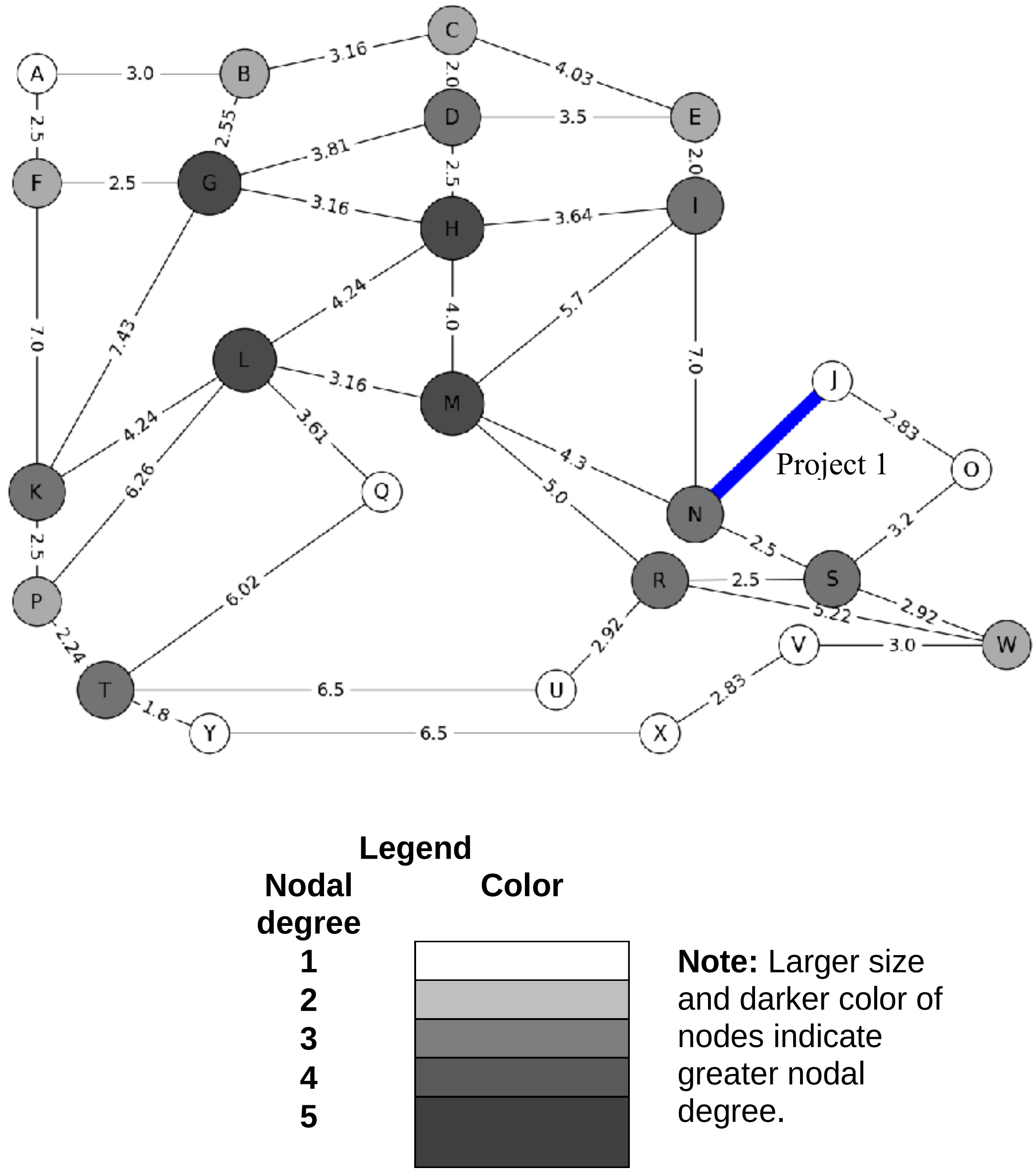


Figure 2.3 Degree of nodes (network with project 1)

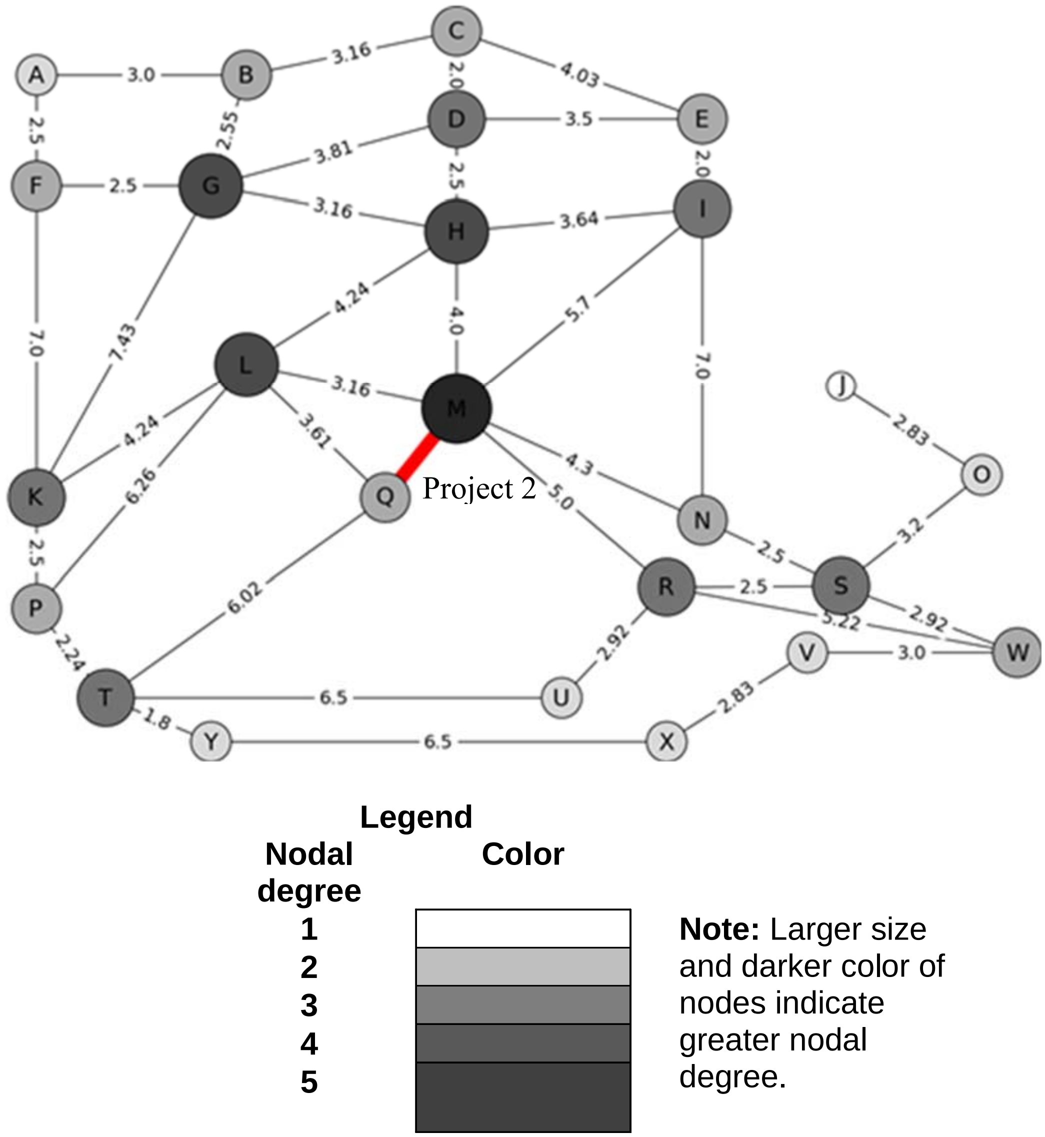
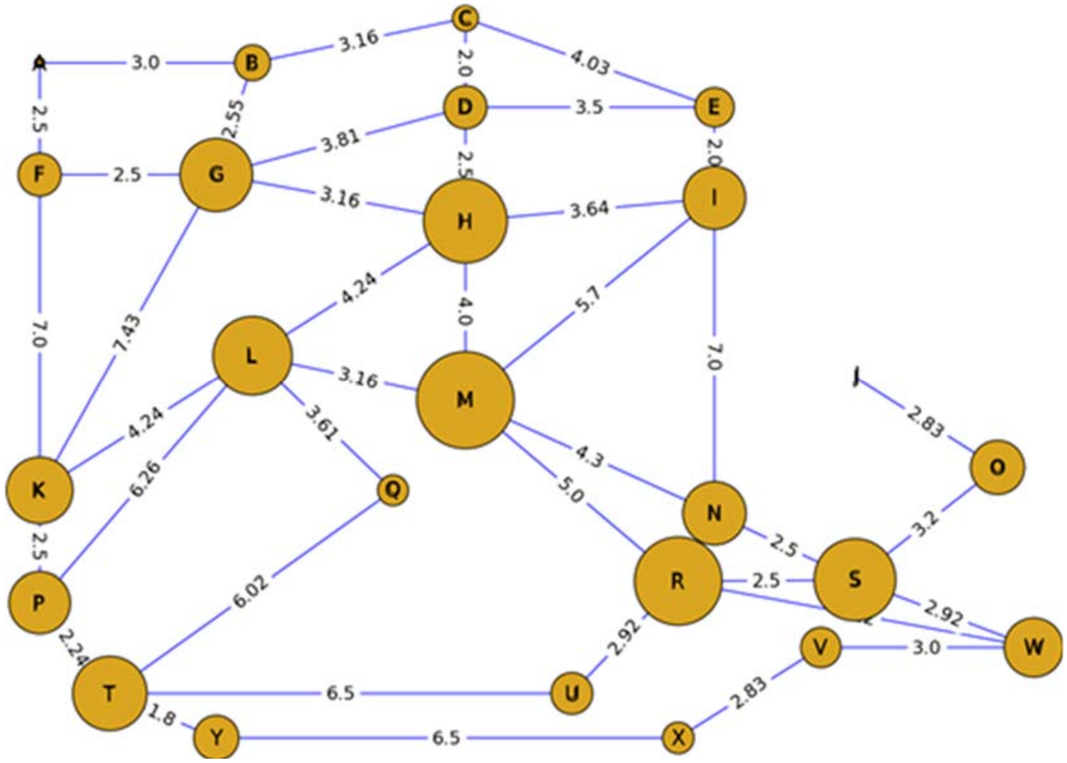


Figure 2.4 Degrees of nodes (network with project 2)

The node sizes in Figure 2.5 through 2.7 imply the magnitude of the BCs of the nodes (i.e., the larger the size of a node, the higher the BCs of the node). It is therefore possible to discern visually the effect of project selection on the BCs of the nodes by comparing the BCs of the nodes in the *BN*, *NP1* and *NP2* cases.

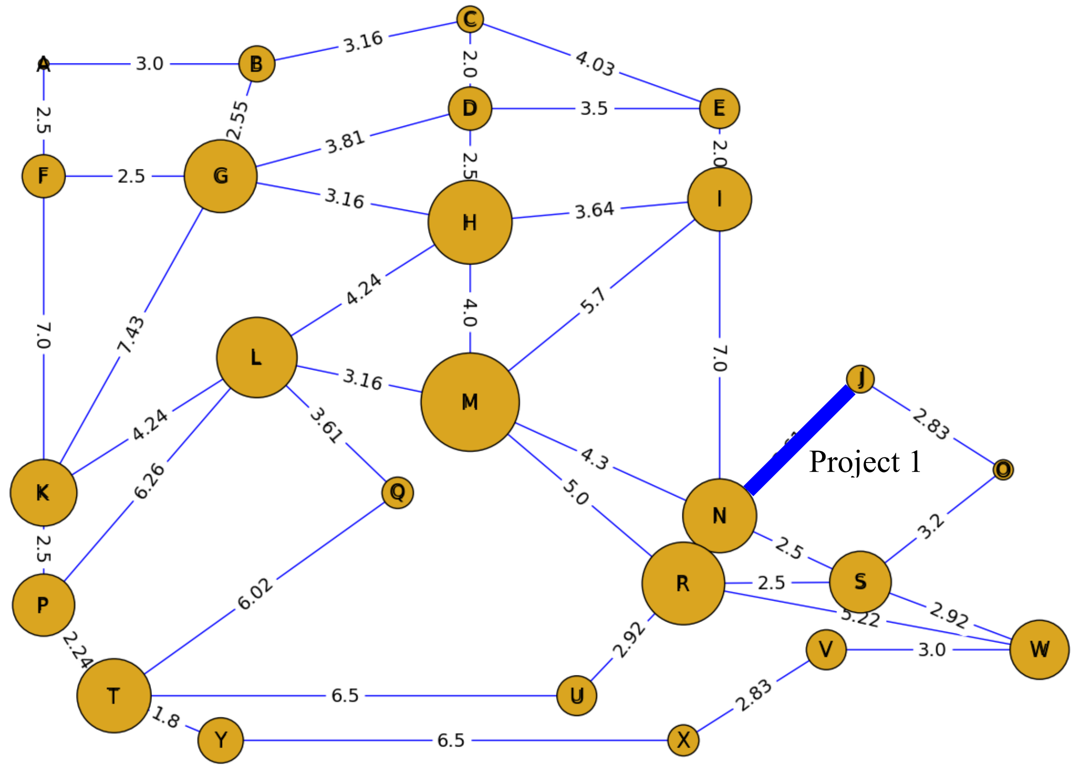
Compared to the base network, implementation of project 1 decreased the BCs of nodes *O*, *R*, and *S* and increased those of nodes *N* and *J*. On the other hand, implementation of project 1 improved the BCs of node *J* and *N*. Also, compared to the base network, implementation of project 2 caused the BCs of nodes *L*, *U*, *R*, *V* and *P* to decrease and those of nodes *M* and *Q* to increase.



Note: Larger node size indicates greater BC

BC	Nodes
$BC \leq 0.050$	A,C,B,E,J,Q,X
$0.050 < BC \leq 0.100$	D,F,I,K,O,U,V,Y
$0.100 < BC \leq 0.150$	P,R,T,W
$0.150 < BC \leq 0.200$	G,L
$B > 0.200$	H,M,N,S

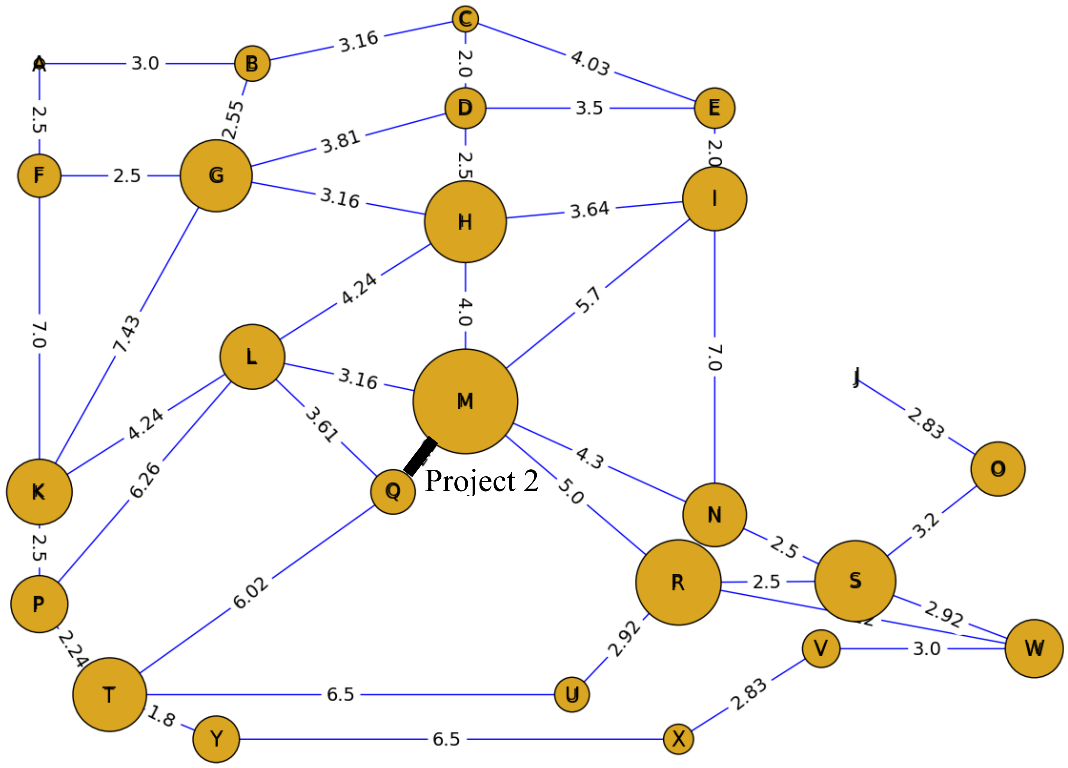
Figure 2.5 Betweenness centrality (BC) of nodes (base network)



Note: Larger node size indicates greater BC

BC	Nodes
$BC \leq 0.050$	A,C,B,E,J,O,Q,U,X
$0.050 < BC \leq 0.100$	D,F,I,K,V,Y
$0.100 < BC \leq 0.150$	P,R,T,W
$0.150 < BC \leq 0.200$	G,L
$B > 0.200$	H,M,N,S

Figure 2.6 Betweenness centrality (BC) of nodes (network with project 1)



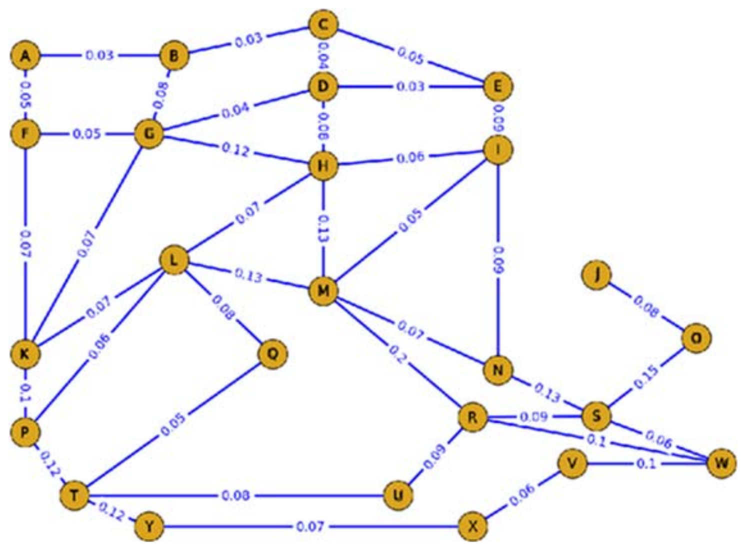
Note: Larger node size indicates greater BC

BC	Nodes
$\boldsymbol{BC \leq 0.050}$	A,C,B,E,J,U,X
$\boldsymbol{0.050 < BC \leq 0.100}$	D,F,I,K,L,O,Q,P,V,Y
$\boldsymbol{0.100 < BC \leq 0.150}$	R,T,W
$\boldsymbol{0.150 < BC \leq 0.200}$	G
$\boldsymbol{B > 0.200}$	H,M,N,S

Figure 2. 7 Betweenness centrality (BC) of nodes (network with project 2)

The BC values of the links in the three networks, (i.e., base network, network with project 1, and network with project 2) are presented in Figures 2.8 through 2.10. The figures were developed using Python programming language (van Rossum, 2012) and Networkx® software package (Hagberg et al., 2008) to enhance visualization of the results. The link labels represent the link BC values. Similarly, the BC of a link is a measure of the proportion of shortest paths between all the networks OD node pairs that pass through the link.

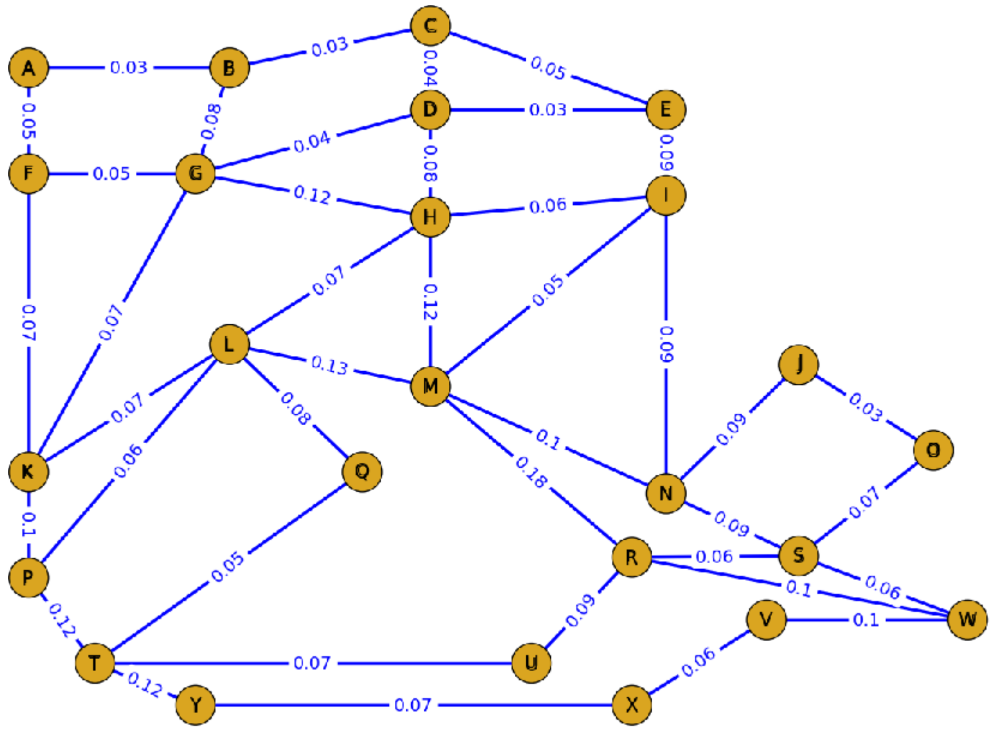
When either project 1 or project 2 was implemented, the link BCs change from their "base network values" when either project 1 or project 2 was selected (see Figures 2.8 and 2.9 for project 1; and Figures 2.8 and 2.10 for project 2). For the following links, there was a change in their BCs when project 1 was implemented: *T-U*, *H-M*, *M-R*, *M-N*, *N-S*, *R-S,* and *S-O*; the BCs of all other links remained constant. On the other hand, for project 2 implementation, almost 18 of 25 links (approximately 72% of the links) experienced a change in their BCs (Figures 2.8 and 2.9). With respect to the direction of change, the BCs of *T-U*, *H-M,* and *R-S* decreased and that of *M-N* increased for either project.



Note: Link labels represent values of link betweenness centrality (LBC) (NOT travel times between nodes)

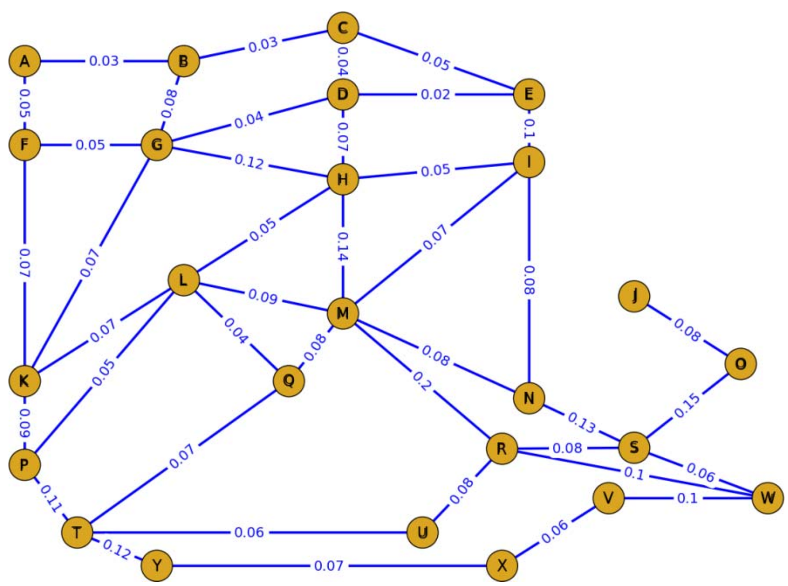
Figure 2.8 Betweenness centrality (BC) of links (base network)

The above results suggest that the importance of links with respect to their BCs can be affected by project selection. It is, therefore, recommended to consider this measure of network topology in the evaluation of transportation investments, particularly projects that modify the topological structure of the transportation network.



Note: Link labels represent the values of link BC (NOT distances) between nodes)

Figure 2.9 Betweenness centrality (BC) of links (network with project 1)

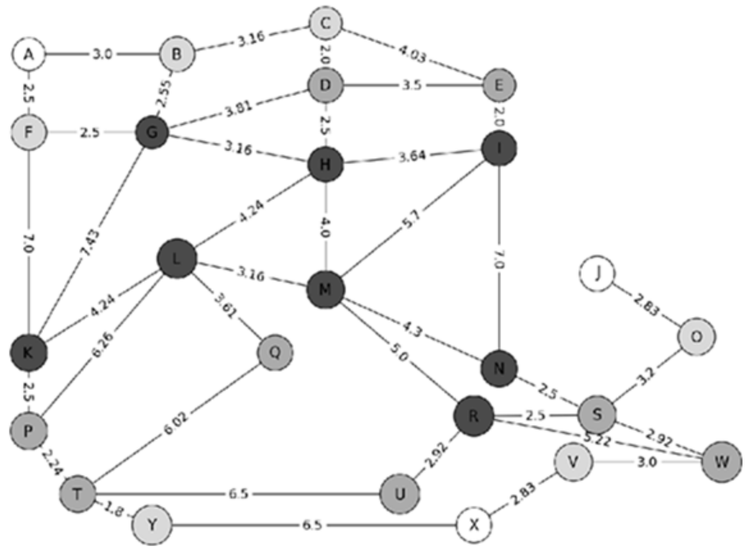


Note: Link labels represent link BC (NOT distances between nodes)

Figure 2.10 Betweenness centrality (BC) of links (network with project 2)

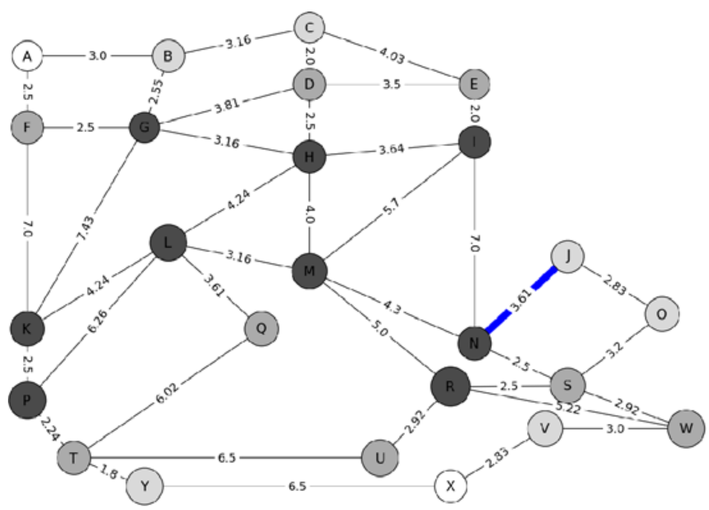
Closeness centrality (CC) is another network PM that could be considered in evaluating the impacts of transportation investments. CC measures how "close" a node is to all others nodes in the network. It is desirable to improve the CC of nodes in a network in order to improve the access to other nodes from any node in the network. Thus, higher values of CC are preferred.

In this demonstration case study, the node CC values were classified into groups to enhance the visualization of the changes in the values after project implementation. The intention was not to compare the nodes with each other with respect to the measure of CC but rather to demonstrate how a project can affect the topological importance of nodes with respect to this measure of network performance. The results show that project 1 improved the closeness centralities of nodes *J*, *F*, *P* compared to the base case (Figures 2.11 and 2.12). Also, the CC of node *P* improved, but that of node *F* degraded when project 2 was implemented instead of project 1 (Figures 2.12 and 2.13). These results suggest that CC can be a useful metric for quantifying the network topological performance during transportation investment evaluation and decision making.



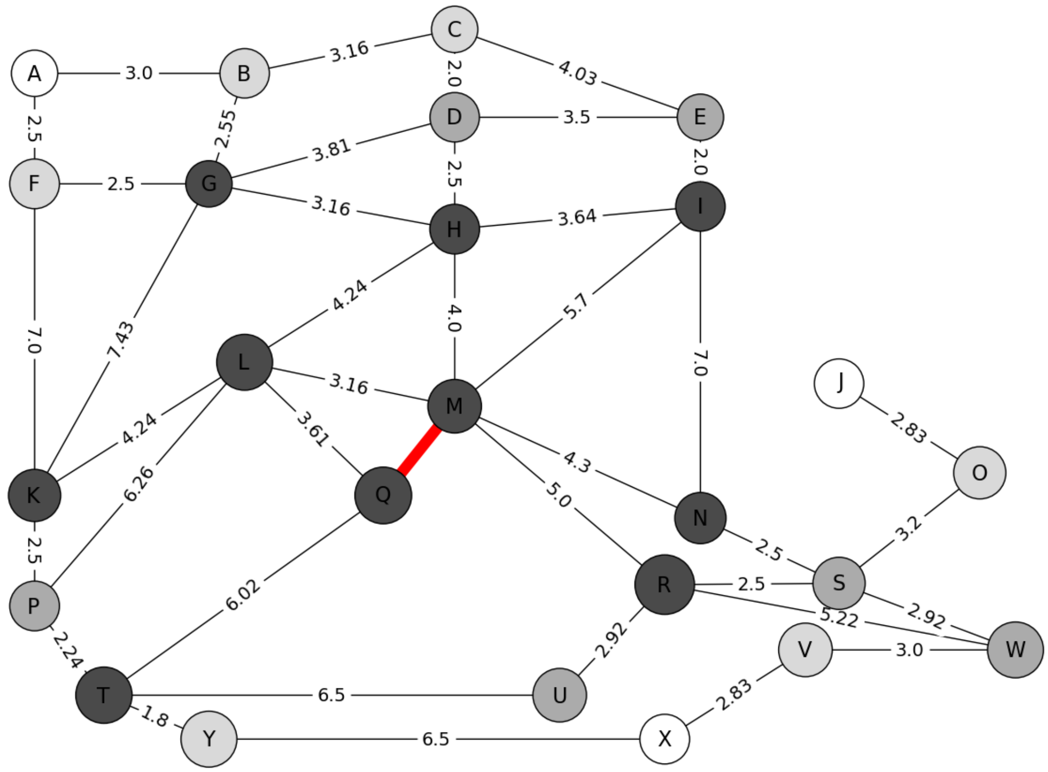
Legend	
CC	Color
$CC \leq 0.200$	
$0.200 \leq CC$ 0.250	
$0.250 \leq CC \leq 0.300$	
$0.300 \leq CC \leq 0.350$	
$CC > 0.350$	

Figure 2.11 Closeness centrality (CC) of nodes (base network)



Legend	
CC	Color
$CC \leq 0.200$	
$0.200 \leq CC$ 0.250	
$0.250 \leq CC \leq 0.300$	
$0.300 \leq CC \leq 0.350$	
$CC > 0.350$	

Figure 2.12 Closeness centrality (CC) of nodes (network with project 1)



Legend	
CC	Color
CC ≤ 0.200	
0.200 ≤ CC 0.250	
0.250 ≤CC ≤ 0.300	
0.300 ≤CC ≤0.350	
CC>0.350	

Figure 2.13 Closeness centrality (CC) of nodes (network with project 2)

2.1.1 General Observation

It was shown in the previous section (Section 2.1) that the network's topological performance was affected according to which project was implemented. The effects were observed both at the network level and the individual elements the network (nodes and links). The effect of each project on the network topological performance was observed to be very complex. That is, a given project can improve the topological performance of the network as a whole, but at the same time it can affect the network elements (nodes or links) in different ways, both in magnitude and direction of change. Therefore, the motivation of this dissertation emanates in part from the above-mentioned effects of different projects on the topological performance of a transportation network and the current lack of consideration of these effects in most investment decisions as seen from the literature.

Table 2.3 Descriptive statistics of network PMs for selected projects

Network PM	Mean			Standard deviation			Range		
	BN	NP1	NP2	BN	NP1	NP2	BN	NP1	NP2
Nodal degree	3.200	3.280	3.280	1.155	1.100	1.100	4.00	3.00	3.00
BC	0.103	0.099	0.101	0.099	0.097	0.100	0.330	0.330	0.330
LBC	0.077	0.075	0.076	0.039	0.034	0.037	0.198	0.183	0.195
CC	0.319	0.328	0.326	0.055	0.055	0.059	0.216	0.189	0.237

Notation*:* BN= Base Network; NP1=Network with project 1; NP2=Network with project 2.

2.2 Scope of the Dissertation

Based on the motivation discussed in the previous section, the scope of this dissertation is as follows.

The framework in this dissertation is mostly applicable to:

a) Sparse networks.

b) Low volume networks (where the link traffic demand is far less than the link capacities) and therefore congestion and link travel time are of far less interest compared to the provision of access and connection to nodes.

c) Networks where link weights may be not only distances or costs but also traffic performance outcomes such as travel time.

The past literature on transportation project evaluation does not include explicitly a project's impacts on the topological performance of the parent network in which the project belongs as a PM. In addressing this lacuna in the literature, this dissertation developed a framework with a scope that (i) develops an overall measure of network connectivity for use in project evaluation, (ii) provides a means to rank projects on the basis of their topological contributions, (iii) makes it possible to rank links or nodes on the basis of their contribution to connectivity in the network, (iv) develops PM comparison curves that can be used to assess the tradeoffs between conflicting measures of topological performance. Therefore, the framework is intended to enhance the consideration of topological performance in transportation decision making, either from an ex ante or ex poste perspective, as well as for either feasibility studies of a single proposed project or ranking studies of multiple proposed projects. In order to address such a scope, this dissertation make a strong argument for the inclusion of topological PMs in the suite of traditional evaluation criteria for such agency business processes.

2.3 Research Objectives

This dissertation generally aims to develop a methodology that will make the inclusion of the topological performance of a transportation network possible as one of the PMs during investment evaluation. This dissertation particularly addresses network connectivity measures on the basis of the network's topological characteristics.

The specific objectives of the dissertation are as follows:

1. Develop a framework for quantifying network connectivity.
2. Develop a measure to quantify the connectivity of sparse networks (networks that are characterized by poor connectivity).
3. Develop PM tradeoff curves that could be used to compare the impacts of each pair of network topological PMs during multi-criteria analysis (MCA) of these measures.
4. Use network analysis to demonstrate how transportation project interdependencies could be established.

This dissertations intends to quantify network connectivity by considering the different topological performance aspects of a network and its constituent elements (nodes and links) as well as incorporating transportation stakeholders' preferences in that regard. Overall, this dissertation seeks to develop topology-related PMs thatcould be used with other PMs in transportation system evaluation, specifically project feasibility analysis or project ranking. This dissertation also seeks to develop a measure that could be used to characterize the connectivity of networks such as rural road networks in developing countries where poor connectivity problems are of great concern to government administrators, farmers, businesses, and the general public. In addition, this dissertation seeks to develop indifference curves for estimating the marginal rates of substitution between the topological PMs, which will facilitate determination of the tradeoffs related to topological PMs. Using the framework developed in this dissertation, decision makers will be in a better position to rank multiple candidate road projects based on their contributions (on the basis of topological performance) to network connectivity or to include topological performance as a separate PM for evaluation in the overall portfolio of PMs in investment decision making.

2.4 Chapter Summary

This chapter demonstrated the motivation for this dissertation using a real network, through which it was concluded that projects at different locations can influence the topological performance of a transportation network differently. Therefore, adding network topological performance to the traditional suite of PMs, particularly where the project is associated with a sparse network is a feasible supposition, in the evaluation of a single project vs. the do-nothing alternative (to ascertain the project feasibility) or to evaluate and rank a number of projects. After laying out the driving force for this dissertation, this chapter presented the research scope and objectives. Chapter 3 summarizes the literature on the fundamental theory of complex networks, network types, topological PMs, network connectivity concepts, and transportation investment prioritization practices.

CHAPTER 3. LITERATURE REVIEW

This chapter begins by defining network terminologies, describing network representations, and explaining different network types. Then, the network connectivity concepts are discussed, followed by a description of existing network topological attributes that could serve as PMs for transportation systems evaluation. Finally, the transportation systems evaluation criteria traditionally used in the literature are presented as well as the gaps, particularly with respect to network topological connectivity.

3.1 Evaluation of transportation projects: the state of practice

Transportation investment decisions are often made focusing on specific corridors without considering the topological relationships that exist between road corridors and the transportation network. Also, the analysis tools and techniques that are used to compare investment options mostly focus on addressing transportation issues related to congestion, air pollution, or travel time reduction at project corridors (An and Casper, 2011). For example, Gurganus and Gharaibeh (2012) used visual distress, traffic volume, and pavement condition as project selection criteria. Their project selection process does not consider the impacts of projects on the network connectivity nor does it account for the possibility that some road sections may be relatively more important than others to keep the network connectivity at a higher level in order to handle disruptions due to man-made or natural disasters. Based on the pavement condition index (PCI) or pavement condition rating, their approach is a commonly used one, particularly to prioritize transportation projects (Chandran et al., 2007). The PCI is based on an assessment of the severity and extent level of each pavement distress type. The pavement condition rating technique is based on an overall visual pavement condition assessment. These technique only focus on the condition of each pavement section and therefore may not take into account the importance of each pavement section for the overall network connectivity performance, and the assessment of bridges is handled in a similar fashion. In prioritizing bridges for Virginia's bridge infrastructure systems, Gokey et al. (2009) considered factors including bridge, traffic, and detour length, but the impacts of bridge projects on network-level connectivity were not explicitly considered.

Sinha and Labi (2007) recommended that transportation project decisions should include, among other criteria, the mobility of system users and the connectivity and connectivity of the transportation network but did not provide a detailed framework for measuring network topological performance. Sandra and Laurie (2004) described general project selection criteria that could be implemented by different districts to prioritize rural transportation infrastructure projects in the state of Montana. Lane closure was one of the criteria; this could be assumed as a surrogate, but not direct PM for network connectivity. The World Bank (2008) suggests that project selection processes should consider the impact of the projects at local level, how the project could improve average passenger travel time, average vehicle operating cost (VOC), number of annual vehicle-related fatalities on the project locations. This suggests that the Bank's selection process could be enhanced further if network topology-related impacts of the projects are considered in project selection. Similarly, for highway in developing regions, the World Bank uses an index referred to as rural accessibility index (RAI). RAI measures the proportion of rural communities that live within 2 km (which translates into 20 to 25 minutes of walking) from an all-season road, to help transport aid decisions in Sub-Saharan Africa and other developing countries, and improve network connectivity (Faiz, 2012). The index could be expanded to cover investment decisions over the entire transportation network, both urban and rural.

The southeast Michigan Council of Governments prioritizes their transportation investments on the basis of % pavements in good or fair condition, hours of congestion delay per 1,000 vehicle miles traveled, percent of bridges in good or fair condition, fatalities per 100 VMT, % of bridges in good or fair condition, fatalities per 100 VMT, extent of transit network and the % of population and % of population and employment within ½ mile of a non-motorized facility (Guerre and Evans, 2012); there is no MOE that addresses the importance of pavement section or bridge for the entire network with respect to network connectivity. Also in Norfolk, Virginia, the Divisions of Transportation identifies, evaluates, and prioritizes projects on the basis of safety enhancing and congestion mitigation in all intersections and transportation corridors on the city's road network (Akan and Brich, 1996). They do not address how the individual projects affect directly the connectivity of the city's network.

The network connectivity measures that exist in the literature are not comprehensive, i.e., they deal with a single attribute of network topological performance (Bon, 1979; Gattuso and Miriello, 2005; Derrible, 2009; Derrible, 2012). Also, the existing measures do not incorporate weights that reflect PM preferences to specific measures of network topology based on their appropriateness with respect to the policy or operations of transportation agency or service organization (Sullivan et al., 2010). That is, there is no widely-used network PM that enables decision makers to incorporate special consideration to specific routes (linksor nodes in the network)or specific measures of network performance.

Table 3.1 presents network topology PMs that have been mentioned, demonstrated or used for evaluation of transportation policies, projects or programs. Bell (2000) considered the cost of traversing a link in the network as a PM. Forkenbrock and Weisbrod (2001) provided detailed steps for network-level and local level connectivity measurement and such connectivity measures as change in travel time, change in travel costs, change in number of choices in terms of the number of reachable destinations with a given criteria such as travel time, were suggested. Cambridge Systematics (2000) and Sinha and Labi (2007) provide average O-D travel time and average trip length as connectivity PMs for passenger and freight travel. Travel time was mentioned as a measure of level of satisfaction in OECD (2001). Travel time and hours of congestion delay are mentionedindirectly by Karlaftis and Kepaptsoglou (2012) as topological PMs. Novak et al. (2012) have developed and demonstrated a network-level performance metric called the network trip robustness (NTR) which takes into account the network-level travel time, and the total number of trips between all origins and destinations in the network. Sullivan et al. (2010) developed an index called network robustness index and used network-wide travel time as a PM. Scott et al. (2006) evaluated the impact of a highway section to the change in network level travel-time using the network robustness index.

For non-sparse networks such as those typically associated with urban streets, congestion is considered a more important (even if indirect) measure of network topological performance. On the other hand, for sparse networks (such as rural roads in many developing countries as an example), topological connectivity is a more pressing challenge compared to congestion. To bridge the difference in contexts between sparse and non-sparse networks, travel time could be used as the cost associated with each link. In that case, the poor connectivity of a sparse network and high congestion of a non-spare network would both reflect in (and could be analyzed using) a common attribute of their links: the average travel time in the network.

Table 3.1 Network PMs in evaluation of transportation policies, projects or programs

	Mentioned	Demonstrated or Used	Comments
Forkenbrock and Weisbrod (2001)	✓		Suggested connectivitymeasures include change in travel time, change in travel costs, and change in number of choices interms of the number of destinations that are reachable in a given travel time
Cambridge Systematics (2000)	✓		Average travel time and average trip length are suggested as PMs.
OECD (2001)	✓		Travel time is mentioned as a measure of level of satisfaction
Karlaftis and Kepaptsoglou (2012)	✓		Travel time and hours of congestion delay are mentioned.
Sinha and Labi (2007)	✓		Average travel time and average trip length are suggested as PMs.
Novak et al. (2012)		✓	Network-level performance metric called The Network Trip Robustness (NTR) is demonstrated.
Sullivan et al. (2010)		✓	Network-wide travel time is used as a PM in the developed network robustness index.
Scott et al. (2006)		✓	The impact of a highway section to the change in network level travel-time is evaluated using a developed index called network robustness index
Bell (2000)		✓	The cost of traversing a link is considered.

3.2 Basics of complex networks

Complex networks are networks that not only have a large number of components with complex interconnections with each other but also have complex interactions among these components (Yazdani and Jeffrey, 2012).Complex networks are holistic; in other words, the performance of a complex network (which is determined by the behavior and interactions of its elements as governed by communications and distribution laws) is often superior to the summation of the performance of its individual elements. Examples of complex networks include urban highway systems, the internet, and electricity distribution grids.

Transportation networks can be represented as complex networks because, as in complex networks, transportation networks contain nodes as their basic components in which links connect pairs of nodes that create transfer of information between the nodes. For example, in a city road network, nodes can represent traffic intersections and link represent road sections between nodes. In a regional highway network, nodes can represent cities or counties while links can represent the road connections between the cities or counties (Crucitti et al., 2004).

In the current era, complex networks continue to receive unprecedented attention because they are found useful to adequately represent and analyze different complex systems in the physical world (such as transportation networks) and virtual world, for example, social networks(Wang and Chen, 2003).

There are different types of complex network models: random, small-world and scale-free network models. Random network models are characterized by nodes that have approximately the same number of links. Among real-world networks, a road network is considered as one of random networks (Xie and Levinson, 2007). Random networks often possess small-world effect (Dorogovtsev and Mendes, 2002). The small-world effect describes the situation where every element of the network is close to every other network element in the network (Watts, 1999); this effect is due to the existence of smalldiameter even for largenetworks (Dorogovtsev and Mendes, 2002); in small-world networks, the change in diameter is very small for largechanges in network size.A scale-free network model represents a growing network that is characterized by two properties: incremental growth and preferential attachment (Yao et al., 2007). Incremental growth implies that the networks grow by adding new nodes to the system and preferential attachment refers to the fact that new nodes connect to nodes with higher direct connection with other nodes (Barabasi et al., 2001). This incremental growth and preferential attachment is called self-organization phenomenon (Wang and Chen, 2003). It was found that the probability (p_n) that a node is connected to *n* nodes in the network is proportional to the inverse of degree of the node (which is *n)* raised to some constant parameter c (Xie and Levinson, 2007), i.e.

$$p_n \propto {}^{1}/_{n^c} \tag{3.1}$$

Equation 3.1 represents distribution of degrees of nodes in scale-free networks; this distribution is known as the power-law distribution (Xie and Levinson, 2007).The existence of power-law distribution in scale-free networks implies that these networks are characterized by smaller number of nodes with higher nodal degrees and larger number of nodes with smaller nodal degrees (Dunn and Wilkinson, 2013).The scale-free phenomenon has been observed in the World Wide Web, citation networks, metabolic networks and network of human sexual contacts (Xie and Levinson, 2007).An illustration of a scale-free networkis shown in Figure 3.1. Scale-free networks have higher resistance to failure arising from random events due to existence of hubs that dominate the network structure and reduce the chance that a node is isolated from other nodes. However, the scale-free nature of such networks can render the network particularly exposed to significant disruption if the hub is impaired due to natural or man-made attacks (Strogatz, 2001).

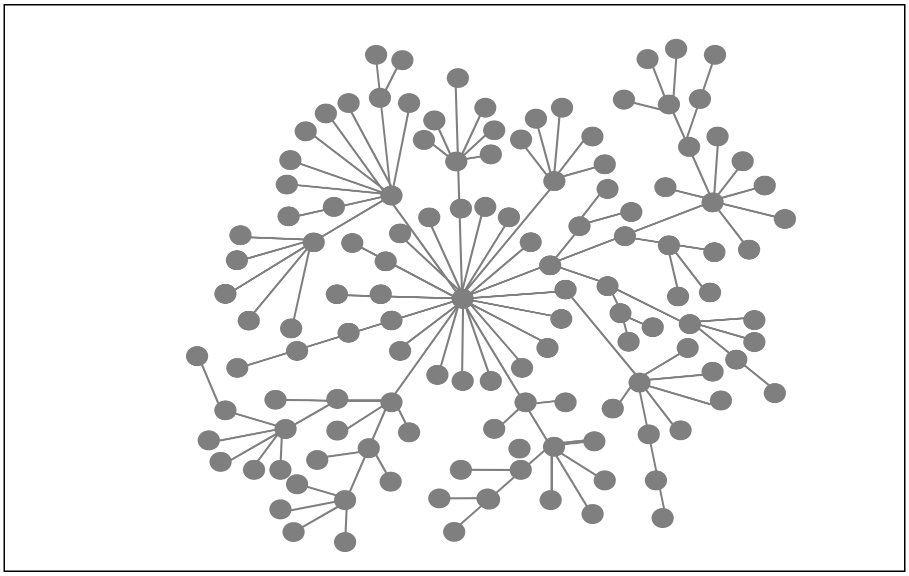


Figure 3.1 A scale-free network

There are many reasons why it is difficult for an urban road network to be considered as a scale-free network. Firstly, it is costly to construct and operate either a grade-separated interchange or a signalized road intersection. Therefore, each road intersection can connect to only a few adjacent intersections. Secondly, due to limited road capacity, it is impractical to connect a road intersection to many adjacent intersections. Thirdly, due to high investment requirement, it is often common to connect road intersections with shorter distance apart (Xie and Levinson, 2007).The degree distribution of transportation infrastructure networks is also affected by the fact that nodes and links of these networks exists only in a one-dimensional plane of the stationary three dimensional Euclidean space; this makes it difficult to physically connect each node to nodes of other dimensions of the network (Erath et al., 2009).

3.3 Network topological PMs

3.3.1 Basic indices for measuring connectivity

A number of measures are used in order to characterize the extent to which the network, i.e., nodes and links, are connected. Few of the network connectivity measures have already been discussed in Chapter 2. In this section, traditionally existing all network connectivity measures are identified, described and interpreted.

The degree of a node (DN) is the total number of nodes that are attached directly to the node(Rodrigue et al., 2006; Costa et al., 2010) (Equation 3.2.):

$$C_i = \sum_j^n C_{ij} \tag{3.2}$$

where C_i= degree of node*i*; C_{ij} =Connectivity between node *i* and node *j* (1 if connected, 0 otherwise); and *n* = number of nodes, excluding the node in question.

The DN is a representation of the node's importance relative to others in a network. From a topological viewpoint, the level of nodal importance is directly proportional to the number of incident links to the node. For example, hub nodes are generally considered to be more important compared to terminal nodes (Rodrigue et al., 2006).

The cyclomatic number is the maximum number of independent cycles of a network (Kansky, 1963; Bon, 1979; Gattuso and Miriello, 2005) (Equation 3.3):

$$\mu = e - v + p \tag{3.3}$$

whereμ= cyclomatic number;*e*=the number of links; and *v*=the number of nodes in the network.

The cyclomatic number measures the network spatial structure and therefore can be used to compare the levels of development of the transportation networksof different countries or of different modes in a given country. Generally, less-developed countries have transportation networks that have low cyclomatic number and thus resemble disconnected graphs or trees whereas transportation networks in developed countrieshave a highcyclomatic number, that is, they are highly interconnected(Kansky, 1963).

The diameter of a network is defined as the length of the longest path between an origin and destination pair (Kansky, 1963; Gatusso and Miriello, 2005).

$$\delta(G) = {}_{x}max_{y}\ d(x, y) \qquad (3.4)$$

where$\delta(G)$ = Diameter of network G; d = topological length measuring the number of links between origin and destination.

The diameter of a transportation network can be used to represent the network extent which, in topological terms, refers to the number of links in the network. The drawback of this connectivity measure is that two different networks may have the same diameter due to their difference in degree of connectivity. Conversely, two networks with the same extent may have different diameter; a network with higher degree of connectivity is generally more likely to have a lower diameter (Kansky, 1963).

The radius of a network.The center of a network is a node or a set of nodes whose greatest shortest distance to any other nodes in the network is the smallest in the network (Diestel, 2000); in other words, the node or set of nodes whose maximum shortest distance to any other nodes in the network is the minimum. This minimum distance is referred to as the radius of the network (Diestel, 2000).

The alpha index is the ratio between the actual number of circuits in the network and the maximum possible number of circuits. Circuits in a network represent closed paths that start and end at the same link. The alpha index is computedfor planar networks using Equation 3.5 (Kansky, 1963; Gatusso and Miriello, 2005).

$$\propto = \frac{\mu}{2v-5)} \qquad (3.5)$$

where $\propto$= alpha index for planar graphs; μ= cyclomatic number; and v=the number of nodes.

The alpha index is a relative measure of connectivity of a network comparing the actual number of circuits with the maximum possible number of circuits in a network.

The beta index is the ratio between number of links and number of nodes in the network (Kansky, 1963; Gatusso and Miriello, 2005):

$$\beta = \frac{e}{v} \qquad (3.6)$$

where β= the beta index; e =the number of links; and v=the number of nodes.

The more complicated the transportation network, the higher the beta index. The beta index value, β, is < 1 for tree structures and disconnected networks; β= 1 for transportation networks with only one circuit; β>1 for complicated transportation networks with a large number of circuits.

The gamma index is the ratio between the existing number of links and the maximumpossible number of links in the network (Kansky, 1963; Sullivan et al., 2010; Bon, 1979; Gattuso, 2005; Taaffe, 1996) and, for planar networks, it can be computed using Equation 3.7.

$$\gamma = \frac{e}{3(v-2)} \tag{3.7}$$

where γ=gamma index; e =the number of links; and v=the number of nodes.

A gamma index 1 (or 100%) represents a completely connected network. The index can be interpreted as the percentage of connectivity (Kansky, 1963).

The eta indexisaratio of sum of all possible links to the actual number of links of the network (Kansky, 1963):

$$\eta = \frac{\mathrm{M}}{\mathrm{e}} \tag{3.8}$$

whereη = eta index; M= total network mileage; and e =the number of links.

Clearly, the eta index of a network is inversely proportional to the number of links. From a topological viewpoint, the eta index can be defined as the sum of all nodes and links in a network to the number of links. However, to give it more meaningful application, it is usually represented by a ratio between network total mileage and the numberof links.

The pi indexmeasures the relation between the entire transportation network and individual links of the network and is represented as a ratio between the total mileage of the network and the diameter of the network (Kansky, 1963; Rodrigue, 2006), and is computed by

$$\pi = \frac{c}{d} \tag{3.9}$$

where: π = pi index; c= the total length or mileage of the entire transportation network; and d =the total length or mileage of the network's diameter.

The pi index, which is equal or greater than 1, expresses the distance per units of diameter and is an indicator of the network shape. A more developed network has higher pi index than a less developed network(Rodrigue et al., 2006).

The theta index is a ratio between the entire network length and its nodes and expressesfunction of the average index (Kansky, 1963):

$$\theta = \frac{M}{V} \tag{3.10}$$

where θ = theta index; M= total network mileage; and v=the number of nodes.

If the total network size is represented by the total mileage of the network, then the theta index represents the average size of the network per node. The theta index simultaneously provides three types of information on the network: length, structure and degree of connectivity (Kansky, 1963).

The Iota index is represented by the ratio between the entire network and its weighted nodes, and is computed using Equation 3.11 (Kansky, 1963).

$$\iota = \frac{M}{W} \tag{3.11}$$

where ι=iota index;*M*= total network mileage; and *w*=the sum of network's nodes weighted by their function.

The iota index is similar to theta index except that the iota index is represented by the ratio between the entire network and its weighted nodes. The nodes are given different weights to account for their differences in length or function. The Iota index takes into consideration three aspects of a network: structure, length and function (Kansky, 1963).

The degree of Connectivity compares a network's connectivity to the minimum and maximum connectivity ratios (Taaffe, 1996)and is represented mathematically (Equation 3.12):

$$d.c. = \frac{\frac{v(v-1)}{2}}{e} \tag{3.12}$$

where*d.c.* = degree of connectivity; *v*=the number of nodes; and *e* =the number of links.

The associated number provides information on the maximum number of links from a given node to each other node in the network. Since the number of links between two nodes can be considered as a measure of topological distance, the associated number, similar to network diameter, can be used as a measure of the topological extent of the

The degree of circuity is a measure of the relative location of nodes of a network. It is computed as follows:

$$DC=\frac{\sum_{i=1}^{n}(E-D)^2}{V} \tag{3.13}$$

where*DC*= Degree of circuity;E, *D*= real and straight-line distances, respectively between nodes; and *n*=number of nodes.

3.3.2 Demonstration of basic indices using example network

As described in Section 3.3.1, there are several indices that can be used to measure the connectivity performance of a network. In this section, an example network is considered to demonstrate how these indices can be applied to evaluate the performance of a network. To interpret the connectivity measures described in Section 3.3.1, consider a small 4-link, 5-node sample network shown as Figure 3.2. The distance across the links (in miles) is taken as the cost of the link. In real –world problems, these costs could be link travel time, generalized travel cost, etc.

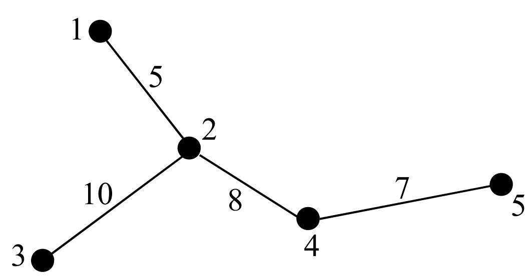


Figure 3.2 Sample network

Table 3.2 presents the results of the connectivity and connectivity analyses for the sample network. From a topological perspective, node 2 is the most accessible, followed by node 4. Nodes 1, 3, and 5 are equally the least accessible nodes in the network. The cyclomatic number of the sample network is zero which confirms that there are no circuits (closed paths) in the network. The diameter of the network is 25 miles.

The alpha index of the network (as a percentage) is zero, implying that the network attains zero percent of the maximum connectivity possible. The beta index is an indication of the degree of complication of the network. For trees (such this sample network) and disconnected graphs, the beta index is less than zero. The gamma index is a ratio between the actual number of links in the network and the maximum possible number of links, this represents the relative connectivity of the network.In this regard, the sample network is 67% connected compared with the maximum connectivity possible. The eta index of the network is 7.5 miles/link. For a given network, addition of nodes will resultin a decrease in the eta index.Therefore, a lower eta index indicates a more developed network. The pi index of the sample network is 1.2; the higher the pi index, the more developed the network. The sample network has a theta index of 6 miles per node and an iota index is 2.31 miles per weighted node. The iota index takes into consideration the importance of nodes. In the sample network, the end points and the interior (intersection) nodes were taken as having two and eight practical functions, respectively (Kansky, 1963). The degree of connectivity of the network is 2.5 which shows the relative position of the connectivity between the maximum connectivity ratio, given by $\frac{\frac{v(v-1)}{2}}{\frac{v(v-1)}{2}}$, where v is the number of nodes, which is1, and the minimum connectivity ratio, given by $\frac{\frac{v(v-1)}{2}}{v-1}$, which is 2.5.

The Shimbel distance (D-matrix) displays, in matrix form, the number of links required to go from each node to every other node in the network. For the network example, node 2 is the most accessible network because it takes the least number of links to go from that node to every other node in the network. On the other hand, node 5 is the least accessible node by similar reasoning. In terms of nodal connectivity index, node 3 has the highest connectivity (68 miles) whereas node 2 has the lowest (38 miles).

The degree of circuity of the network is 0 which implies that the real distance between any two nodes in the network is the straight line (the shortest) distance between the nodes. This is obvious for the network example since we assumed straight line connection between nodes.In real world application, however, the real distances between nodes may be different from the straight line distances because constraints such as physical, environmental and land use restrictions may not allow nodes to be connected to each other using straight-line distances.

Table 3.2 Calculated indices for example network shown in Figure 3.2

Measures	Calculated Index
Degree of a node (C_i)	C_1=1; C_2=3;C_3=1; C_4=2; C_5=1.
Cyclomatic number (μ)	μ=0
Diameter (δ(G))	δ(G) = 25 miles
Alpha index (∝)	∝ = 0
Beta index (β)	β=0.8
Gamma index (γ)	γ=0.67
Eta index (η)	η=7.5 miles per link
Pi index (π)	π = 1.2
Theta index (θ)	θ=6 miles per node
Iota index (ι)	ι =2.31 miles per weighted node
Degree of Connectivity ($d.c.$)	$d.c.$ = 2.5
Degree of Circuity (DC)	DC=0

3.3.3 Centrality measures

3.3.3.1 Degree centrality

Degree centrality measures the importance of a node is based on the number of connections it has with other nodes in the network (Latora and Marchiori, 2007). Consider a network *G* with adjacency matrix *N* x *N*, where *N* is the number of nodes, with matrix elementsa_{ij} represented as:

$$a_{ij} = \begin{cases} 1 \text{ if nodes } i \text{ and } j \text{are connected} \\ \quad 0, \quad \text{otherwise} \end{cases}$$

The degree centrality of node *i*,C_i^D,can be computed using Equation 3.18.

$$C_i^D = \frac{k_i}{N-1} = \frac{\sum_{j \epsilon G} a_{ij}}{N-1} \quad (3.18)$$

where C_i^D= degree centrality of node *i*; k_i= the degree of node *i*.

For the sample network shown in Figure 3.2, *N*= 5, k_1= k_3= k_5= 1, k_2= 3 and k_4= 2, and applying Equation 3.16, the degree centralities of the nodes are C_1^D= C_3^D= C_5^D= 0.25, C_2^D= 0.60and C_4^D= 0.5.

3.3.3.2 Closeness centrality (CC)

CC is a measure of the inverse of the average shortest path from a given node *i* to all other nodes in the network (Erath et al., 2009). It can be calculated as:

$$C_i^C = \frac{N-1}{\sum_{j \epsilon N;\, i \neq j} d_{ij}} \tag{3.19}$$

where C_i^C = CC of node *i*; *N*= number of nodes in the network; d_{ij}= shortest path between node*I* and *j*.

The CC of a node depends on its geographical location in the considered network under consideration (Erath et al., 2009).

For the sample network shown in Figure 3.2,*N*= 5; d_{12}= 5, d_{13} = d_{31}=15, d_{14}=d_{41}=13, d_{15} =d_{51}=20, d_{23}=d_{32}=10, d_{24}=d_{42}=8, d_{25}=d_{52}=15, d_{34}=d_{43}=18, d_{35}=d_{53}=25, and d_{45}=d_{54}=7; $\sum_{j \epsilon N;\, 1 \neq j} d_{1j}$=53, $\sum_{j \epsilon N;\, 2 \neq j} d_{2j}$=38, $\sum_{j \epsilon N;\, 3 \neq j} d_{3j}$= 68, $\sum_{j \epsilon N;\, 4 \neq j} d_{4j}$= 46, $\sum_{j \epsilon N;\, 15 \neq j} d_{5j}$= 67. Therefore, applying Equation 2.17, the closeness centralities of nodes 1 through 5 are C_1^C = 0.075, C_2^C= 0.105, C_3^C =0.059, C_4^C =0.087 and C_5^C =0.060.

3.3.3.3 Betweenness Centrality (BC)

The BC of a node measures the number of shortest paths in a network that pass through the node ((Erath et al., 2009). It is computed as:

$$C_i^B = \frac{1}{(N-1)(N-2)} \sum_{j,k \epsilon N; j \neq k; j; k \neq i} \frac{n_{jk}(i)}{n_{jk}} \tag{3.20}$$

in which C_i^B= BC of node*i;N*=number of nodes in the network; n_{jk}= *the number of shortest paths between the nodes j and k;* $n_{jk}(i)$=*the number of* pathbetween nodes *j* and *k* that pass through node *i*.

For the sample network shown in Figure 3.2, N= 5; $\frac{1}{(N-1)(N-2)} = \frac{1}{(5-1)(5-2)} =$ 0.083; $C_1^B = 0.083 * \left(\frac{n_{12}(1)}{n_{12}} + \frac{n_{13}(1)}{n_{13}} + \frac{n_{14}(1)}{n_{14}} + \frac{n_{15}(1)}{n_{15}} + \frac{n_{23}(1)}{n_{23}} + \frac{n_{24}(1)}{n_{24}} + \frac{n_{25}(1)}{n_{25}} + \frac{n_{32}(1)}{n_{32}} + \frac{n_{34}(1)}{n_{34}} + \frac{n_{35}(1)}{n_{35}} + \frac{n_{42}(1)}{n_{42}} + \frac{n_{43}(1)}{n_{43}} + \frac{n_{45}(1)}{n_{45}} + \frac{n_{52}(1)}{n_{52}} + \frac{n_{53}(1)}{n_{53}} + \frac{n_{54}(1)}{n_{54}}\right) = 0.083*$ $\left(\frac{0}{1} + \frac{0}{1} + \frac{0}{1} + \frac{0}{1} + \frac{0}{1} + \frac{0}{1} + \frac{0}{1} + \frac{0}{1} + \frac{0}{1} + \frac{0}{1} + \frac{0}{1} + \frac{0}{1} + \frac{0}{1} + \frac{0}{1} + \frac{0}{1} + \frac{0}{1}\right) = 0.000.$ Similarly, $C_2^B = 0.664$; $C_3^B = 0.000$, $C_4^B = 0.249$, $C_5^B = 0.000$.

3.3.3.4 Link Betweenness Centrality (LBC)

The LBC is defined as the number of shortest paths in a network that pass through a link ((Erath et al., 2009). It can be determined in a similar fashion as between centrality described in Section 3.3.3.3.

3.3.4 Tour-related PMs

Transportation infrastructure projects can and do change the topological characteristics of the transportation network, and therefore affect how stakeholders carry out routing operations on the networkin order to minimize the cost of doing businesses. Therefore, in order to improve network performance by implementing projects, it is vital to know the different types of trips that are typically could be made by the stakeholders. This section describes the types of trips through a network, their definitions and characteristics.

3.3.4.1 Shortest path through a network

Shortest paths are often preferred when sending goods, services or information from an origin to a destination in a network. This is because the shortest path between any two nodes in the network is the optimal route (Boccaletti et al., 2006) in terms of the cost, or convenience associated with traversing the path.

A number of network topology PMs incorporate, directly or indirectly, the concept of shortest paths. For example, BC of a node is a measure of the percentage of all shortest paths in the network that pass through that node in the network. Other PMs associated with shortest path length and used in this dissertation include the BC of a link and network diameter. For a highly-connected network, it is reasonable to expect that the shortest-path length between any two nodes in the network is generally likely to besmall.

3.3.4.2 Minimum spanning trees

A tree is a connected network with no cycle. Every path in the network is regarded as a tree; therefore, a tree can be defined as the minimum possible connected path in a network (Wallis, 2007).A spanning tree is a sub-network in a network that is a tree by itself (Wallis, 2007). A spanning tree exists in every connected network (Diestel, 2000) and a network may have one or more spanning trees. Thus, minimum spanning tree of the network is a spanning tree whose total link weight is minimum(Wallis, 2007, Ahuja et al., 1993).

In rural areas of developing countries, the main objective may be to connect the different populations living in different locations. There is often limitation of budget to provide adequate infrastructure to maximize connectivity. Therefore, to achieve some desired or minimum connection among the various rural populations, the concept of minimum spanning tree may be applicable.

3.3.4.3 The traveling salesman path in a network

The traveling salesman path (TSP) is the least-cost route taken to visit each node in the network exactly once and return to the starting node. The cost of traversing the links may be represented in terms of out-of-pocket travel costs, distance or time for traveling along the link. It is computationally challenging to solve the TSP problem. There is no algorithm that is capable of solving the TSP problem other than listing all Hamilton cycles which are cycles that visit each node exactly once (Wallis, 2007).

The TSP has been applied to solve problems in a variety of disciplines to solve problems. For example, logistics problems such as salesman routing, tourist routing, school bus routing, postal deliveries and inspection of working areas; genome sequencing, i.e., mapping of human genome; aiming telescope to take images of a large number of galaxies; data clustering to organize data based on their similarities; machine scheduling for certain tasks; minimizing wall-paper waste; pattern-cutting in a glass industry; and controlling photo plotter during drawing(David et al., 2011).

3.3.4.4 The Chinese postman path in a network

The Chinese Postman Problem(CPP) is one of combinatorial optimization problems that are widely studied and are useful problems to solve (Gutin et al., 2013). It has been applied to solve problems such as analysis of DNA, routing robots, routing snow removal in winter season or planning road maintenance activities (Thimbleby, 2003). If *G* is a connected network containing *N* vertices andlinks, then the CPP is about finding a closed path in the network, that contains all links of *G* and the total cost of the closed path is the minimum (Gutin et al., 2013).

There are some variations of the CPP. The problem may be that the postman or the traveler may want to return to the starting node after traversing all the nodes with the minimum possible cost, a problem often known as Closed CPP or CPP cycle. If the postman or the traveler is not planning to return to the starting node, the problem is called Open CPP or CPP trail. In some cases, the postman or the traveler must visit certain nodes and may not be required to visit other links. In this case the problem is called Rural CPP. In this dissertation, a closed CPP is considered and CPP refers to Closed CPP unless and otherwise stated.

3.4 Chapter summary

This chapter presented the literature on the traditional transportation investment prioritization practices. It was known that these traditional practices do not take into consideration the impact of the project selection on network connectivity.This chapter also presented a literature review on networks and their topological properties, and dealt specifically with network types and basic topological indices.A sample network was used to demonstrate how the topological PM could be computedand interpreted. It is observed from the sample network analysis that these topological indices measure different topological aspects of a network, and could also be used to compare network performance in terms of network connectivity. The chapter also presented the different types of centrality measures, trips, and routing a network. The next chapter, Chapter 4, presents results of network performance analyses that were conducted on a real-world network, utilizing some of the network PMs discussed in this chapter. This was done to evaluate the impact of transportation investment selection on the network performance.

CHAPTER 4. PROJECT PROGRAMMING IMPACTS ON INDIVIDUALNETWORK TOPOLOGICAL PERFORMANCE MEASURES (PMCS)

This chapter presents results of network performance analyses that were conducted on a real-world network. Typical network PMs were considered to evaluate the impact of transportation link construction projects on the network performance. The implications of the results are discussed.

4.1 Network Definition

The case study network considered is the highway network system of Ethiopia. The graphical representation of the Ethiopian highway network is showninFigure 4.1. The considered highway network is composed of90 nodes and 119 links. The lengths in miles betwee nodes are given in Appendix B. Some of the nodes represent major cities in the country. For example, thecapital city, Addis Ababa, is represented by node 35. Other cities such as Bahir Dar, Mekelle, Dire Dawa, Jijiga, Dese and Asosaare located at nodes 20, 8, 38, 40, 21 and 31, respectively. Some cities are located along links, such as Harer along link 38-39, Gonder along link 9-12, Debre Markos along link 27-29 and Awasa along link 57-62.

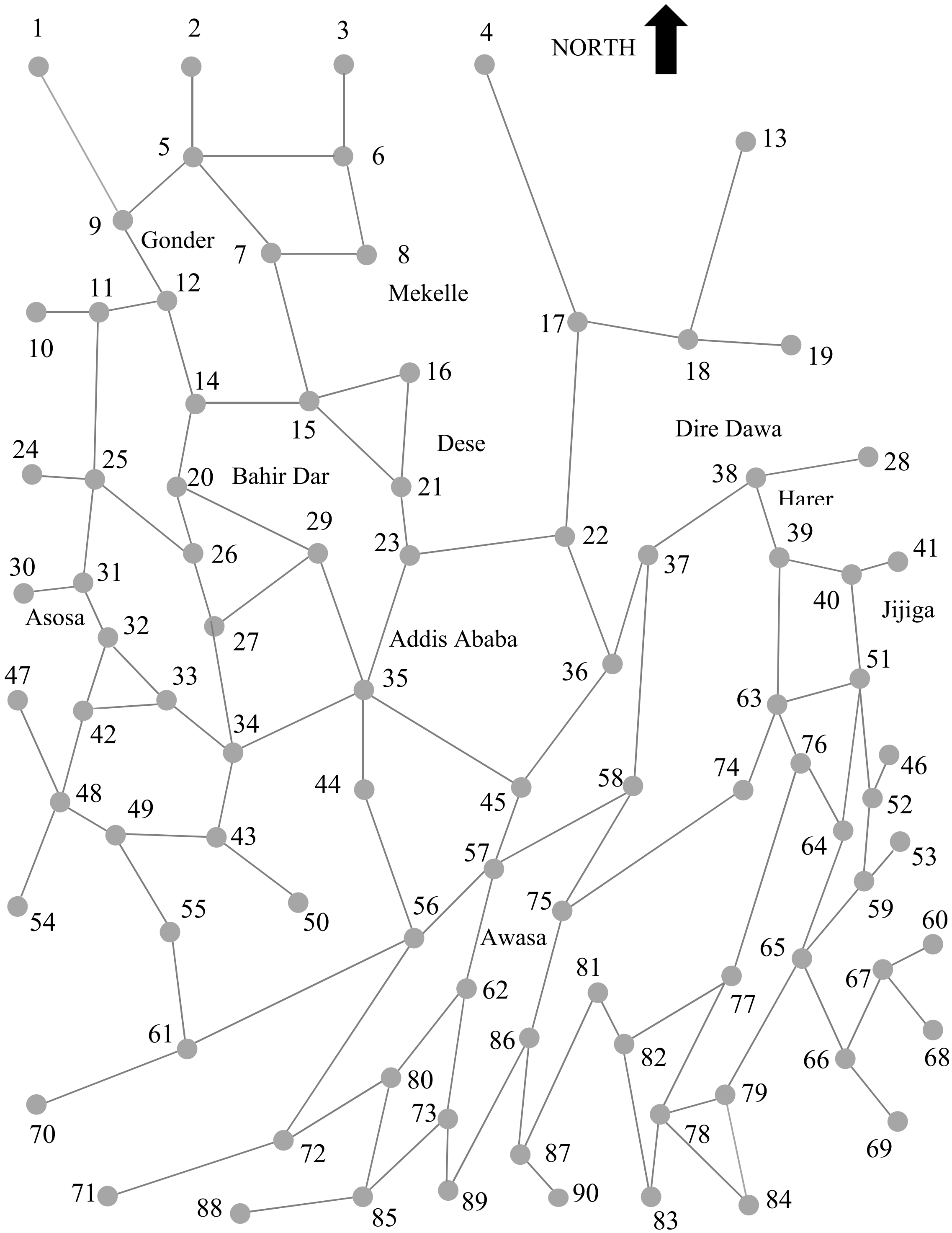


Figure 4.1 Graphical representation of Ethiopian highway network

4.2 Investment selection and network topological performance

Some network-level PMs, namely network diameter, pi index, network connectivity, were considered to evaluate how link construction projects could affect the topological performance of the network with respect to the considered PMs. The significances of the considered PMs were discussed in Section 3.3 .

The main objective of the analysis made in this chapter is to show that construction projects could affect the network topological performance with respect to the considered PMs, and argue that network topological performance should be considered along with other project selection criteria such as economic, environmental efficiency and social factors. Forty candidate link construction projects are considered. Of these projects, some are assumed to be selected for implementation. The computer program written using Python programing language to compute the topological performance values in this chapter is given in Appendix C.

Figure 4.2 shows how candidate link construction projects could impact the network diameter if implemented. It is shown in the Figure that candidate project 65-67 brings the highest percent reduction in network diameter (1.39), followed by projects 36-36 and 35-43 both of which cause reduction of based network diameter by about 0.39 percent. It is shown that other projects do not have any impact on the network diameter. These observations show that some projects are very useful in reducing the network diameter. A smaller network diameter indicates that the network is well-developed in terms of connectivity since the farthest nodes in the network are closer to each other when the diameter is relatively smaller. Therefore, projects which minimize network diameter are most likely desirable in order to improve network topological performance.

As shown in Figure 4.3, except project 13-17 which has zero impact on the network connectivity, all other projects have positive but highly variable impacts on the network connectivity. Projects 22-38 and 71-85 bringthe highest (4.01 percent) and the lowest (0.01 percent) percent increase in the network connectivity, respectively. 33 projects increase the network connectivity at most by about 0.8 percent, 6 projects improve the network connectivity by more than 0.8 percent. 4 projects increase the network connectivity by more than 1.5 percent. These results show the need to evaluate the impact of projects on network topological performance with respect to the connectivity measure, and prioritize projects for the sake of improving this PM.

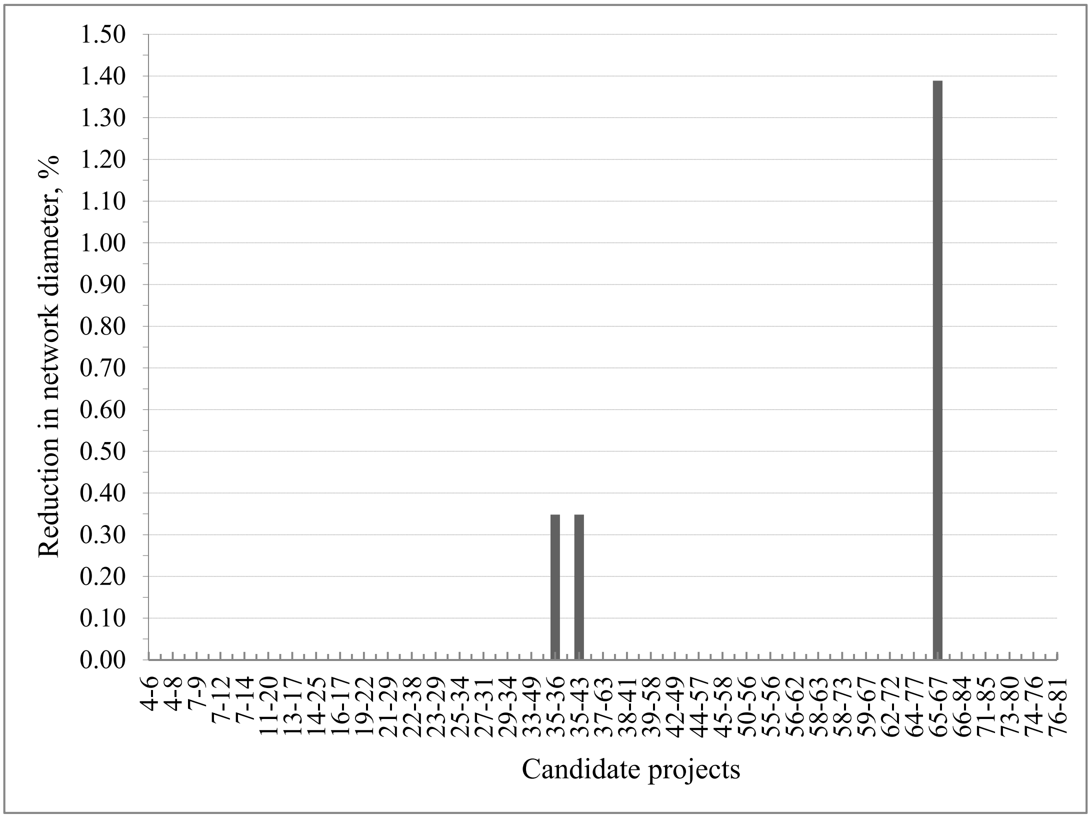


Figure 4.2 Impact of projects on network diameter

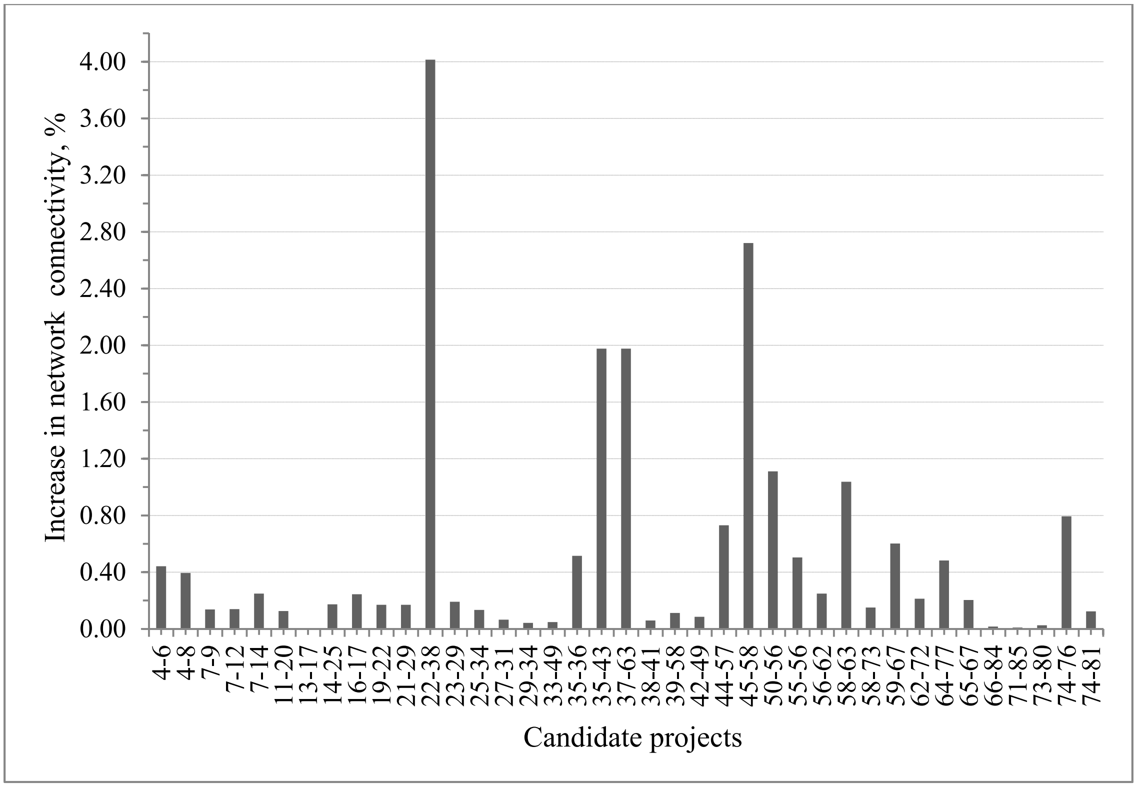


Figure 4.3 Impact of projects on network connectivity

Figure 4.4 presents how projects could affect the pi index of the network. As described in Section 3.3, a network with higher pi index is relatively highly developed compared to a network with a lower pi index because in the case of the network with higher pi index, relatively higher mileage can be traversed without significant increase in the network diameter. Link 59-67 improved the pi index by about 6.4 percent, followed by link 65-67 with 1.4 percent, and 35-36 and 35-43 each with 0.35 percent. The remaining projects do not show any improvement with respect to the pi index. Therefore, with respect to this PM and when a single project should be implemented, link 59-67 is the best candidate. However, if two or more projects should be simultaneously implemented, further analysis is required, as described in the next section, because selection of, for example, links 59-67 and 65-67, may not guarantee the best network performance because other pairs of projects may significantly improve the network pi index.

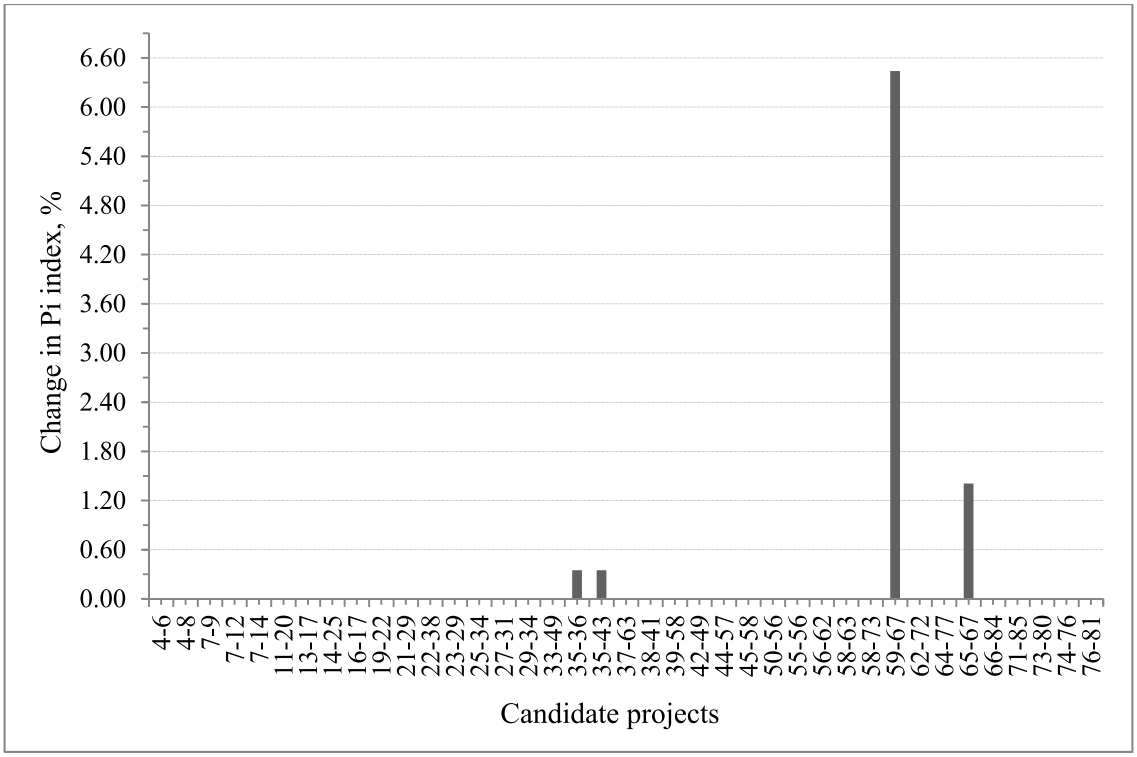


Figure 4.4 Impact of projects on pi index

4.3 Project prioritization and network topological performance

Prioritization of projects and selecting the best performing projects may not necessarily guarantee higher network topological performance, for example, in terms of network connectivity, because the combined effects of the selected projects may not necessarily be the same as the summation of individual effects of the projects. To investigate this hypothesis, consider the connectivity results discussed in section 4.2 and assume that decision maker chooses three projects based on their rank in terms of network connectivity. From Figure 4.3, it is shown that link 22-38 increases the network connectivity by the highest percentage compared to other projects (by about 4.01 percent) followed by link 45-58 (about 2.72 percent) and 35-43 and 37-63 (both by 1.98 percent). The label for candidate projects is given in

Table 4.1. As it can be noted from Figure 4.3, links 22-38, 35-43 and 45-58 can bring the first three highest percent change in network connectivity of 4.01, 1.98 and 2.72, respectively, compared to the other projects. However, if the decision maker decides to

select and implement these three projects, the combined network connectivity due to these project is not the highest improvement when compared with network connectivity improvements duet to the three individual projects. The highest percent change in the network connectivity of 7.29 comes from simultaneous implementation of links 22-38, 45-58, and 58-63, represented by Label 6 in Figure 4.5, rather than simultaneous implementation of links 22-38, 35-43 and 45-58, implying that the combined effects of projects on network topological performance with respect to a topological measure should be considered in addition to the effect of each project.

Table 4.1 Group of Candidate Projects shown in Figures 4.5 and 4.6

Possible Combination of Projects	Group Number
22-38, 35-43, 45-58	1
22-38, 35-43, 50-56	2
22-38, 35-43, 58-63	3
22-38, 35-43, 74-76	4
22-38, 45-58, 50-56	5
22-38, 45-58, 58-63	6
22-38, 45-58, 74-76	7
22-38, 50-56, 58-63	8
22-38, 50-56, 74-76	9
22-38, 58-63, 74-76	10
35-43,45-58,50-56	11
35-43,45-58,58-63	12
35-43,45-58,74-76	13
35-43, 50-56, 58-63	14
35-43, 50-56, 74-76	15
35-43, 58-63, 74-76	16
45-58,50-56, 58-63	17
45-58,50-56, 74-76	18
45-58, 58-63, 74-76	19
50-56, 58-63, 74-76	20

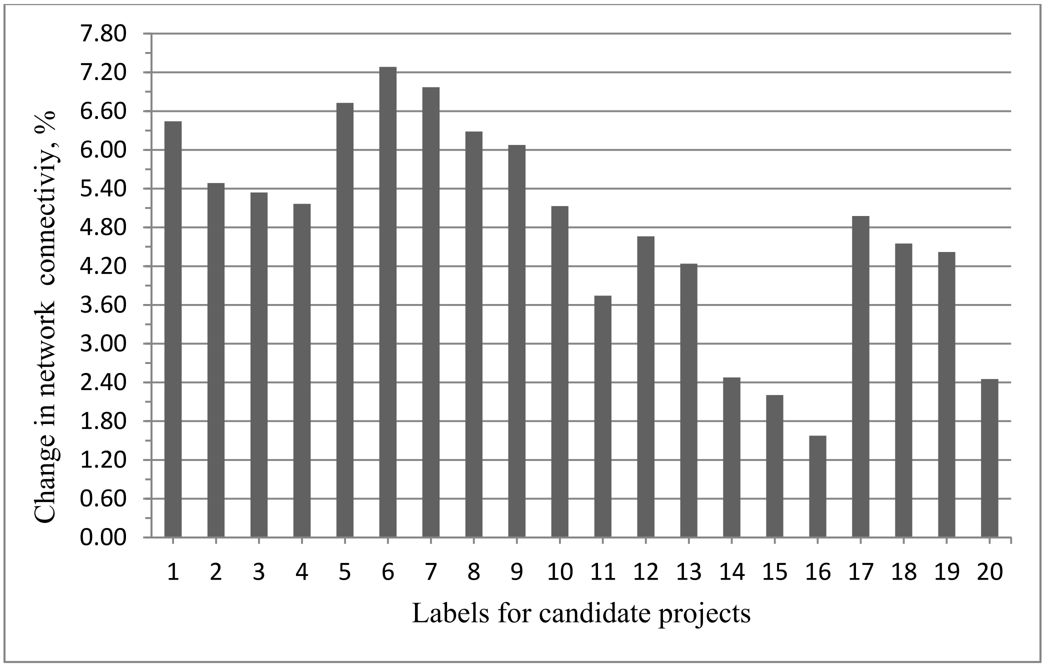


Figure 4.5 Effect of group of projects on network connectivity

Link 65-67 has reduced the network diameter by about 1.39 % (the highest reduction compared to all other links). Links 35-36 and 35-43 both reduced the network diameter by approximately 0.35%.All other links did not reduce the network diameter. Therefore, in situations where a single project should be implemented, link 65-67 is the most preferable. However, in situations where two or more links should be implemented, ranking and prioritization of projects merely based on their individual importance in improving network topological performance may not guarantee improved network performance. For example, asshown in Figure 4.2, links 22-38, 50-56, 58-63 do not bring any reduction in network diameter if they are selected by analyzing their performance individually; they are, in fact, the least preferable compared to other projects. However, when these links are simultaneously considered and their performance analyzed, these links offer the highest reduction in network diameter (about 3.14 percent) (see Label 8 in Figure 4.6). Therefore, project selection should broadly consider all link performance scenarios to guarantee improved network performance.

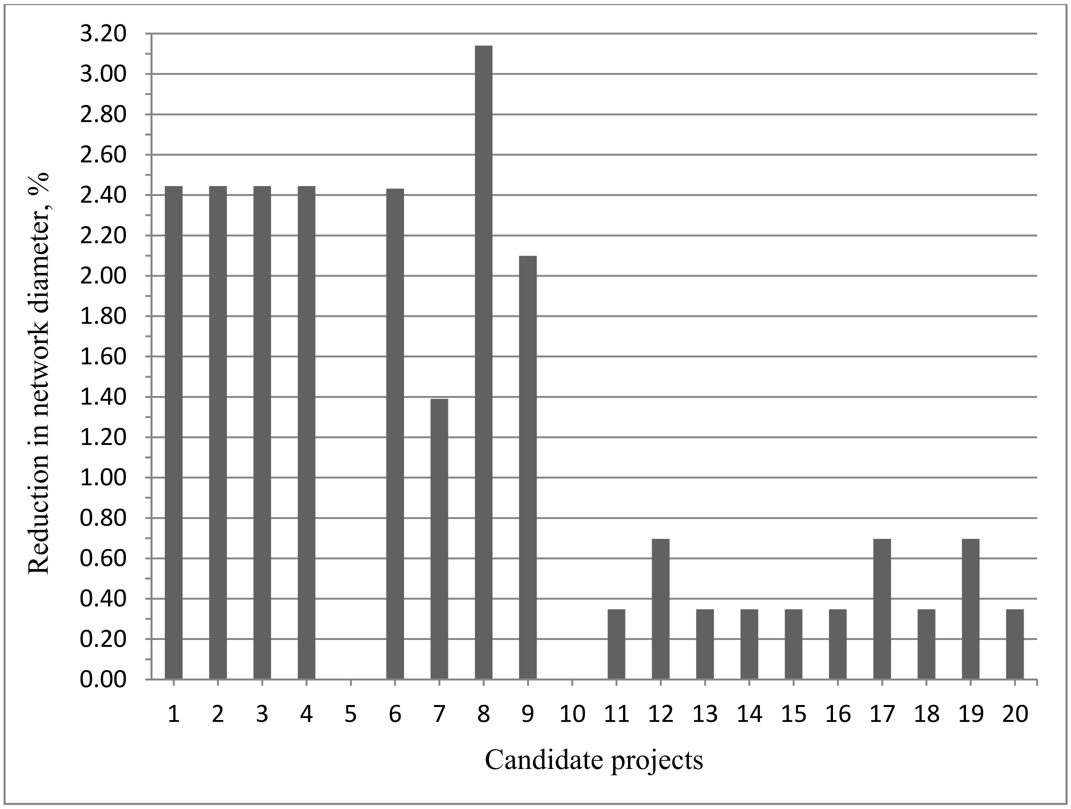


Figure 4.6 Effectof group of projects on network diameter

4.4 Discussion

As demonstrated in the previous sections of this chapter, projects influence network topological performance in various ways depending on whether they are considered individually or together with other candidate projects during network topological analysis. It is demonstrated that the overall topological performance impact of a number of projects can be significantly different from the sum of their individual topological performance impacts. In other words, the effect of the sum of the stimuli is superior to the sum of the individual effects of the stimuli; this is consistent with holism, a basic concept in systems engineering. More importantly, this finding suggests that inter-project interdependencies, a phenomenon whose characterization has been largely elusive in investment evaluation literature, can finally be demonstrated and measured in terms of network topological performance.

4.5 Chapter summary

In this chapter, a case study using a real-world network was conducted to show how project selection could impact individual PM values. It was shown that network topological performance analysis by merely considering individual projects at a time during the analysis could provide ranking of projects that may not guarantee the maximum possible network topological performance that could be obtained by implementing the top ranked projects; this chapter showed the presence of inter-project interdependencies and the existence of holism that affect network topological performance. The next chapter, Chapter 5, presents the developed PMTCs thatwould be used during transportation investment decisions.

CHAPTER 5. EVALUATION OF TRANSPORTATION NETWORKS USING MULTIPLE NETWORK TOPOLOGY-RELATED PERFORMANCE MEASURES

5.1 Introduction

This chapter describes the process of developing PM tradeoff curves (PMTCs). This is important for supporting decisions pertinent to transportation network PMs. First, the steps used in generating the PMTCs are described followed by description of the process of random network generation that was used in developing the PMTCs. Then, the PMs that were considered in PMTC generation are described. Next, the developed PMTCs are presented and their descriptions are provided.

5.2 Tradeoffs and indifference curves

5.2.1 Prelude

By implementing a project, the extent to which a given network PM is impacted may be different from the extent to which another network PM is impacted. Tradeoff analysis can be conducted to investigate the relationship between each pair of network PMs. Indifference curves can be used to analyze such tradeoffs. For example, if the PMTC shows a strong inverse relationship between BC and CC PMs, tradeoff analysis can be conducted to show how the change in one of the PMs causes a change in the other perfroamcne measure.

5.2.2 Steps for generating PMTCs

The PMTCs were developed to compare each pair of network PMs that could be considered in transportation infrastructure investment decision making.

In developing the PMTCs, randomly-generated networks were considered to obtain representative PM values for real-world transportation networks. In addition, many topological PMs were considered.

The PMTC was developed using the following steps:

Step 1. Generate a network

Step 2. Compute PM values

Step 3.Record the PM values

Step 4. Repeat Steps 1 – 3 for each of randomly-generated networks.

Step 5.Plot each pair of PMs

The PMs used in developing PMTCs are BC, LBC, nodal degree, network diameter, CC, shortest path length and number of independent paths. Network average PM values were used, whenever applicable, in generating the curves. The descriptions of these and other PMs are given sections 3.3, 3.3.4 and 6.3.3.

5.3 Random network generation

Random networks (RNs) were generated and network PMs were computed using a computer program that was written using python programming language (van Rossum, 2012), python-igraph network package (Csárdi and Nepusz, 2006) and Pandas network package (McKinney, 2013). The computer program is given in Appendix D and the general pseudo-code is given in Figure 5.1. A random network with a randomly-determined number of nodes between 30 and 35 nodes and random number of links was generated. Average values of PMs were determined for each generated network and were automatically saved into a spreadsheet file for further analysis of the data. Graphs showing the relationship between pairs of network-level PMs were plotted.

.

```
Start the Program
Set number of nodes randomly between 30 and 35
Generate connected networks
    For each network, do the following:
        Compute BC, LBC, ND, CC, SPL, Diam, and
            NIndPath
        Save the network attributes as network.csv
End the program
```

Figure 5.1 Pseudo-code for random network generation and computation of PM values

5.4 PMTC generation and discussion

Tables D1 through D17 in Appendix E present regression equations that show the functional relationships between pairs of PMs and the corresponding R^2 values. The PMs were discussed in section 3.3. In order to ensure that the outputs obtained using randomly-generated networks are representative of actual functional relationships, six computer runs were made and the regression equations and their R^2 values were compared. Also, regressions equations based on the average values of data obtained from six computer runs were developed.

The functional relationships between the following PMs were found to be insignificant with very low R^2 values ranging from 0.003 to 0.246, as shown in Tables D1 through D17 in Appendix E: AvgBC and AvgND, AvgBC and Diam, AvgBC and AvgSPL, AvgBC and NIndPath, AvgLBC and AvgND, AvgLBC and Diam, AvgLBC and AvgSPL, AvgLBC and NIndPath, AvgND and Diam, AvgND and AvgCC, AvgND and AvgSPL, Diam and AvgCC, Diam and AvgSPL, AvgCC and AvgSPL, AvgCC and NIndPath, and AvgSPL and NIndPath. The relationships are consistent for all computer runs and hence it can be concluded that in actual situations there is no functional relationship between the pairs of PMs mentioned above.

The repeatability of the computer output for randomly-generated networks was evaluated by plotting all outputs of all computer runs and evaluating the pattern of relationship between pairs of PMs. These plots are shown in Appendix E in Tables D1 through 17.

Figure 5.2 shows similar relationships between network average BC and LBC for all computer runs. Based on the best fit regression line, linear relationship exists between network average BC and LBC. A decision maker can utilize any of this relationship from any of the computer runs to evaluate the impact of transportation infrastructure investment decisions.

It is generally known that a decision maker would like to maximize network PMs that have desirable properties. For example, BC is a desirable PM and therefore a decision maker would like to maximize network-level BC. Whenever inverse relationship exists between pairs of desirable PMs which a decision maker would like to maximize, tradeoff analysis can be conducted between the pairs of desirable PMs (for example, see Figure 5.3 and Figure 5.4).

Figure 5.3 shows that there is inverse linear relationship between network average BC and CC. All the computer runs showed very similar results and hence the developed functional relationship between the two PMs can be used in analyzing transportation decision making.

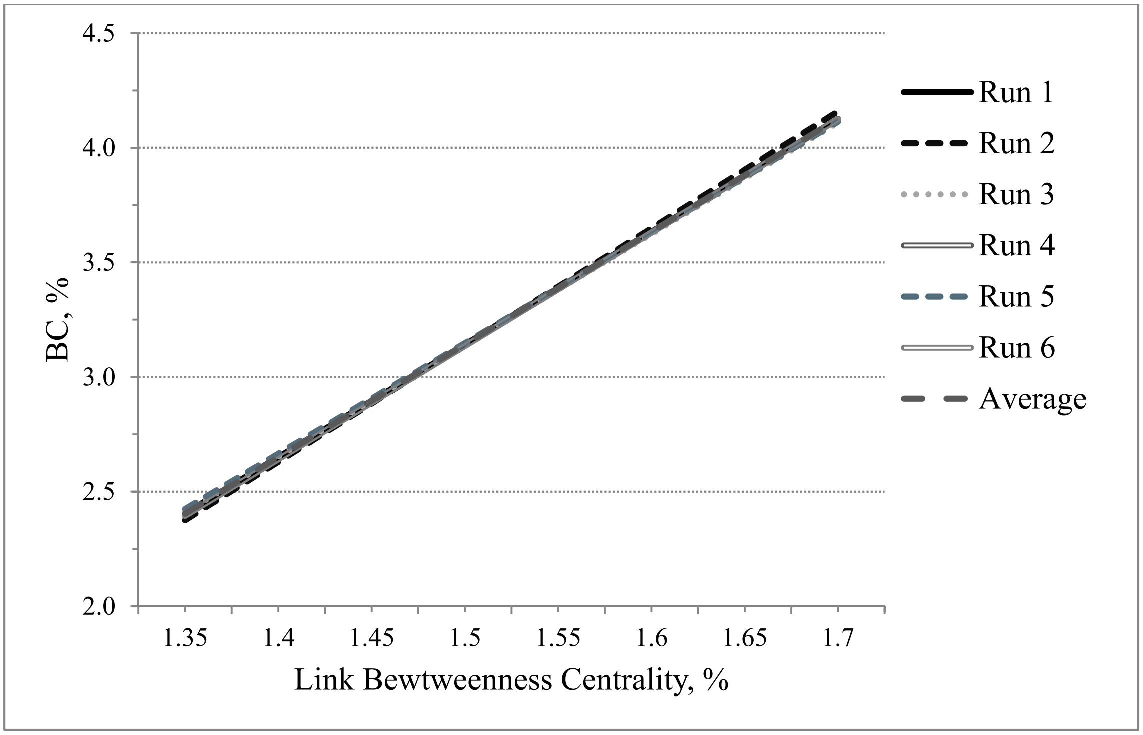


Figure 5.2 Avg. betweenness centrality (BC) vs. avg. link betweenness centrality (LBC)

A nonlinear inverse relationship was found to exist between network average LBC and CC (Figure 5.4), and therefore tradeoff analysis can be conducted between the two PMs. All computer outputs showed similar results, implying that the existing relationship can be applied for actual transportation network to evaluate how a link construction can affect the network topological performance with respect to these PMs.

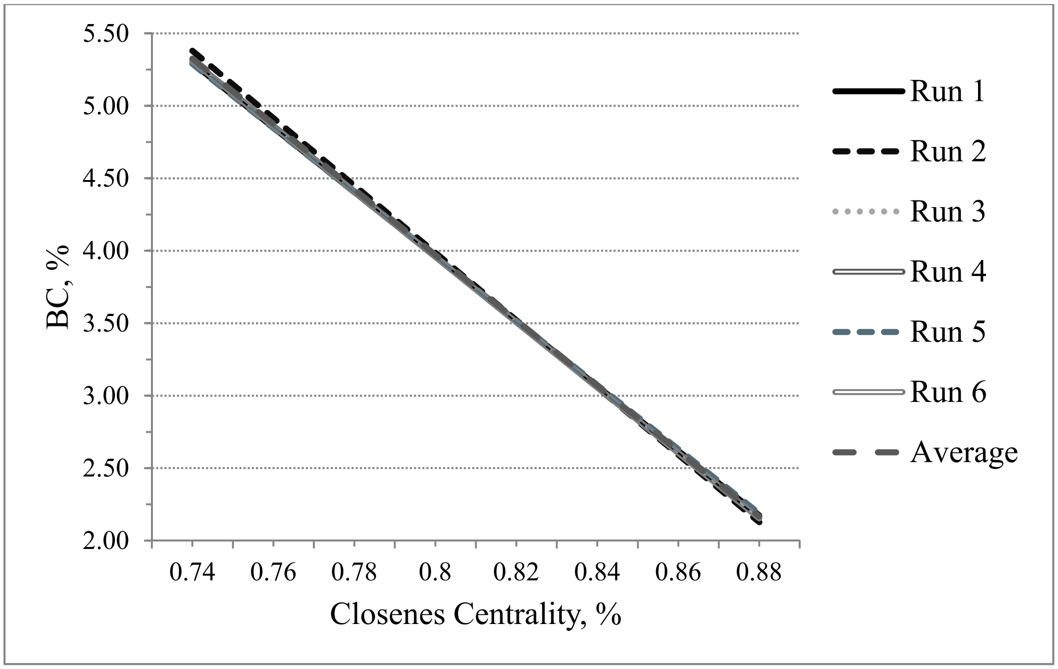


Figure 5.3 Tradeoff plot: BC vs. closeness centrality (CC)

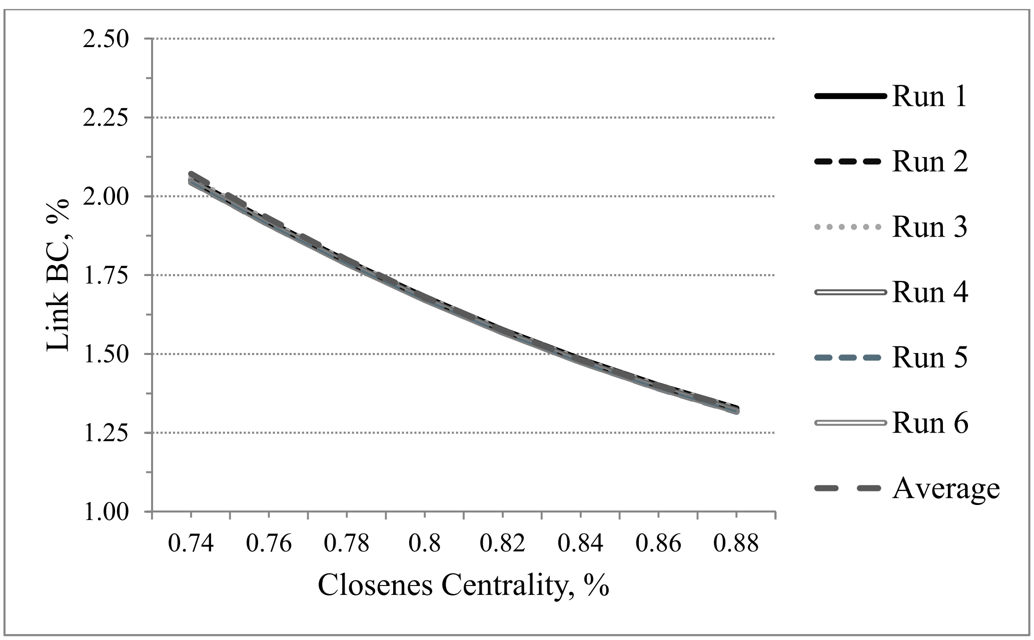


Figure 5.4 Tradeoff plot: link BC vs. closeness centrality (CC)

Figure 5.5 shows that the computer outputs for different runs show linear relationship between network average nodal degree and number of independent paths between nodes. The relationships between the two PMs obtained for all computer runs are generally similar except for a few variations. These relationships can be utilized by a decision maker to predict the level of network average LBC if the network average BC is set to a particular level.

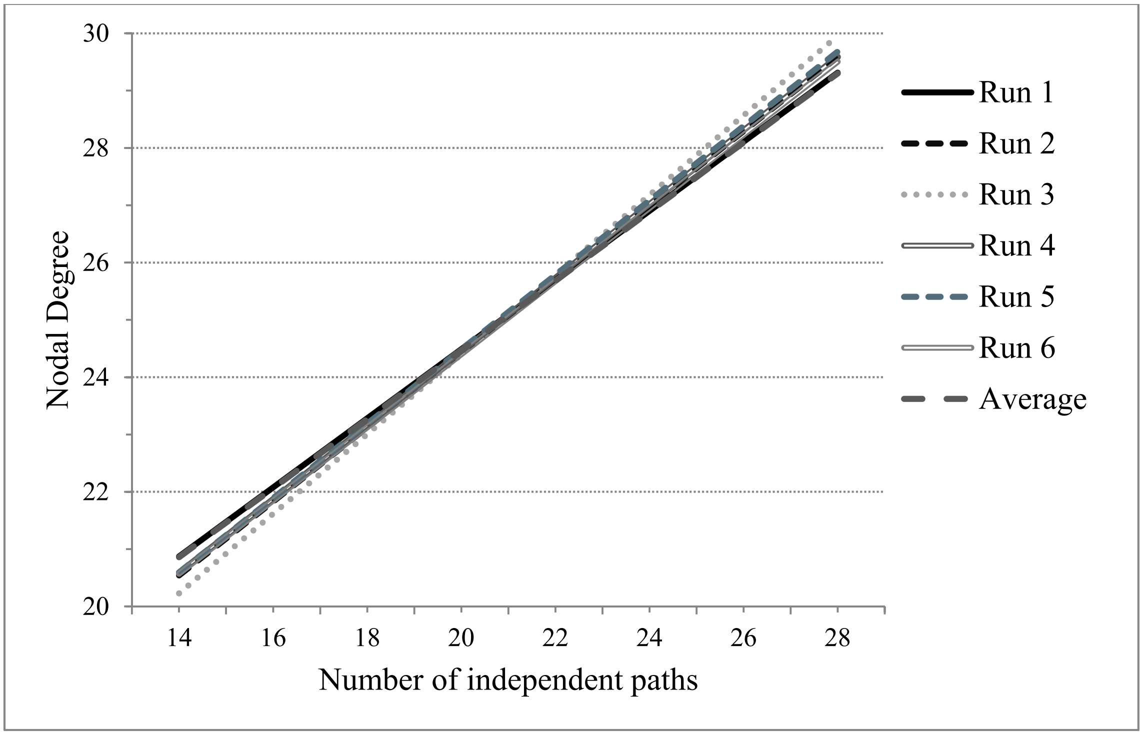


Figure 5.5 Avg. Nodal degree vs. avg. number of independent paths

The resulting graphs showing the relationship between pairs of PMs were prepared. These graph are shown in Figures 5.6 through 5.8 and Figures F1 though F18 in Appendix F. The developed graphs can be used to perform trade-off analysis between any two PMs whenever the functional relationship is significant, there is an inverse functional relationship and both PMs have desirable properties. The trade-off analysis can be used to choose desirable values of PMs and evaluate how other PMs are affected, and help the transportation infrastructure investment decision process.

The practical use of the PMTCs shown in Figures 5.6 through 5.8 is described below. Suppose a decision maker wants to evaluate PM values using the developed PMTCs. The decision maker starts with fixing one of the PMs. Let us assume that the decision maker fixes average BC to a minimum value of 3.40 percent, which is within the range in which the developed functional relationship is valid. From Figure 5.6, applying the regression equation of the PMTC, the corresponding minimum value for the network average link BC is 1.55 percent.

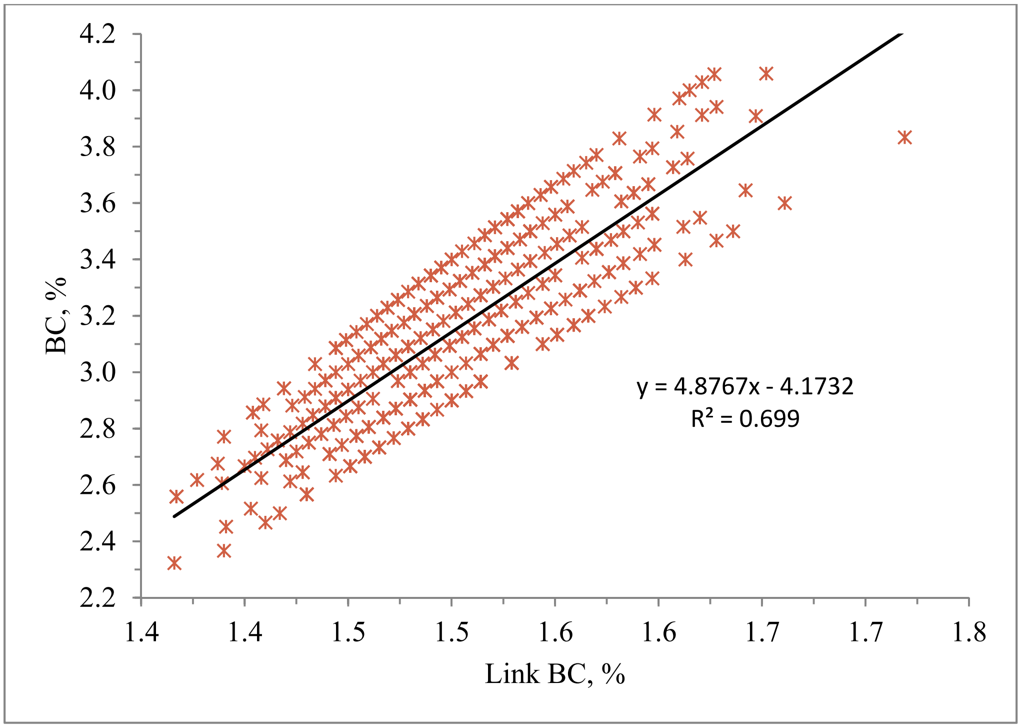


Figure 5.6 Avg. Betweenness centrality (BC) vs. avg. link LBC

Figure 5.7 shows that there exists a functional linear relationship (R^2=0.713) between the network average BC and network average CC. Using the regression equation, the marginal rate of substitution (MRS) of network average BC for network average CC is calculated as:

$$\mathrm{MRS} = -\frac{dy}{dx} = -\frac{d}{dx}(-22.43x + 21.90) = 22.43$$

i.e., increase of the network average BC by 22.43 percent causes 1 percent decrease in network average CC. This MRS value remains constant within the range of data points for which the regression line is valid due to the linear functional relationships between the two PMs. The decision maker can utilize this information to evaluate how marginal improvementof network level BC reduces network level CC.

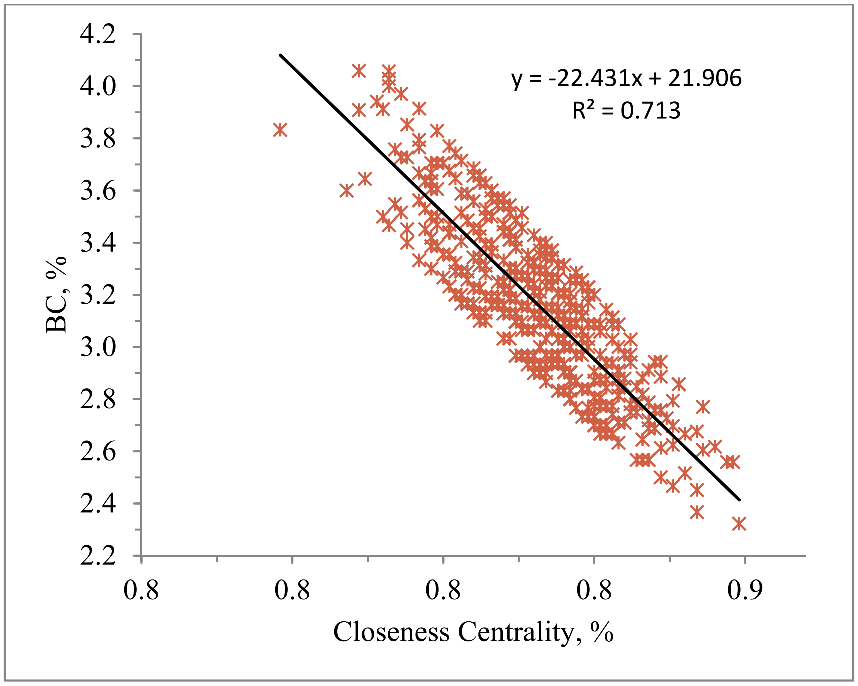


Figure 5.7 Tradeoff plot: Betweenness centrality (BC) vs. closeness centrality (CC)

The MRS of network average LBC for network average CC can be computed using the non-linear regression equation given in Figure 5.8:

$$\text{MRS} = -\frac{\text{dy}}{\text{dx}} = -\frac{\text{d}}{\text{dx}}(12.816x^2 - 25.947\text{x} + 14.235)$$

$$=25.632\text{x} - 25.947.$$

This can be used by the decision maker to conduct network performance analysis by learning how the percent change in network average CC causes the percent change on the network average LBC.

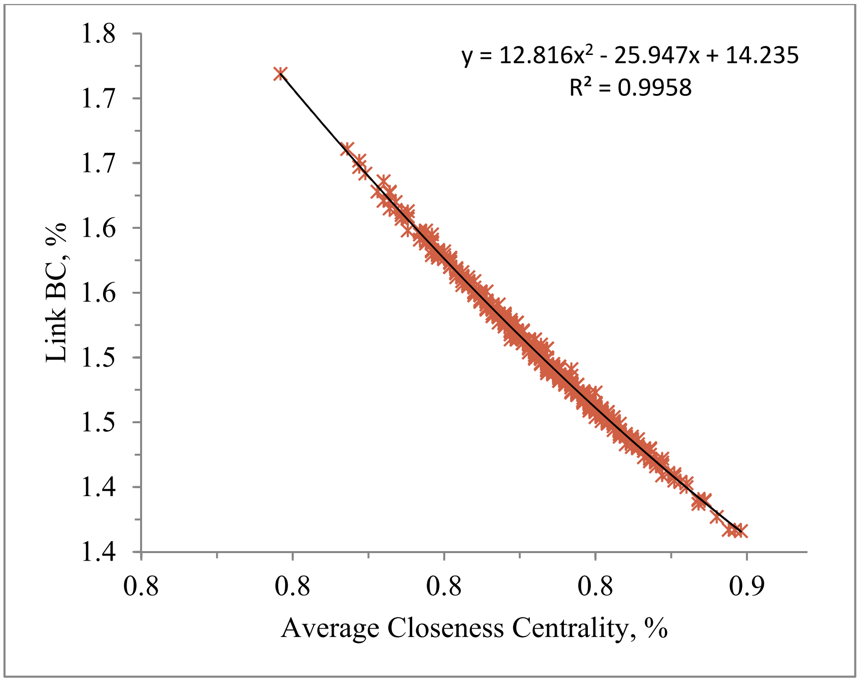


Figure 5.8 Tradeoff plot and function: link betweenness centrality (BC) vs. closeness centrality (CC)

It is generally known that a decision maker would like to maximize network PMs that have desirable properties. For example, BC is a desirable PM and therefore a decision maker would like to maximize network-level BC. Whenever inverse relationship exists between pairs of desirable PMs, tradeoff analysis can be conducted between the pairs of desirable PMs (for example, see Figure 5.3 and Figure 5.4). On the other a decision maker is able to conduct tradeoff analysis between a performance with an desirable property (for example, CC) and another PM with an undesirable property (for example, network diameter) only if there two PMs have direct functional relationship.

The positive functional relationship between network average nodal degree and NIndPath with higher R^2 value of 0.5394 is shown in Figure F.12. Increase in one of the PM value generally leads to increase in the value of the other PM. However, the rate of increase may be slightly different at different PM levels. The decision maker may utilize this information to conduct various scenarios of the network performance with respect to these PMs. However, because both PMs are desirable, the decision maker cannot conduct tradeoff analysis using Figure F.12.

As plots of pairs of PMs given in Figures F1 through F18 in Appendix F show, a very poor or no definite functional relationship exist between the following PMs: avgBC vs avgND, avgBC vs Diam, avgBC and avgSPL, avgBC vs NIndPath, avgLBC vs Diam, avgLBC vs avgSPL, avgLBC vs NIndPath, avgND vs Diam, avgND vs avgCC, avgND vs avgSPL, Diam vs AvgCC, Diam vs NIndPath, avgCC vs avgSPL, avgSPL vs NIndPath and avgCC vs NIndPath. In all these cases, the impact of change in value of one of the PMs on the other PM cannot be determined. The levels of functional relationships between all pairs of PMs that have been considered in this chapter have been summarized in Table 5.1.

Table 5.1 Levels of functional relationships between pairs of PMs

PM	avgBC	avgLBC	avgCC	avgND	avgSPL	Diam	NIndPath
avgBC	-						
avgLBC	S	-					
avgCC	S	VS	-				
avgND	VW	VW	VW	-			
avgSPL	VW	VW	VW	VW	-		
Diam	VW	VW	VW	VW	VW	-	
NIndPath	VW	VW	VW	F	VW	VW	-

Notations:
VW=Very weak; W=Weak; F=Fair; S=Strong; VS=Very strong
VW: $0<R^2\leq0.25$; W: $0.25<R^2\leq0.5$; F: $0.5<R^2\leq0.65$; S: $0.65<R^2\leq0.75$
VS: $0.75<R^2\leq1.00$

5.5 Chapter summary

In this chapter, the process of developing PMTCs was presented. The PMTCs were developed using the PM values of randomly-generated networks. PM values were determined for each network and plots of each pair of PM values were prepared.

Regression curves were fit to the data points, whenever possible, and regression equations were used to show how these equations could be used to evaluate the impact of specifying a PM value on another. When it was not possible to develop regression equations, due to poor functional relationship between the PMs, it is not possible to carryout tradeoffs because none seemed to exist. Data points were used to determine the value of a PM corresponding value of the other PM.

Linear and non-linear relationships were observed among various PMs. The R^2 values range from 0.003 up to 0.995. In order to ensure that the observed relationships remain the same in all situations for each pair of PMs, computer outputs of six runs and the average of the six runs were plotted together for those relationships which showed significant R^2 values. It was found that these relationships remain consistent and hence the decision maker can utilize the developed relationship during transportation decision making.

Chapter 5 developed a framework for developing PM tradeoff curves. These were developed to assist transportation investment decision makers to assess the extent to which a given measure of network topological performance is generally potentially sacrificed when a certain level of another measure of network topological performance is expected to be gained through the investment.

CHAPTER 6. A MULTI-CRITERIA FRAMEWORK FOR QUANTIFYING NETWORK CONNECTIVITY

6.1 Introduction

This chapter first presents a methodology for measuring overall network connectivity, followed by a discussion of the network PMs used in the methodology and how the weights of the individual PMs were determined. Next, a methodology for quantifying the overall connectivity of a network is introduced and some associated PMs are discussed.

There is a certain category of networks in which the number of links is relatively small compared with the number of nodes. For a network with N nodes and l links, the maximum possible number of links is given by $\binom{N}{2} = \frac{N(N-1)}{2}$. If the number of links is smaller than this quantity, then the network is called a sparse network (Barabasi, 2012). Based on this definition, most transportation networks are sparse as each of the pairs of nodes in the networks are not connected with each other because it is not practical or economical to do so. Transportation networks clearly differ in their degree of sparseness; for example, highway networks that exist in rural areas in most developing countries are generally sparser than streets in urban areas. Therefore, it can be argued that the term sparseness is relative as far as transportation networks are concerned.

Sparse networks are characterized by a low degree of connectivity between nodes which typically represent population centers or low traffic volumes that the capacity of a road section in the network accommodates without causing traffic congestion. The performance of sparse networks is affected by the level of connectivity among their nodes. It is important to quantify the connectivity of these networks to serve as input to transportation investment decisions that improve the functional performance of the networks, reduce their vulnerability to natural or man-made disruptions, and enhance the resilience of the transportation system.

6.2 General overview of multi-criteria analysis (MCA)

MCA is often employed by decision makers when the problems to be solved involves multiple and often conflicting objectives and the considered criteria are relatively weighed based on their importance (Klein and Whalley 2015; Mutikanga et al., 2011). MCA plays a very important role in solving such types of problems in our daily lives (Jahan and Edwards, 2013). In fact, the MCA was primarily developed to solve operational research problems with the aforementioned characteristics (Mutikanga et al., 2011). Because of its importance, MCA has now become a well-developed discipline.The main steps in the MCA process are identification of alternatives and criteria and assigning relative importance to these criteria and ranking the alternatives (Klein and Whalley 2015). MCA is widely used in practical situations in such professions as engineering systems, information science, and decision science (Kou and Wu, 2014).

6.3 Measuring network connectivity using multiple criteria: Type I

6.3.1 General framework

The general framework for this part of the dissertation is shown in Figure 6.1. The framework allows the selection of network PMs of interest to be included in the proposed model as well as to provide individual weights for the measures and their sub-criteria. The framework also can be applied both to proposed or existing networks for quantifying the overall topological performance of a network or the performance of individual nodes and links.

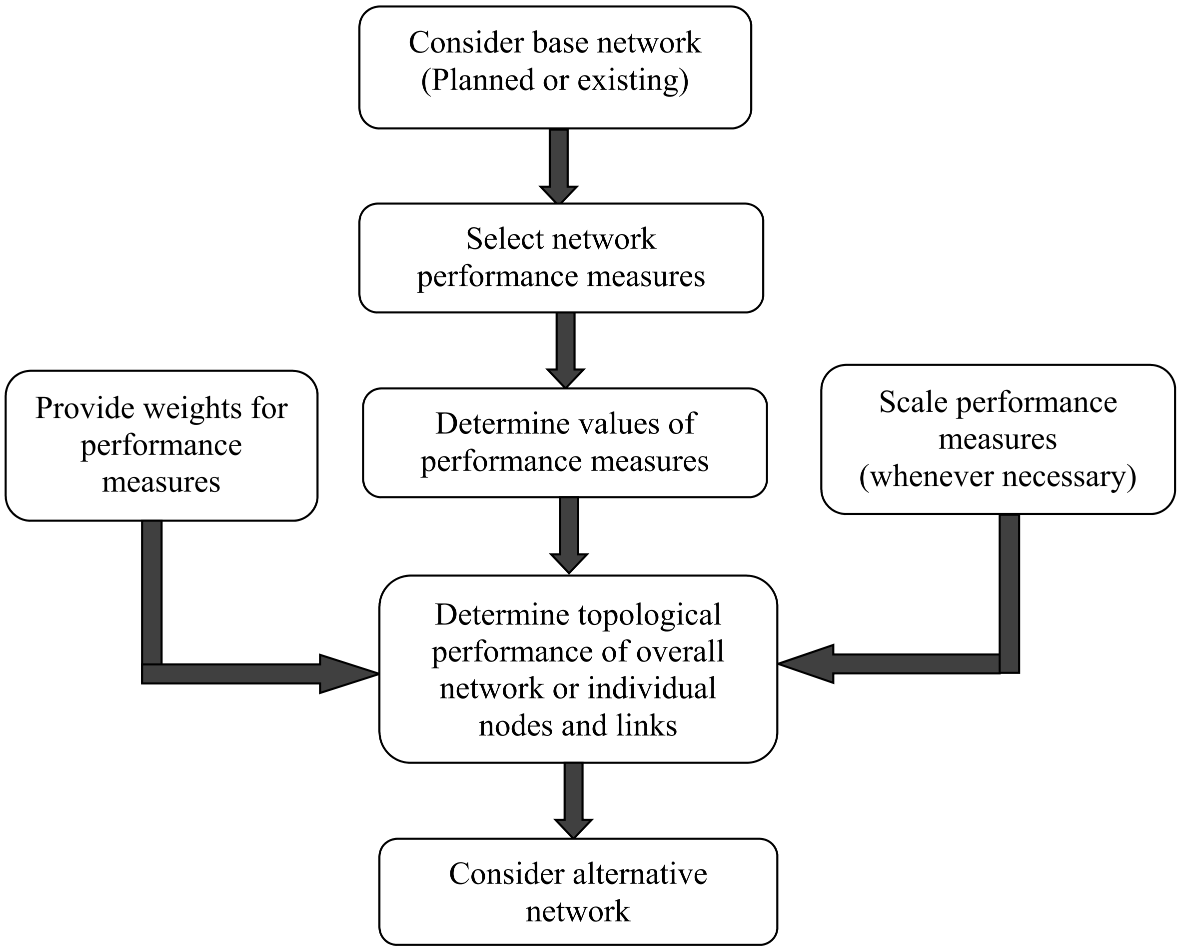


Figure 6.1 General framework for quantifying network connectivity

Consider planned or existing network. The methodology can be used to quantify the network connectivity performance of proposed transportation networks, proposed improvements to an existing network, or existing network without improvement.

Select network PMs. Based on the context of the evaluation, the network PMs should be selected appropriately. For example, if the objective is to quantify the percentage of shortest paths that pass through links, a link BC PM is considered in the evaluation.

Provide weights for PMs. At this stage, the decision maker assigns weights to the individual measures of network topological performance which reflect the relative importance of the PMs compared to each other, and are generally derived by the decision maker on the basis of the inputs of multiple stakeholders.

Scale PMs (whenever necessary). PMs may have different units of measurement, which in some cases may be unit-less. In order to be able to quantify network connectivity, these PMs are converted into the same scale of measurement.

Determine values of topological PMs. The values of the topological measures are determined by applying suitable formulas and algorithms. The topological performance values may be associated with nodes, links, or the entire network. See Section 6.3.2.

Analyze node, link, and network importance. In this step, the PM values obtained in the previous step are analyzed and the nodes or links are prioritized by their importance. The entire network performance is also determined.

6.3.2 Proposed general model – Type I

The proposed model was conceptualized in order to quantify network topological performance as a single composite quantity that incorporates multiple PMs. The general proposed model is given in Equation 6.1.

$$NCI = \frac{\sum_{k=1}^{l}\sum_{i=1}^{n} W^k \alpha^k \gamma_i^k w_i^k}{\sum_{t=1}^{s}\sum_{j=1}^{m} W^t \alpha^t \beta_j^t w_j^t} \tag{6.1}$$

where:

NCI =Network connectivity index

$k$or t = PM

l or s = Number of trip types or criteria

$n$or m = Number of nodes, routes, or links

i or j =Node, link, or criteria

W^k= Weight given to a PM k

α^k= Normalization factor for network PM k

γ_i^k = Value of network PM k for a node, link, or criteria i

w_i^k =Weight for network PM k for node, link, or criteria i

W^t= Weight given to a PM t

α^t= Normalization factor for network PM t

β_j^t = Value of a network PM t for a node, link, or criteria j

w_j^t =Weight for network PM *t* for a node, link, or criteria *j*

The normalization factor is an adjustment that seeks to cancel out bias due to the effects of certain network features or properties. For example, in comparing the diameter of two or more network topologies which differ in their number of links, it is essential to cancel out the effect of the number of links because those network topologies with a higher number of links are likely to have a smaller diameter due to the possibility of more route options which could reduce the diameter value.

In some situations, a network PM may have sub-criteria. In these cases, individual weights could be assigned to the sub-criteria. Equation 6.2 specifies that the sum of the weights of the sub-criteria of a network PM should be equal to the weight given to that network PM:

$$\sum_{i=1}^{n} w_i^k = W^k \text{ and } \sum_{j=1}^{n} w_j^t = W^t \quad (6.2)$$

The model places the network PMs which the decision maker seeks to maximize in the numerator, and those to be minimized in the denominator. For example, if the objective involves maximization of the average nodal degree and the minimization of the network diameter, the former appears in the numerator and the latter in the denominator.

6.3.3 Performance measures (PMs) for network connectivity

To demonstrate the application of the general network connectivity model described in Equation 6.1, the following PMs were considered: node BC, LBC, nodal degree, CC, shortest path length, Chinese postman cost, and network diameter. In Section 3.3, we discussed the concepts of node BC, LBC, CC, DN, and network diameter.

The shortest path length is a network PM which helps to consider the total shortest path from a node to all other nodes in the network.This measure may be of special interest to decision makers who want to prioritize nodal features in the network with respect to total shortest path length between a specific node and all other nodes.The shortest-path concept is important in areas such as rural areas where the main objective is usually maximization of network connectivity, where the traffic volume is low compared to the capacity of the network, i.e., in areas where the volume-capacity (*v/c*) ratio is very low. In urban areas where the *v/c* ratio is very high, other PMs such as delay or congestion reduction are more likely to be used in transportation investment decision evaluations from a network-level perspective.

The Chinese postman problem is a type of network tour that starts from a node and ends at the same node without traversing a link in the network more than once. Similar to the explanation for the *TSP* criterion, transportation agencies and private sector shippers may seek to make transportation-related decisions partially based on this measure of network topological performance.

6.3.4 Connectivity model – Type I

Equation 6.3 provides the network connectivity index (NCI) model which incorporates the afore-mentioned network PMs that were considered in the case study of this dissertatio.

$$NCI = \frac{\frac{W^{BC}}{n}\sum_{i=1}^{n}\gamma_i^{BC}w_i^{BC} + \frac{W^{LBC}}{l}\sum_{m=1}^{l}\gamma_m^{LBC}w_m^{LBC} + \frac{W^{\theta}}{n}\sum_{i=1}^{n}\gamma_i^{\theta}w_i^{\theta} + \frac{W^{CC}}{n}\sum_{i=1}^{n}\gamma_i^{CC}w_i^{CC}}{\frac{W^{SPL}}{n(n-1)/_2}\sum_{i=1,j=1,i\neq j}^{n}\beta_{i,j}^{SPL}w_{i,j}^{SPL} + \frac{1}{n}\beta^{MST}W^{MST} + \frac{W^{CPP}}{n}\sum_{i=1}^{n}\beta_i^{CPP}w_i^{CPP} + \frac{1}{n}\beta^{D}W^{D}} \quad (6.3)$$

where:

NCI = Network connectivity index

BC = Betweennes centrality

LBC = Link BC

θ = Degreeof a node

CC = Closeness centrality

SPL = Shortest path length

MST = Minimum spanning tree

CPP = Chinese postman cost

D = Network diameter

n = Number of nodes

l = Number of links

m =Name of link

i,j= Name of node

$\frac{1}{n}, \frac{1}{l}, \frac{2}{n(n-1)}$= normalization factors

γ_i^{BC} = BC value for node i

γ_m^{LBC} = LBC value for link m

γ_i^{θ} =Value for DN i

γ_i^{CC} = Closeness centrality value for node i

$\beta_{i,j}^{SPL}$ =Shortest path length between nodes i and j

β^{MST} = Length of minimum spanning tree

β_i^{CPP} = Chinese postman cost that starts and ends at node i

β^{D} = Network diameter value

W^{BC} = Weight for BC PM

W^{LBC} = Weight for LBC PM

W^{θ} = Weight for nodal degree PM

W^{CC} = Weight for closeness centrality PM

W^{SPL} = Weight for shortest path length PM

W^{MST} = Weight for minimum spanning tree PM

W^{CPP} = Weight for Chinese postman cost PM

W^{D} = Weight for network diameter PM

w_i^{BC} =Weight for node i w.r.t BC PM

w_m^{LBC} =Weight for link m w.r.t LBC PM

w_i^{θ} =Weight for node i w.r.t nodal degree PM

w_i^{CC} =Weight for node i w.r.t closeness centrality PM

$w_{i,j}^{SPL}$ = Weight for SPL PM for shortest pathbetween nodes i and$j$

Equation 6.4 satisfies the condition that the sum of the weights of sub-criteria must equal the weight given to the network PM to which the sub-criteria belongs.

$$\sum_{i=1}^{n} w_i^{BC} = W^{BC};\ \sum_{m=1}^{l} w_m^{LBC} = W^{LBC}; \sum_{i=1}^{n} w_i^{\theta} = w^{\theta}\ ; \sum_{i=1}^{n} w_i^{CC} = W^{CC}$$

$$\sum_{i=1,j=1,i\neq j}^{n} w_{i,j}^{SPL} = W^{SPL}; \sum_{m=1}^{l} w_m^{CPP} = W^{CPP} \quad (6.4)$$

6.3.5 Weighting and scaling

Transportation network stakeholders typically have different network performance preferences with regard to certain PMs based on their importance in the stakeholder's day-to-day operations. Therefore, in the framework for NCI development in this dissertation, the stakeholders were requested to assign weights to the PMs as well as the individual elements of the network. The weights for the PMs and their sub-criteria were determined through a questionnaire survey.

Scaling (also referred to as metricization) of PMs is common in multiple criteria evaluation, particularly when there is a need to combine the PMs to yield a single combined value of overall performance for each alternative (Sinha and Labi, 2007). The PMs used in this dissertation to quantify network connectivity have different units of measurement. There is a need therefore to scale the units so that they can be represented in the same scale of measurement. That way, the PMs can be used to characterize the network connectivity level described by Equation 6.3. The PM values were scaled to the same scale of measurement using Equation 6.5.

$$PM_{scaled} = \left(1 - \frac{PM_{max} - PM}{PM_{max} - PM_{min}}\right) * 100 \qquad (6.5)$$

where

PM_{scaled} = Scaled PM value

PM= Actual PM value

PM_{max} =Maximum computed PM value

PM_{min} =Minimum computed PM value

For example, if the actual BC of a node (*PM*) in a sparse network is 20 percent and the minimum and maximum BCs of the nodes in the network, respectively, are 10 and 40 percent, using Equation 6.5, their scaled value, PM_{scaled}, equals 33.33 percent.

6.4 Measuring network connectivity using multiple criteria : Type II

6.4.1 General framework

The general framework for determining a network connectivity level is described below.

Consider planned or existing network. The sparse network to be evaluated should first be identified. This network could be a planned or existing network.

Select network PMs. The PMs are selected based on the evaluation objectives that are associated with the network's connectivity. For example, a decision maker may consider the number of independent paths between pairs of nodes in the network as a measure to evaluate the reliability of the network in cases of network disruptions because higher numbers of independent paths between pairs of nodes is desirable to minimize the effect of network disruptions.

Provide weights for the network topology PMs. The decision maker assigns weights to the individual PMs. As described in Section 6.3.1, the decision maker assigns weights to the individual PMs based on their relative importance to the sparse network connectivity. These weights can be derived from inputs obtained from multiple stakeholders.

Determine nodal connectivity level. The connectivity level of each node is determined as the sum of the weighted values of each PM.

Determine the sparse network connectivity level. Once the connectivity level of each node is determined, the sparse network connectivity level is determined as the sum of the weighted values of each nodal connectivity level. The connectivity level of each node is weighted based on the importance of the node with respect to factors which the decision maker seeks to consider, such as economic, societal, or political factors.

6.4.2 Proposed general model – Type II

The proposed general model is given in Equations 6.6 and 6.7. Equation 6.6 can be used to determine the connectivity level of nodes in the network, and Equation 6.7 can be applied to determine the connectivity level of the sparse network.

$$NCL_i = \sum_{i=1}^{n} w_\beta \beta_i \qquad (6.6)$$

$$SNCL = \sum_{i=1}^{n} e_i \, NAL_i \quad (6.7)$$

where:

NCL_i = Connectivity level for node i

n =Number of network topology PMs

w_β = Weight for a PM β

β_i =Value for PM β corresponding to node i

$SNAL$ = Sparse network connectivity level

e_i = Weight representing the economic, societal, or political importance of node i

6.4.3 Performance measures (PMs)

In modeling the connectivity of sparse networks, the following PMs were considered: BC, nodal degree, and number of independent paths between two nodes in the network, for the reasons explained below.

By definition, BC measures the percentage of shortest paths that pass through a node in a network. BC therefore can be used to measure the importance of a node in a network from the shortest path length perspective. BC is especially useful as a PM for sparse networks, such as rural road networks, because the mobility of people and goods between nodes in sparse networks mostly takes place along the shortest path length strictly in terms of topological distance. Specifically, in rural road networks, the traffic volume is generally low and such roads are devoid of congestion (which makes travelers choose routes that have the shortest travel times not the shortest distances) unless there is disruption of the road links on the shortest path route.

It may be the case that some nodes (rural population centers) are more often traversed than others by the network users through the shortest path; this is typical at sparse networks where link capacity is not an issue. It is likely that those easily-connected population centers derive benefits in terms of economic activity such as development of business centers, markets, etc. Therefore, it is vital to consider how often population centers are traversed from other populations centers from the shortest distance origin-destination perspective. BC is therefore used in this dissertation as one of the inputs in modeling the connectivity level of sparse networks.

Independent paths between pairs of nodes refer to paths which do not share any common nodes or links except the origin and destination nodes. The availability of many independent paths between pairs of nodes in a network is an indication of the degree of the network's resilience to disruptions. For example, if a path between node A and node B in a network is blocked, due to flood for example, a resilient network would provide another path to travel from node A to node B. This is particularly important in the case of sparse networks where the connectivity between pairs of nodes is a vital consideration in the modeling process so that the connectivity performance of sparse networks can be adequately characterized.

In sparse networks some nodes may benefit economically as a result of having higher levels of direct connections with other nodes compared to other nodes in the network. It is therefore worth considering the nodal degree as one of the important parameters during transportation investment decisions to address economic and societal issues.

6.4.4 Connectivity model – Type II

Taking into consideration the above PMs for connectivity of sparse networks, the mathematical model shown in Equation 6.8 was developed in this dissertation. Equation 6.8 is easy to apply and provides a robust means to measure the different aspects of connectivity. It can also be applied readily during road investment evaluation as one of the inputs for multi-criteria analysis.

$$NAL_i = w_{BC}BC_i + w_{PATH} * \frac{1}{N}\left(\sum_i \sum_{\substack{j=1 \\ i \neq j}}^{n-1} PATH_{ij}\right) + w_{DN}DN_i \tag{6.8}$$

where:

NCL_i = Connectivity level for node i

BC_i = BC for node i

$\sum_i \sum_{\substack{j=1 \\ i \neq j}}^{n-1} PATH_{ij}$ = The sum of the number of independent paths between node *i*and all other nodes j

DN_i = Degree of node i, which measures the number of direct connection between node i and its neighboring nodes.

n = Number of nodes in the network

N = Number of pairs of nodes in the network

$PATH_{i,j}$ = Number of independent paths between node i and node j

w_{BC} = Assigned weight given for the BC PM

w_{PATH} = Assigned weight given for the number of independent paths PM

w_{DN} = Weight given for the nodal degree PM

The connectivity level of the sparse network under consideration can be computed using Equation 6.9, as the sum of the connectivity level of each node (population center as in the case of a rural network) in the network, each node being weighed with economic, social, or political related factors that a decision maker may seek to consider.

$$SNCL = \sum_{i=1}^{n} e_i \, NCL_i \tag{6.9}$$

where:

$SNCL$ = Connectivity level of the sparse network

e_i =Weight representing the economic, social, or political importance of node i

NCL_i = Network connectivity level associated with node i

n= Number of nodes in the network.

The values for w_{BC},w_{PATH} and w_{DN} may be different for different rural populations taking into account the importance of each individual PM shown in Equation 6.8.The decision maker seeks to maximize the sparse network connectivity level (SNCL). For a network with isolated node, the $SNCL$ is zero.

6.4.5 Weights of the performance measures (PMs)

It may be true that the model parameters discussed above (namely BC, number of independent paths and nodal degree) can have different degree of impact for the overall connectivity of sparse networks. The degree of impact of these PMs on the network connectivity may depend on other factors such aslocation(geographical and environmental factors), societal equity issues, etc.For example, in flood-prone rural areas, in order to ensure connectivity and connectivity of rural areas, it is important that nodes can be linked to each other using as many independent paths as possible. In this case, the PM representing the number of independent paths between nodes may be given higher weight compared to otherparameters in the model. It is therefore important to incorporate relative weights in modeling network connectivity.

CHAPTER 7. CASE STUDIES FOR THE MULTI-CRITERIA FRAMEWORK FOR QUANTIFYING NETWORK CONNECTIVITY

7.1 Introduction

This chapter presents the case study results and discusses these results with respect to network connectivity. First, the case study network is described. Next, the PMs and their weights assigned by stakeholders are presented. Finally, the network connectivity indices for the case study networks are determined.The network connectivity case study area, shown in Figure 5.1, is located in West Lafayette, Indiana. The case study network is composed of 17 nodes and 24 links and is used to demonstrate how the framework developed in this dissertation can be utilized to determine network connectivity. A hypothetical network (Figure 5.10) composed of 14 nodes and 15 links is used. In both networks, the link labels represent distances (in miles) between nodes.

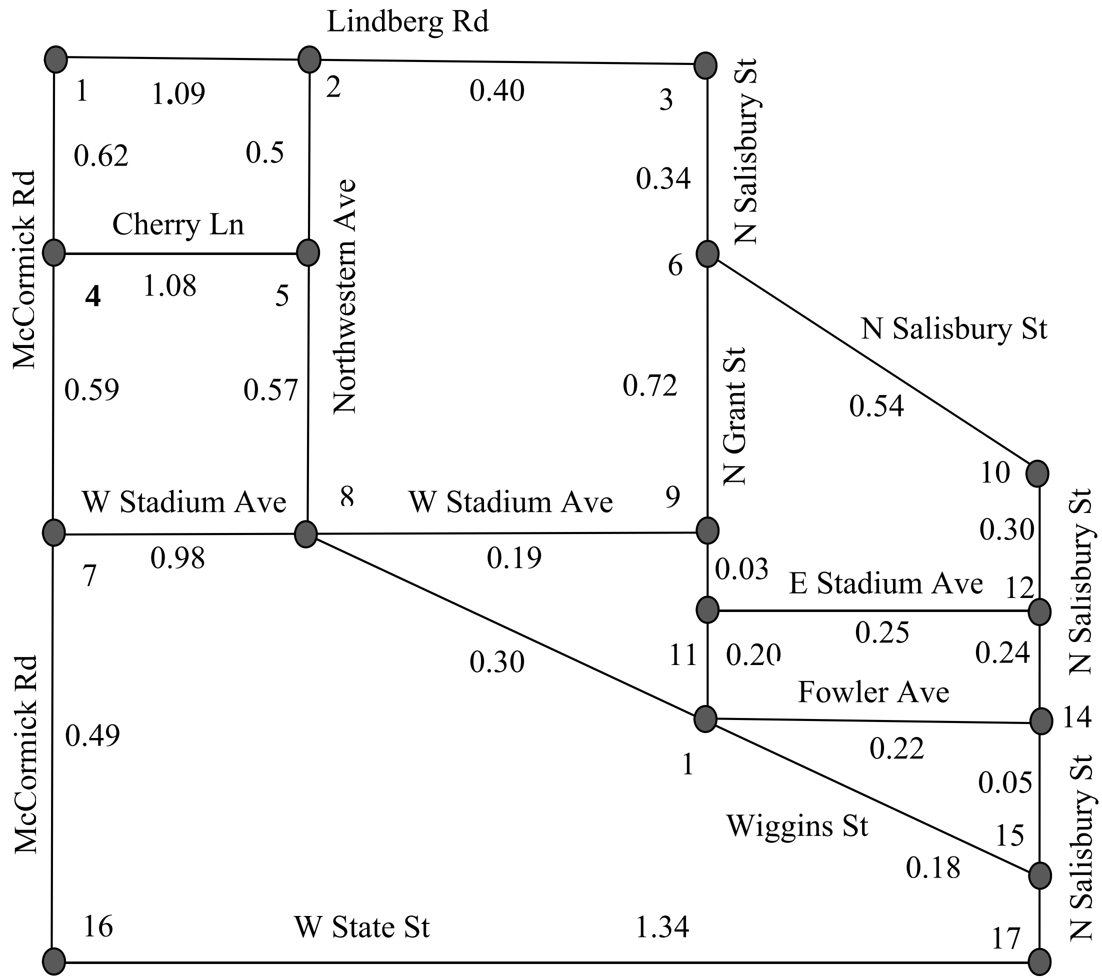


Figure 7.1 Case study network, West Lafayette, Indiana

7.2 Stakeholders considered in this dissertation

There are many transportation stakeholders in the case study area. Due to the limitations of time and difficulty in collecting data for the entire population of stakeholders, only representative stakeholders were solicited for data: the City of West Lafayette Engineering Department (WLED), the West Lafayette Fire Department (WLFD), the Greater Lafayette Public Transportation Corporation (CityBus) and the Lafayette Limo Company

7.2.1 The City of West Lafayette Engineering Department

The City of West Lafayette Engineering Department was established in the 1950s. Since its establishment, the organizational structure has evolved. Currently, various staff in the department, in collaboration with staff from other departments, provide input to the capital improvement plan as well as the annual budget. The West Lafayette City Council approves the budget each year by approving,cutting, or deferring proposed infrastructure investments. Most of the department's work has been focused on the maintenance and repairs of existing infrastructure, but also significant improvements have been made to improve performance for other travel modes such as transit, walking, and cycling. The West Lafayette road network is funded from multiple sources: tax increment funding, motor vehicle highway funds, economic development income taxes, and federal highway funds.

7.2.2 Lafayette Limo

Lafayette Limo, one of the main shuttle service providers in the Lafayette/West Lafayette area (Limo 2014), was established in 1986 by Darrell Charles Florian and sold to Jeffery Charles Florian in 2001.

The company provides shuttle service nine times a day to the Indianapolis Airport and a share-a-ride service three times daily to Chicago O'Hare airport from the West Lafayette/Lafayette area. In addition, it provides driver staffing to local businesses that own buses. It performs ground transportation, operations and helps coordinate conventions, conferences, and private events and parties. Lafayette Limo follows specific routes when providing shuttle services. The routes of all shuttle service users are mapped the day before the service using mapping tools such as Bing® and Google®.

The employees of Lafayette Limo are registered at the WLFI website where schedules and delays are updated via text message and relayed to drivers via computer programs. Lafayette Limo employees use GPS units, maps, and driver knowledge of the area in deciding which routes to follow and to pick up the users. The company employs approximately 100 people, which include office staff, garage staff, management, and drivers. It has over 50 vehicles of various sizes, ranging from a 3-passenger sedan to a 59-passenger coach (sedans, SUVs, limos, limo buses, RV limos, mini buses, vans, full-size coaches, and mini coaches).

In 2013, Lafayette Limo was awarded the West Lafayette Humanitarian of the year award by the Mayor of West Lafayette for its service to the city.. The company also provided buses for the Super Bowl that was held in Indianapolis and for the Olympics that took place in Atlanta in 1996.

7.2.3 Greater Lafayette Public Transportation Corporation

The Greater Lafayette Public Transportation Corporation (also called CityBus) was established in 1971 when a private company operating bus transportation (Lafayette Transit) closed its operations due to financial collapse. CityBus then became a public enterprise and has since operated as a division of local municipal government.

About 80% of its capital expenses such as buses, facilities and repair parts come from federal funds. Operating expenses are covered by state funds through sales and use taxes and local tax revenues (CityBus, 2014). Also, the expenses of CityBus are covered with earnings obtained from cash fares, and pass and token sales. Service planning is a collaborative process at CityBus that engages riders and community stakeholders as well as internal employees working in operations, planning, finance, and development. After estimating their needs, service proposals are generated, tested, presented for public review before they are adopted by the board of directors of CityBus, and then implemented.

CityBus owns 73 buses in lengths of 35, 40, and 60 feet, 20 of which hybrid diesel-electric buses. The organization employs 130 people in all departments: operations, development, facilities and maintenance, finance, and general administration (CityBus 2014).CityBus is managed by a seven-member board of directors that is appointed by the mayors and city councils of the cities of Lafayette and West Lafayette, and this boards hire a general manager to lead the management team that includes the managers of the departments mentioned above. The operating and capital budgets of the organization are subsidized by local, state, and federal taxes. About 32% of the operating budget is covered through fare and contract revenue. The operating budget is reviewed and approved annually by the Lafayette City Council and the CityBus board of directors.

CityBus is focused on improving the quality of life in Lafayette and West Lafayette areas by providing safe, reliable, and environmentally-friendly transit services to the people and helping grow local economy. CityBus is regulated by the Federal Transit Administration and the Indiana Department of Transportation. The current strategic plan of CityBus mainly focuses on economic stability for the organization; and has a plan to increase revenue and control costs. It also prioritizes the needs for transit service based upon their organization's preference to meet the needs derived by urban development density rather than serving the needs of suburban sprawl. The organization intends toconduct a market research in 2015 study to consider customer and community needs to help CityBus plan service for 2016 and beyond.

7.2.4 West Lafayette Fire Department

The West Lafayette Fire Department (WLFD) provides fire and emergency medical services to residents of West Lafayette. It also provides emergency medical services (EMS) at city festivals and other public events. WLFD, on average, responds to approximately 1,700 incidents that occur in the city annually (WLFD 2014). WLFD responds to fire and other medical emergencies using its three fire stations. The first station, Station No. 1, was built in 1917 and is located near the Purdue University campus, at 300 North Street. The second station, Station No. 2, is located at 531 W. Navajo Street, and the third station, Station No. 3, is located at 1100 W. Kalberer Road (WLFD, 2014).The WLFD deals with several incident types as described in the National Fire Incident Reporting System (NFIRS): fire, overpressure rupture, explosion, overhear (no ensuing fire), rescue and EMS incidents, hazard conditions (no fire), service calls, good intent calla, false alarms and false calls, severe weather and natural disasters, special incident types. In 2009, there were about 1,641 total incidents compared with 1,593 incidents in 2008.

7.3 Survey results

Survey questions that measured various aspects of the network performance were prepared as part of this dissertation. All network performance concepts given in Equation 6.3 were taken into consideration. Stakeholders were first asked to weigh the PMs. Then, with respect to each PM, they were asked to weight the nodes and links with respect to the PMs relevant to the nodes or links. The survey was conducted face-to-face with awritten questionnaire provided to the decision makers. A supplementary Powerpoint presentation was also given in order to clarify technical concepts that were mentioned in the questionnaire. The survey questions are shown in Appendix F.

Table 7.1 shows the descriptive statistics for the PM weights that were provided by the stakeholders considered in this dissertation. The maximum given weight was 10, which is the maximum possible weight that could be given to a PM by a stakeholder. The minimum weight given was 5, which shows that all the PMs were considered important to the stakeholders. The LBC PM was found to have the lowest mean weight (7.75 out of 10) and the network diameter was found to have the highest mean weight (9.5). This is an indication that the stakeholders placed the highest premium on the ability to travel between the farthest nodes in the network.

Table7.1 Descriptive statistics for weights of PMs
(Provided by stakeholders)

PM	Minimum	Maximum	Mean
Nodal Degree	7	10	8.75
BC	5	10	8.00
LBC	5	10	7.75
CC	7	10	9.25
Shortest Path Length	5	10	8.00
Chinese Postman Tour	8	10	8.25
Diameter	5	10	9.5

Table 7.2 and Table 7.3 provide descriptions of the node and link numbers and their respective node and link names as a reference to better understand the subsequent discussions.

Table 7.2 Node number and corresponding intersection name

Node	Intersection Name
1	McCormick-Lindberg Rd
2	Lindberg Rd. - Northwestern Ave.
3	Lindberg Rd. - N. Salisbury St.
4	McCormick-Cherry Lane
5	Cherry Lane – Northwestern Ave.
6	N. Grant St. - N. Salisbury St.
7	McCormick - W. Stadium Ave.
8	W. Stadium Ave. - Northwestern Ave.
9	W. Stadium Ave. - N. Grant St.
10	Robinson St. - N. Salisbury St.
11	N. Grant St. - E. Stadium Ave.
12	E. Stadium Ave. - N. Salisbury St.
13	Northwestern Ave. - Fowler Ave.
14	Fowler Ave. - N. Salisbury St.
15	Wiggins St. - N. Salisbury St.
16	McCormick Rd. - W. State St.
17	W. State St. - N. Salisbury St.

Table 7.3 Link numbers and corresponding link names

Link	Link Name
1-2	Lindberg Rd, from McCormick Intersection to Northwestern Ave. Intersection
1-4	McCormick Rd from Lindberg Rd intersection to Cherry Ln intersection
2-3	Lindberg Rd from Northwestern Ave. intersection to N. Salisbury St. intersection
2-5	Northwestern Ave. from Lindberg Rd intersection to Cherry Ln intersection
3-6	N. Salisbury St. from Lindberg Rd. intersection to N. Grant St. intersection
4-5	Cherry Lane
4-7	McCormick Rd from Cherry Lane intersection to W. Stadium Ave. intersection
5-8	Northwestern Ave. from Cherry Ln intersection to W. Stadium Ave. intersection
6-9	N. Grant St. from W. Stadium Ave. intersection to N. Salisbury St. intersection
6-10	N. Salisbury St. from N. Grant St. intersection to Robinson St. intersection
7-8	W. Stadium Ave. from McCormick Rd. intersection to Northwestern Ave. intersection
7-16	McCormick Rd. from W. Stadium Ave. intersection to W. State St. intersection
8-9	W. Stadium Ave. from Northwestern Ave. intersection to N. Grant St. intersection
8-13	Northwestern Ave. from W. Stadium Ave. intersection to Wiggins St. intersection
9-11	N. Grant St. from W. Stadium Ave. intersection to E. Stadium Ave. intersection
10-12	N. Salisbury St. from E. Stadium Ave. intersection Robinson St. intersection
11-12	E. Stadium Ave. from N. Grant St. intersection to N. Salisbury St. intersection
11-13	N. Grant St. from Fowler Ave. intersection to E. Stadium Ave. intersection
12-14	N. Salisbury St. from E. Stadium Ave. intersection to Fowler Ave. intersection
13-14	Fowler Ave. from Wiggins St. intersection to N. Salisbury St. intersection
13-15	Wiggins St. from Northwestern intersection to N. Salisbury St. intersection
14-15	N. Salisbury St. from Fowler Ave. intersection to Wiggins St. intersection
15-17	N. Salisbury St. from W. State St. intersection to Wiggins St. intersection
16-17	W. State St. from McCormick Rd. intersection to N. Salisbury St. intersection

Figure 7.2 compares the preferences of the stakeholders for the nodal degree PM for each node in the network. Nodes 1, 3, 6, 7, 8, 15, 16, and 17 were assigned a weight value of 10 by WLFD. Node 8 was also assigned a weight value of 10 by CityBus and Lafayette Limo. The minimum node preference of 4 was assigned to nodes 3, 6, 9, 10, 11, and 12 by Lafayette Limo; and to nodes 10, 11, 12 and 13 by CityBus.

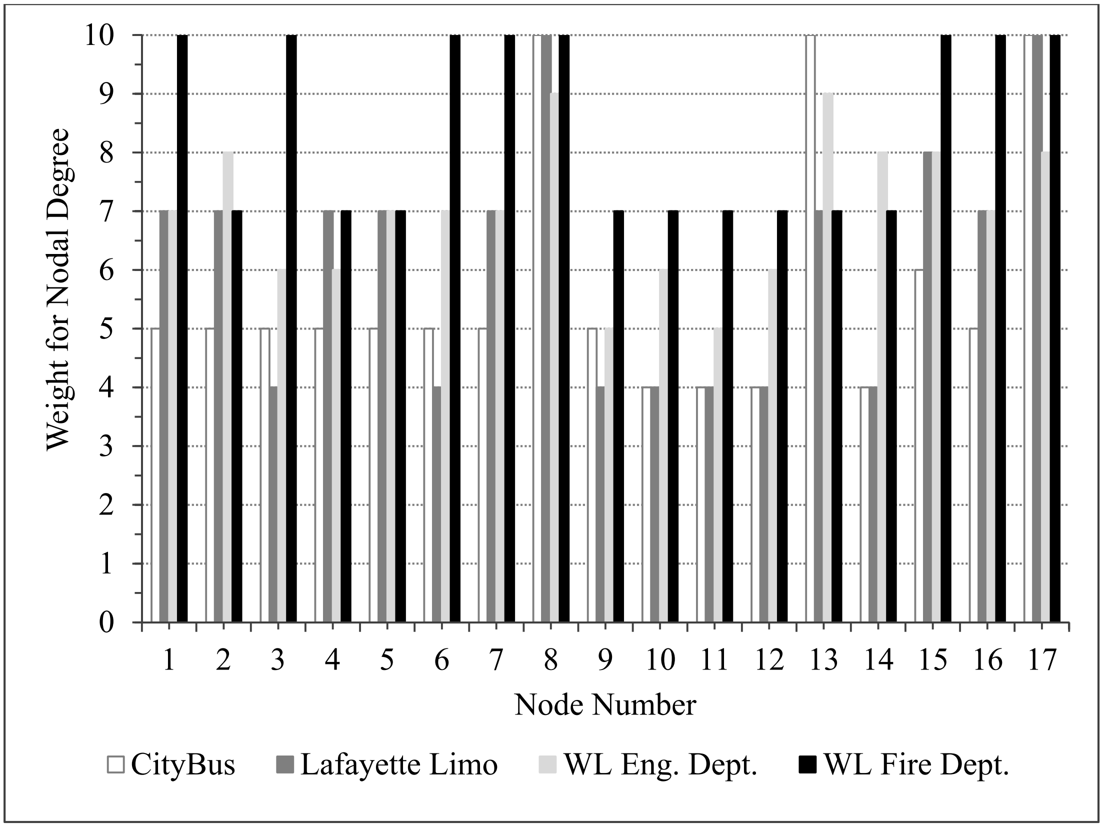


Figure 7.2 Stakeholder preferences for nodes on basis of nodal degree performance

Similar observations regarding the preference of stakeholders to the nodal degree PM can be made from Figure 7.2. The most important point here is that for any region, the stakeholders can be expected to provide different preferences to different nodes based on their operations in the network and their intent to reduce the distance associated with using the network. The link distance was assumed in this dissertation to be a good surrogate for link cost. The stakeholders could also intend to maximize their reach and extent by assigning higher preferences to certain nodes in the network based on where their customers are located relative to the nodes.

Figure 7.3 presents the stakeholder preferences for nodes with respect to the BC PM. Nodes 1, 2, 3, 4, 5, 7, 8, 13, 15, 16, and 17 were assigned a weight of 5 or greater by all stakeholders; this is an indication of the relatively higher importance of these nodes to all stakeholders. Nodes 6, 9, 10, 11, and 14 were assigned weights not exceeding 5 by at least one of the stakeholders.

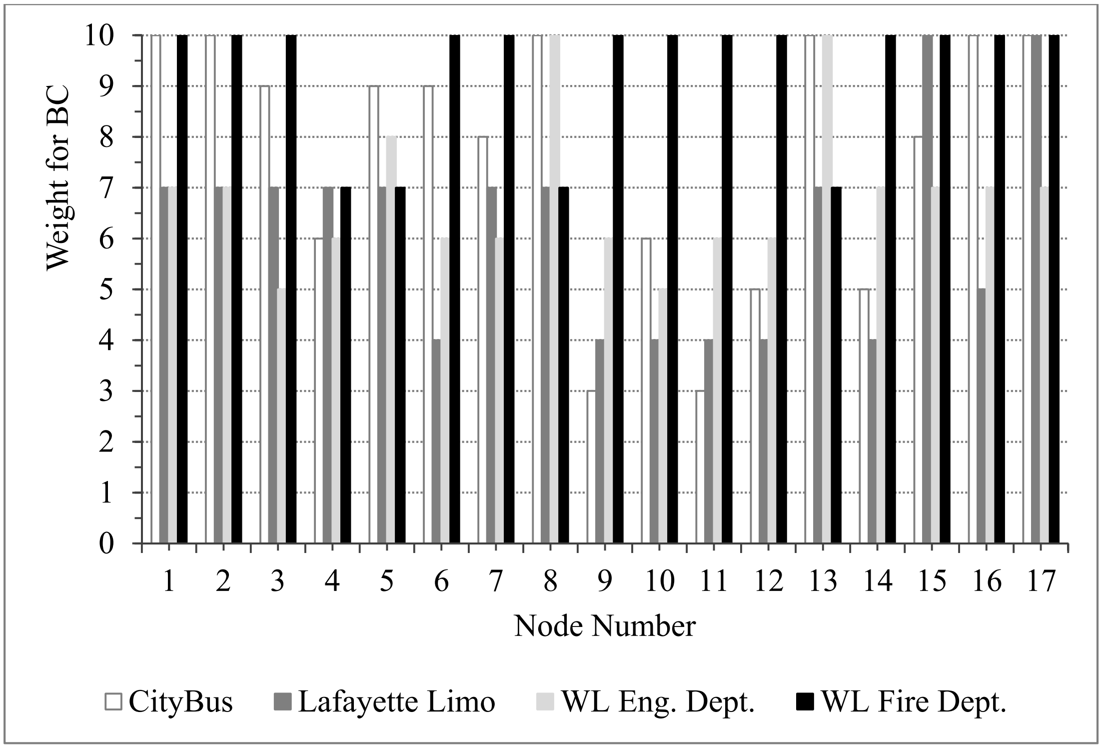


Figure 7.3 Stakeholderpreferences for nodes on the basis of betweenness centrality (BC) performance measure (PM)

Figure 7.4 presents the preferences of the stakeholders for link in the network with respect to the LBC PM. A significant number of links were assigned a maximum weight of 10. A number of links received low weights. For example, a weight of 1 was assigned to links 7-8 and 13-14; a weight of 2 was given to links 4-5, 11-12, and 11-13; and a weight of 3 was given to links 9-11, 13-15, and 14-15 by CityBus. In general, all links were assigned higher weights with respect to the LBC PM.

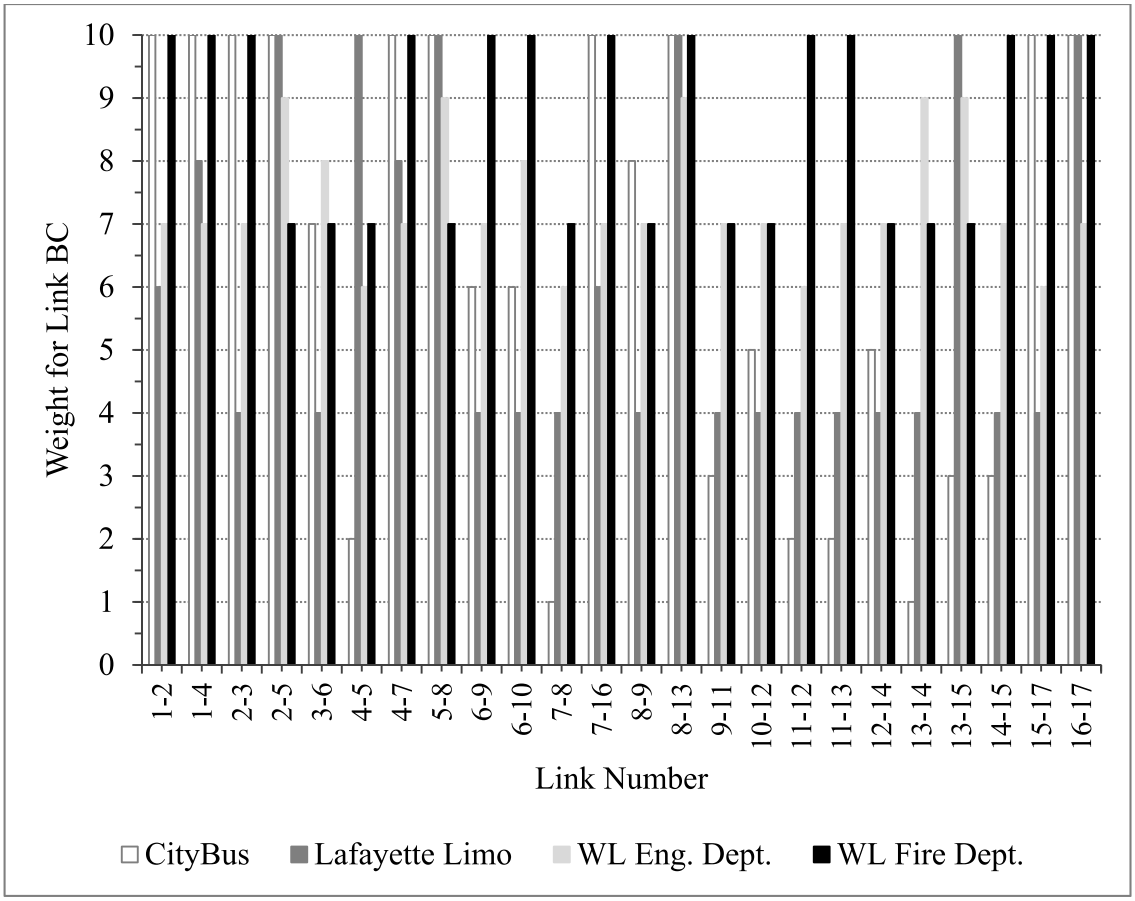


Figure 7.4 Stakeholderpreferences for links for link betweenness centrality (LBC) performance measure (PM)

As shown in Figure 7.5, nodes 4, 7, 9, 10, 11, 12, 14, 15, and 16 were given the lowest weight, 2, which was given by CityBus. Except for these phenomena, all nodes were assigned a weight greater than 5, showing the importance of these nodes for all stakeholders with respect to the CC PM. Unlike the CC PM, the stakeholders provided lower weights for most of the nodes with respect to this PM, as shown in Figure 7.6, with the minimum weight being 2 provided to nodes 2, 3, 6, 9, 10, and 12 assigned by Lafayette Limo, and nodes 10 and 11 given by CityBus.

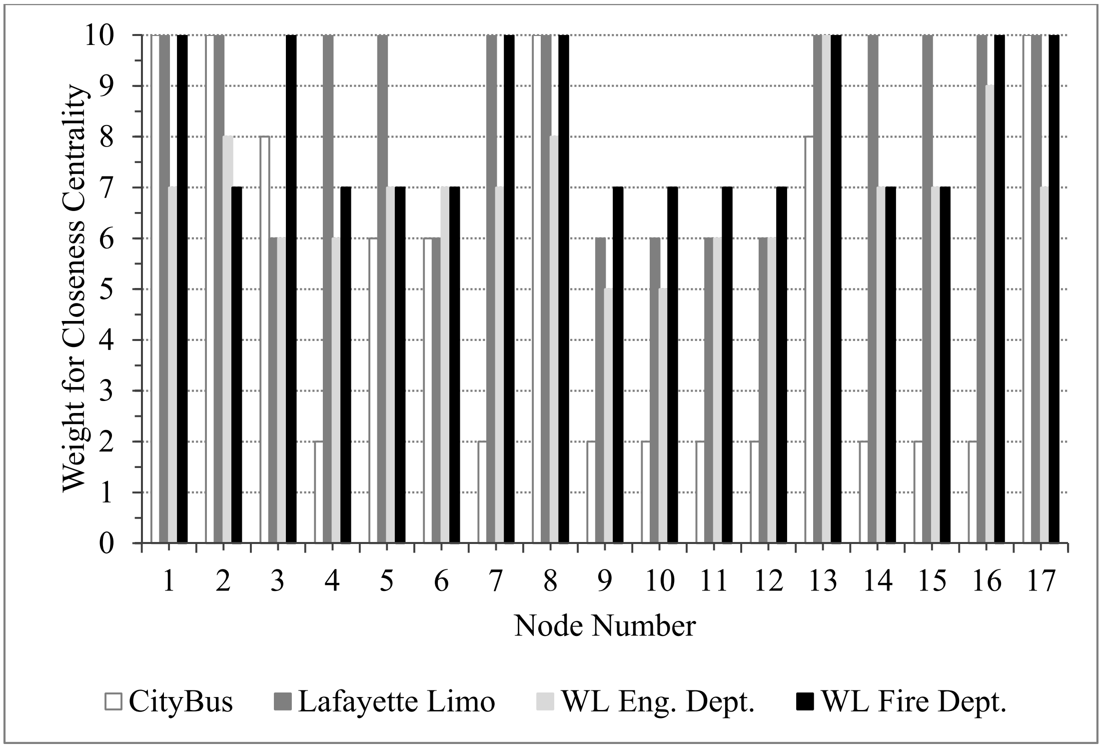


Figure 7.5 Stakeholderpreferences for nodes on the basis of closeness centrality (CC)

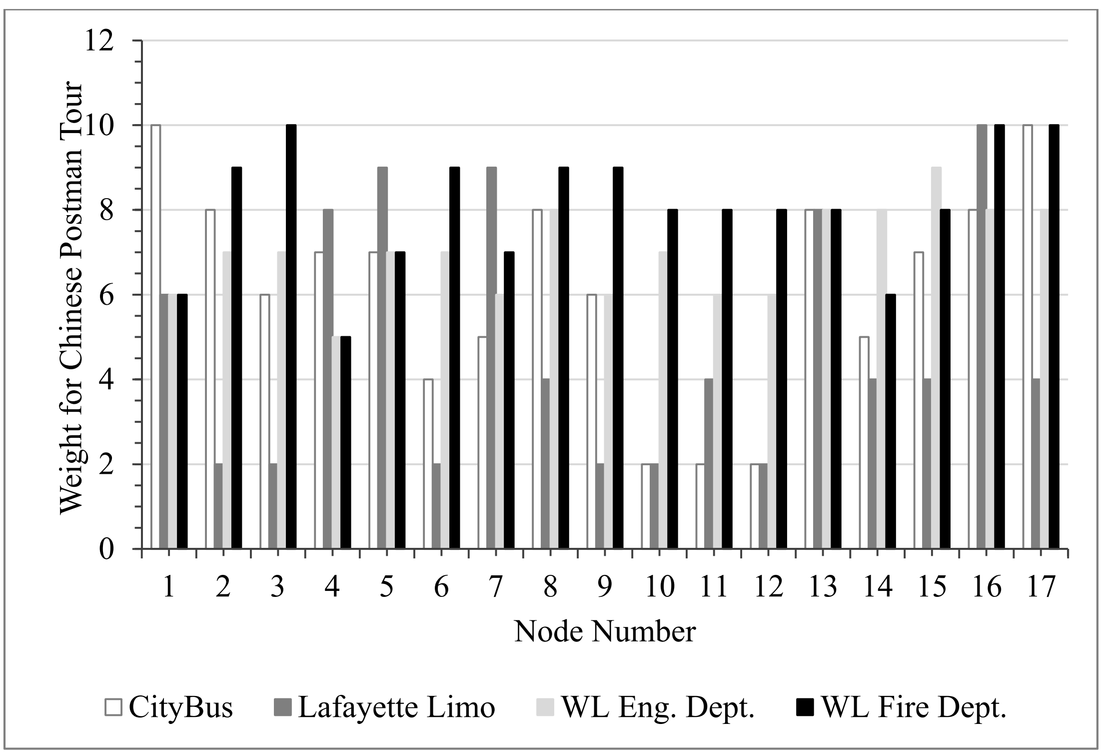


Figure 7.6 Stakeholderpreferences for nodes on the basis of Chinese postman tour

Figure 7.7 presents the average weight provided by stakeholders to the nodes of the network with respect to each PM considered in the study. It is shown that all nodes were provided weights of 5 or greater by all stakeholders; the only exceptions are nodes 10 and 11 that received weights slightly lower than 5 for the case of the Chinese postman tour (CPP) and the LBC PMs. Also, node 12 received a weight less than 5 for the CPP PM. Each node was assigned a different weight based on the PM under consideration, showing that the importance of a node relative to other nodes depends on the type of PM under consideration. The preferences of stakeholders for the nodes based on the average weights assigned to the PMs were compared (Figure 7.7).With the exception of nodes 10, 11, and 12, all nodes were assigned an average of 5 or more for all the PMs. Nodes 10 and 12 were assigned averageweights less than 5 for the CPP PM and node 11 received an average weight less than 5 for the LBC PM. It is generally observed that each node has different average weights from the perspective of different PMs. A given PM was assigned a higher weight for a given node but a lower weight for another node. For example, LBC was assigned an average weight of 9 for node 4 and an average weight of 6.5 for node 5.

Figure 7.8 compares the preferences of stakeholder for the network diameter PM. WLED assigned the highest importance (with an average weight of 8.2) to this PM followed by WLFD (weight equals about 7.9). CityBus assigned a weight of 4. The lowest weight for this PM was assigned by Lafayette Limo. A higher weight was assigned by WLFD, most likely due to their need to be able to reach all corners of the network. A lower diameter means that the WLFD can quickly arrive at the incident location and provide services anywhere in the network when needed. On the other hand, CityBus and Lafayette Limo have routine routes in the network and therefore may not be highly concerned with increasing or decreasing the network diameter because changes in the network diameter may not affect their routine business.

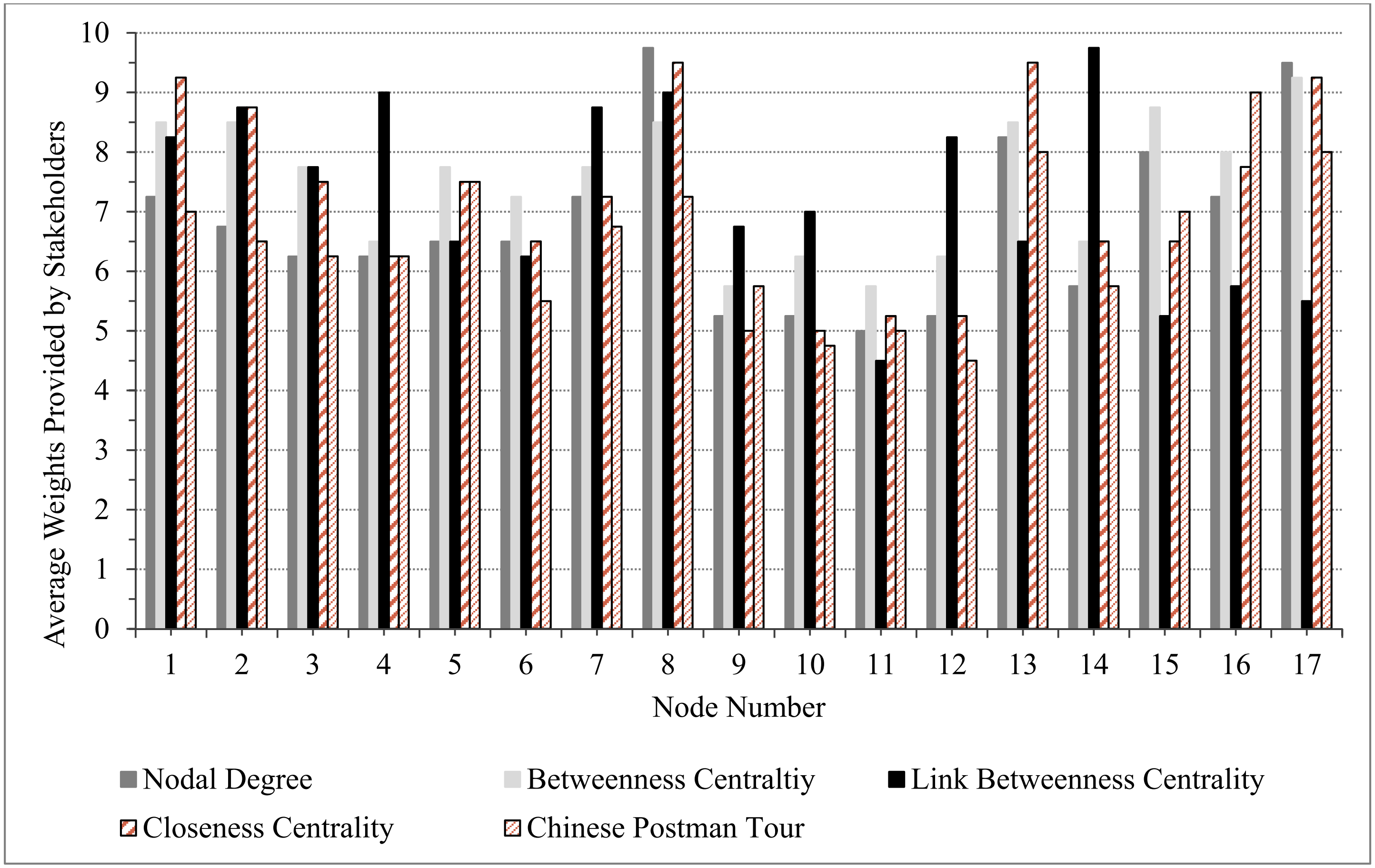


Figure 7.7 Importance of nodes as indicated by stakeholders for each PM

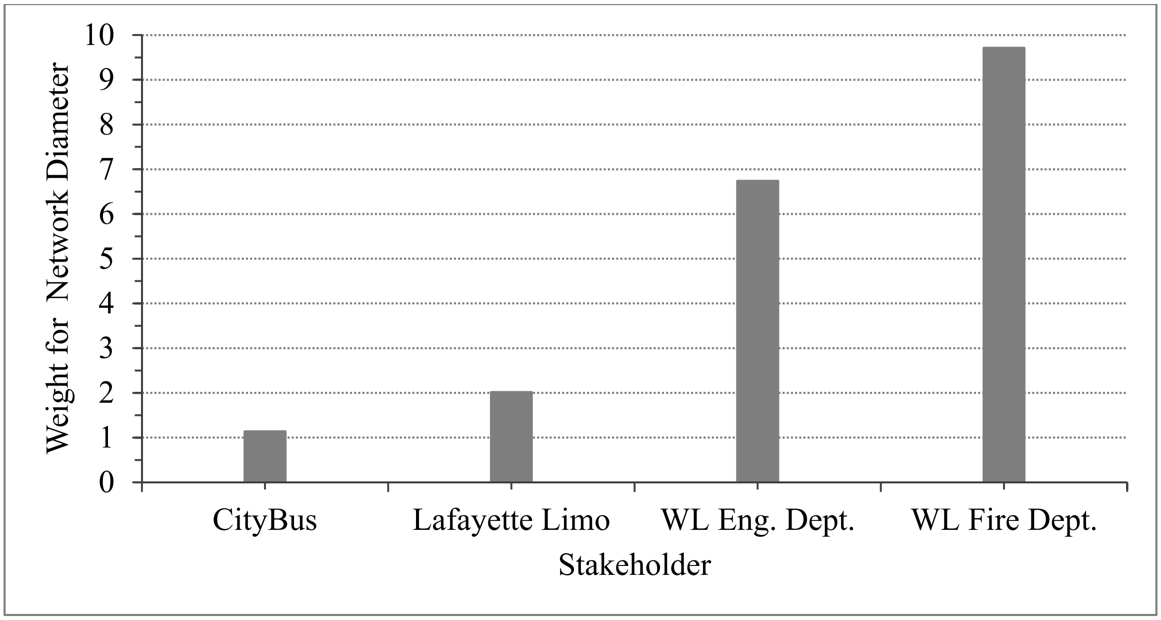


Figure 7.8 Stakeholderpreferences for network diameter

7.3.1 Categories of stakeholders' preferences for nodes and links

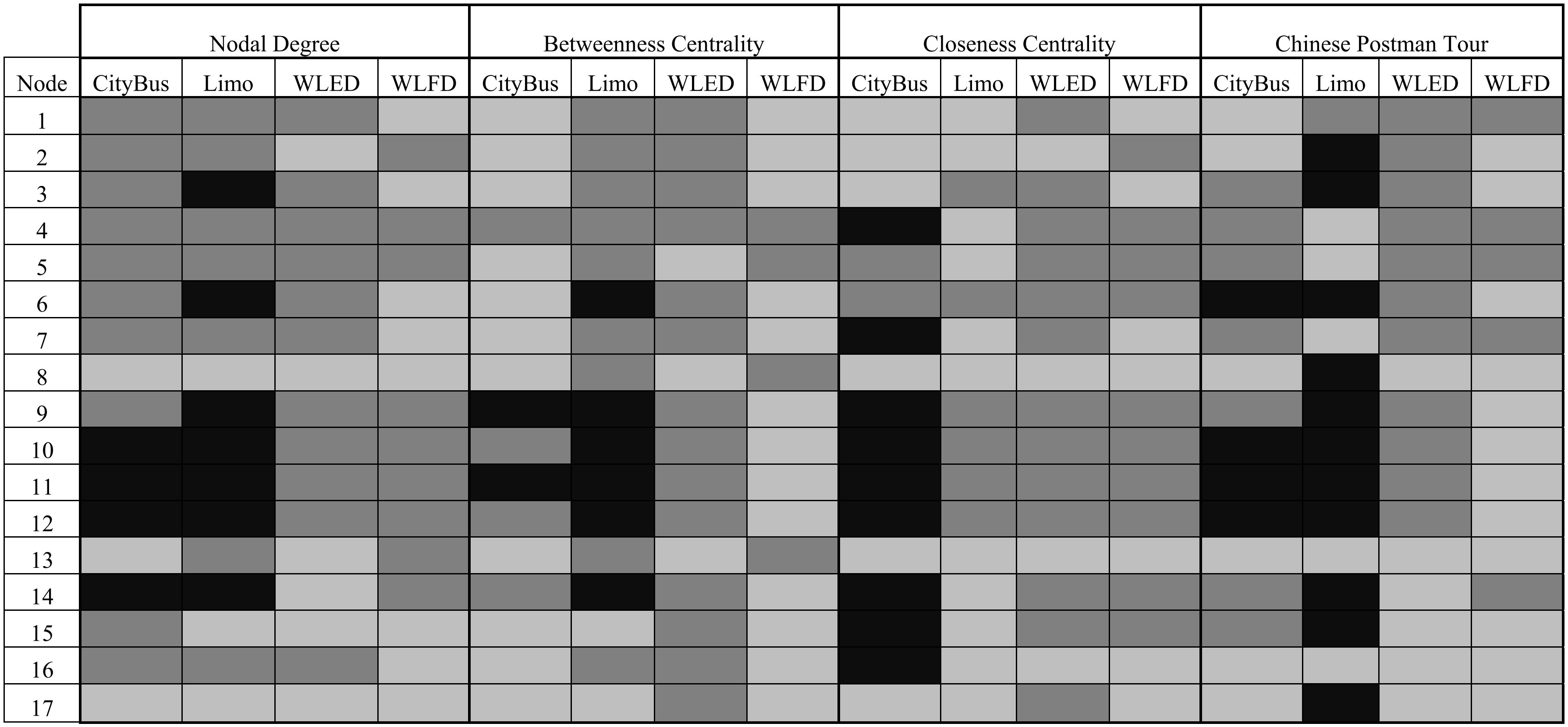
The stakeholders' preferences for nodes and links in the network with respect to considered PMs were divided into three categories based on weight values: weight less than 5, weight between 5 and 8 including 5 but excluding 8, and weight greater than or equal to 8.The classifications of nodes and links based on these weight groups are given in Table 7.4 and Table 7.5.

It is shown in Table 7.4 that for all the PMs, no node has the same degree of preferences as per the preference criteria. For example, node 8 was assigned a preference of 8 or greater for all PMs, except for BC in the case of Lafayette Limo and WLFD, and for CPP in the case of Lafayette Limo. It also canbeen seen that a given stakeholder has different preferences for a given node for different PMs. For example, CityBus assigned the highest preference for nodes 8 and 13. When nodal degree (ND) was considered and node 13 for BC, nodes 1, 2, 3, 4, 8, 13, and 17 in the case of CC, and nodes 1, 2, 8, 13,16, and 17 for the case of CPP. On the other hand, CityBus assigned its lower preferences to nodes 10, 11, 12, 13, and 14 for the network diameter PM, nodes 9 and 11 for BC, nodes 4, 7, 9, 10, 11, 12, 14, 15, and 16 for CC, and nodes 6, 10, 11, and 12 for Chinese postman cost. Similar observations can be made for other stakeholders.

Table 7.5 presents the preferences of the stakeholders for links in the network with respect to the LBC PM. It is shown that the stakeholders have variable preferences for links with respect to LBC. For example, CityBus and WLFD assigned a high preference to link 1-2 compared to Lafayette Limo and WLED which indicated medium preferences to the link. All stakeholders provided higher importance to link 8-13. Using Table 7.5, it is also possible to analyze how each stakeholder assigned its preferences for all links in the network. For instance, WLFD assigned higher importance for links 1-2 than to links 2-5. Lafayette Limo assigned the lowest importance to link 8-9 and the highest importance for link 13-15.

The above results generally show that transportation decision making could incorporate the preferences of stakeholders for network elements (nodes and links) in a given transportation network with respect to the PMs of interest. This approach is useful for minimizing the negative impact that a transportation project may have on some stakeholders and an unfairly high advantage for other stakeholders.

Table 7.4 Stakeholders' preferences for nodes with respect to PMs



Legend	Weight Criterion
(black)	$w<5$
(dark grey)	$5 \leq w < 8$
(light grey)	$w \geq 8$

Notation: CityBus= Greater Lafayette Public Transportation Corporation; Limo = Lafayette Limo; WLED=West Lafayette Municipality Engineering Department; WLFD: West Lafayette Municipality Fire Department

Table 7.5 Stakeholders' preferences for links with respect to link betweenness centrality (LBC) performance measure (PM)

Stakeholder	Link Number											
	1-2	1-4	2-3	2-5	3-6	4-5	4-7	5-8	6-9	6-10	7-8	7-16
CityBus	$w \geq 8$	$w \geq 8$	$w \geq 8$	$w \geq 8$	$5 \leq w < 8$	$w < 5$	$w \geq 8$	$w \geq 8$	$5 \leq w < 8$	$5 \leq w < 8$	$w < 5$	$w \geq 8$
Limo	$5 \leq w < 8$	$w \geq 8$	$w < 5$	$w \geq 8$	$w < 5$	$w \geq 8$	$w \geq 8$	$w \geq 8$	$w < 5$	$w < 5$	$w < 5$	$5 \leq w < 8$
WLED	$5 \leq w < 8$	$5 \leq w < 8$	$5 \leq w < 8$	$w \geq 8$	$w \geq 8$	$5 \leq w < 8$	$5 \leq w < 8$	$w \geq 8$	$5 \leq w < 8$	$w \geq 8$	$5 \leq w < 8$	$5 \leq w < 8$
WLFD	$w \geq 8$	$w \geq 8$	$w \geq 8$	$5 \leq w < 8$	$5 \leq w < 8$	$5 \leq w < 8$	$w \geq 8$	$5 \leq w < 8$	$w \geq 8$	$w \geq 8$	$5 \leq w < 8$	$w \geq 8$
Stakeholder	Link Number											
	8-9	8-13	9-11	10-12	11-12	11-13	12-14	13-14	13-15	14-15	15-17	16-17
CityBus	$w \geq 8$	$w \geq 8$	$w < 5$	$5 \leq w < 8$	$w < 5$	$w < 5$	$5 \leq w < 8$	$w < 5$	$w < 5$	$w < 5$	$w \geq 8$	$w \geq 8$
Limo	$w < 5$	$w \geq 8$	$w < 5$	$w < 5$	$w < 5$	$w < 5$	$w < 5$	$w < 5$	$w \geq 8$	$w < 5$	$w < 5$	$w \geq 8$
WLED	$5 \leq w < 8$	$w \geq 8$	$5 \leq w < 8$	$5 \leq w < 8$	$5 \leq w < 8$	$5 \leq w < 8$	$5 \leq w < 8$	$w \geq 8$	$w \geq 8$	$5 \leq w < 8$	$5 \leq w < 8$	$5 \leq w < 8$
WLFD	$5 \leq w < 8$	$w \geq 8$	$5 \leq w < 8$	$5 \leq w < 8$	$w \geq 8$	$w \geq 8$	$5 \leq w < 8$	$5 \leq w < 8$	$5 \leq w < 8$	$w \geq 8$	$w \geq 8$	$w \geq 8$

Notation: CityBus= Greater Lafayette Public Transportation Corporation; Limo = Lafayette Limo; WLED=The City of West Lafayette Engineering Department; WLFD: West Lafayette Fire Department

Legend	Weight Criterion
(black)	w <5
(dark grey)	$5 \leq w < 8$
(light grey)	$w \geq 8$

7.4 Network connectivity index (NCI)

In determining the NCI for the network given in Figure7.1, values of all PMs were first computed using python code given inAppendix H and Graph Magics® software (Ciubatii, 2005) for computing Chinese postman problem (CPP) given in Appendix I. Then, the PM values were scaled into the same unit of measurement in order to apply the NCI model. Scaling of PMs was done based on the procedure presented in Section6.3.5. The NCI was determined using average weights provided by stakeholders to each network element corresponding to each PM. For network-level PMs (such as network diameter), a single weight was given; there was no need to consider the network elements.

Equation 7.1 shows a simplified NCI model for the case network after inserting constant values into Equation (6.3). These constant values are average weights of PMs given by all stakeholders as shown in Table 7.1, , and the number of nodes and links in the network which are 17 and 24, respectively.

$$NCI = \frac{\frac{8.00}{17}\sum_{i=1}^{n}\gamma_i^{BC}w_i^{BC} + \frac{7.75}{24}\sum_{i=1}^{l}\gamma_m^{LBC}w_m^{LBC} + \frac{8.75}{17}\sum_{i=1}^{n}\gamma_i^{\theta}w_i^{\theta} + \frac{9.25}{17}\sum_{i=1}^{n}\gamma_i^{CC}w_i^{CC}}{\frac{8.25}{17(17-1)/2}\sum_{i=1,j=1,i\neq j}^{n}\beta_{i,j}^{SPL}w_{i,j}^{SPL} + \frac{9.5}{17}\sum_{i=1}^{n}\beta_i^{CPP}w_i^{CPP} + \frac{8}{17}\beta^{D}}$$

(7.1)

Table7.6 provides weighted sum of PM values which were computed by multiplying the PM value corresponding to each node or link in the case network by the average weight given to the same node or link by the stakeholders.

Table7.6 Weighted sum of PM values

PM	Scaled, Weighted Sum of PMs $\sum_{i=1}^{n}\gamma_i^{PM}w_i^{PM}$ OR $\sum_{i=1}^{l}\gamma_i^{PM}w_i^{PM}$
Nodal Degree	265.44
BC	232.49
LBC	289.18
CC	271.99
Shortest Path Length	2031.82
Chinese Postman Tour	651.47
Diameter	55.88

If the weighted sum values of the PMs are inserted into Equation 7.1, the NCI model can be further simplified as

$$NCI = \frac{\frac{8.00}{17} * 232.49 + \frac{7.75}{24} * 289.18 + \frac{8.75}{17} * 265.44 + \frac{9.25}{17} * 271.99}{\frac{8.25*2}{17*16} * 2031.82 + \frac{9.5}{17} * 651.47 + \frac{8}{17} * 55.88}$$

and the NCI value for the case network shown in Figure 7.1 can be determined to be 1.04.This NCI value does not imply anything by itself. However, when different projects are evaluated for implementation, their importance could be compared with respect to the NCI values of the network when these projects are considered for implementation during the analysis. Projects which provide higher NCI values are preferable to projects which cause lower NCI values when they are implemented. A thorough investigation of the impact of the projects on the NCI should be conducted in order to identify two or more projects for implementation. The maximum possible number of combinations of projects should be evaluated in order to select projects which relatively maximize the NCI value. For example, if there are 10 projects and only two projects are to be implemented, $\binom{10}{2} =$ 45 combinations of projects should be considered and the corresponding 45 NCI values should be computed and ranked, and those projects which provide the highest NCI values should be selected for implementation based on the network connectivity evaluation criteria.

7.5 Determination of sparse network connectivity level

This section discusses the results of the case study with respect to the network connectivity. First, the hypothetical network is described. Then, the SNAL model application results are presented. Finally, the impacts of alternative projects on the sparse network connectivity are described.

7.5.1 Hypothetical sparse network

Figure 7.9 is a hypothetical sparse network that is used to analyze the connectivity levels of sparse networks. The network is composed of 14 nodes and 15 links. This sparse network is characterized by having very low connectivity between its nodes. Shown in dotted lines are link construction projects. These projects may be the construction of a highway or the reconstruction of a destroyed bridge on these links. The network is used to demonstrate how the different projects affect nodal and network connectivity levels.

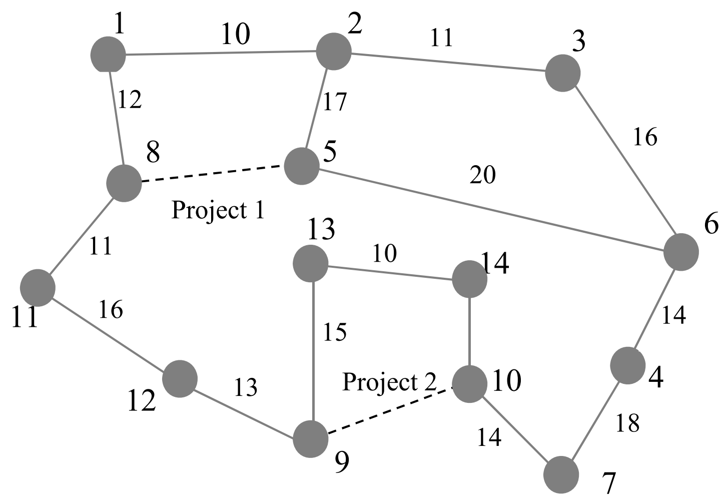


Figure 7.9 Hypothetical sparse network used for case study

7.5.2 SNCL model application results

Figure 7.10 compares connectivity levels of nodes in the example sparse network. The sparse network connectivity (SNCLs) of nodes 2 and 6 are each 18.9. The NCLs of nodes 1 and 7 are 17.8. Nodes 3 and 8 have 17.6 NALs, followed by nodes 9 and 10, each having a NAL of 17.4. Nodes 11 and 13 have of 17.0. The nodes with the lowest NCL value (15.6) are nodes 4 and 5. These results show that NALs of nodes in a sparse network, determined by Equation 6.8, may vary depending on the importance level of a node, as captured by BC, NIndPath and DN, as well as weight attributes provided to the node with respect to these PMs.

A random number generator was used to assign the e_i term in Equation 3.6, which represents the economic, societal, or political importance of each node. In a real-life situation, the value of e_i could be provided by decision makers. For a node with higher, economic, societal, or political importance, a higher e_i value is assigned. Using Equation 6.9, the overall SNCL of the hypothetical sparse network was found to be 17.3. The SNCL values obtained for different cases of link disruptions, link construction, etc. can be compared, and the impact of transportation decisions for sparse networks can be evaluated on the basis of increased connectivity.

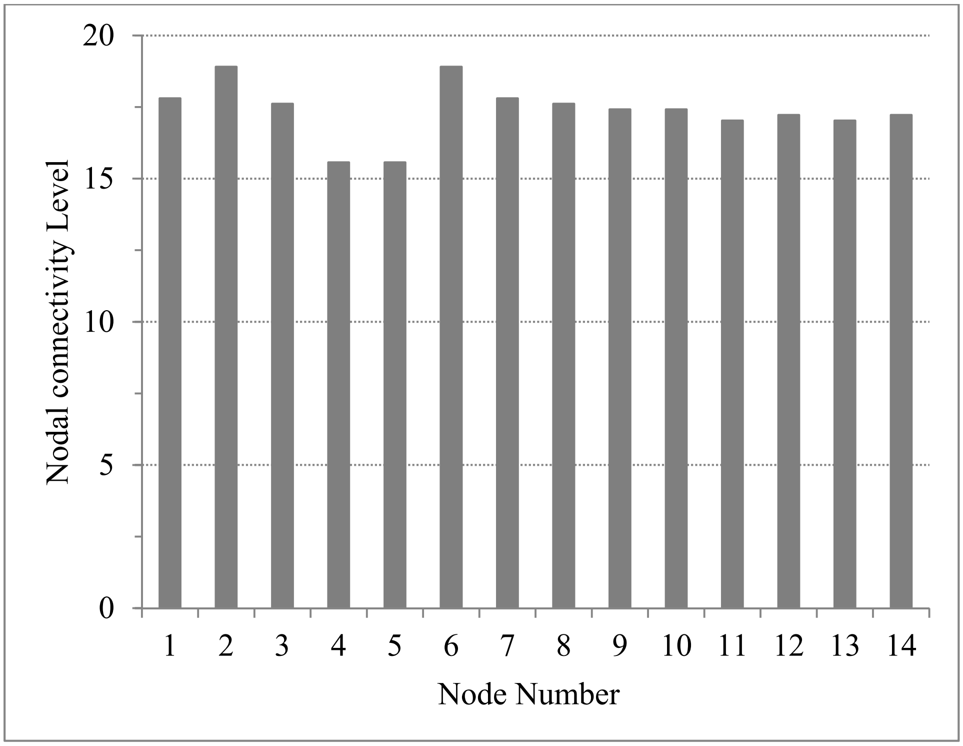


Figure 7.10 Comparison of connectivity levels of nodes

7.5.3 Project impacts based on network connectivity level

In sparse networks such as rural networks in developing countries, the construction of a new link can play an important role in improving connectivity of a node (which could represent population centers). Candidate projects are considered to evaluate how different projects could affect the nodal connectivity in the network.

As shown in Figure 7.11, the choice of a transportation project can affect nodal connectivity. It is interesting to observe that the two considered projects have brought both positive and negative change in NcLs across the nodes. Implementation of either of the projects causes reduction of the SNcL for nodes 1, 2, 4, 13, and 14 compared to the do-nothing option. Comparing the impact of the two projects, it is shown that project 1 is preferred to project 2 for nodes 3, 5, 6, 10, 13, and 14; and project 2 is preferred to project 1 for nodes 1, 2, 4, 7, 8, 9, 11, and 12 because project 1 improves their NALs to a greater extent. Nodes 3, 5, 6, and 10 benefit from project 1 because their NCLs improve compared to the do-nothing option. Similarly, for project 2, the NCLs of nodes 7, 8, 9, 11, and 12 improved compared to the do-nothing option. For nodes 7 and 12, do-nothing and project 1 have the same impact on the NCL. It is interesting to note that none of the nodes have their NALs improved in project 1 and project 2; and the probability that a node's NCL improves whether project 1 or project 2 is implemented is either 0, which is when the NCL reduces, or 1 which is when either of the projects improved the NCL of the node from the do-nothing case.

Change in NCL with respect to the do-nothing option can have economic, societal, and political impacts. Nodes with improved NCLs are likely to yield economical benefit because their higher NCLs may attract people and businesses to these nodes, thereby bringing economic development such as new business centers and social services such as schools, hospitals, etc. On the other hand, nodes with reduced NCLs may suffer from the lack of such development as well as the loss of their current businesses when these businesses shift from nodes of lower NCLs to those of higher NCLs. The change in NCLs can cause societal issues among the population living in different nodes in the network, such as population centers. These issues may arise from inequality due to transportation investment decisions as manifested by a decrease in the NCLs in these nodes. As described in the previous paragraphs, these equity issues are a result of not considering the impact of project implementation on nodal connectivity. In some networks where natural disasters such as flooding or earthquake are prevalent, NCLs may be a major concern. Emergency evacuation procedures and delivery of assistance such as medical and fire prevention services can be highly affected by the connectivity levels of nodes. Therefore, it is worth considering the impact of project selection on the economic, societal, and political aspects of the residents at each node of the network.

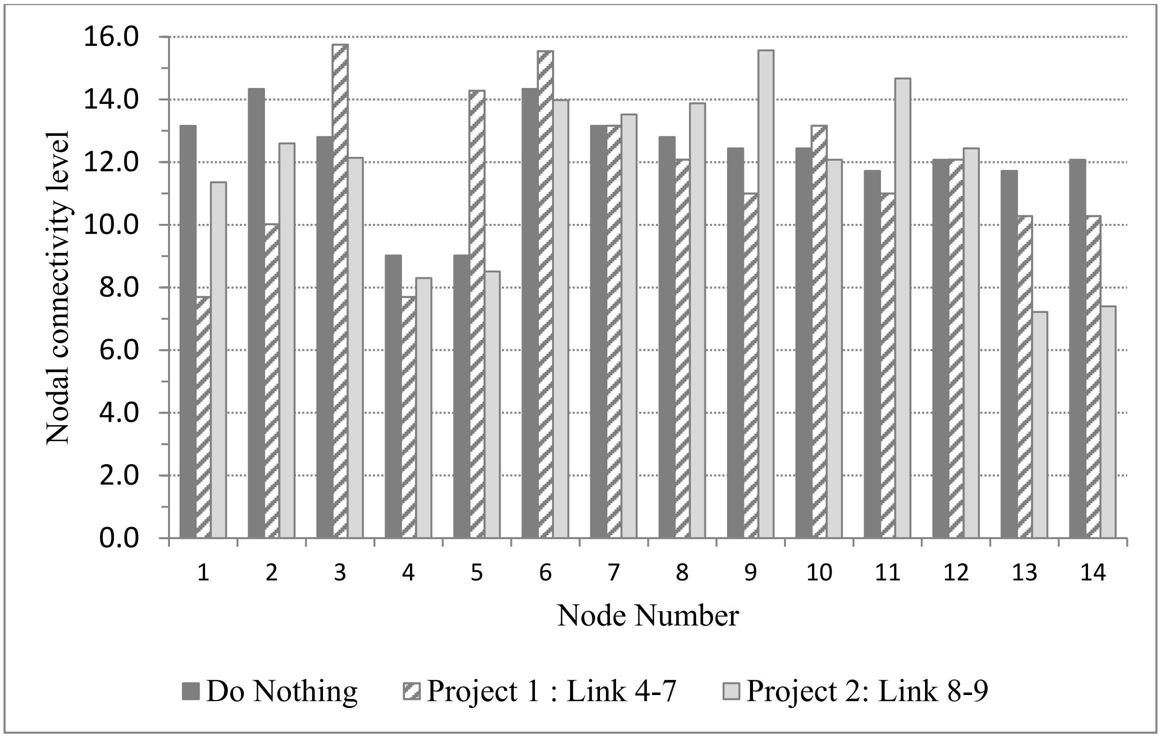


Figure 7.11 Impact of project implementation on nodal connectivity level (NAL)

Figure 7.12 compares the connectivity level of the network for different cases: do-nothing, implement project 1 or implement project 2. It is interesting to note that implementation of project 1, which is construction of link 4-7, does not improve the SNCL, when compared with the do-nothing case (11.78 vs. 12.36). It is shown that implementation of project 2 improved the SNCAL when compared with do-nothing and project 1 cases (12.45 vs. 12.36 or 11.78).

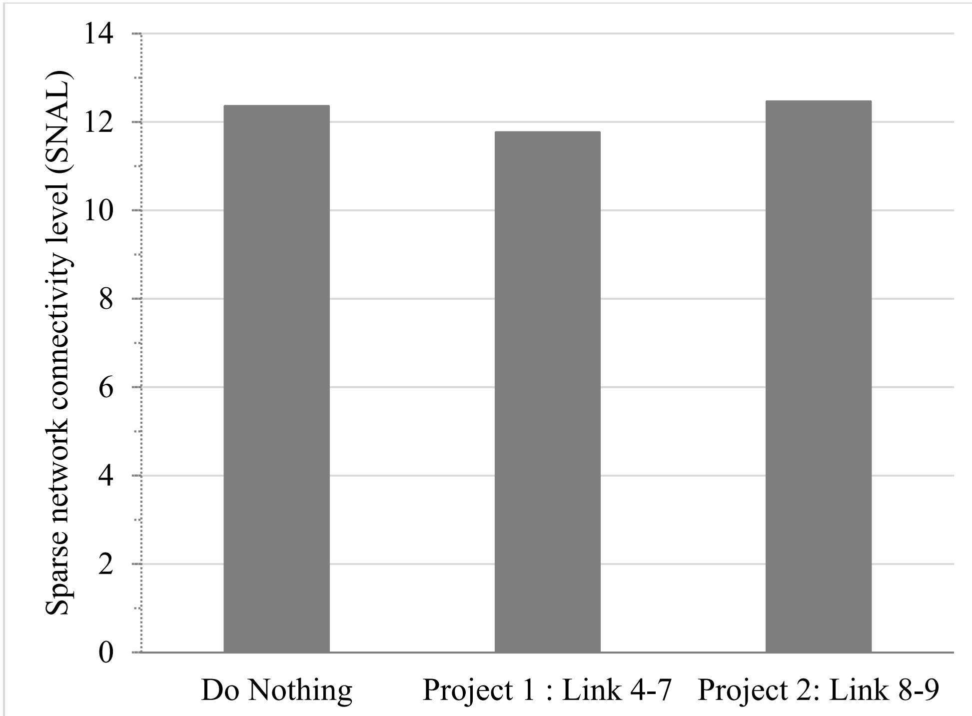


Figure 7.12 Impact of project implementation on connectivity of the network

7.6 Chapter summary

In this chapter, the results of the NCI and SNCL analyses were discussed. A case study network located in West Lafayette, Indiana was used to demonstrate the proposed framework that was presented in Chapter 3.The survey results were also presented as well as descriptions of the establishment and operation histories of the transportation stakeholders. The network connectivity computation and scaling of PMs was demonstrated; and using a hypothetical network to analyze the effect of projects, the chapter also presented the plots of the nodal connectivity level vs. the node number. The impacts of different projects on nodal and network connectivity levels were also presented.

The results show that stakeholders tend to give different levels of importance to nodes and links in the network from the perspective of their operations. The network connectivity indices of the stakeholders were found to vary because of the differences in their perceptions of the relative importance of network PMs and elements (nodes and links). It is shown that transportation project selection could affect the nodal and network connectivity level and hence it is recommended that candidate projects should be evaluated in terms of the nodal and network connectivity levels, among other traditional criteria for evaluation.

The final chapter, Chapter 8, provides a summary of the research discussed in Chapters 1 through Chapter 7. It also presents the conclusions of the various aspects of the research, identifies the research contribution, and presents areas of possible related research for future work.

CHAPTER 8. SUMMARY AND CONCLUSIONS

This chapter first summarizes the dissertation's motivation and methodology and then briefly recaps the significance of the network connectivity framework that was developed, followed by an explanation of the significance of the performance tradeoff curves developed in this dissertation, the major conclusions from this dissertation, and the scope of future work.

8.1 Summary

8.1.1 Dissertation Motivation

A primary hypothesis for this dissertation is that the implementation of different projects affects the topological performance of a transportation network or its constituent elements (nodes and links) differently. Project selection that could affect the topological performance of the entire transportation network or the network elements (i.e. nodes and links) was demonstrated using case study networks. It was shown also that each project could bring variable impacts on the topological performance of nodes and elements.

A sparse network was used to investigate whether the transportation project selection process could affect the connectivity level of nodes in such networks. The results showed that implementation of a transportation project could bring variable effects on connectivity of nodes, i.e., it could change network connectivity levels, improve the connectivity of certain nodes, and decrease the connectivity of other nodes. In addition, a given project may be more desirable from a topological perspective because it increases the overall network connectivity compared to other projects. For this reason, it is worth considering the network topological impacts associated with each candidate project (for ranking purposes) or with a single project (for feasibility purposes).

However, from the literature review, it was established that network topological performance is not typically considered during transportation infrastructure evaluation and project selection.

This dissertation hypothesized that simultaneous implementation of multiple projects could bring different results on network connectivity when compared to their effects on the network connectivity when they are implemented individually. Therefore, it was determined that a framework is needed to identify the interdependencies of projects in terms of their effects on network connectivity.

Existing network connectivity indices do not allow incorporation of stakeholders' preferences. However, in making decisions from the agency perspective alone, the full benefits of projects may not be realized. As such, in developing a framework for incorporating network connectivity in decision making, a process is needed to incorporate the preferences of the various stakeholders.

8.1.2 Framework for transportation network connectivity

In addressing the motivation for this research, a transportation network connectivity modeling framework was developed. This framework can be applied to a new or existing network to quantify the network connectivity considering the network's PMs. The framework also allows the decision maker to provide stakeholder-assigned weights for the PMs. Also, the framework can be used to evaluate and rank the topological importance of individual nodes and links to the entire network connectivity.

The developed framework was applied to a case study network located in West Lafayette, Indiana. The West Lafayette Fire Department (WLFD), the Greater Lafayette Public Transportation Corporation (CityBus), and Lafayette Limo were the transportation stakeholders in the case study as well as the City of West Lafayette Engineering Department, which is responsible for making road network investment decision. A survey questionnaire was administered to collect data from the stakeholders regarding the importance they attached to individual PMs and to specific network nodes or links.

A sparse network connectivity model was developed in this dissertatain to incorporate the BC, the number of independent paths, and the nodal degree to characterize such networks. The proposed NAL model was used to characterize the connectivity of each node in the network, and the proposed SNCL model was used to characterize the connectivity of the entire network.

Also, this dissertation investigated the impact of project selection on sparse network connectivity by considering various hypothetical candidate investment projects and evaluating their impact on the network connectivity. It was observed that different projects have different impacts on network connectivity, thereby establishing a strong case for including network connectivity in the traditional portfolio of evaluation criteria for investment evaluation and prioritization.

8.1.3 Comparison of multiple transportation network performance measures (PMs)

Against the background of the notion that certain network topological PMs can be achieved by scarifying others, this dissertation developed PMTCs to support decision making processes that involve (or seek to involve) transportation network topological performance. The PMs considered in this part of the dissertation were betweenness centrality, link betweenness centrality, nodal degree, closeness centrality, shortest path length, network diameter and the number of independent paths. The PMTCs are particularly useful in cases where the PMs of interest conflict with each other. The PMTCs were developed using simulated performance data from each of approximately a thousand randomly-generated networks. Using these PM values, plots were prepared for each pairof PMs. Decision makers can utilize these PMTCs to support their decisions by analyzing how investments could yield a positive return for certain PMs but the corresponding negative return for other PMs, and to ascertain whether such tradeoffs are acceptable.

8.2 Conclusions

8.2.1 Importance of network connectivity framework

It was found that the framework developed in this dissertation can be used to quantify network connectivity and therefore support transportation investment decision making. Also, the developed network connectivity model is capable of incorporating stakeholders' preferences for specific nodes and links with respect to each PM. Using a case study, it was demonstrated that the modeling framework can allow a decision maker to utilize PMs of interest and apply the network connectivity model to determine an overall index of network connectivity.

The NCL and SNCL models can be used to quantify the connectivity levels of the network nodes and the entire network, respectively.The NCL model is very useful for comparing the connectivity levels of nodes and prioritize them based on the preferences of the decision maker or stakeholders. The SNCL model allows the decision maker to incorporate the importance of a node with respect to its economic, societal, or political importance in the network.

This dissertation demonstrated that transportation infrastructure projects can affect the levels of network connectivity. In transportation investment evaluation, it is therefore important to consider network connectivity impacts and duly weigh such impacts in terms of the economic, societal, and political considerations associated with specific nodes and links.

8.2.2 Considering performance measures (PMs) in the transportation decision making process

As mentioned earlier in this chapter, this dissertation validated the hypothesis that different projects can lead to different impact in terms of network topological performance. A more subtle but critical finding is related to holism and project interdependencies: the implementation of two or more projects based merely on their ranks in terms of improving the network topological performance may not necessarily guarantee the maximum possible network topological performance. It was clearly demonstrated in this dissertation that different combinations of candidate projects can provide different levels of network topological performance. For example, two projects ranked individually as 3 and 4 could provide the highest network topological performance if implemented simultaneously compared to the simultaneous implementation of the projects ranked individually as 1 and 2. Similar results indicate that only after an exhaustive evaluation of all combinations of projects can projects be ranked or selected on the basis of their topological performance.

This dissertation also proved that network topological PMs are not only of immense interest to transportation stakeholders but that the PMs are weighed differently by different stakeholders as well. This suggests that the topological performance of a given network depends not only on which PMs are considered but also on the weight attached to each PM by the stakeholders. Further, a single PM could be given different preference when it is weighted with respect to different nodes or links in the network.

The PM tradeoff curves developed in this dissertation can be used to conduct pair-wise comparison of PMs and to analyze how a particular level or value of a PM affects other PMs of interest. This analysis is particularly important where the decision maker seeks to prioritize investments that are geared towards enhancement of network connectivity performance and where the PMs are not only multiple but often conflicting.

The functional relationships between pairs of PMs were investigated using regression analysis based on the network average PM values whenever appropriate. Regression analysis was conducted for each of the six computer runs and the average of the six computer runs. A direct functional relationship was observed between the network average BC and the network average LBC. On the other hand, an inverse functional relationship was observed between the network average BC and the network average closeness centrality, network average LBC, and network averages ND and NIndPath. However, no functional relationship was found to exist between the BC and the following PMs: nodal degree, network diameter, shortest path length, and number of independent paths. Similarly, no functional relationship was found between the LBC and the following PMs: nodal degree, network diameter, shortest path length, and number of independent paths. Also, no functional relationship was observed between the nodal degree and the following PMs: network diameter, CC, and the shortest path length. No functional relationship was observed as well between the network diameter and the shortest path length, CC and the shortest path length, CC and the number of independent paths, and the shortest path length and the number of independent paths.

Graphs showing the functional relationships that exist between pairs of PMs were found particularly useful in conducting trade-off analysis between each pair of PMs. Using the developed PMs, a decision maker can ascertain how much the gain in one PM can be traded off for another PM when projects are implemented in a transportation network. This dissertation introduced the concept of marginal rate of substitution (MRS) into the research domain of transportation network topological performance. The MRS can be utilized together with the developed network performance tradeoff curves to investigate how a percent change in one of the PMs is generally associated with a given change in the level of the other PMs.

8.3 Future Work

Future research in this area could expand the number of measures of network topological performance to include, for example, the cyclomatic number, alpha index, beta index, and gamma index. These measures can be incorporated in the developed connectivity framework to capture specific structural and topological characteristics of a network that are related to the efficiency of transportation operations in the network.

This dissertation solicited the preferences of only a limited number of real-life network operations stakeholders due to time constraints and the reluctance of certain groups of stakeholders (particularly the private-sector package delivery service companies) to participate in the survey. Future research efforts could reach out to such stakeholders to acquire their inputs as their routine operations are very dependent on the connectivity of the network, and their preferences for the topological PMs could help generate results that further represent the overall performance of the network.

The framework in this dissertation is deterministic in nature. However, in real life, certain projects may not be 100% implemented due to factors such as the availability of funds. Also, the framework addressed the effect of only 0% or 100% link disruption. Therefore enhancements to the framework can be made by considering that a link may suffer a partial disruption (less than 100%). The incorporation of stochastic elements in the framework will make it more robust.

The network connectivity framework developed in this dissertation could be incorporated in the general transportation investment evaluation framework. In addition, applying the general investment evaluation framework, the significance of network connectivity criteris could be evaluated by evaluating the impact of project programming and prioritization on transportation system performance with and without considering network connectivity.

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APPENDICES

Appendix A Python code for network plot generation and performance measure (PM) value computation

```
#!/usr/bin/python
importnetworkx as nx
importpylab as pylab
frompylab import *
importmatplotlib.pyplot as plt
import collections
importnumpy as np
from operator import itemgetter
import igraph
from igraph import *

# Create the Case Network
g=nx.Graph()
g.add_node('A', pos=[2.0,11.0])
g.add_node('B', pos=[3.0,11.0])
g.add_node('C', pos=[4.0,11.33])
g.add_node('D', pos=[4.0,10.67])
g.add_node('E', pos=[5.17,10.67])
g.add_node('F', pos=[2.0,10.17])
g.add_node('G', pos=[2.83,10.17])
g.add_node('H', pos=[4.0,9.83])
g.add_node('I', pos=[5.17,10.0])
g.add_node('J', pos=[5.83,8.67])
g.add_node('K', pos=[2.0,7.83])
g.add_node('L', pos=[3.0,8.83])
g.add_node('M', pos=[4.0,8.5])
g.add_node('N', pos=[5.17,7.66])
g.add_node('O', pos=[6.5,8.0])
g.add_node('P', pos=[2.0,7.0])
g.add_node('Q', pos=[3.66,7.83])
g.add_node('R', pos=[5.0,7.16])
g.add_node('S', pos=[5.83,7.17])
g.add_node('T', pos=[2.33,6.33])
g.add_node('U', pos=[4.5,6.33])
g.add_node('V', pos=[5.67,6.67])
g.add_node('W', pos=[6.67,6.67])
g.add_node('X', pos=[5.0,6.0])
g.add_node('Y', pos=[2.83,6.0])
g.add_edge('A','B',weight=3.0)
g.add_edge('A','F',weight=2.5)
g.add_edge('B','C',weight=3.16)
g.add_edge('B','G',weight=2.55)
```

```
g.add_edge('C','D',weight=2.0)
g.add_edge('C','E',weight=4.03)
g.add_edge('D','E',weight=3.5)
g.add_edge('D','G',weight=3.81)
g.add_edge('D','H',weight=2.5)
g.add_edge('E','I',weight=2.0)
g.add_edge('F','G',weight=2.5)
g.add_edge('F','K',weight=7.0)
g.add_edge('G','H',weight=3.16)
g.add_edge('G','K',weight=7.43)
g.add_edge('H','I',weight=3.64)
g.add_edge('H','L',weight=4.24)
g.add_edge('H','M',weight=4.0)
#g.add_edge('I','J',weight=5.0)
g.add_edge('I','M',weight=5.70)
g.add_edge('I','N',weight=7.0)
g.add_edge('J','O',weight=2.83)
g.add_edge('K','L',weight=4.24)
g.add_edge('K','P',weight=2.5)
g.add_edge('L','M',weight=3.16)
g.add_edge('L','P',weight=6.26)
g.add_edge('L','Q',weight=3.61)
g.add_edge('M','N',weight=4.30)
g.add_edge('M','R',weight=5.0)
g.add_edge('N','S',weight=2.5)
g.add_edge('O','S',weight=3.20)
g.add_edge('P','T',weight=2.24)
g.add_edge('Q','T',weight=6.02)
g.add_edge('R','S',weight=2.5)
g.add_edge('R','U',weight=2.92)
g.add_edge('R','W',weight=5.22)
g.add_edge('S','W',weight=2.92)
g.add_edge('T','U',weight=6.5)
g.add_edge('T','Y',weight=1.80)
g.add_edge('V','W',weight=3.0)
g.add_edge('V','X',weight=2.83)
g.add_edge('X','Y',weight=6.5)
pos=nx.get_node_attributes(g,'pos')
edge_labels=(dict([((u,v,),d['weight']) for u,v,d in g.edges(data=True)]))

#Determine network characteristics
print "Network Characteristics –Base Network "
print "Number of Nodes in the Network: " + str (g.number_of_nodes())
print "Number of Links in the Network: " + str (g.number_of_edges())
cen=nx.center(g)
print "The Center of the Network: " + str(cen)
diam= nx.diameter(g)
print "Network Diameter\n" + str(diam)
```

```
rad =nx.radius(g)
print " Network Radius\n" + str(rad)
print "Degree of Each Node:" + str(g.degree())
print “\n”
print "Nodal Degree"
dgr=nx.degree(g)
for nodes, values in dgr.items():
        avg_ndvalue= sum(dgr.values()) / g.number_of_nodes()
print "Average Nodal Degree in the Network: " + str(avg_ndvalue)
print "\n"
print "Betweenness Centrality"
bet_cen=nx.betweenness_centrality(g, normalized=True, weight='weight', endpoints=False)
avg_bcvalue= sum(bet_cen.values()) / g.number_of_nodes()
print "Average Betweenness Centrality: " + str(avg_bcvalue)
print "Max" + str(round(max(bet_cen.values()),3))
print "Min" + str(round(min(bet_cen.values()),3))
print "\n"
print "Link Betweenness Centrality"
link_bet_cen=nx.edge_betweenness_centrality(g,normalized=True)
avg_ebc= sum(link_bet_cen.values()) / g.number_of_edges()
print "Average link betweenness centrality:" + str(avg_ebc)
print "Max" + str(round(max(link_bet_cen.values()),3))
print "Min" + str(round(min(link_bet_cen.values()),3))
print "\n"
print "Closeness Centrality"
close_cen=nx.closeness_centrality(g, normalized=True)
avg_clcvalue= sum(close_cen.values()) / g.number_of_nodes()
print "Average Network Closeness Centrality: " + str(avg_clcvalue)
print "Max" + str(round(max(close_cen.values()),3))
print "Min" + str(round(min(close_cen.values()),3))
print "\n"
print "Maximum Degree and Node with Maximum Degree"
defmax_degree_node(g):
        node, degree=max(g.degree_iter(),key=itemgetter(1))
        return node
print "Node with maximum degree: " + max_degree_node(g)
print "Maximum degree in the network: " + str(max(nx.degree(g).values()))

print "Network Characteristics –Network with Project 1"
g.add_edge("J","N", weight = 3.61)
print "Number of Nodes in the Network: " + str (g.number_of_nodes())
print "Number of Links in the Network: " + str (g.number_of_edges())
cen=nx.center(g)
print "The Center of the Network: " + str(cen)
diam= nx.diameter(g)
print "Network Diameter\n" + str(diam)
rad =nx.radius(g)
print " Network Radius\n" + str(rad)
```

```
print "Degree of Each Node:" + str(g.degree())
print "\n"
print "Nodal Degree"
dgr=nx.degree(g)
for nodes, values in dgr.items():
        avg_ndvalue= sum(dgr.values()) / g.number_of_nodes()
print "Average Nodal Degree in the Network: " + str(avg_ndvalue)
print "\n"
print "Betweenness Centrality"
bet_cen=nx.betweenness_centrality(g, normalized=True, weight='weight', endpoints=False)
avg_bcvalue= sum(bet_cen.values()) / g.number_of_nodes()
print "Average Betweenness Centrality: " + str(avg_bcvalue)
print "Max" + str(round(max(bet_cen.values()),3))
print "Min" + str(round(min(bet_cen.values()),3))
print "\n"
print "Link Betweenness Centrality"
link_bet_cen=nx.edge_betweenness_centrality(g,normalized=True)
avg_ebc= sum(link_bet_cen.values()) / g.number_of_edges()
print "Average link betweenness centrality:" + str(avg_ebc)
print "Max" + str(round(max(link_bet_cen.values()),3))
print "Min" + str(round(min(link_bet_cen.values()),3))
print "\n"
print "Closeness Centrality"
close_cen=nx.closeness_centrality(g, normalized=True)
avg_clcvalue= sum(close_cen.values()) / g.number_of_nodes()
print "Average Network Closeness Centrality: " + str(avg_clcvalue)
print "Max" + str(round(max(close_cen.values()),3))
print "Min" + str(round(min(close_cen.values()),3))
print "\n"
print "Maximum Degree and Node with Maximum Degree"
defmax_degree_node(g):
        node, degree=max(g.degree_iter(),key=itemgetter(1))
        return node
print "Node with maximum degree: " + max_degree_node(g)
print "Maximum degree in the network: " + str(max(nx.degree(g).values()))

print "Network Characteristics –Network with Project 2"
g.remove_edge("J","N")
g.add_edge("Q","M", weight=2.24)
print "Number of Nodes in the Network: " + str (g.number_of_nodes())
print "Number of Links in the Network: " + str (g.number_of_edges())
cen=nx.center(g)
print "The Center of the Network: " + str(cen)
diam= nx.diameter(g)
print "Network Diameter\n" + str(diam)
rad =nx.radius(g)
print " Network Radius\n" + str(rad)
print "Degree of Each Node:" + str(g.degree())
```

```
print “\n”
print "Nodal Degree"
dgr=nx.degree(g)
for nodes, values in dgr.items():
            avg_ndvalue= sum(dgr.values()) / g.number_of_nodes()
print "Average Nodal Degree in the Network: " + str(avg_ndvalue)
print "\n"
print "Betweenness Centrality"
bet_cen=nx.betweenness_centrality(g, normalized=True, weight='weight', endpoints=False)
avg_bcvalue= sum(bet_cen.values()) / g.number_of_nodes()
print "Average Betweenness Centrality: " + str(avg_bcvalue)
print "Max" + str(round(max(bet_cen.values()),3))
print "Min" + str(round(min(bet_cen.values()),3))
print "\n"
print "Link Betweenness Centrality"
link_bet_cen=nx.edge_betweenness_centrality(g,normalized=True)
avg_ebc= sum(link_bet_cen.values()) / g.number_of_edges()
print "Average link betweenness centrality:" + str(avg_ebc)
print "Max" + str(round(max(link_bet_cen.values()),3))
print "Min" + str(round(min(link_bet_cen.values()),3))
print "\n"
print "Closeness Centrality"
close_cen=nx.closeness_centrality(g, normalized=True)
avg_clcvalue= sum(close_cen.values()) / g.number_of_nodes()
print "Average Network Closeness Centrality: " + str(avg_clcvalue)
print "Max" + str(round(max(close_cen.values()),3))
print "Min" + str(round(min(close_cen.values()),3))
print "\n"
print "Maximum Degree and Node with Maximum Degree"
defmax_degree_node(g):
            node, degree=max(g.degree_iter(),key=itemgetter(1))
            return node
print "Node with maximum degree: " + max_degree_node(g)
print "Maximum degree in the network: " + str(max(nx.degree(g).values()))

#Graph the base network
g.remove_edge("Q","M", weight=2.24)
edge_labels=(dict([((u,v,),d['weight']) for u,v,d in g.edges(data=True)]))
pos=nx.get_node_attributes(g,'pos')
nx.draw_networkx(g,pos,node_size=1000,edge_color='green', node_color='GoldenRod', width=
1.2)
nx.draw_networkx_edge_labels(g,pos,edge_labels=edge_labels,font_color='k',font_size=14,bbox
=None)
nx.draw_networkx_labels(g,pos,font_size=16, font_color='k')
plt.axis('off')
plt.title("Base Network")
plt.show(g)
```

```
#Graph based on Nodal Degrees – Base Network
print "\n"
nd1=[]
for nodes , values in nx.degree(g).items():
	if values == 1:
		nd1.append(nodes)
nd2=[]
for nodes , values in nx.degree(g).items():
	if values == 2:
		nd2.append(nodes)
nd3=[]
for nodes , values in nx.degree(g).items():
	if values == 3:
		nd3.append(nodes)
nd4=[]
for nodes , values in nx.degree(g).items():
	if values == 4:
		nd4.append(nodes)
nd5=[]
for nodes , values in nx.degree(g).items():
	if values == 5:
		nd5.append(nodes)
nd6=[]
for nodes , values in nx.degree(g).items():
	if values == 6:
	nd6.append(nodes)
nd7gr=[]
for nodes , values in nx.degree(g).items():
	if values >= 7:
		nd7gr.append(nodes)
pos=nx.get_node_attributes(g,'pos')
nodeSize=[475*g.degree(x) for x in g]
ns1=[475*g.degree(x) for x in nd1]
nx.draw_networkx_nodes(g,pos,nodelist=nd1,node_color='1.00',node_size=ns1)
ns2=[475*g.degree(x) for x in nd2]
nx.draw_networkx_nodes(g,pos,nodelist=nd2,node_color='0.86',node_size=ns2)
ns3=[475*g.degree(x) for x in nd3]
nx.draw_networkx_nodes(g,pos,nodelist=nd3,node_color='0.67',node_size=ns3)
ns4=[475*g.degree(x) for x in nd4]
nx.draw_networkx_nodes(g,pos,nodelist=nd4,node_color='0.45',node_size=ns4)
ns5=[475*g.degree(x) for x in nd5]
nx.draw_networkx_nodes(g,pos,nodelist=nd5,node_color='0.29',node_size=ns5)
ns6=[475*g.degree(x) for x in nd6]
nx.draw_networkx_nodes(g,pos,nodelist=nd5,node_color='0.29',node_size=ns6)
ns7gr=[475*g.degree(x) for x in nd7gr]
nx.draw_networkx_nodes(g,pos,nodelist=nd5,node_color='0.29',node_size=ns7gr)
nx.draw_networkx_edges(g,pos)
nx.draw_networkx_edge_labels(g,pos,edge_labels=edge_labels,font_color='k',font_size=14)
```

```
nx.draw_networkx_labels(g,pos,font_size=16, font_color='k')
plt.axis('off')
plt.title("Graph Based on Degree of Nodes – Base Network")
plt.show(g)
print "\n"

#Graph based on Nodal Degrees – Network with Project 1
g.add_edge('J','N',weight=3.61)
print “\n”
print "Graph Based on Degree of Nodes"
nd1=[]
for nodes , values in nx.degree(g).items():
        if values == 1:
                nd1.append(nodes)
nd2=[]
for nodes , values in nx.degree(g).items():
        if values == 2:
                nd2.append(nodes)
nd3=[]
for nodes , values in nx.degree(g).items():
        if values == 3:
                nd3.append(nodes)
nd4=[]
for nodes , values in nx.degree(g).items():
        if values == 4:
                nd4.append(nodes)
nd5=[]
for nodes , values in nx.degree(g).items():
        if values == 5:
                nd5.append(nodes)
nd6=[]
for nodes , values in nx.degree(g).items():
        if values == 6:
        nd6.append(nodes)
nd7gr=[]
for nodes , values in nx.degree(g).items():
        if values >= 7:
                nd7gr.append(nodes)
pos=nx.get_node_attributes(g,'pos')
nodeSize=[475*g.degree(x) for x in g]
ns1=[475*g.degree(x) for x in nd1]
nx.draw_networkx_nodes(g,pos,nodelist=nd1,node_color='1.00',node_size=ns1)
ns2=[475*g.degree(x) for x in nd2]
nx.draw_networkx_nodes(g,pos,nodelist=nd2,node_color='0.86',node_size=ns2)
ns3=[475*g.degree(x) for x in nd3]
nx.draw_networkx_nodes(g,pos,nodelist=nd3,node_color='0.67',node_size=ns3)
ns4=[475*g.degree(x) for x in nd4]
nx.draw_networkx_nodes(g,pos,nodelist=nd4,node_color='0.45',node_size=ns4)
```

```
ns5=[475*g.degree(x) for x in nd5]
nx.draw_networkx_nodes(g,pos,nodelist=nd5,node_color='0.29',node_size=ns5)
ns6=[475*g.degree(x) for x in nd6]
nx.draw_networkx_nodes(g,pos,nodelist=nd5,node_color='0.29',node_size=ns6)
ns7gr=[475*g.degree(x) for x in nd7gr]
nx.draw_networkx_nodes(g,pos,nodelist=nd5,node_color='0.29',node_size=ns7gr)
nx.draw_networkx_edges(g,pos)
nx.draw_networkx_edge_labels(g,pos,edge_labels=edge_labels,font_color='k',font_size=14)
nx.draw_networkx_labels(g,pos,font_size=16, font_color='k')
plt.axis('off')
plt.title("Graph Based on Degree of Nodes – Network with Project 1")
plt.show(g)

#Graph based on Nodal Degrees – Network with Project 2
g.remove_edge('J','N')
g.add_edge('Q','M',weight=2.24)
print “\n”
nd1=[]
for nodes , values in nx.degree(g).items():
        if values == 1:
                nd1.append(nodes)
nd2=[]
for nodes , values in nx.degree(g).items():
        if values == 2:
                nd2.append(nodes)
nd3=[]
for nodes , values in nx.degree(g).items():
        if values == 3:
                nd3.append(nodes)
nd4=[]
for nodes , values in nx.degree(g).items():
        if values == 4:
                nd4.append(nodes)
nd5=[]
for nodes , values in nx.degree(g).items():
        if values == 5:
                nd5.append(nodes)
nd6=[]
for nodes , values in nx.degree(g).items():
        if values == 6:
        nd6.append(nodes)
nd7gr=[]
for nodes , values in nx.degree(g).items():
        if values >= 7:
                nd7gr.append(nodes)
pos=nx.get_node_attributes(g,'pos')
nodeSize=[475*g.degree(x) for x in g]
ns1=[475*g.degree(x) for x in nd1]
```

```
nx.draw_networkx_nodes(g,pos,nodelist=nd1,node_color='1.00',node_size=ns1)
ns2=[475*g.degree(x) for x in nd2]
nx.draw_networkx_nodes(g,pos,nodelist=nd2,node_color='0.86',node_size=ns2)
ns3=[475*g.degree(x) for x in nd3]
nx.draw_networkx_nodes(g,pos,nodelist=nd3,node_color='0.67',node_size=ns3)
ns4=[475*g.degree(x) for x in nd4]
nx.draw_networkx_nodes(g,pos,nodelist=nd4,node_color='0.45',node_size=ns4)
ns5=[475*g.degree(x) for x in nd5]
nx.draw_networkx_nodes(g,pos,nodelist=nd5,node_color='0.29',node_size=ns5)
ns6=[475*g.degree(x) for x in nd6]
nx.draw_networkx_nodes(g,pos,nodelist=nd5,node_color='0.29',node_size=ns6)
ns7gr=[475*g.degree(x) for x in nd7gr]
nx.draw_networkx_nodes(g,pos,nodelist=nd5,node_color='0.29',node_size=ns7gr)
nx.draw_networkx_edges(g,pos)
nx.draw_networkx_edge_labels(g,pos,edge_labels=edge_labels,font_color='k',font_size=14)
nx.draw_networkx_labels(g,pos,font_size=16, font_color='k')
plt.axis('off')
plt.title("Graph Based on Degree of Nodes – Network with Project 2")
plt.show(g)
print "\n"

#Graph based on Betweenness Centrality – Base Network
g.remove_edge('Q','M')
bet_cen=nx.betweenness_centrality(g, normalized=True, weight='weight', endpoints=False)
pos=nx.get_node_attributes(g,'pos')
nodeSize=[20000*values for values in nx.betweenness_centrality(g).values()]
nx.draw_networkx(g,pos,node_size=nodeSize, edge_color='b', node_color='GoldenRod')
nx.draw_networkx_edge_labels(g,pos,edge_labels=edge_labels,font_color='k',font_size=14)
nx.draw_networkx_labels(g,pos,font_size=16, font_color='k')
plt.axis('off')
plt.title("Betweenness Centrality – Base Network")
plt.show(g)

#Graph based on Betweenness Centrality – Network with Project 1
g.add_edge('J','N', weight=3.61)
bet_cen=nx.betweenness_centrality(g, normalized=True, weight='weight', endpoints=False)
pos=nx.get_node_attributes(g,'pos')
nodeSize=[20000*values for values in nx.betweenness_centrality(g).values()]
nx.draw_networkx(g,pos,node_size=nodeSize, edge_color='b', node_color='GoldenRod')
nx.draw_networkx_edge_labels(g,pos,edge_labels=edge_labels,font_color='k',font_size=14)
nx.draw_networkx_labels(g,pos,font_size=16, font_color='k')
plt.axis('off')
plt.title("Betweenness Centrality – Network with Project 1")
plt.show(g)

#Graph based on Betweenness Centrality – Network with Project 2
g.remove_edge('J','N')
g.add_edge('Q','M', weight=2.24)
```

```
bet_cen=nx.betweenness_centrality(g, normalized=True, weight='weight', endpoints=False)
pos=nx.get_node_attributes(g,'pos')
nodeSize=[20000*values for values in nx.betweenness_centrality(g).values()]
nx.draw_networkx(g,pos,node_size=nodeSize, edge_color='b', node_color='GoldenRod')
nx.draw_networkx_edge_labels(g,pos,edge_labels=edge_labels,font_color='k',font_size=14)
nx.draw_networkx_labels(g,pos,font_size=16, font_color='k')
plt.axis('off')
plt.title("Betweenness Centrality – Network with Project 2")
plt.show(g)

#Graph based on Link Betweenness Centrality – Base Network
g.remove_edge('Q','M')
edge_lab = nx.edge_betweenness_centrality(g,normalized=True)
for values in edge_lab:
        edge_lab[values] = round(edge_lab[values],2)
edge_labels = edge_lab
print "Graph Based on Link Betweenness Centrality"
pos=nx.get_node_attributes(g,'pos')
nx.draw_networkx(g,pos,node_size=1000,edgeWidth = [50*values for values in
nx.edge_betweenness_centrality(g,weight='weight').values()],edge_color='blue',
node_color='GoldenRod', width= 1.2)
nx.draw_networkx_edge_labels(g,pos,edge_labels=edge_labels,font_color='k',font_size=14,bbox
=None)
nx.draw_networkx_labels(g,pos,font_size=16, font_color='k')
plt.axis('off')
plt.title("Link Betweenness – Base Network")
plt.show(g)

#Graph based on Link Betweenness Centrality – Network with Project 1
g.add_edge("J","N",weight=3.61)
edge_lab = nx.edge_betweenness_centrality(g,normalized=True)
for values in edge_lab:
        edge_lab[values] = round(edge_lab[values],2)
edge_labels = edge_lab
pos=nx.get_node_attributes(g,'pos')
nx.draw_networkx(g,pos,node_size=1000,edgeWidth = [50*values for values in
nx.edge_betweenness_centrality(g,weight='weight').values()],edge_color='blue',
node_color='GoldenRod', width= 1.2)
nx.draw_networkx_edge_labels(g,pos,edge_labels=edge_labels,font_color='k',font_size=14,bbox
=None)
nx.draw_networkx_labels(g,pos,font_size=16, font_color='k')
plt.axis('off')
plt.title("Link Betweenness Centrality - Network with Project 1")
plt.show(g)

#Graph based on Link Betweenness Centrality – Network with Project 2
g.remove_edge("J","N")
g.add_edge("Q","M", weight=2.24)
```

```
edge_lab = nx.edge_betweenness_centrality(g,normalized=True)
for values in edge_lab:
        edge_lab[values] = round(edge_lab[values],2)
edge_labels = edge_lab
pos=nx.get_node_attributes(g,'pos')
nx.draw_networkx(g,pos,node_size=1000,edgeWidth = [50*values for values in
nx.edge_betweenness_centrality(g,weight='weight').values()],edge_color='blue',
node_color='GoldenRod', width= 1.2)
nx.draw_networkx_edge_labels(g,pos,edge_labels=edge_labels,font_color='k',font_size=14,bbox
=None)
nx.draw_networkx_labels(g,pos,font_size=16, font_color='k')
plt.axis('off')
plt.title("Link Betweenness Centrality - Network with Project 2")
plt.show(g)

#Graph based on Closeness Centrality – Base Network
g.remove_edge('Q','M')
close_cen=nx.closeness_centrality(g, normalized=True)
cc1=[]
for nodes , values in close_cen.items():
        if round(values,3) <= 0.200:
                cc1.append(nodes)
cc2=[]
for nodes , values in close_cen.items():
        if 0.200 < round(values,3) <= 0.250:
                cc2.append(nodes)
cc3=[]
for nodes , values in close_cen.items():
        if 0.250 < round(values,3) <= 0.300:
                cc3.append(nodes)
cc4=[]
for nodes , values in close_cen.items():
        if 0.300 < round(values,3) <= 0.350:
                cc4.append(nodes)
cc5=[]
for nodes , values in close_cen.items():
        if round(values,3) > 0.350:
                cc5.append(nodes)
print " Graph Based on Closeness Centrality"
edge_labels=(dict([((u,v,),d['weight']) for u,v,d in g.edges(data=True)]))
pos=nx.get_node_attributes(g,'pos')
nodeSize=[5200*values for values in nx.closeness_centrality(g).values()]
nx.draw_networkx_nodes(g,pos,nodelist=cc1,node_color='1.00',node_size=nodeSize)
nx.draw_networkx_nodes(g,pos,nodelist=cc2,node_color='0.85',node_size=nodeSize)
nx.draw_networkx_nodes(g,pos,nodelist=cc3,node_color='0.67',node_size=nodeSize)
nx.draw_networkx_nodes(g,pos,nodelist=cc4,node_color='0.40',node_size=nodeSize)
nx.draw_networkx_nodes(g,pos,nodelist=cc5,node_color='0.29',node_size=nodeSize)
nx.draw_networkx_edges(g,pos)
```

```
nx.draw_networkx_edge_labels(g,pos,edge_labels=edge_labels,font_color='k',font_size=14)
nx.draw_networkx_labels(g,pos,font_size=16, font_color='k')
plt.axis('off')
plt.title("Closeness Centrality")
plt.show(g)

#Graph based on Closeness Centrality – Project 1
g.add_edge('J','N',weight=3.61)
close_cen=nx.closeness_centrality(g, normalized=True)
cc1=[]
for nodes , values in close_cen.items():
	if round(values,3) <= 0.200:
		cc1.append(nodes)
cc2=[]
for nodes , values in close_cen.items():
	if 0.200 < round(values,3) <= 0.250:
		cc2.append(nodes)
cc3=[]
for nodes , values in close_cen.items():
	if 0.250 < round(values,3) <= 0.300:
		cc3.append(nodes)
cc4=[]
for nodes , values in close_cen.items():
	if 0.300 < round(values,3) <= 0.350:
		cc4.append(nodes)
cc5=[]
for nodes , values in close_cen.items():
	if round(values,3) > 0.350:
		cc5.append(nodes)
print " Graph Based on Closeness Centrality"
edge_labels=(dict([((u,v,),d['weight']) for u,v,d in g.edges(data=True)]))
pos=nx.get_node_attributes(g,'pos')
nodeSize=[5200*values for values in nx.closeness_centrality(g).values()]
nx.draw_networkx_nodes(g,pos,nodelist=cc1,node_color='1.00',node_size=nodeSize)
nx.draw_networkx_nodes(g,pos,nodelist=cc2,node_color='0.85',node_size=nodeSize)
nx.draw_networkx_nodes(g,pos,nodelist=cc3,node_color='0.67',node_size=nodeSize)
nx.draw_networkx_nodes(g,pos,nodelist=cc4,node_color='0.40',node_size=nodeSize)
nx.draw_networkx_nodes(g,pos,nodelist=cc5,node_color='0.29',node_size=nodeSize)
nx.draw_networkx_edges(g,pos)
nx.draw_networkx_edge_labels(g,pos,edge_labels=edge_labels,font_color='k',font_size=14)
nx.draw_networkx_labels(g,pos,font_size=16, font_color='k')
plt.axis('off')
plt.title("Closeness Centrality")
plt.show(g)

#Graph based on Closeness Centrality – Project 2
g.remove_edge('J','N')
g.add_edge('Q','M',weight=2.24)
```

```
close_cen=nx.closeness_centrality(g, normalized=True)
cc1=[]
for nodes , values in close_cen.items():
        if round(values,3) <= 0.200:
                cc1.append(nodes)
cc2=[]
for nodes , values in close_cen.items():
        if 0.200 < round(values,3) <= 0.250:
                cc2.append(nodes)
cc3=[]
for nodes , values in close_cen.items():
        if 0.250 < round(values,3) <= 0.300:
                cc3.append(nodes)
cc4=[]
for nodes , values in close_cen.items():
        if 0.300 < round(values,3) <= 0.350:
                cc4.append(nodes)
cc5=[]
for nodes , values in close_cen.items():
        if round(values,3) > 0.350:
                cc5.append(nodes)
print " Graph Based on Closeness Centrality"
edge_labels=(dict([((u,v,),d['weight']) for u,v,d in g.edges(data=True)]))
pos=nx.get_node_attributes(g,'pos')
nodeSize=[5200*values for values in nx.closeness_centrality(g).values()]
nx.draw_networkx_nodes(g,pos,nodelist=cc1,node_color='1.00',node_size=nodeSize)
nx.draw_networkx_nodes(g,pos,nodelist=cc2,node_color='0.85',node_size=nodeSize)
nx.draw_networkx_nodes(g,pos,nodelist=cc3,node_color='0.67',node_size=nodeSize)
nx.draw_networkx_nodes(g,pos,nodelist=cc4,node_color='0.40',node_size=nodeSize)
nx.draw_networkx_nodes(g,pos,nodelist=cc5,node_color='0.29',node_size=nodeSize)
nx.draw_networkx_edges(g,pos)
nx.draw_networkx_edge_labels(g,pos,edge_labels=edge_labels,font_color='k',font_size=14)
nx.draw_networkx_labels(g,pos,font_size=16, font_color='k')
plt.axis('off')
plt.title("Closeness Centrality")
plt.show(g)
```

Appendix B Distances between nodes in the Ethiopian highway network

B.1 Link length in the Ethiopian highway network

From node	To node	Length (miles)	From node	To node	Length (miles)	From node	To node	Length (miles)
1	9	117.19	11	20	121.88	20	29	145.31
2	5	28.125	11	25	150.00	21	23	14.06
3	6	23.44	12	14	51.56	21	29	126.56
4	6	51.56	13	17	84.38	22	23	70.31
4	8	79.69	13	18	70.31	22	36	168.75
4	17	220.31	14	15	117.19	22	38	135.94
5	6	56.25	14	20	42.19	23	29	126.56
5	7	46.89	14	25	178.13	23	35	182.81
5	9	135.94	15	16	32.81	24	25	32.81
6	8	56.25	15	21	42.19	25	26	112.50
7	8	42.19	16	17	117.19	25	31	93.75
7	9	95.00	16	21	46.89	25	34	173.44
7	12	135.94	17	18	32.81	26	27	14.06
7	15	154.69	17	22	65.63	27	31	173.44
9	12	46.88	18	19	18.75	27	34	131.25
10	11	18.75	19	22	89.06	28	38	135.94
11	12	93.75	20	26	65.63	29	34	140.63

From node	To node	Length (miles)	From node	To node	Length (miles)	From node	To node	Length (miles)
29	35	126.56	38	39	46.88	50	56	89.06
30	31	37.50	38	41	107.81	51	52	46.88
31	32	32.81	40	41	42.19	51	63	196.88
32	33	75.00	40	51	93.75	51	64	107.81
32	42	89.06	42	48	28.13	52	59	84.38
33	34	65.63	42	49	60.94	53	59	28.13
33	49	79.69	43	49	70.31	55	56	145.31
34	35	164.06	43	50	65.63	55	61	51.56
34	43	51.56	44	56	107.81	56	57	70.31
35	36	98.44	44	57	98.44	56	62	46.88
35	43	178.13	45	57	107.81	56	72	112.50
35	44	93.75	45	58	150.00	57	58	145.31
35	45	42.19	46	52	51.56	57	62	37.50
36	37	51.56	47	48	70.31	58	63	121.88
36	45	84.38	48	49	79.69	58	73	135.94
37	58	304.69	48	54	150.00	58	75	117.19
37	63	210.94	49	55	107.81	59	65	75.00

From node	To node	Length (miles)	From node	To node	Length (miles)	From node	To node	Length (miles)
59	67	103.13	67	68	89.06	79	84	60.94
60	67	56.25	71	72	117.19	80	85	46.88
61	70	65.63	71	85	187.50	81	82	42.19
62	72	112.50	72	80	70.31	81	87	46.88
62	73	145.31	73	80	107.81	82	83	23.44
62	80	103.13	73	85	126.56	85	88	75.00
63	74	56.25	73	89	187.50	86	87	70.31
63	76	70.31	74	75	18.75	86	89	18.75
64	65	89.06	74	76	70.31	87	90	9.38
64	76	112.50	74	81	131.25			
64	77	79.69	75	86	89.06			
65	66	79.69	76	77	93.75			
65	67	112.50	77	78	28.13			
65	79	103.13	77	82	37.50			
66	67	56.25	78	79	32.81			
66	69	42.19	78	83	42.19			
66	84	159.38	78	84	60.94			

Appendix C Python code for computing network performance measure (PM) values

```
#!/usr/bin/python
import networkx as nx
from igraph import *
#Create the case network
g=nx.Graph()
g.add_edge('1','9',weight=117.19)
g.add_edge('2','5',weight=28.13)
g.add_edge('3','6',weight=23.44)
g.add_edge('4','17',weight=220.31)
g.add_edge('5','6',weight=56.25)
g.add_edge('5','7',weight=46.88)
g.add_edge('5','9',weight=135.94)
g.add_edge('6','8',weight=56.25)
g.add_edge('7','8',weight=42.19)
g.add_edge('7','15',weight=154.69)
g.add_edge('8','16',weight=112.5)
g.add_edge('9','12',weight=46.88)
g.add_edge('10','11',weight=18.75)
g.add_edge('11','12',weight=93.75)
g.add_edge('11','25',weight=150.00)
g.add_edge('12','14',weight=51.56)
g.add_edge('13','18',weight=70.31)
g.add_edge('14','15',weight=117.19)
g.add_edge('14','20',weight=42.19)
g.add_edge('15','16',weight=32.81)
g.add_edge('15','21',weight=42.19)
g.add_edge('16','21',weight=46.88)
g.add_edge('17','18',weight=32.81)
g.add_edge('17','22',weight=65.63)
g.add_edge('18','19',weight=18.75)
g.add_edge('20','26',weight=65.63)
g.add_edge('20','29',weight=145.31)
g.add_edge('21','23',weight=14.06)
g.add_edge('22','23',weight=70.31)
g.add_edge('22','36',weight=168.75)
g.add_edge('23','35',weight=182.81)
g.add_edge('24','25',weight=32.81)
g.add_edge('25','26',weight=112.50)
g.add_edge('25','31',weight=93.75)
g.add_edge('26','27',weight=14.06)
g.add_edge('27','29',weight=98.44)
g.add_edge('27','34',weight=131.25)
g.add_edge('28','38',weight=135.94)
g.add_edge('29','35',weight=126.56)
g.add_edge('30','31',weight=37.50)
g.add_edge('31','32',weight=32.81)
g.add_edge('31','42',weight=103.13)
g.add_edge('32','33',weight=75.00)
```

```
g.add_edge('32','42',weight=89.06)
g.add_edge('33','34',weight=65.63)
g.add_edge('33','42',weight=98.44)
g.add_edge('34','35',weight=164.06)
g.add_edge('34','43',weight=51.56)
g.add_edge('35','44',weight=93.75)
g.add_edge('35','45',weight=42.19)
g.add_edge('36','37',weight=51.56)
g.add_edge('36','45',weight=84.38)
g.add_edge('37','38',weight=79.69)
g.add_edge('37','58',weight=304.69)
g.add_edge('38','39',weight=46.88)
g.add_edge('39','40',weight=42.19)
g.add_edge('39','63',weight=210.94)
g.add_edge('40','41',weight=42.19)
g.add_edge('40','51',weight=93.75)
g.add_edge('42','48',weight=28.13)
g.add_edge('43','49',weight=70.13)
g.add_edge('43','50',weight=65.63)
g.add_edge('44','50',weight=89.06)
g.add_edge('44','56',weight=107.81)
g.add_edge('45','57',weight=107.81)
g.add_edge('46','52',weight=51.56)
g.add_edge('47','48',weight=70.31)
g.add_edge('48','49',weight=79.69)
g.add_edge('48','54',weight=150.00)
g.add_edge('49','55',weight=107.81)
g.add_edge('50','55',weight=103.13)
g.add_edge('51','52',weight=46.88)
g.add_edge('51','63',weight=196.88)
g.add_edge('51','64',weight=107.81)
g.add_edge('52','59',weight=84.38)
g.add_edge('52','65',weight=131.25)
g.add_edge('53','59',weight=28.13)
g.add_edge('55','61',weight=51.56)
g.add_edge('56','57',weight=89.06)
g.add_edge('56','61',weight=182.81)
g.add_edge('56','72',weight=112.50)
g.add_edge('57','58',weight=145.31)
g.add_edge('57','62',weight=37.50)
g.add_edge('58','75',weight=117.19)
g.add_edge('59','65',weight=75.00)
g.add_edge('60','67',weight=56.25)
g.add_edge('61','70',weight=65.63)
g.add_edge('62','73',weight=145.31)
g.add_edge('62','80',weight=103.13)
g.add_edge('63','74',weight=56.256)
g.add_edge('63','76',weight=70.31)
g.add_edge('64','65',weight=89.06)
g.add_edge('64','76',weight=112.50)
g.add_edge('65','66',weight=79.69)
g.add_edge('65','79',weight=103.13)
g.add_edge('66','67',weight=56.25)
```

```
g.add_edge('66','69',weight=42.19)
g.add_edge('67','68',weight=89.06)
g.add_edge('71','72',weight=117.19)
g.add_edge('72','80',weight=70.31)
g.add_edge('73','85',weight=126.56)
g.add_edge('73','89',weight=187.50)
g.add_edge('74','75',weight=18.75)
g.add_edge('74','81',weight=131.25)
g.add_edge('75','86',weight=89.06)
g.add_edge('76','77',weight=93.75)
g.add_edge('77','78',weight=28.13)
g.add_edge('77','82',weight=37.5)
g.add_edge('78','79',weight=32.81)
g.add_edge('78','83',weight=42.19)
g.add_edge('78','84',weight=60.94)
g.add_edge('79','84',weight=60.94)
g.add_edge('80','85',weight=46.88)
g.add_edge('81','82',weight=42.19)
g.add_edge('81','87',weight=46.88)
g.add_edge('82','83',weight=23.44)
g.add_edge('85','88',weight=75.00)
g.add_edge('86','89',weight=18.75)
g.add_edge('87','90',weight=9.38)

#Compute network topological performance measure values forindividual projects
Nds = [('4', '6',51.56), ('4','8',79.69), ('7','9',93.75), ('7','12',135.94), ('7','14',150.00),('11','20',117.19),
('13','17',131.25), ('14','25',178.13), ('16','17',117.19), ('19','22',84.38), ('21','29',126.56), ('22','38',154.69),
('23','29',126.56), ('25','34',173.44), ('27','31',173.44), ('29','34',140.63),
('33','49',79.69),('35','36',98.44),('35','43',173.44),('37','63',206.25),('38','41',107.81),('39','58',206.25),('42','4
9',60.94),('44','57',98.44),('45','58',150.00),('50','56',89.06),('55','56',145.31),('56','62',46.88),('58','63',121.88
),('58','73',135.94),('59','67',101.13),('62','72',112.50),('64','77',79.69),('65','67',117.19),('66','84',164.06),('71'
,'85',187.50),('73','80',107.81),('74','76',70.31),('76','81',79.69)]
for i in Nds:
        g.add_weighted_edges_from([i])
        sumlist=[]
        for j in g.nodes():
                sp=nx.shortest_path_length(g,source=j, weight='weight')
                summ = sum(k for k in sp.values())
                sumlist.append(summ)
        total = sum(l for l in sumlist)

        print "Total Accessiblity due to Construction of link " + str(i) + " :" + str(total/pow(10,6))
        minlist=[]
        for j in g.nodes():
                sp=nx.shortest_path_length(g,source=j, weight='weight')
                sp_val=[k for k in sp.values()]
                maxx = max(l for l in sp_val)
                minlist.append(maxx)
        diam = max(minlist)
        print "Network diameter due to construction of link:" + str(i) + " :" + str(diam/pow(10,3))
        w=[]
        eattr=nx.get_edge_attributes(g,'weight')
        ln=eattr[m]
```

```
        w.append(ln)
        tl=sum(w)
        print "total network length: " + str(tl)
        pi=tl/diam
        print "Pi index of the network when link " + str(i) + " is added: " + str(pi)
        g.remove_edges_from([i])
        ne=g.number_of_edges()
        print "number of edges: " + str(ne)

#Compute network topological performance measure values considering implementation of three projects
print "1.******************Link 22-38, 35-43, 45-58 Added************************"
g.add_weighted_edges_from([('22','38', 154.69), ('35','43', 173.44), ('45','58', 150.00)])
#Dispersion
sumlist=[]
for i in g.nodes():
        sp=nx.shortest_path_length(g,source= i, weight='weight')
        summ = sum(k for k in sp.values())
        sumlist.append(summ)
total = sum(j for j in sumlist)
print "Total Accessiblity due to Construction of links 22-38, 35-43, 45-58: " + str(total/pow(10,6))
#Diameter
minlist=[]
for i in g.nodes():
        sp=nx.shortest_path_length(g,source=i, weight='weight')
        sp_val=[k for k in sp.values()]
        maxx = max(k for k in sp_val)
        minlist.append(maxx)
diam = max(minlist)
print "Network diameter due to construction of links 22-38, 35-43, 45-58: " + str(diam/pow(10,3))
print "\n"
g.remove_edges_from([('22','38'), ('35','43'), ('45','58')])

print "2.******************Link 22-38, 35-43, 50-56 Added************************"
g.add_weighted_edges_from([('22','38', 154.69), ('35','43', 173.44), ('50','56', 89.06)])
#Dispersion
sumlist=[]
for i in g.nodes():
        sp=nx.shortest_path_length(g,source= i, weight='weight')
        summ = sum(k for k in sp.values())
        sumlist.append(summ)
total = sum(j for j in sumlist)
print "Total Accessiblity due to Construction of links 22-38, 35-43, 50-56: " + str(total/pow(10,6))
#Diameter
minlist=[]
for i in g.nodes():
        sp=nx.shortest_path_length(g,source=i, weight='weight')
        sp_val=[k for k in sp.values()]
        maxx = max(k for k in sp_val)
        minlist.append(maxx)
diam = max(minlist)
print "Network diameter due to construction of links 22-38, 35-43, 50-56: " + str(diam/pow(10,3))
g.remove_edges_from([('22','38'), ('35','43'), ('50','56')])
```

```
print "3.******************Link 22-38, 35-43, 58-63 Added************************"
g.add_weighted_edges_from([('22','38', 154.69), ('35','43', 173.44), ('58','63',121.88)])
#Dispersion
sumlist=[]
for i in g.nodes():
	sp=nx.shortest_path_length(g,source= i, weight='weight')
	summ = sum(k for k in sp.values())
	sumlist.append(summ)
total = sum(j for j in sumlist)
print "Total Accessiblity due to Construction of links 22-38, 35-43, 58-63: " + str(total/pow(10,6))
#Diameter
minlist=[]
for i in g.nodes():
	sp=nx.shortest_path_length(g,source=i, weight='weight')
	sp_val=[k for k in sp.values()]
	maxx = max(k for k in sp_val)
	minlist.append(maxx)
diam = max(minlist)
print "Network diameter due to construction of links 22-38, 35-43, 58-63: " + str(diam/pow(10,3))
g.remove_edges_from([('22','38'), ('35','43'), ('58','63')])

print "4.******************Link 22-38, 35-43, 74-76 Added************************"
g.add_weighted_edges_from([('22','38', 154.69), ('35','43', 173.44), ('74','76', 70.31)])
#Dispersion
sumlist=[]
for i in g.nodes():
	sp=nx.shortest_path_length(g,source= i, weight='weight')
	summ = sum(k for k in sp.values())
	sumlist.append(summ)
total = sum(j for j in sumlist)
print "Total Accessiblity due to Construction of links 22-38, 35-43, 74-76: " + str(total/pow(10,6))
#Diameter
minlist=[]
for i in g.nodes():
	sp=nx.shortest_path_length(g,source=i, weight='weight')
	sp_val=[k for k in sp.values()]
	maxx = max(k for k in sp_val)
	minlist.append(maxx)
diam = max(minlist)
print "Network diameter due to construction of links 22-38, 35-43, 74-76: " + str(diam/pow(10,3))
g.remove_edges_from([('22','38'), ('35','43'), ('74','76')])

print "5.******************Link  22-38, 45-58, 50-56 Added************************"
g.add_weighted_edges_from([('22','38', 154.69), ('45','58', 150.00), ('50','56', 89.06)])
#Dispersion
sumlist=[]
for i in g.nodes():
	sp=nx.shortest_path_length(g,source= i, weight='weight')
	summ = sum(k for k in sp.values())
	sumlist.append(summ)
total = sum(j for j in sumlist)
print "Total Accessiblity due to Construction of links 22-38,45-58,50-56: " + str(total/pow(10,6))
#Diameter
```

```
minlist=[]
for i in g.nodes():
            sp=nx.shortest_path_length(g,source=i, weight='weight')
            sp_val=[k for k in sp.values()]
            maxx = max(k for k in sp_val)
            minlist.append(maxx)
diam = max(minlist)
print "Network diameter due to construction of links 22-38,45-58,50-56: " + str(diam/pow(10,3))
g.remove_edges_from([('22','38'), ('45','58'), ('50','56')])

print "6.******************Link  22-38, 45-58, 58-63 Added************************"
g.add_weighted_edges_from([('22','38', 154.69), ('45','58', 150.00), ('58','63', 121.88)])
#Dispersion
sumlist=[]
for i in g.nodes():
            sp=nx.shortest_path_length(g,source= i, weight='weight')
            summ = sum(k for k in sp.values())
            sumlist.append(summ)
total = sum(j for j in sumlist)
print "Total Accessiblity due to Construction of links 22-38,45-58,58-63: " + str(total/pow(10,6))
#Diameter
minlist=[]
for i in g.nodes():
            sp=nx.shortest_path_length(g,source=i, weight='weight')
            sp_val=[k for k in sp.values()]
            maxx = max(k for k in sp_val)
            minlist.append(maxx)
diam = max(minlist)
print "Network diameter due to construction of links 22-38,45-58,58-63: " + str(diam/pow(10,3))
g.remove_edges_from([('22','38'), ('45','58'), ('58','63')])

print "7.******************Link  22-38, 45-58, 74-76 Added************************"
g.add_weighted_edges_from([('22','38', 154.69), ('45','58', 150.00), ('74','76', 70.31)])
#Dispersion
sumlist=[]
for i in g.nodes():
            sp=nx.shortest_path_length(g,source= i, weight='weight')
            summ = sum(k for k in sp.values())
            sumlist.append(summ)
total = sum(j for j in sumlist)
print "Total Accessiblity due to Construction of links 22-38, 45-58, 74-76: " + str(total/pow(10,6))
#Diameter
minlist=[]
for i in g.nodes():
            sp=nx.shortest_path_length(g,source=i, weight='weight')
            sp_val=[k for k in sp.values()]
            maxx = max(k for k in sp_val)
            minlist.append(maxx)
diam = max(minlist)
print "Network diameter due to construction of links 22-38, 45-58, 74-76: " + str(diam/pow(10,3))
g.remove_edges_from([('22','38'), ('45','58'), ('74','76')])

print "8.******************Link  22-38, 50-56, 58-63 Added************************"
```

```
g.add_weighted_edges_from([('22','38', 154.69), ('50','56', 89.06), ('58','63', 121.88)])
#Dispersion
sumlist=[]
for i in g.nodes():
        sp=nx.shortest_path_length(g,source= i, weight='weight')
        summ = sum(k for k in sp.values())
        sumlist.append(summ)
total = sum(j for j in sumlist)
print "Total Accessiblity due to Construction of links 22-38, 50-56, 58-63: " + str(total/pow(10,6))
#Diameter
minlist=[]
for i in g.nodes():
        sp=nx.shortest_path_length(g,source=i, weight='weight')
        sp_val=[k for k in sp.values()]
        maxx = max(k for k in sp_val)
        minlist.append(maxx)
diam = max(minlist)
print "Network diameter due to construction of links 22-38, 50-56, 58-63: " + str(diam/pow(10,3))
g.remove_edges_from([('22','38'), ('50','56'), ('58','63')])

print "9.******************Link  22-38, 50-56, 74-76 Added************************"
g.add_weighted_edges_from([('22','38', 154.69), ('50','56', 89.06), ('74','76', 70.31)])
#Dispersion
sumlist=[]
for i in g.nodes():
        sp=nx.shortest_path_length(g,source= i, weight='weight')
        summ = sum(k for k in sp.values())
        sumlist.append(summ)
total = sum(j for j in sumlist)
print "Total Accessiblity due to Construction of links 22-38, 50-56, 74-76: " + str(total/pow(10,6))
#Diameter
minlist=[]
for i in g.nodes():
        sp=nx.shortest_path_length(g,source=i, weight='weight')
        sp_val=[k for k in sp.values()]
        maxx = max(k for k in sp_val)
        minlist.append(maxx)
diam = max(minlist)
print "Network diameter due to construction of links 22-38, 50-56, 74-76: " + str(diam/pow(10,3))
g.remove_edges_from([('22','38'), ('50','56'), ('74','76')])

print "10.******************Link  22-38, 58-63, 74-76 Added************************"
g.add_weighted_edges_from([('22','38', 154.69), ('58','63', 121.88), ('74','76', 70.31)])
#Dispersion
sumlist=[]
for i in g.nodes():
        sp=nx.shortest_path_length(g,source= i, weight='weight')
        summ = sum(k for k in sp.values())
        sumlist.append(summ)
total = sum(j for j in sumlist)
print "Total Accessiblity due to Construction of links 22-38, 58-63, 74-76: " + str(total/pow(10,6))
#Diameter
minlist=[]
```

```
for i in g.nodes():
            sp=nx.shortest_path_length(g,source=i, weight='weight')
            sp_val=[k for k in sp.values()]
            maxx = max(k for k in sp_val)
            minlist.append(maxx)
diam = max(minlist)
print "Network diameter due to construction of links 22-38, 58-63, 74-76: " + str(diam/pow(10,3))
g.remove_edges_from([('22','38'), ('58','63'), ('74','76')])

print "11.*******************Link  35-43, 45-58, 50-56 Added*************************"
g.add_weighted_edges_from([('35','43', 173.44), ('45','58', 150.00), ('50','56', 89.06)])
#Dispersion
sumlist=[]
for i in g.nodes():
            sp=nx.shortest_path_length(g,source= i, weight='weight')
            summ = sum(k for k in sp.values())
            sumlist.append(summ)
total = sum(j for j in sumlist)
print "Total Accessiblity due to Construction of links 35-43, 45-58, 50-56: " + str(total/pow(10,6))
#Diameter
minlist=[]
for i in g.nodes():
            sp=nx.shortest_path_length(g,source=i, weight='weight')
            sp_val=[k for k in sp.values()]
            maxx = max(k for k in sp_val)
            minlist.append(maxx)
diam = max(minlist)
print "Network diameter due to construction of links 35-43, 45-58, 50-56: " + str(diam/pow(10,3))
g.remove_edges_from([('22','38'), ('45','58'), ('50','56')])


print "12.*******************Link  35-43, 45-58, 58-63 Added*************************"
g.add_weighted_edges_from([('35','43', 173.44), ('45','58', 150.00), ('58','63', 121.88)])
#Dispersion
sumlist=[]
for i in g.nodes():
            sp=nx.shortest_path_length(g,source= i, weight='weight')
            summ = sum(k for k in sp.values())
            sumlist.append(summ)
total = sum(j for j in sumlist)
print "Total Accessiblity due to Construction of links 35-43, 45-58, 58-63: " + str(total/pow(10,6))
#Diameter
minlist=[]
for i in g.nodes():
            sp=nx.shortest_path_length(g,source=i, weight='weight')
            sp_val=[k for k in sp.values()]
            maxx = max(k for k in sp_val)
            minlist.append(maxx)
diam = max(minlist)
print "Network diameter due to construction of links 35-43, 45-58, 58-63: " + str(diam/pow(10,3))
g.remove_edges_from([('22','38'), ('45','58'), ('58','63')])

print "13.*******************Link  35-43, 45-58, 74-76 Added*************************"
```

```
g.add_weighted_edges_from([('35','43', 173.44), ('45','58', 150.00), ('74','76', 70.31)])
#Dispersion
sumlist=[]
for i in g.nodes():
        sp=nx.shortest_path_length(g,source= i, weight='weight')
        summ = sum(k for k in sp.values())
        sumlist.append(summ)
total = sum(j for j in sumlist)
print "Total Accessiblity due to Construction of links 35-43, 45-58, 74-76: " + str(total/pow(10,6))
#Diameter
minlist=[]
for i in g.nodes():
        sp=nx.shortest_path_length(g,source=i, weight='weight')
        sp_val=[k for k in sp.values()]
        maxx = max(k for k in sp_val)
        minlist.append(maxx)
diam = max(minlist)
print "Network diameter due to construction of links 35-43, 45-58, 74-76: " + str(diam/pow(10,3))
g.remove_edges_from([('35','43'), ('45','58'), ('74','76')])

print "14.******************Link  35-43, 50-56, 58-63 Added************************"
g.add_weighted_edges_from([('35','43', 173.44), ('50','56', 89.06), ('58','63', 121.88)])
#Dispersion
sumlist=[]
for i in g.nodes():
        sp=nx.shortest_path_length(g,source= i, weight='weight')
        summ = sum(k for k in sp.values())
        sumlist.append(summ)
total = sum(j for j in sumlist)
print "Total Accessiblity due to Construction of links 35-43, 50-56, 58-63: " + str(total/pow(10,6))
#Diameter
minlist=[]
for i in g.nodes():
        sp=nx.shortest_path_length(g,source=i, weight='weight')
        sp_val=[k for k in sp.values()]
        maxx = max(k for k in sp_val)
        minlist.append(maxx)
diam = max(minlist)
print "Network diameter due to construction of links 35-43, 50-56, 58-63: " + str(diam/pow(10,3))
g.remove_edges_from([('35','43'), ('50','56'), ('58','63')])

print "15.******************Link  35-43, 50-56, 74-76 Added************************"
g.add_weighted_edges_from([('35','43', 173.44), ('50','56', 89.06), ('74','76', 70.31)])
#Dispersion
sumlist=[]
for i in g.nodes():
        sp=nx.shortest_path_length(g,source= i, weight='weight')
        summ = sum(k for k in sp.values())
        sumlist.append(summ)
total = sum(j for j in sumlist)
print "Total Accessiblity due to Construction of links 35-43, 50-56, 74-76: " + str(total/pow(10,6))
#Diameter
minlist=[]
```

```
for i in g.nodes():
        sp=nx.shortest_path_length(g,source=i, weight='weight')
        sp_val=[k for k in sp.values()]
        maxx = max(k for k in sp_val)
        minlist.append(maxx)
diam = max(minlist)
print "Network diameter due to construction of links 35-43, 50-56, 74-76: " + str(diam/pow(10,3))
g.remove_edges_from([('35','43'), ('50','56'), ('74','76')])

print "16.******************Link  35-43, 58-63, 74-76 Added************************"
g.add_weighted_edges_from([('35','43', 173.44), ('58','63', 121.88), ('74','76', 70.31)])
#Dispersion
sumlist=[]
for i in g.nodes():
        sp=nx.shortest_path_length(g,source= i, weight='weight')
        summ = sum(k for k in sp.values())
        sumlist.append(summ)
total = sum(j for j in sumlist)
print "Total Accessiblity due to Construction of links 35-43, 58-63, 74-76: " + str(total/pow(10,6))
#Diameter
minlist=[]
for i in g.nodes():
        sp=nx.shortest_path_length(g,source=i, weight='weight')
        sp_val=[k for k in sp.values()]
        maxx = max(k for k in sp_val)
        minlist.append(maxx)
diam = max(minlist)
print "Network diameter due to construction of links 35-43, 58-63, 74-76: " + str(diam/pow(10,3))
g.remove_edges_from([('35','43'), ('58','63'), ('74','76')])

print "17.******************Link  45-58, 50-56, 58-63 Added************************"
g.add_weighted_edges_from([('45','58', 150.00), ('50','56', 89.06), ('58','63', 121.88)])
#Dispersion
sumlist=[]
for i in g.nodes():
        sp=nx.shortest_path_length(g,source= i, weight='weight')
        summ = sum(k for k in sp.values())
        sumlist.append(summ)
total = sum(j for j in sumlist)
print "Total Accessiblity due to Construction of links 45-58, 50-56, 58-63: " + str(total/pow(10,6))
#Diameter
minlist=[]
for i in g.nodes():
        sp=nx.shortest_path_length(g,source=i, weight='weight')
        sp_val=[k for k in sp.values()]
        maxx = max(k for k in sp_val)
        minlist.append(maxx)
diam = max(minlist)
print "Network diameter due to construction of links 45-58, 50-56, 58-63: " + str(diam/pow(10,3))
g.remove_edges_from([('45','58'), ('50','56'), ('58','63')])

print "18.******************Link  45-58, 50-56, 74-76 Added************************"
g.add_weighted_edges_from([('45','58', 150.00), ('50','56', 89.06), ('74','76', 70.31)])
```

```
#Dispersion
sumlist=[]
for i in g.nodes():
        sp=nx.shortest_path_length(g,source= i, weight='weight')
        summ = sum(k for k in sp.values())
        sumlist.append(summ)
total = sum(j for j in sumlist)
print "Total Accessiblity due to Construction of links 45-58, 50-56, 74-76: " + str(total/pow(10,6))
#Diameter
minlist=[]
for i in g.nodes():
        sp=nx.shortest_path_length(g,source=i, weight='weight')
        sp_val=[k for k in sp.values()]
        maxx = max(k for k in sp_val)
        minlist.append(maxx)
diam = max(minlist)
print "Network diameter due to construction of links 45-58, 50-56, 74-76: " + str(diam/pow(10,3))
g.remove_edges_from([('45','58'), ('50','56'), ('74','76')])

print "19.******************Link  45-58, 58-63, 74-76 Added************************"
g.add_weighted_edges_from([('45','58', 150.00), ('58','63',121.88), ('74','76', 70.31)])
#Dispersion
sumlist=[]
for i in g.nodes():
        sp=nx.shortest_path_length(g,source= i, weight='weight')
        summ = sum(k for k in sp.values())
        sumlist.append(summ)
total = sum(j for j in sumlist)
print "Total Accessiblity due to Construction of links 45-58, 58-63, 74-76: " + str(total/pow(10,6))
#Diameter
minlist=[]
for i in g.nodes():
        sp=nx.shortest_path_length(g,source=i, weight='weight')
        sp_val=[k for k in sp.values()]
        maxx = max(k for k in sp_val)
        minlist.append(maxx)
diam = max(minlist)
print "Network diameter due to construction of links 45-58, 58-63, 74-76: " + str(diam/pow(10,3))
g.remove_edges_from([('45','58'), ('58','63'), ('74','76')])

print "20.******************Link 50-56, 58-63 and 74-76 Added***********************"
g.add_weighted_edges_from([('50','56', 89.06), ('58','63', 121.88), ('74','76', 70.31)])
#Dispersion
sumlist=[]
for i in g.nodes():
        sp=nx.shortest_path_length(g,source= i, weight='weight')
        summ = sum(k for k in sp.values())
        sumlist.append(summ)
total = sum(j for j in sumlist)
print "Total Accessiblity due to Construction of links 50-56, 58-63, 74-76: " + str(total/pow(10,6))
#Diameter
minlist=[]
for i in g.nodes():
```

```
            sp=nx.shortest_path_length(g,source=i, weight='weight')
            sp_val=[k for k in sp.values()]
            maxx = max(k for k in sp_val)
            minlist.append(maxx)
diam = max(minlist)
print "Network diameter due to construction of links 50-56, 58-63, 74-76: " + str(diam/pow(10,3))
print "\n"
g.remove_edges_from([('50','56', 89.06), ('58','63', 121.88), ('74','76', 70.31)])
```

Appendix D Python code for generating random network and computing performance measure (PM) values

```
#!/usr/bin/python
from random import random, randint
from operator import itemgetter
importnumpy as np
fromigraph import Graph
fromapgl.graph import *
fromapgl.generator.ErdosRenyiGenerator import ErdosRenyiGenerator
import pandas as pd
import csv
fromopenpyxl import workbook, load_workbook

#Generate Random Network
for x in range(1,501):
    n=randint(30,35)
    g=Graph.Erdos_Renyi(n,0.8)
    cg = g.is_connected()
    edgeList=g.get_edgelist()
    edgeListLength=len(edgeList)
    defll(q):
        randlist=[]
        for x in xrange(0,q):
            randlist.append(randint(1,15))
        returnrandlist
    rlist=ll(edgeListLength)
    g.es["weight"]=rlist
    dictionary = dict((zip(edgeList,rlist)))

#Calculate Network Performance Measure Values
     BC=g.betweenness()
    sumBC=sum(BC)
    avgBC=round(sumBC/n,3)
    edgeBC=g.edge_betweenness()
    sumEdgeBC=sum(edgeBC)
    avgEdgeBC=round(sumEdgeBC/edgeListLength,3)
        Degree = g.degree()
        sumDegree = sum(i for i in Degree)
        avgND=round(sumDegree / n,3)
        Diameter = round(g.diameter(weights='weight'),3)
        CC=g.closeness()
        sumCC=sum(i for i in CC)
        avgCC=round(sumCC / n,3)
        SPL=g.shortest_paths_dijkstra(weights='weight')
        for item in SPL:
```

```
        sumSPL=sum(item)
    avgSPL=round(sumSPL/len(SPL),3)
    NIndPath = g.vertex_connectivity()

#Save output
    data = {'Network':[x], 'avgBC':[avgBC],'avgEdgeBC':[avgEdgeBC], 'avgND':[avgND],
'Diam': Diameter, 'avgCC':[avgCC], 'avgSPL':[avgSPL], 'NIndPath':[NIndPath]}
    dataF=pd.DataFrame(data, columns=['Network','avgBC','avgEdgeBC','avgND',
'Diam','avgCC', 'avgSPL', 'NIndPath'], index=[x])
    if x==1:
        with open('NetworkData.csv', 'wb') as nd:
            dataF.to_csv(nd,sep='\t')
    else:
        dataF=pd.DataFrame(data, columns=['Network', 'avgBC','avgEdgeBC','avgND',
    'Diam', 'avgCC', 'avgSPL', 'NIndPath'], index=[x])
        with open('NetworkData.csv', 'a') as nd:
            dataF.to_csv(nd,sep='\t', header=False)
```

Appendix E Functional relationships between network topological performance measures (PMs)

Table E.1 Functional relationship between network average betweenness centrality (BC) and nodal degree

Iteration #	Best Fit Regression Equations	R^2
1	$y = 0.000x^6 - 0.077x^5 + 4.698x^4 - 151.2x^3 + 2733x^2 - 26274x + 10502$	0.107
2	$y = 0.000x^6 - 0.067x^5 + 4.020x^4 - 127.7x^3 + 2275.x^2 - 21571x + 85007$	0.177
3	$y = -0.000x^4 + 0.045x^3 - 0.919x^2 + 2.464x + 65.21$	0.116
4	$y = 0.000x^5 - 0.063x^4 + 3.116x^3 - 76.24x^2 + 924.5x - 4440$	0.100
5	$y = -0.02x^3 + 1.47x^2 - 36.26x + 300.04$	0.140
6	$y = 0.035x + 2.282$	0.027
Average	$y = -0.0031x^6 + 0.4517x^5 - 27.679x^4 + 904.41x^3 - 16619x^2 + 162836x - 664601$	0.040

y= Network average BC; x= Average nodal degree

Table E.2 Functional relationship between network average betweenness centrality (BC) and network diameter

Iteration	Best Fit Regression Equations	R^2
1	$y = -0.002x^6 + 0.141x^5 – 3.145x^4 + 36.86x^3 – 239.8x^2 + 821.1x – 1153$	0.023
2	$y = 0.007x^4 – 0.232x^3 + 2.741x^2 – 14.23x + 30.65$	0.010
3	$y = -0.002x^6 + 0.119x^5 – 2.723x^4 + 32.6x^3 – 216.7x^2 + 758.8x – 1088$	0.021
4	$y = 0.004x^5 – 0.202x^4 + 3.454x^3 – 29.06x^2 + 120.5x – 194.2$	0.006
5	$y = -0.006x^5 + 0.256x^4 – 4.206x^3 + 34.03x^2 – 135.7x + 216.4$	0.013
6	$y = -0.001x^6 + 0.101x^5 – 2.225x^4 + 25.85x^3 – 167.1x^2 + 570.1x – 799.2$	0.021
Average	$y = 0.0246x^6 - 1.1934x^5 + 24.107x^4 - 259.37x^3 + 1567.2x^2 - 5041.9x + 6748.6$	0.010

y= Network average BC; x= Network diameter

Table E.3 Functional relationship between network average betweenness centrality (BC) and shortest path length

Iteration #	Best Fit Regression Equations	R^2
1	$y = 0.047x^6 – 1.199x^5 + 12.43x^4 – 67.33x^3 + 200.7x^2 – 312.3x + 201.2$	0.031
2	$y = -0.044x^6 + 1.090x^5 – 11.04x^4 + 58.72x^3 – 172.9x^2 + 267.6x – 166.6$	0.008
3	$y = -0.000x^6 + 0.025x^5 – 0.308x^4 + 2.029x^3 – 7.633x^2 + 15.39x – 9.722$	0.016
4	$y = 0.020x^6 – 0.521x^5 + 5.572x^4 – 31.29x^3 + 97.37x^2 – 159.0x + 109.6$	0.007
5	$y = -0.009x^6 + 0.243x^5 – 2.630x^4 + 14.57x^3 – 43.80x^2 + 67.78x – 39.13$	0.015
6	$y = 0.015x^6 – 0.398x^5 + 4.152x^4 – 22.90x^3 + 70.62x^2 – 115.5x + 81.44$	0.027
Average	$y = 0.1103x^5 - 1.9592x^4 + 13.793x^3 - 48.098x^2 + 83.063x - 53.681$	0.007

y= Network average BC; x= Average shortest path length

Table E.4 Functional relationship between network average betweenness centrality (BC) and number of independent paths

Iteration #	Best Fit Regression Equations	R^2
1	$y = 3E-05x^6 - 0.004x^5 + 0.212x^4 - 5.795x^3 + 88.31x^2 - 711.9x + 2375$	0.015
2	$y = -2E-05x^6 + 0.002x^5 - 0.116x^4 + 3.440x^3 - 56.25x^2 + 484.1x - 1710$	0.031
3	$y = 0.000x^6 - 0.014x^5 + 0.701x^4 - 18.51x^3 + 273.3x^2 - 2141.x + 6959$	0.045
4	$y = -1E-05x^6 + 0.001x^5 - 0.059x^4 + 1.497x^3 - 21.13x^2 + 158.7x - 492.6$	0.010
5	$y = 9E-05x^6 - 0.010x^5 + 0.501x^4 - 13.08x^3 + 191.0x^2 - 1481x + 4767$	0.056
6	$y = 0.000x^6 - 0.046x^5 + 2.287x^4 - 60.02x^3 + 882.3x^2 - 6889.x + 22324$	0.047
Average	$y = -0.0017x^5 + 0.1692x^4 - 6.7769x^3 + 135.57x^2 - 1354.3x + 5408.5$	0.003

y= Network average BC; x= Network average number of independent paths

Table E.5 Functional relationship between network average link betweenness centrality (LBC) and nodal degree

Iteration]#	Best Fit Regression Equations	R^2
1	$y = 8E\text{-}05x^6 - 0.012x^5 + 0.729x^4 - 23.45x^3 + 423.0x^2 - 4060.x + 16208$	0.204
2	$y = 7E\text{-}05x^6 - 0.009x^5 + 0.589x^4 - 18.70x^3 + 333.1x^2 - 3157.x + 12443$	0.227
3	$y = -0.003x^3 + 0.230x^2 - 5.721x + 48.82$	0.220
4	$y = -0.003x^3 + 0.236x^2 - 5.874x + 50.13$	0.197
5	$y = 1E\text{-}04x^5 - 0.012x^4 + 0.599x^3 - 14.55x^2 + 175.1x - 834.3$	0.246
6	$y = -0.000x^6 + 0.018x^5 - 1.123x^4 + 36.31x^3 - 658.7x^2 + 6357.x - 25494$	0.183
Average	$y = -0.0005x^4 + 0.0484x^3 - 1.6916x^2 + 26.16x - 149.35$	0.135

y= Network average LBC; x= Network average nodal degree

Table E.6 Functional relationship between network average link betweenness centrality (LBC) and network diameter

Iteration #	Best Fit Regression Equations	R^2
1	$y = -0.000x^6 + 0.015x^5 – 0.347x^4 + 4.117x^3 – 27.00x^2 + 93.09x – 130.3$	0.049
2	$y = -0.000x^5 + 0.007x^4 – 0.126x^3 + 1.063x^2 – 4.376x + 8.552$	0.009
3	$y = -0.000x^6 + 0.024x^5 – 0.552x^4 + 6.625x^3 – 44.10x^2 + 154.4x – 220.9$	0.032
4	$y = -0.000x^6 + 0.035x^5 – 0.789x^4 + 9.254x^3 – 60.28x^2 + 206.9x – 290.9$	0.025
5	$y = -0.000x^5 + 0.031x^4 – 0.505x^3 + 4.047x^2 – 15.97x + 26.34$	0.020
6	$y = -0.000x^6 + 0.023x^5 – 0.519x^4 + 6.102x^3 – 39.86x^2 + 137.3x – 193.4$	0.018
Average	$y = -0.0049x^6 + 0.2274x^5 - 4.4227x^4 + 45.657x^3 - 263.88x^2 + 809.5x - 1028.2$	0.024

y= Network average BC; x= Network diameter

Table E.7 Functional relationship between network average link betweenness centrality (LBC) and shortest path length

Iteration #	Best Fit Regression Equations	R^2
1	$y = 0.005x^6 - 0.144x^5 + 1.497x^4 - 8.128x^3 + 24.30x^2 - 37.93x + 25.64$	0.026
2	$y = 0.001x^6 - 0.022x^5 + 0.189x^4 - 0.862x^3 + 2.203x^2 - 3.026x + 3.252$	0.005
3	$y = -0.001x^6 + 0.035x^5 - 0.381x^4 + 2.110x^3 - 6.423x^2 + 10.23x - 5.204$	0.034
4	$y = 0.005x^4 - 0.093x^3 + 0.574x^2 - 1.524x + 2.972$	0.014
5	$y = -0.001x^6 + 0.031x^5 - 0.329x^4 + 1.775x^3 - 5.113x^2 + 7.437x - 2.746$	0.023
6	$y = 0.003x^6 - 0.096x^5 + 1.029x^4 - 5.762x^3 + 17.95x^2 - 29.50x + 21.5$	0.016
Average	$y = 0.0127x^4 - 0.1728x^3 + 0.8639x^2 - 1.8729x + 2.973$	0.014

y= Network average LBC; x= Network average shortest path length

Table E.8 Functional relationship between network average link betweenness centrality (LBC) and number of independent paths

Iteration #	Best Fit Regression Equations	R^2
1	$y = 5E\text{-}06x^6 – 0.000x^5 + 0.033x^4 – 0.929x^3 + 14.53x^2 – 120.1x + 411.4$	0.165
2	$y = -7E\text{-}06x^6 + 0.000x^5 – 0.042x^4 + 1.148x^3 – 17.54x^2 + 142.3x – 477.2$	0.127
3	$y = 2E\text{-}05x^6 – 0.002x^5 + 0.130x^4 – 3.467x^3 + 51.65x^2 – 408.2x + 1339$	0.165
4	$y = -5E\text{-}06x^6 + 0.000x^5 – 0.026x^4 + 0.671x^3 – 9.523x^2 + 71.56x – 221.0$	0.135
5	$y = 8E\text{-}06x^6 – 0.001x^5 + 0.050x^4 – 1.352x^3 + 20.15x^2 – 159.7x + 527.8$	0.182
6	$y = 6E\text{-}05x^6 – 0.007x^5 + 0.351x^4 – 9.293x^3 + 137.5x^2 – 1081.x + 3530.$	0.142
Average	$y = 0.0002x^6 - 0.0269x^5 + 1.377x^4 - 37.537x^3 + 574.84x^2 - 4688.9x + 15917$	0.145

y= Network average LBC; x= Network average number of independent paths

Table E.9 Functional relationship between network average nodal degree and network diameter

Iteration #	Best Fit Regression Equations	R^2
1	$y = 4E{+}09x^6 – 2E{+}10x^5 + 4E{+}10x^4 – 4E{+}10x^3 + 3E{+}10x^2 – 9E{+}09x + 1E{+}09$	0.167
2	$y = 3E{+}09x^6 – 2E{+}10x^5 + 3E{+}10x^4 – 4E{+}10x^3 + 2E{+}10x^2 – 8E{+}09x + 1E{+}09$	0.111
3	$y = 5E{+}09x^6 – 3E{+}10x^5 + 5E{+}10x^4 – 6E{+}10x^3 + 4E{+}10x^2 – 1E{+}10x + 2E{+}09$	0.160
4	$y = -8E{+}09x^6 + 4E{+}10x^5 – 8E{+}10x^4 + 9E{+}10x^3 – 5E{+}10x^2 + 2E{+}10x – 3E{+}09$	0.152
5	$y = 4E{+}09x^6 – 2E{+}10x^5 + 4E{+}10x^4 – 4E{+}10x^3 + 3E{+}10x^2 – 9E{+}09x + 1E{+}09$	0.167
6	$y = -4E{+}09x^6 + 2E{+}10x^5 – 4E{+}10x^4 + 4E{+}10x^3 – 3E{+}10x^2 + 9E{+}09x – 1E{+}09$	0.133
Average	$y = -4E{+}10x^6 + 2E{+}11x^5 - 5E{+}11x^4 + 5E{+}11x^3 - 3E{+}11x^2 + 1E{+}11x - 1E{+}10$	0.14

y= Network average nodal degree; x= Network diameter

Table E.10 Functional relationship between network average nodal degree and closeness centrality

Iteration #	Best Fit Regression Equations	R^2
1	$y = -0.014x^5 + 0.634x^4 – 10.90x^3 + 92.31x^2 – 385.2x + 659.4$	0.042
2	$y = 0.033x^4 – 1.091x^3 + 13.27x^2 – 71.37x + 168.3$	0.067
3	$y = -0.014x^5 + 0.634x^4 – 10.90x^3 + 92.31x^2 – 385.2x + 659.4$	0.042
4	$y = 0.025x^6 – 1.354x^5 + 29.47x^4 – 338.4x^3 + 2162.x^2 – 7288.x + 10147$	0.056
5	$y = -0.013x^5 + 0.573x^4 – 9.721x^3 + 81.01x^2 – 332.4x + 563.1$	0.043
6	$y = 0.006x^6 – 0.347x^5 + 7.917x^4 – 94.86x^3 + 630.6x^2 – 2204.x + 3189$	0.066
Average	$y = 0.3074x^6 - 14.686x^5 + 291.54x^4 - 3078.7x^3 + 18238x^2 - 57464x + 75258$	0.0368

y= Network average nodal degree; x= Network average CC

Table E.11 Functional relationship between network average nodal degree and shortest path length

Iteration #	Best Fit Regression Equations	R^2
1	$y = 4E+09x^6 – 2E+10x^5 + 5E+10x^4 – 5E+10x^3 + 3E+10x^2 – 1E+10x + 2E+09$	0.017
2	$y = 9E+08x^6 – 4E+09x^5 + 9E+09x^4 – 1E+10x^3 + 6E+09x^2 – 2E+09x + 3E+08$	0.030
3	$y = -1E+07x^5 + 4E+07x^4 – 7E+07x^3 + 6E+07x^2 – 3E+07x + 4E+06$	0.020
4	$y = 2E+09x^6 – 9E+09x^5 + 2E+10x^4 – 2E+10x^3 + 1E+10x^2 – 4E+09x + 6E+08$	0.018
5	$y = -2E+09x^6 + 9E+09x^5 – 2E+10x^4 + 2E+10x^3 – 1E+10x^2 + 5E+09x – 7E+08$	0.032
6	$y = 4E+09x^6 – 2E+10x^5 + 5E+10x^4 – 5E+10x^3 + 3E+10x^2 – 1E+10x + 2E+09$	0.017
Average	$y = -3E+10x^6 + 1E+11x^5 - 3E+11x^4 + 3E+11x^3 - 2E+11x^2 + 6E+10x - 8E+09$	0.0228

y= Network average nodal degree; x= Network average shortest path length

Table E.12 Functional relationship between network diameter and network average closeness centrality (CC)

Iteration #	Best Fit Regression Equations	R^2
1	$y = -0.013x^5 + 0.241x^4 – 1.457x^3 + 2.741x^2 + 2.585x + 15.44$	0.019
2	$y = -0.433x^6 + 10.49x^5 – 104.6x^4 + 549.6x^3 – 1603.x^2 + 2464.x – 1531$	0.038
3	$y = 0.053x^6 – 1.366x^5 + 13.97x^4 – 73.30x^3 + 207.1x^2 – 297.7x + 194.0$	0.042
4	$y = 0.205x^6 – 5.285x^5 + 55.59x^4 – 305.5x^3 + 924.6x^2 – 1461.x + 967.5$	0.030
5	$y = -0.013x^5 + 0.241x^4 – 1.457x^3 + 2.741x^2 + 2.585x + 15.44$	0.019
6	$y = -0.051x^6 + 1.383x^5 – 15.24x^4 + 87.86x^3 – 279.8x^2 + 467.1x – 294.3$	0.015
Average	$y = -0.3455x^6 + 9.0806x^5 - 96.55x^4 + 533.71x^3 - 1621.8x^2 + 2572.5x - 1640.8$	0.0158

y= Network diameter; x= Network average CC

Table E.13 Functional relationship between network diameter and network average shortest path length

Iteration #	Best Fit Regression Equations	R^2
1	$y = 0.061x^5 – 1.363x^4 + 11.93x^3 – 51.08x^2 + 107.3x – 81.17$	0.084
2	$y = 2.224x^6 – 47.13x^5 + 411.1x^4 – 1889.x^3 + 4822.x^2 – 6485.x + 3596$	0.016
3	$y = 13.70x^6 – 263.8x^5 + 2105.x^4 – 8913.x^3 + 21111x^2 – 26523x + 13818$	0.024
4	$y = 1.540x^5 – 26.09x^4 + 174.7x^3 – 578.4x^2 + 947.2x – 606.2$	0.007
5	$y = 9.090x^6 – 173.8x^5 + 1377.x^4 – 5790.x^3 + 13619x^2 – 16984x + 8780$	0.004
6	$y = 0.061x^5 – 1.363x^4 + 11.93x^3 – 51.08x^2 + 107.3x – 81.17$	0.084
Average	$y = -30.266x^6 + 593.61x^5 - 4837x^4 + 20963x^3 - 50972x^2 + 65939x - 35452$	0.0063

y= Network diameter; x= Network average shortest path length

Table E.14 Functional relationship between network diameter and network average number of independent paths

Iteration#	Best Fit Regression Equations	R^2
1	$y = 0.000x^6 – 0.017x^5 + 0.838x^4 – 20.90x^3 + 289.6x^2 – 2112.x + 6335$	0.042
2	$y = -0.000x^6 + 0.031x^5 – 1.583x^4 + 42.66x^3 – 643.0x^2 + 5139x – 16997$	0.056
3	$y = -0.000x^5 + 0.077x^4 – 3.218x^3 + 66.46x^2 – 684.6x + 2822$	0.036
4	$y = 0.000x^6 – 0.017x^5 + 0.838x^4 – 20.90x^3 + 289.6x^2 – 2112.x + 6335$	0.042
5	$y = -0.000x^6 + 0.025x^5 – 1.257x^4 + 32.97x^3 – 482.6x^2 + 3740.x – 11974$	0.040
6	$y = -0.002x^5 + 0.275x^4 – 11.06x^3 + 220.7x^2 – 2190x + 8650$	0.050
Average	$y = 0.0011x^6 - 0.1235x^5 + 5.8417x^4 - 146.69x^3 + 2060.4x^2 - 15338x + 47236$	0.0222

y= Network diameter; x= Network average number of independent paths

Table E.15 Functional relationship between network average closeness centrality (CC) and shortest path length

Iteration #	Best Fit Regression Equations	R^2
1	$y = 0.000x^6 - 0.022x^5 + 1.129x^4 - 30.60x^3 + 463.9x^2 - 3731.x + 12445$	0.026
2	$y = -9E\text{-}05x^6 + 0.010x^5 - 0.514x^4 + 13.53x^3 - 199.4x^2 + 1559.x - 5053$	0.006
3	$y = -0.000x^6 + 0.060x^5 - 3.090x^4 + 84.16x^3 - 1282.x^2 + 10375x - 34778$	0.054
4	$y = 0.000x^6 - 0.015x^5 + 0.737x^4 - 19.13x^3 + 277.4x^2 - 2130x + 6767$	0.015
5	$y = -0.000x^6 + 0.050x^5 - 2.504x^4 + 66.36x^3 - 983.5x^2 + 7727.x - 25141$	0.025
6	$y = 0.000x^6 - 0.022x^5 + 1.129x^4 - 30.60x^3 + 463.9x^2 - 3731.x + 12445$	0.026
Average	$y = 0.0098x^6 - 1.1734x^5 + 58.504x^4 - 1553.8x^3 + 23184x^2 - 184269x + 609482$	0.017

y= Network average CC; x= Network average shortest path length

Table E.16 Functional relationship between network average closeness centrality (CC) and number of independent paths

Iteration #	Best Fit Regression Equations	R^2
1	$y = -1E\text{-}07x^5 + 5E\text{-}06x^4 + 0.000x^3 – 0.014x^2 + 0.288x – 1.040$	0.158
2	$y = 2E\text{-}06x^6 – 0.000x^5 + 0.010x^4 – 0.274x^3 + 4.174x^2 – 33.67x + 113.4$	0.110
3	$y = -5E\text{-}06x^6 + 0.000x^5 – 0.027x^4 + 0.739x^3 – 11.00x^2 + 86.89x – 283.7$	0.142
4	$y = 1E\text{-}06x^6 – 0.000x^5 + 0.006x^4 – 0.157x^3 + 2.243x^2 – 16.97x + 53.98$	0.115
5	$y = -1E\text{-}07x^5 + 5E\text{-}06x^4 + 0.000x^3 – 0.014x^2 + 0.288x – 1.040$	0.158
6	$y = -1E\text{-}05x^6 + 0.001x^5 – 0.075x^4 + 1.981x^3 – 29.34x^2 + 230.8x – 752.8$	0.124
Average	$y = -4E\text{-}05x^6 + 0.0053x^5 - 0.2726x^4 + 7.4398x^3 - 114.07x^2 + 931.62x - 3165.2$	0.121

y= Network average CC; x= Network average number of independent paths

Table E.17 Functional relationship between network average shortest paths and number of independent paths

Iteration #	Best Fit Regression Equations	R^2
15	$y = -0.000x^6 + 0.022x^5 – 0.238x^4 + 1.329x^3 – 4.128x^2 + 6.764x – 3.733$	0.014
2	$y = -0.000x^6 + 0.003x^5 – 0.025x^4 + 0.103x^3 – 0.230x^2 + 0.274x + 0.695$	0.004
3	$y = 0.000x^6 – 0.007x^5 + 0.076x^4 – 0.422x^3 + 1.296x^2 – 2.086x + 2.220$	0.031
4	$y = 0.000x^6 – 0.003x^5 + 0.032x^4 – 0.151x^3 + 0.356x^2 – 0.371x + 0.934$	0.014
5	$y = 0.000x^6 – 0.006x^5 + 0.068x^4 – 0.364x^3 + 1.033x^2 – 1.473x + 1.652$	0.022
6	$y = -0.000x^6 + 0.022x^5 – 0.238x^4 + 1.329x^3 – 4.128x^2 + 6.764x – 3.733$	0.018
Average	$y = -0.0029x^4 + 0.0389x^3 - 0.1955x^2 + 0.426x + 0.4996$	0.014

y= Network average shortest path length; x= Network average number of independent paths

Appendix F Plots showing functional relationships between pairs of performance measures (PMs)

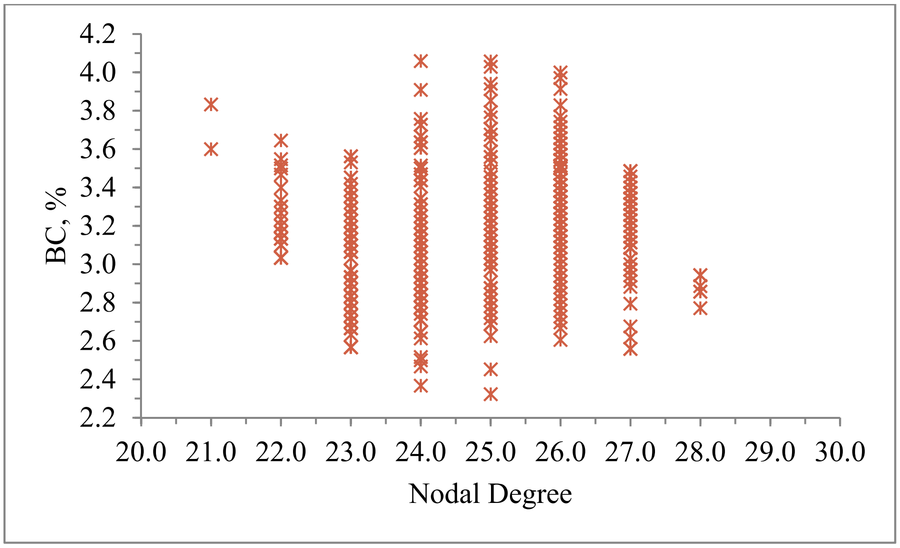


Figure F.1 Avg betweenness centrality (BC) vs. avg. nodal degree

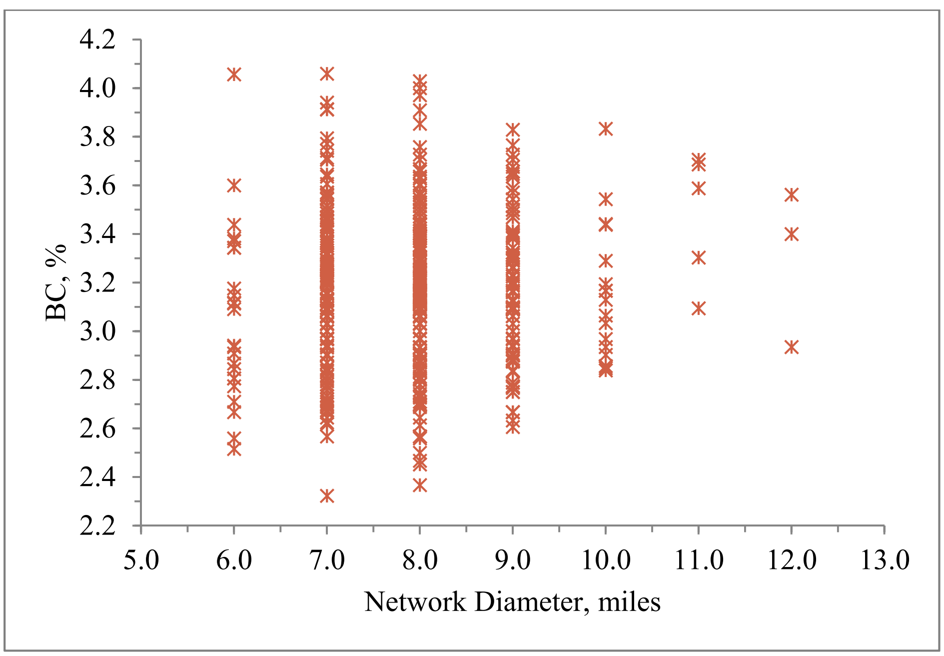


Figure F.2 Avg betweenness centrality (BC) vs. network diameter

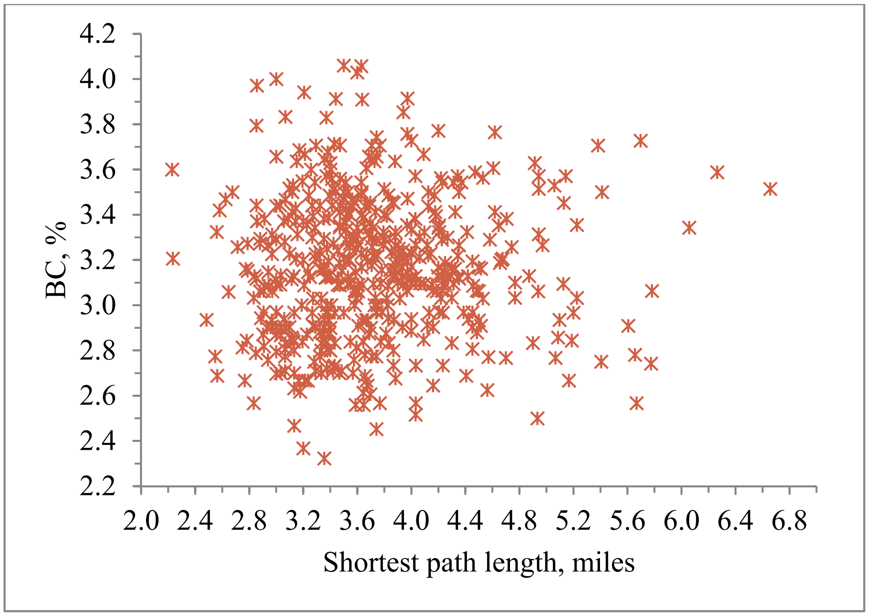


Figure F.3 Avg. betweenness centrality (BC) vs. avg. shortest path length

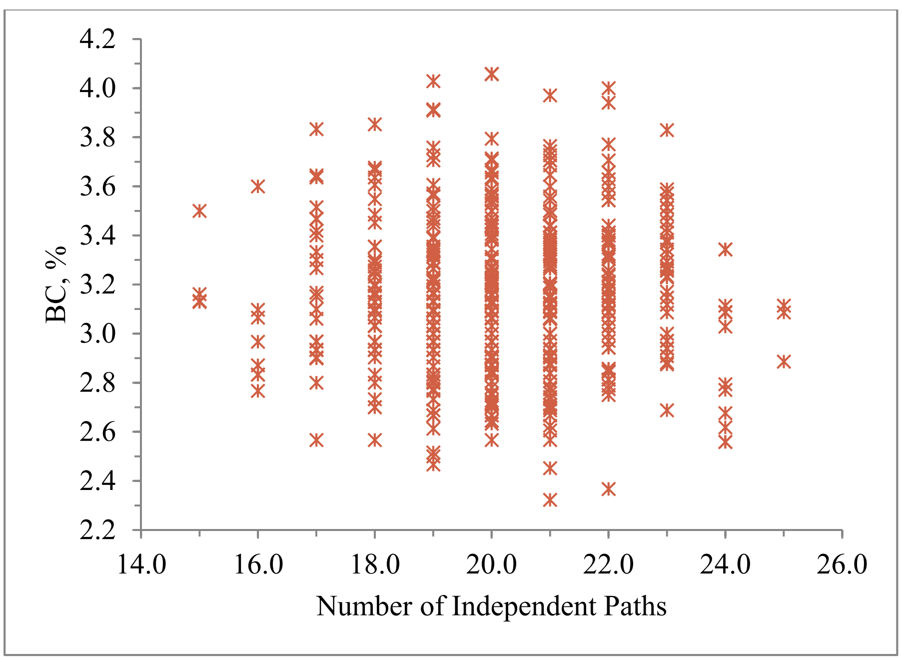


Figure F.4 Avg. betweenness centrality (BC) vs. avg. number of independent paths

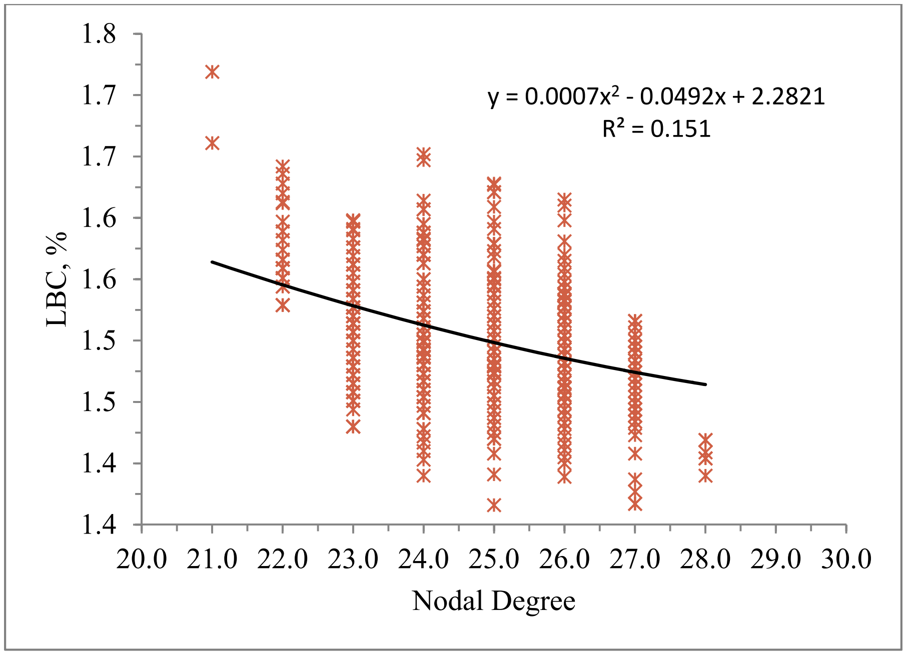


Figure F.5. Avg. link betweenness centrality (LBC) vs. avg nodal degree

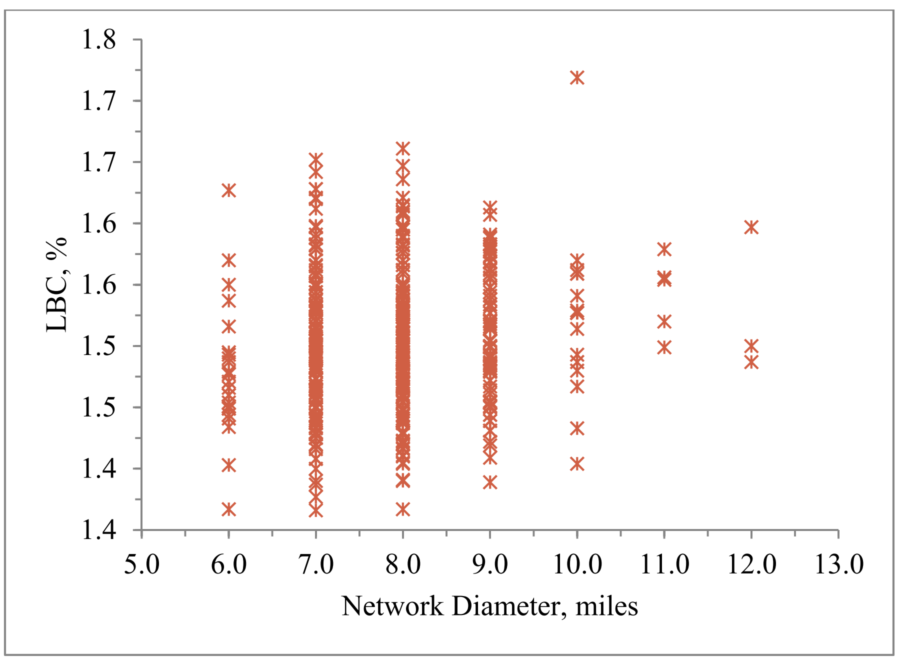


Figure F.6 Avg. link betweenness centrality (LBC) vs.network diameter

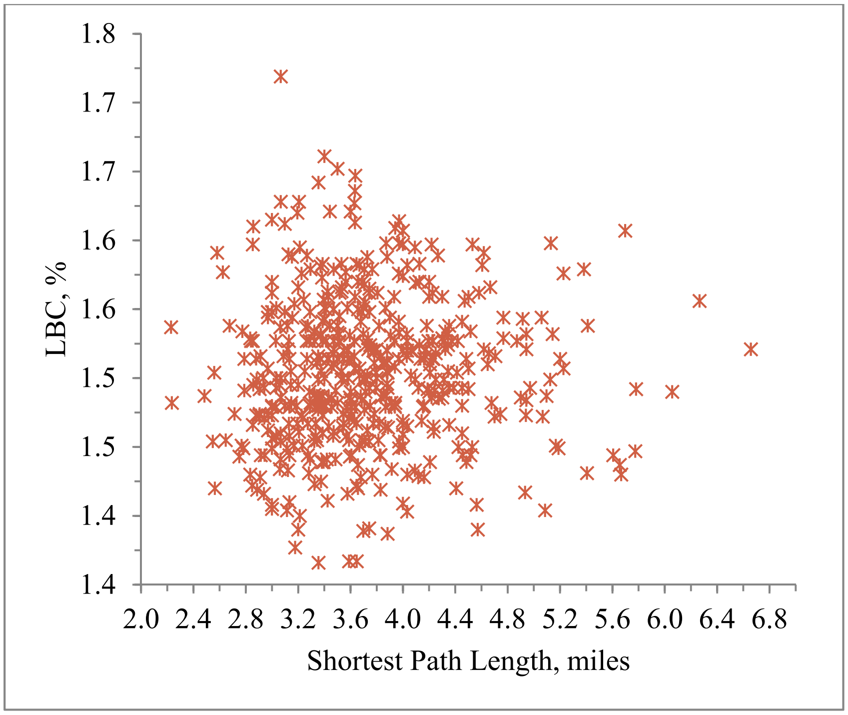


Figure F.7 Avg link betweenness centrality (LBC) vs. avg shortest path length

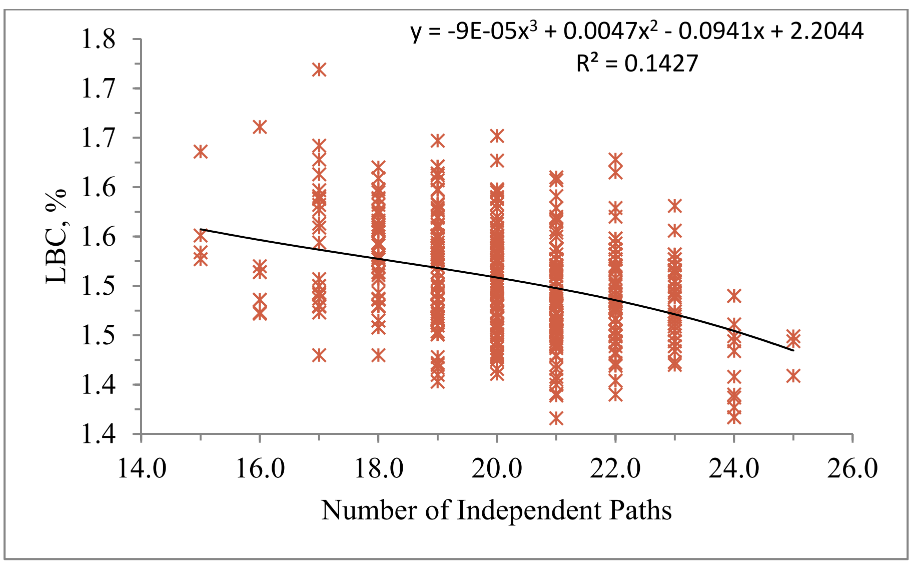


Figure F.8 Avg link betweenness centrality (LBC) vs. avg. number of independent paths

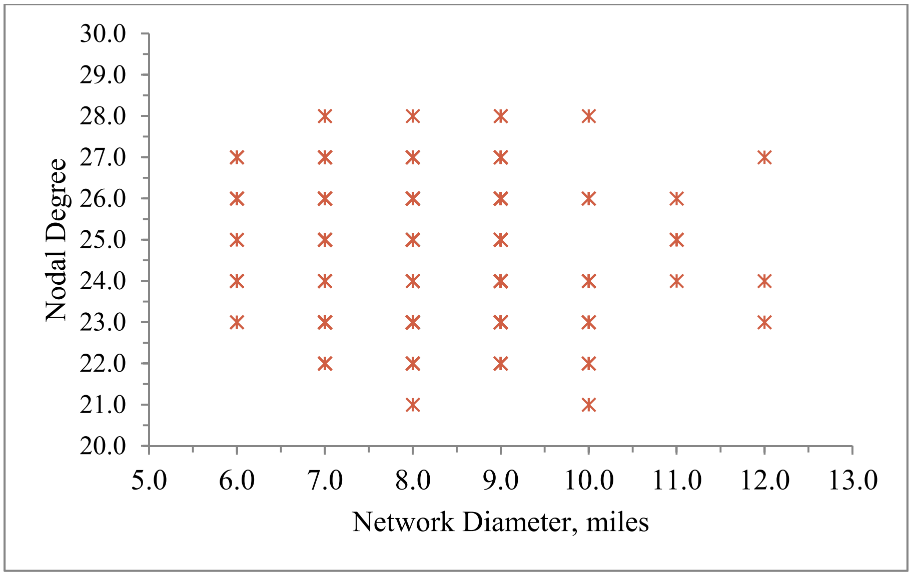


Figure F.9 Avg. nodal degree vs. network diameter

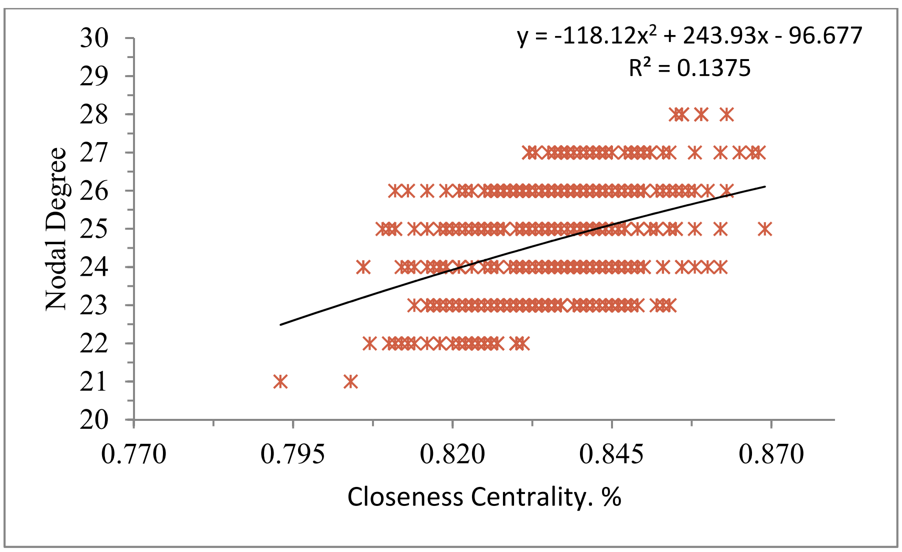


Figure F10. Avg. nodal degree vs. avg. closeness centrality (CC)

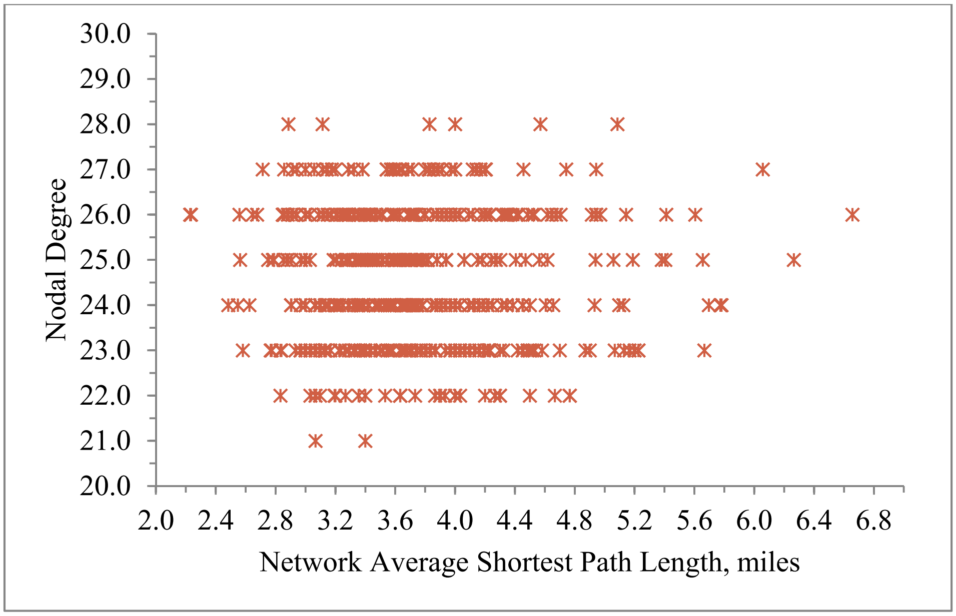


Figure F.11 Avg. nodal degree vs. avg. shortest path length

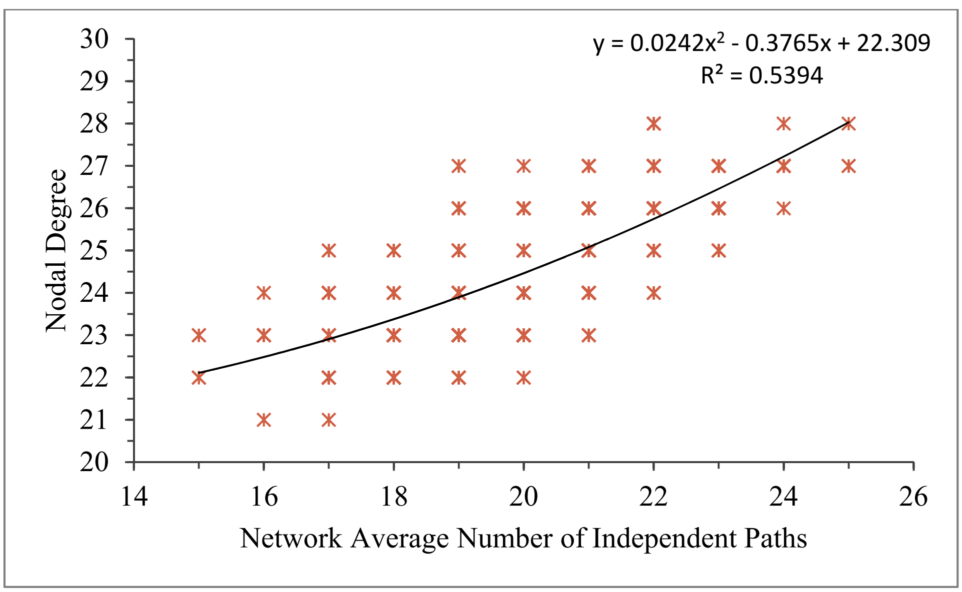


Figure F.12 Avg. nodal degree vs. avg. number of independent paths

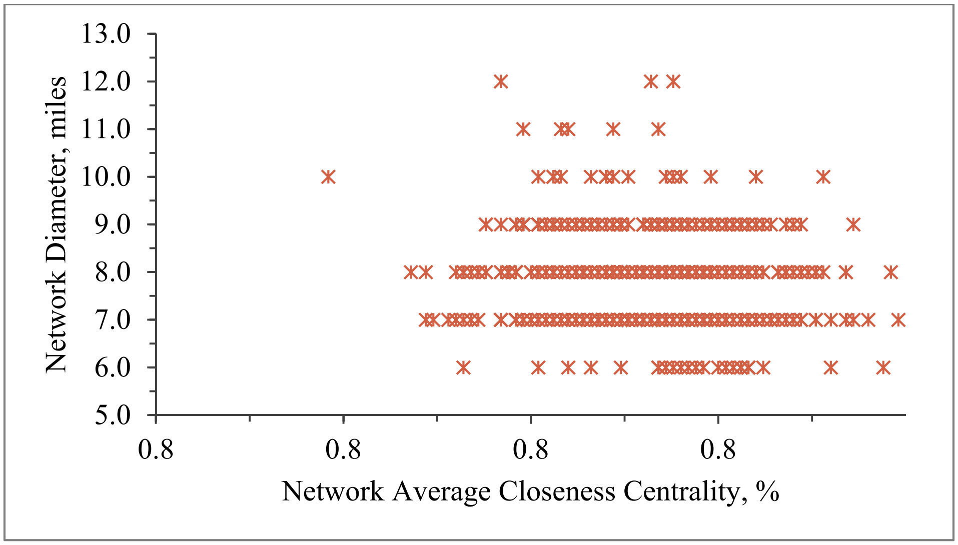


Figure F.13 Avg. network diameter vs. avg. closeness centrality (CC)

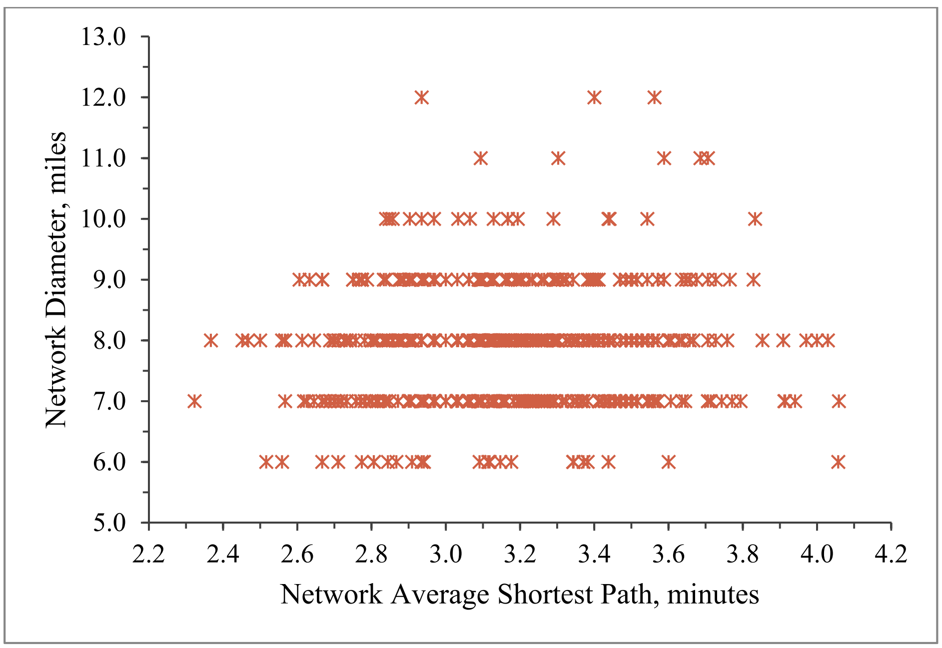


Figure F.14 Avg. network diameter vs. avg. shortest path length

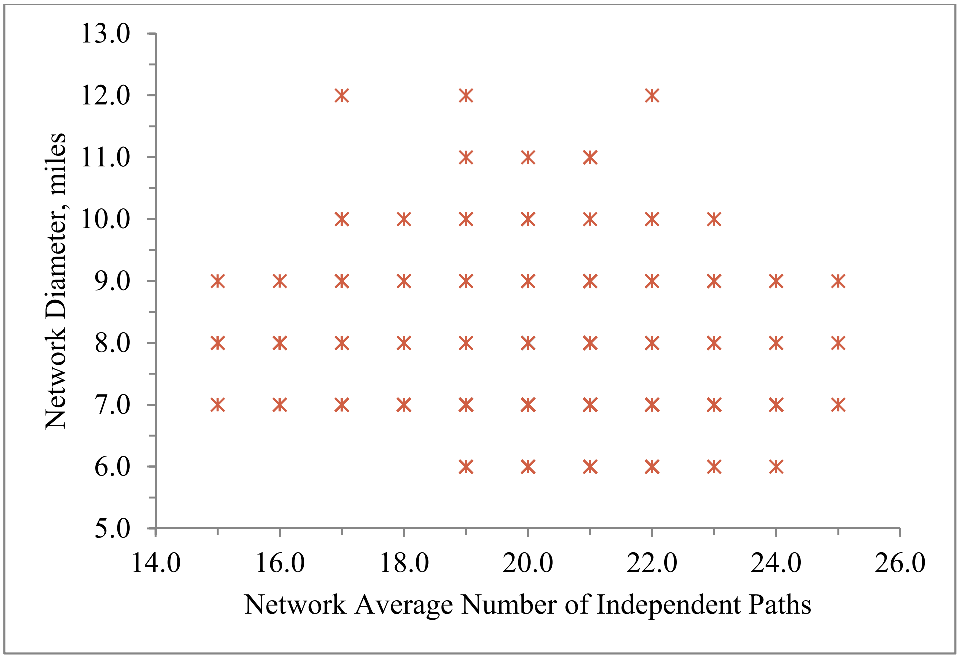


Figure F.15 Network diameter vs. avg. number of independent paths

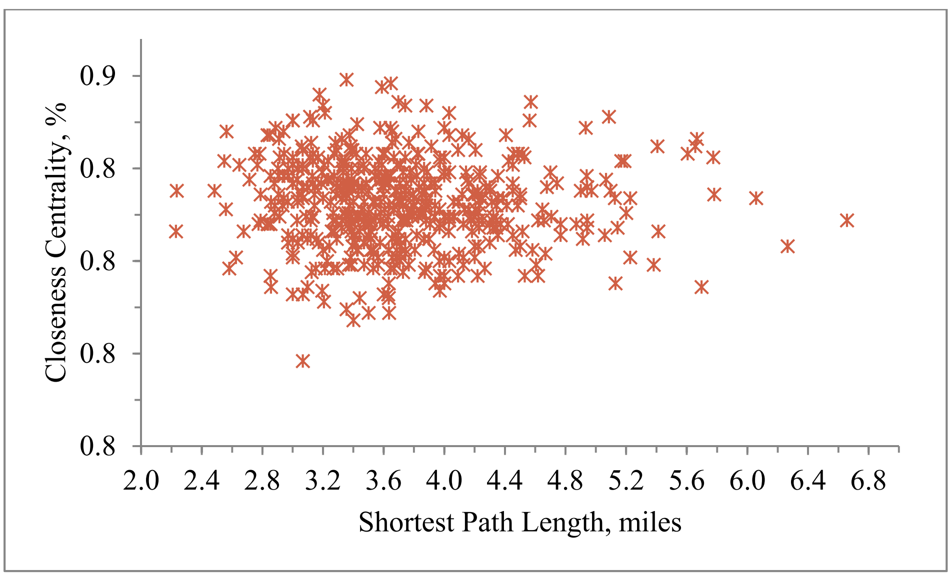


Figure F.16 Avg. closeness centrality (CC) vs. avg. shortest path length

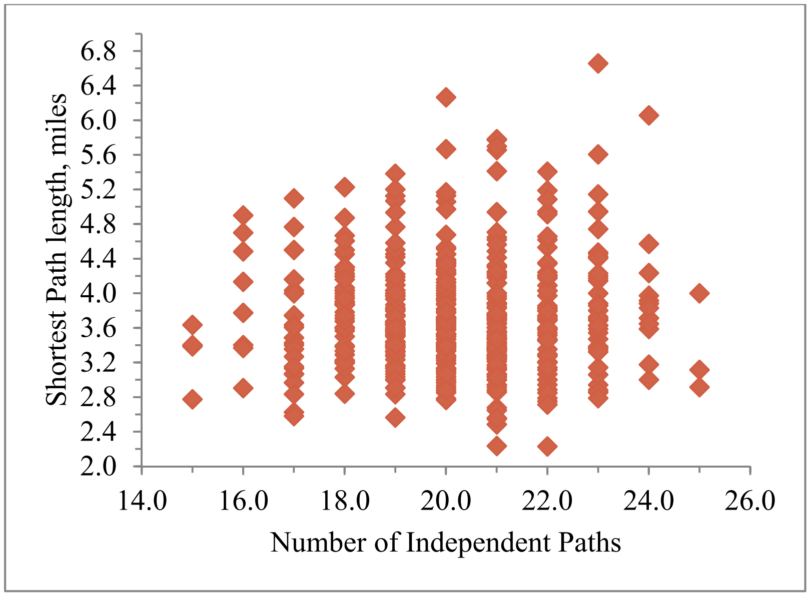


Figure F.17 Avg. shortest path length vs. avg. number of independent paths

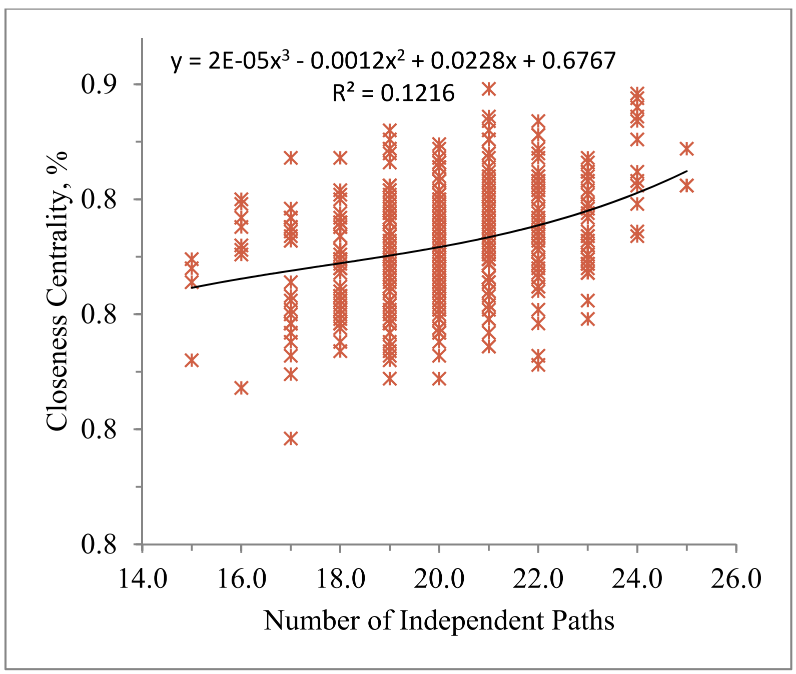
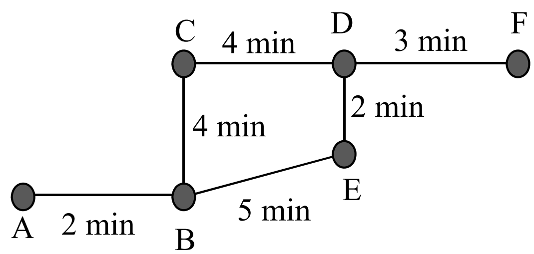


Figure F.18 Avg. closeness centrality (CC) vs. avg. number of independent paths

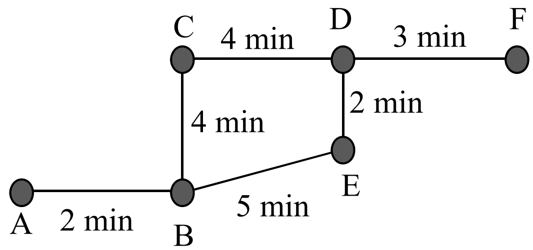
Appendix G Survey questionnaire

1. Shown in the following tables are performance measurs (PMs) that are used in improving the network performance and hence your company's business. How do you weigh these PMs? Please use the scale 1 to 10, where 1 represents the lowest importance and 10 represents the highest importance that you assign to the PMs.



Example Network

<table>
<tr><th>#</th><th>Description of the Performance</th><th>Weight (1-10)</th></tr>
<tr><td>1</td><td>Betweenness centrality (BC). This PM deals with how often you want a given intersection to occur on the shortest paths between all origin-destination pairs in the network.
For example, in Figure above, the shortest paths are given in the following table:
<table>
<tr><th>Origin</th><th>Destination</th><th>Path</th></tr>
<tr><td rowspan="4">A</td><td>B</td><td>A-B</td></tr>
<tr><td>C</td><td>A-B-C</td></tr>
<tr><td>D</td><td>A-B-E-D</td></tr>
<tr><td>E</td><td>A-B-E-D-F</td></tr>
<tr><td rowspan="4">B</td><td>C</td><td>B-C</td></tr>
<tr><td>D</td><td>B-E-D</td></tr>
<tr><td>E</td><td>B-E</td></tr>
<tr><td>F</td><td>B-E-D-F</td></tr>
<tr><td rowspan="3">C</td><td>D</td><td>C-D</td></tr>
<tr><td>E</td><td>C-D-E</td></tr>
<tr><td>F</td><td>C-D-F</td></tr>
<tr><td rowspan="2">D</td><td>E</td><td>D-E</td></tr>
<tr><td>F</td><td>D-F</td></tr>
<tr><td>E</td><td>F</td><td>E-D-F</td></tr>
</table>
It can be seen that Node B, for example, is available along three of shortest paths: A-B-C; A-B-E-D; and A-B-E-D-F. How do you weigh this PM?</td><td></td></tr>
</table>



Example Network

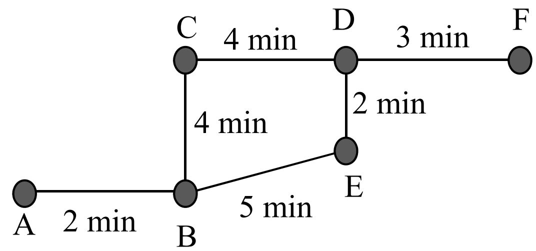
<table>
<tr><th>#</th><th>Description of the Performance</th><th>Weight (1-10)</th></tr>
<tr><td>2</td><td>

Link BC. This performance deals with how often you want a given road link to occur along the shortest paths between all origin-destination pairs in the network.
For example, in Figure above, the shortest paths are given in the following table:

<table>
<tr><th>Origin</th><th>Destination</th><th>Path</th></tr>
<tr><td rowspan="4">A</td><td>B</td><td>A-B</td></tr>
<tr><td>C</td><td>A-B-C</td></tr>
<tr><td>D</td><td>A-B-E-D</td></tr>
<tr><td>E</td><td>A-B-E-D-F</td></tr>
<tr><td rowspan="4">B</td><td>C</td><td>B-C</td></tr>
<tr><td>D</td><td>B-E-D</td></tr>
<tr><td>E</td><td>B-E</td></tr>
<tr><td>F</td><td>B-E-D-F</td></tr>
<tr><td rowspan="3">C</td><td>D</td><td>C-D</td></tr>
<tr><td>E</td><td>C-D-E</td></tr>
<tr><td>F</td><td>C-D-F</td></tr>
<tr><td rowspan="2">D</td><td>E</td><td>D-E</td></tr>
<tr><td>F</td><td>D-F</td></tr>
<tr><td>E</td><td>F</td><td>E-D-F</td></tr>
</table>

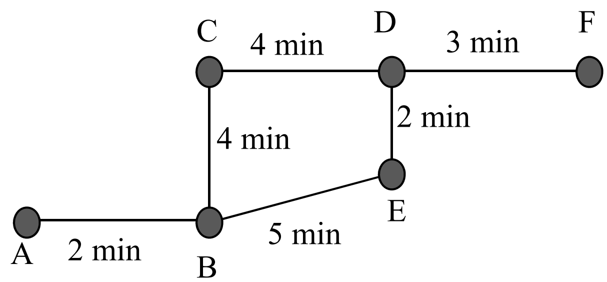
It can be seen that link E-D is occurs 6 times in the above shortest paths.
From your company's day-to-day operation point of view, how do you weigh this PM?

</td><td></td></tr>
</table>



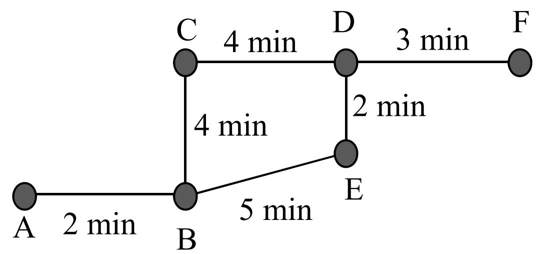
Example Network

#	Description of the Performance	Weight (1-10)
3	**Nodal degree.** This PM deals with the number of direct connection a road intersection has with other road intersections in the network. For example, in Figure 2, intersection B is directly connected to intersections A, C and E, i.e., it has 3 direct connections. On the other hand, intersection C has 2 direction connections because it is directly connected only to B and D. Based on this, how do you weigh this PM?	



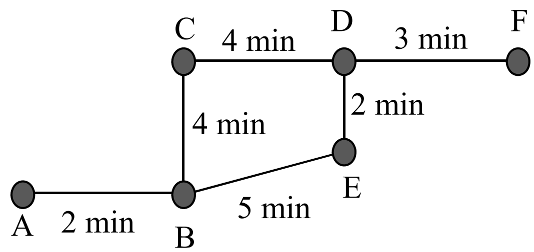
Example Network

<table>
<tr><th>#</th><th>Description of the Performance</th><th>Weight (1-10)</th></tr>
<tr><td>4</td><td>Closeness centrality (CC). This PM deals the closeness of an intersection to all other intersections in the network.
For example, in the figure above, the shortest travel time from intersection A and B to all other intersections in the network is shown in the following table.
<table>
<tr><th>Origin</th><th>Destination</th><th>Shortest path, minutes</th></tr>
<tr><td rowspan="5">A</td><td>B</td><td>2</td></tr>
<tr><td>C</td><td>6</td></tr>
<tr><td>D</td><td>9</td></tr>
<tr><td>E</td><td>7</td></tr>
<tr><td>F</td><td>12</td></tr>
<tr><td colspan="2">Sum</td><td>36</td></tr>
<tr><td rowspan="5">B</td><td>A</td><td>2</td></tr>
<tr><td>C</td><td>4</td></tr>
<tr><td>D</td><td>7</td></tr>
<tr><td>E</td><td>5</td></tr>
<tr><td>F</td><td>10</td></tr>
<tr><td colspan="2">Sum</td><td>28</td></tr>
</table>
It can be seen from the above table that the total shortest travel time from intersection A to all other intersections in the network is 36 minutes and that of B is 28 minutes. This means that intersection B is more accessible to all other intersection than intersection A.
Base on this, how do you weigh this PM from company's operation point of view?</td><td></td></tr>
</table>



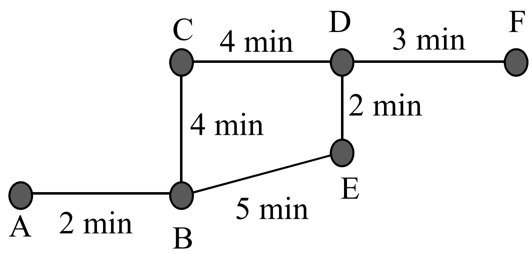
Example Network

#	Description of the Performance	Weight (1-10)
5	**Shortest travel time**. This PM deals with the shortest travel time between any two origin-destination intersections. For example, in the above Figure the shortest travel time between intersection B and D is 7 minute and that between C and E is 6 minute. Based on this, how do you weigh this PM?	



Example Network

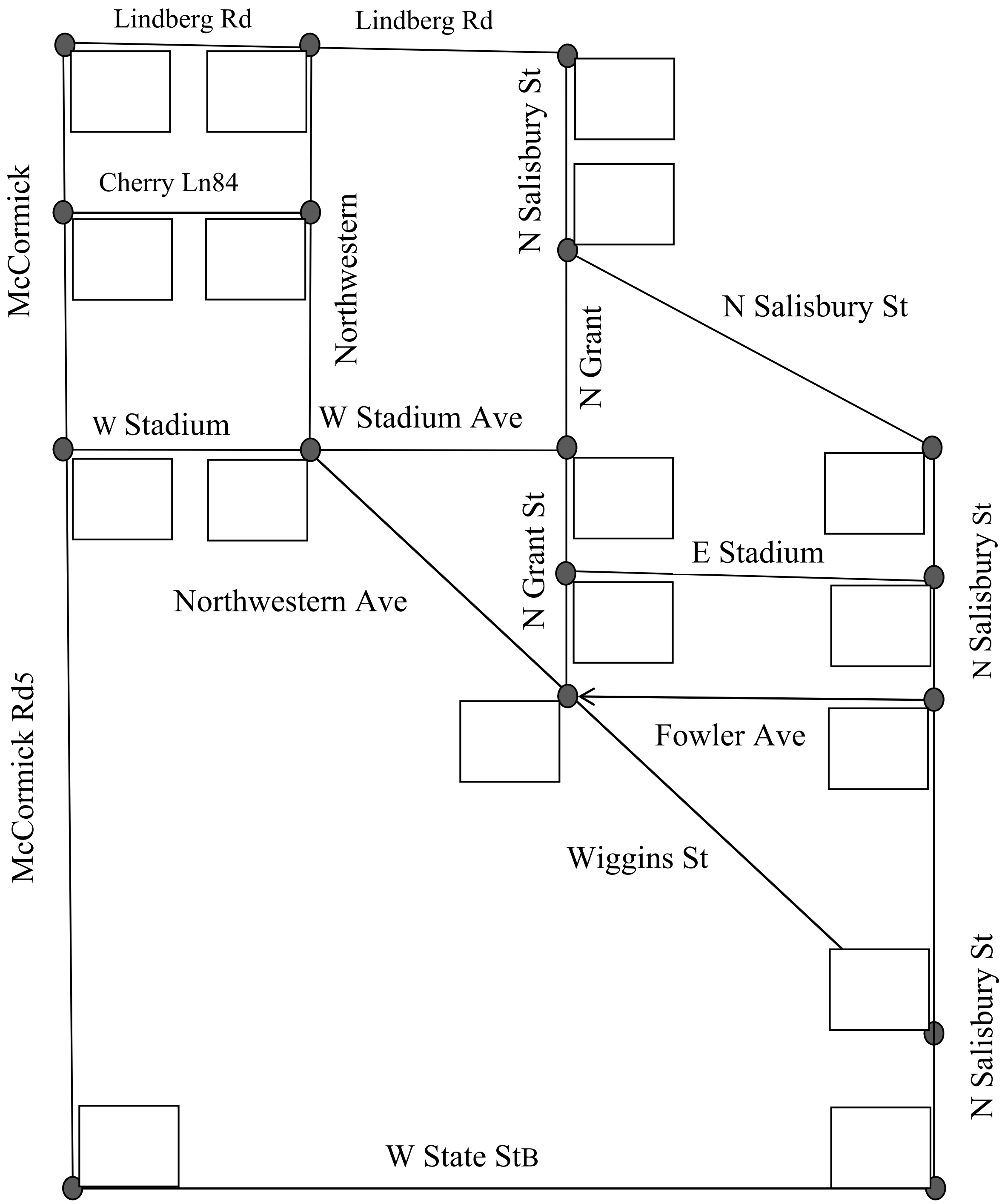
#	Description of the Performance	Weight (1-10)
6	**Traveling Salesman Problem**. This PM deals with the minimum travel time required to visit all road intersections. For example, in the above figure, suppose your company commodity dispatching center is located at intersection C and you want to visit all other intersections and return to the dispatching center. How important is this PM for your day-to-day operation?	
7.	**Chinese Postman Problem**. This PM deals with the minimum travel time required to visit all road links. For example, in the above figure, suppose your company commodity dispatching center is located along road link C-D and you want to visit all other road links and return to the dispatching center. How do you weigh this PM based on your company's operation?	



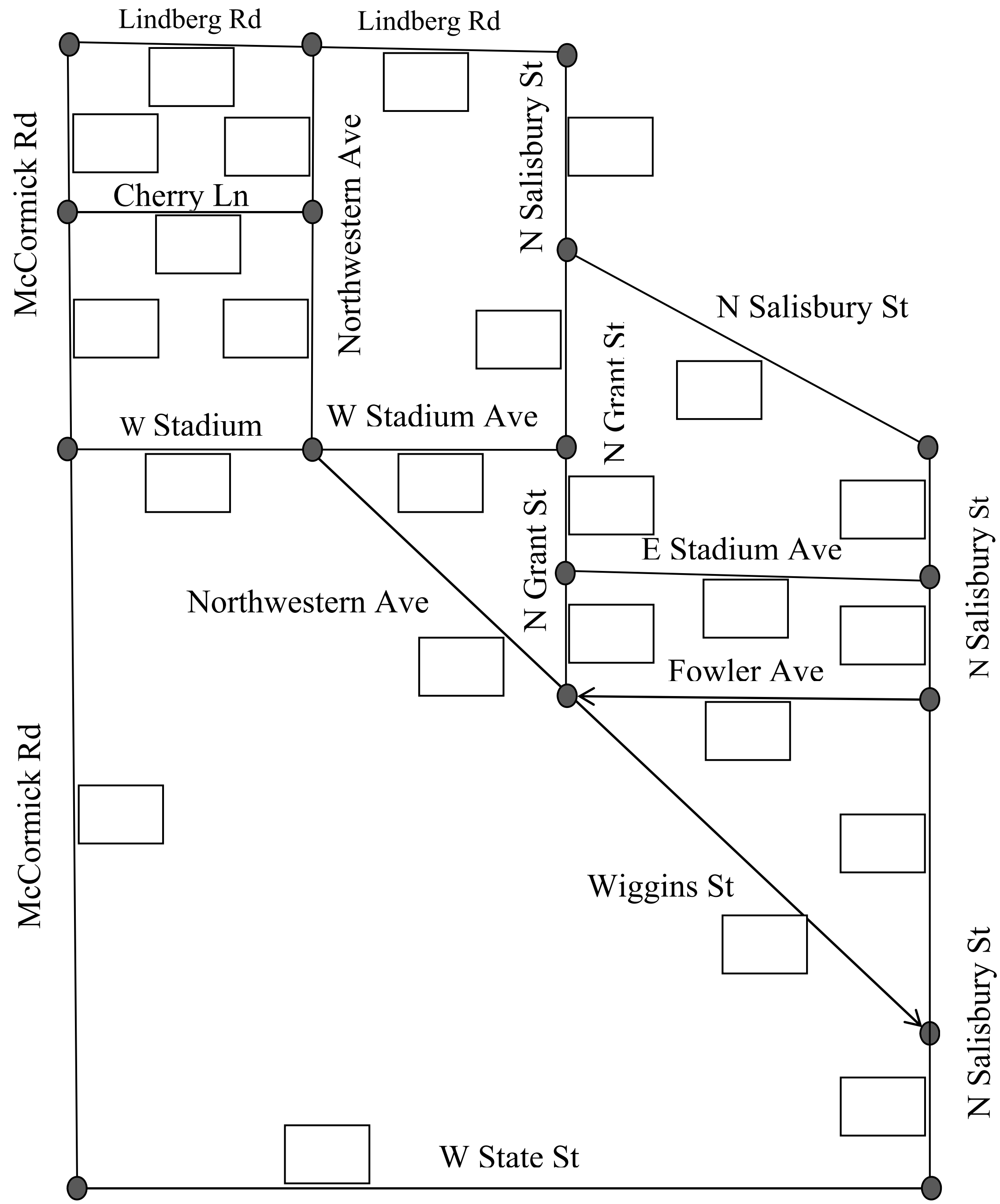
Example Network

<table>
<tr><th>#</th><th>Description of the Performance</th><th>Weight (1-10)</th></tr>
<tr><td>8</td><td>Network Diameter. This PM deals with the maximum travel time among the shortest travel times between intersection pairs. For example, in the above figure, the shortest travel time between intersections is given in the following table
<table>
<tr><th>Origin</th><th>Destination</th><th>Shortest travel time, minutes</th></tr>
<tr><td rowspan="5">A</td><td>B</td><td>2</td></tr>
<tr><td>C</td><td>6</td></tr>
<tr><td>D</td><td>9</td></tr>
<tr><td>E</td><td>7</td></tr>
<tr><td>F</td><td>12</td></tr>
<tr><td rowspan="4">B</td><td>C</td><td>4</td></tr>
<tr><td>D</td><td>7</td></tr>
<tr><td>E</td><td>5</td></tr>
<tr><td>F</td><td>10</td></tr>
<tr><td rowspan="3">C</td><td>D</td><td>4</td></tr>
<tr><td>E</td><td>6</td></tr>
<tr><td>F</td><td>7</td></tr>
<tr><td rowspan="2">D</td><td>E</td><td>2</td></tr>
<tr><td>F</td><td>3</td></tr>
<tr><td>E</td><td>F</td><td>5</td></tr>
<tr><td></td><td>Maximum</td><td>12</td></tr>
</table>
It can be seen the maximum travel time in the above table is 12 minutes which is between intersection A and F.
If this PM is important in your daily operation, how do you weigh it?</td><td></td></tr>
</table>

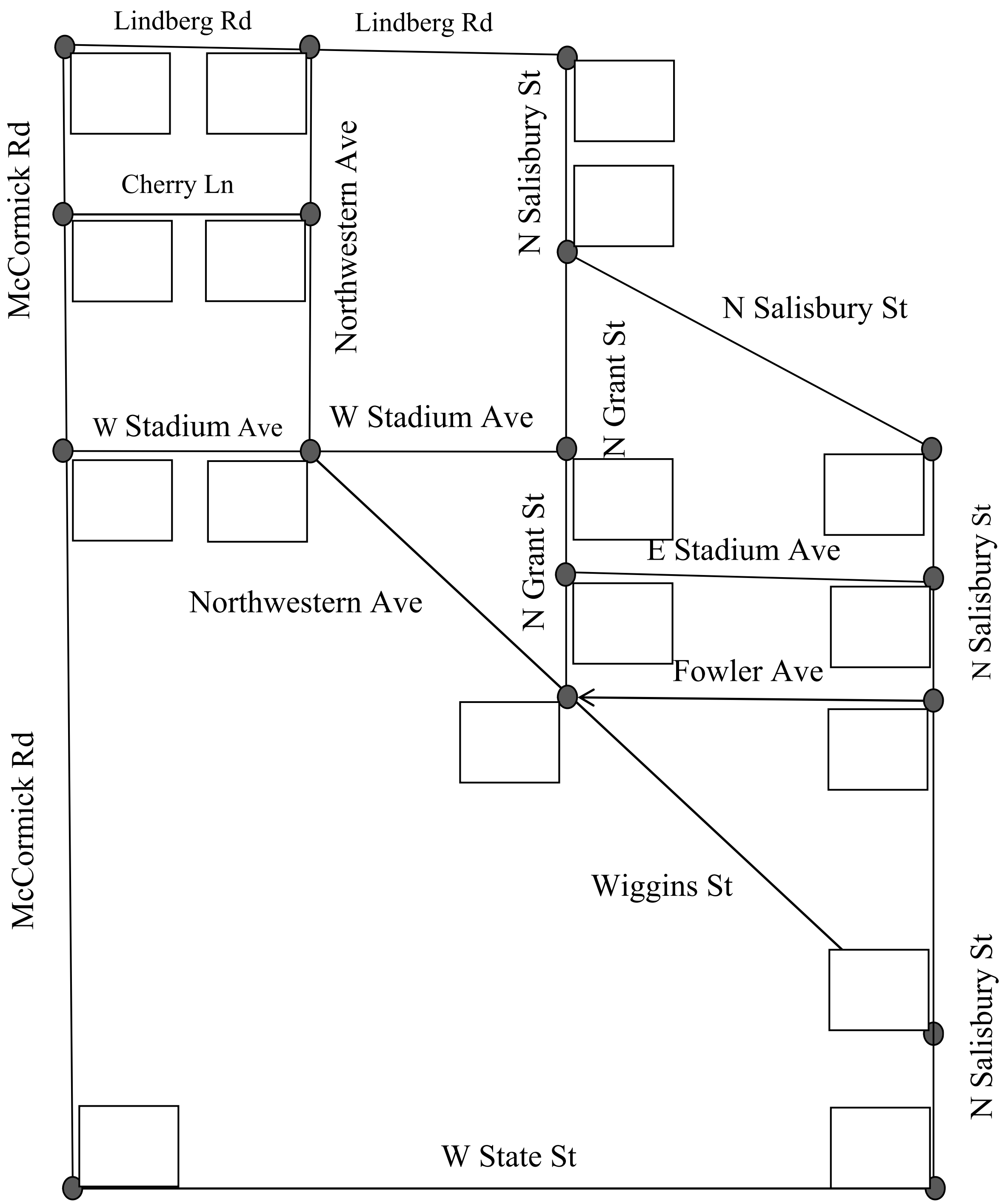
2. As you use the network, you may have found that some road intersections may be more important than others in terms of how frequently they are used. Based on this, how would you weigh the following road intersections? Please use the scale 1 to 10 (1 means least important; 10 means most important). Please refer to the following figure and put your weight in the box provided beside each intersection.



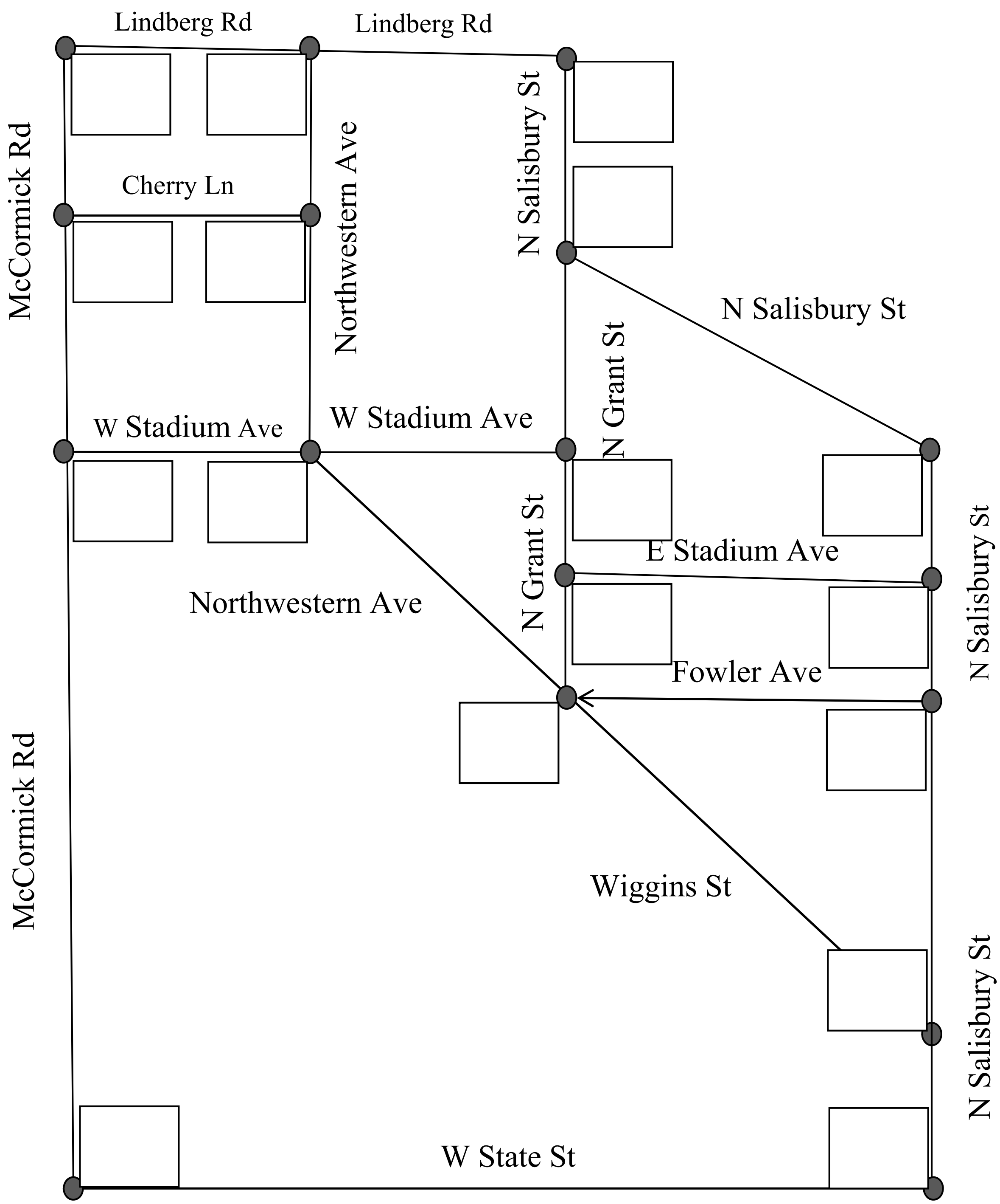
3. As you use the network, you may have found that some road links may be more important than others in terms of how frequently they are used. Based on this, how would you weigh the road links shown in the below network? Please use the scale 1 to 10 (1 means least important; 10 means most important). Please refer to the following figure and put your weight in the box provided beside each road link.



4.To enhance your company's operations, you may seek that road intersections have more direct connections with other road intersections in the network. Based on this, how would you weigh the following road intersections to maximize your company's business? Please use the scale 1 to 10 (1 means least important; 10 means most important).Please refer to the following figure and put your weight in the box provided beside each intersection.

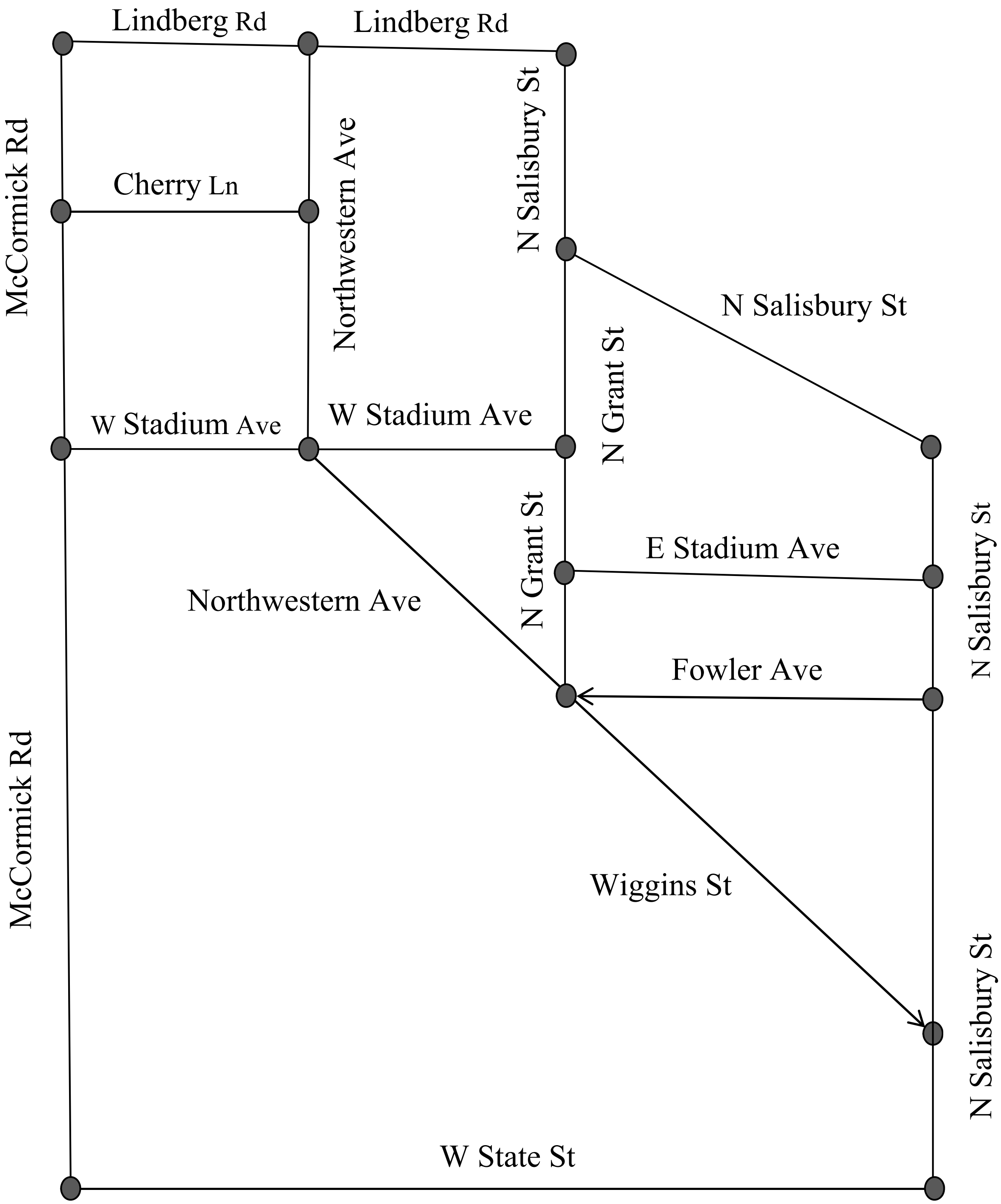


5. Some road intersections may be more important than others and your company may want these important road intersections to have proximity to other road intersections for doing business effectively. Based on this, how would you weigh the following road intersections? Please use the scale 1 to 10 (1 means least important; 10 means most important).Please refer to the following figure and put your weight in the box provided beside each intersection.



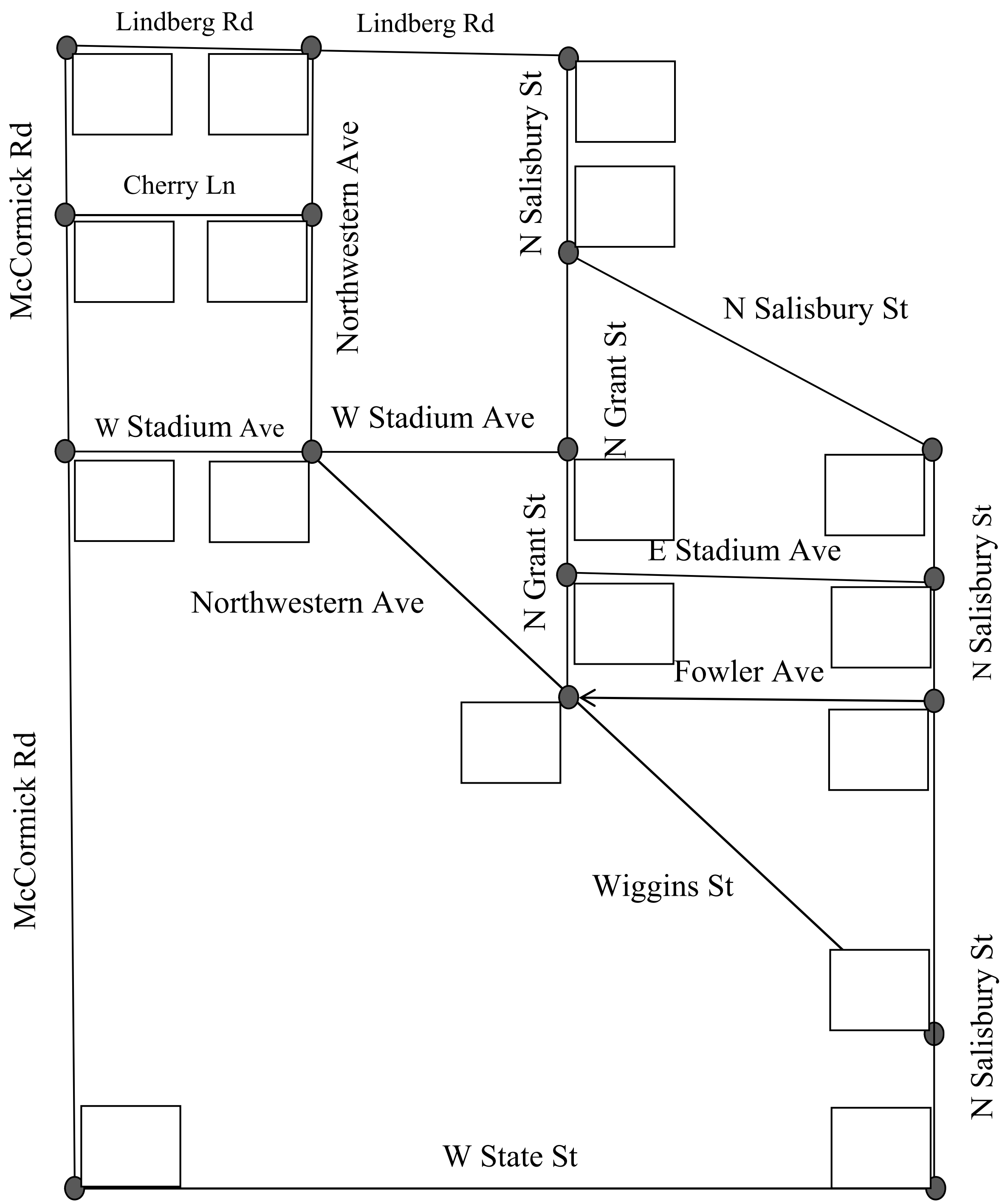
6. In order to facilitate business by shortening travel time, your company may provide variable weights for the shortest travel time between any two road intersections in the network. Based on this, how do you weigh the following road intersections? Please use the scale 1 to 10 (1 means least important; 10 means most important). Please use the figure in the following page to help visualization of the network.

To From	McCormick-Lindberg	McCormick-Cherry Lane	McCormick – West Stadium Ave	McCormick – West State St	Lindberg Rd. – Northwestern Ave	Cherry Lane – Northwestern Ave.	West Stadium Ave. – Northwestern Ave.	Lindberg Rd. – North Salisbury Rd.	North Grant St. – North Salisbury Rd.	West Stadium Ave. – North Grant St.	North Grant St. – East Stadium Ave.	Northwestern Ave. – Fowler Ave.	North Salisbury Rd. – Robinson St.	East Stadium Ave. – North Salisbury St.	Fowler Ave. – North Salisbury St.	Wiggins St. – North Salisbury St.	West State St. –North Salisbury St
McCormick-Lindberg																	
McCormick-Cherry Lane																	
McCormick – West Stadium Ave.																	
McCormick – West State St																	
Lindberg Rd. – Northwestern Ave																	
Cherry Lane – Northwestern Ave.																	
West Stadium Ave. – North Western Ave.																	
Lindberg Rd. – North Salisbury Rd.																	
North Grant St. – North Salisbury Rd.																	
West Stadium Ave. – North Grant St.																	
North Grant St. – West Stadium Ave.																	
Northwestern Ave. – Fowler Ave.																	
North Salisbury Rd. – Robinson St.																	
East Stadium Ave. – North Salisbury St.																	
Fowler Ave. – North Salisbury St.																	
Wiggins St. – North Salisbury St.																	
West State St. – North Salisbury St.																	

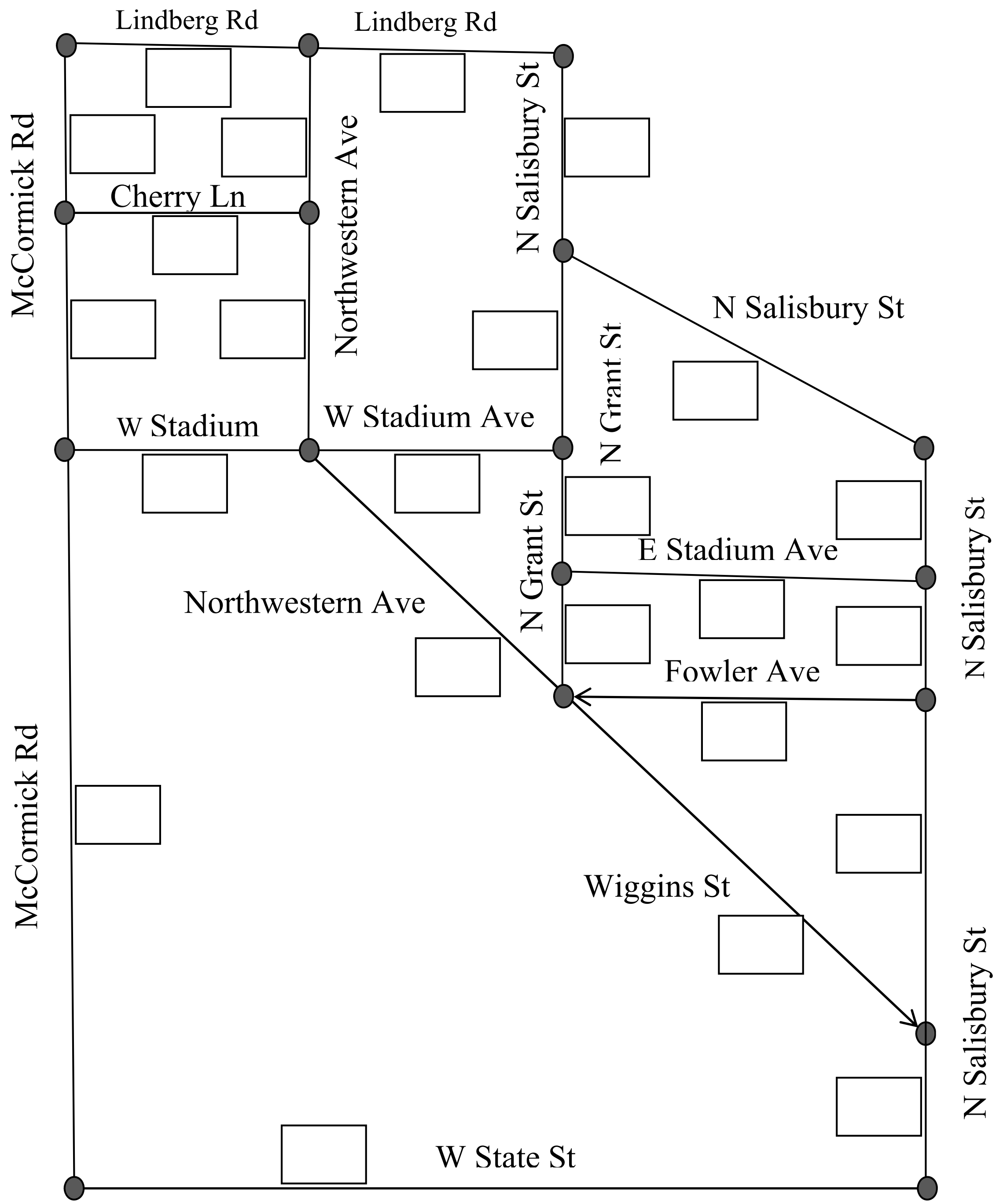


Case Study Road Network (West Lafayette, Indiana)

7. Suppose your company's business requires visiting all intersections starting and ending the visit at the same intersection with minimum travel time. Based on this, how do you weigh the following road intersections? Please use the scale 1 to 10 (1 means least important; 10 means most important).Please refer to the following figure and put your weight in the box provided beside each intersection.



8. Suppose your company's business requires visiting all road links starting and ending the visit at the same road links with minimum travel time. Based on this, how do you weigh the following road links? Please use the scale 1 to 10 (1 means least important; 10 means most important).Please refer to the following figure and put your weight in the box provided beside each road link.



Appendix H Python code for computing network connectivity index (NCI)

```
import networkx as nx
from pylab import *
import matplotlib.pyplot as plt
import numpy as np
from operator import itemgetter
from igraph import *
from mpl_toolkits.mplot3d import Axes3D
import numpy.ma as ma
import pandas as pd
import igraph

# Construct the case study network
weighted_links = [("A", "B", 1.09), ('A', 'D',0.62), ("B", "C", 0.40), ("B", "E", 0.55),
('C','F', 0.34), ("D", "E", 1.08), ("D", "G", 0.59), ('E', 'H', 0.57), ("F", "I", 0.72), ('F', 'J',
0.54), ("G", "H", 0.98), ("G", "P", 0.49), ('H', 'I', 0.19), ("H", "M", 0.30), ("I", "K", 0.03),
('J', 'L', 0.30), ('K', "L", 0.25), ('K', 'M', 0.20), ('L','N', 0.24), ("K", "N", 0.22), ("M", "O",
0.18), ("N", "O", 0.05), ("O", "Q", 0.27), ("P", "Q", 1.34)]
ids=UniqueIdGenerator()
edgelist = [(ids[x], ids[y]) for x, y, _ in weighted_links]
weights = [w for _, _, w in weighted_links]
g=Graph(edgelist, vertex_attrs=dict(name=ids.values()),
edge_attrs=dict(weight=weights))

#compute D
diam=g.diameter(weights='weight')
print "Network diameter: " + str(diam)
print "\n"
#compute BC
n_nodes = len([vertex["name"] for vertex in g.vs])
bet_cen=g.betweenness()
sum_bet_cen = sum (i for i in bet_cen)
print "Maximum BC: " + str(round(max(bet_cen),3))
print "Minimum BC:  " + str(round(min(bet_cen),3))
print "\n"
#compute LBC
edge_bet_cen=g.edge_betweenness()
print "Maximum LBC: " + str(round(max(edge_bet_cen),3))
print "Minimum LBC:  " + str(round(min(edge_bet_cen),3))
print "\n"
#compute Nodal degree
degree_of_a_node=g.degree()
```

```
print "Maximum Nodal degree: " + str(max(degree_of_a_node))
print "Minimum Nodal degree:  " + str(min(degree_of_a_node))
print "\n"
#compute CC
closeness_cen=g.closeness()
print "Maximum CC: " + str(round(max(closeness_cen),3))
print "Minimum CC:  " + str(round(min(closeness_cen),3))
print "\n"
#compute SPL
spl=g.shortest_paths_dijkstra(weights='weight')
SPL=[]
for i in spl:
	SPL.append(i)
a = np.array(SPL)
b = a.ravel() # to change into 1D array
msx = ma.masked_array(b, mask = (b==0)) # to mask zeroes
msxCompressed=msx.compressed() # to remove zeroes from 1D array
print "maximum SPL: " + str(max(msxCompressed))
print "minimum SPL: " + str(min(msxCompressed))
print "\n"
```

Appendix I GaphMagics® output for Chinese postman problem

Algorithm – Chinese postman problem

Circuit's Total Cost – 324; Circuit's Total Length (Edges passed) – 30; Path: 1 >> 4 >> 7 >> 16 >> 17 >> 15 >> 14 >> 15 >> 13 >> 14 >> 12 >> 10 >> 6 >> 10 >> 12 >> 11 >> 9 >> 11 >> 13 >> 8 >> 7 >> 4 >> 5 >> 2 >> 5 >> 8 >> 9 >> 6 >> 3 >> 2 >> 1

Circuit's Total Cost – 324; Circuit's Total Length (Edges passed) – 30; Path: 2 >> 5 >> 8 >> 9 >> 6 >> 3 >> 2 >> 1 >> 4 >> 7 >> 16 >> 17 >> 15 >> 14 >> 15 >> 13 >> 14 >> 12 >> 10 >> 6 >> 10 >> 12 >> 11 >> 9 >> 11 >> 13 >> 8 >> 7 >> 4 >> 5 >> 2

Circuit's Total Cost – 324; Circuit's Total Length (Edges passed) – 30; Path: 3 >> 2 >> 1 >> 4 >> 7 >> 16 >> 17 >> 15 >> 14 >> 15 >> 13 >> 14 >> 12 >> 10 >> 6 >> 10 >> 12 >> 11 >> 9 >> 11 >> 13 >> 8 >> 7 >> 4 >> 5 >> 2 >> 5 >> 8 >> 9 >> 6 >> 3

Circuit's Total Cost – 324; Circuit's Total Length (Edges passed) – 30; Path: 4 >> 7 >> 16 >> 17 >> 15 >> 14 >> 15 >> 13 >> 14 >> 12 >> 10 >> 6 >> 10 >> 12 >> 11 >> 9 >> 11 >> 13 >> 8 >> 7 >> 4 >> 5 >> 2 >> 5 >> 8 >> 9 >> 6 >> 3 >> 2 >> 1 >> 4

Circuit's Total Cost - 324; Circuit's Total Length (Edges passed) – 30; Path: 5 >> 2 >> 5 >> 8 >> 9 >> 6 >> 3 >> 2 >> 1 >> 4 >> 7 >> 16 >> 17 >> 15 >> 14 >> 15 >> 13 >> 14 >> 12 >> 10 >> 6 >> 10 >> 12 >> 11 >> 9 >> 11 >> 13 >> 8 >> 7 >> 4 >> 5

Circuit's Total Cost – 324; Circuit's Total Length (Edges passed) – 30; Path: 6 >> 10 >> 12 >> 11 >> 9 >> 11 >> 13 >> 8 >> 7 >> 4 >> 5 >> 2 >> 5 >> 8 >> 9 >> 6 >> 3 >> 2 >> 1 >> 4 >> 7 >> 16 >> 17 >> 15 >> 14 >> 15 >> 13 >> 14 >> 12 >> 10 >> 6

Circuit's Total Cost – 324; Circuit's Total Length (Edges passed) – 30; Path: 7 >> 16 >> 17 >> 15 >> 14 >> 15 >> 13 >> 14 >> 12 >> 10 >> 6 >> 10 >> 12 >> 11 >> 9 >> 11 >> 13 >> 8 >> 7 >> 4 >> 5 >> 2 >> 5 >> 8 >> 9 >> 6 >> 3 >> 2 >> 1 >> 4 >> 7

Circuit's Total Cost – 324; Circuit's Total Length (Edges passed) – 30; Path: 8 >> 7 >> 4 >> 5 >> 2 >> 5 >> 8 >> 9 >> 6 >> 3 >> 2 >> 1 >> 4 >> 7 >> 16 >> 17 >> 15 >> 14 >> 15 >> 13 >> 14 >> 12 >> 10 >> 6 >> 10 >> 12 >> 11 >> 9 >> 11 >> 13 >> 8

Circuit's Total Cost – 324; Circuit's Total Length (Edges passed) – 30; Path: 9 >> 11 >> 13 >> 8 >> 7 >> 4 >> 5 >> 2 >> 5 >> 8 >> 9 >> 6 >> 3 >> 2 >> 1 >> 4 >> 7 >> 16 >> 17 >> 15 >> 14 >> 15 >> 13 >> 14 >> 12 >> 10 >> 6 >> 10 >> 12 >> 11 >> 9

Circuit's Total Cost – 324; Circuit's Total Length (Edges passed) – 30; Path: 10 >> 6 >> 10 >> 12 >> 11 >> 9 >> 11 >> 13 >> 8 >> 7 >> 4 >> 5 >> 2 >> 5 >> 8 >> 9 >> 6 >> 3 >> 2 >> 1 >> 4 >> 7 >> 16 >> 17 >> 15 >> 14 >> 15 >> 13 >> 14 >> 12 >> 10

Circuit's Total Cost – 324; Circuit's Total Length (Edges passed) – 30; Path: 11 >> 9 >> 11 >> 13 >> 8 >> 7 >> 4 >> 5 >> 2 >> 5 >> 8 >> 9 >> 6 >> 3 >> 2 >> 1 >> 4 >> 7 >> 16 >> 17 >> 15 >> 14 >> 15 >> 13 >> 14 >> 12 >> 10 >> 6 >> 10 >> 12 >> 11

Circuit's Total Cost – 324; Circuit's Total Length (Edges passed) – 30 ; Path: 12 >> 10 >> 6 >> 10 >> 12 >> 11 >> 9 >> 11 >> 13 >> 8 >> 7 >> 4 >> 5 >> 2 >> 5 >> 8 >> 9 >> 6 >> 3 >> 2 >> 1 >> 4 >> 7 >> 16 >> 17 >> 15 >> 14 >> 15 >> 13 >> 14 >> 12

Circuit's Total Cost – 324; Circuit's Total Length (Edges passed) – 30; Path: 13 >> 14 >> 12 >> 10 >> 6 >> 10 >> 12 >> 11 >> 9 >> 11 >> 13 >> 8 >> 7 >> 4 >> 5 >> 2 >> 5 >> 8 >> 9 >> 6 >> 3 >> 2 >> 1 >> 4 >> 7 >> 16 >> 17 >> 15 >> 14 >> 15 >> 13

Circuit's Total Cost – 324; Circuit's Total Length (Edges passed) – 30; Path: 14 >> 15 >> 13 >> 14 >> 12 >> 10 >> 6 >> 10 >> 12 >> 11 >> 9 >> 11 >> 13 >> 8 >> 7 >> 4 >> 5 >> 2 >> 5 >> 8 >> 9 >> 6 >> 3 >> 2 >> 1 >> 4 >> 7 >> 16 >> 17 >> 15 >> 14

Circuit's Total Cost – 324; Circuit's Total Length (Edges passed) – 30; Path: 15 >> 14 >> 15 >> 13 >> 14 >> 12 >> 10 >> 6 >> 10 >> 12 >> 11 >> 9 >> 11 >> 13 >> 8 >> 7 >> 4 >> 5 >> 2 >> 5 >> 8 >> 9 >> 6 >> 3 >> 2 >> 1 >> 4 >> 7 >> 16 >> 17 >> 15

Circuit's Total Cost – 324; Circuit's Total Length (Edges passed) – 30; Path: 16 >> 17 >> 15 >> 14 >> 15 >> 13 >> 14 >> 12 >> 10 >> 6 >> 10 >> 12 >> 11 >> 9 >> 11 >> 13 >> 8 >> 7 >> 4 >> 5 >> 2 >> 5 >> 8 >> 9 >> 6 >> 3 >> 2 >> 1 >> 4 >> 7 >> 16

Circuit's Total Cost – 324; Circuit's Total Length (Edges passed) – 30; Path: 17 >> 15 >> 14 >> 15 >> 13 >> 14 >> 12 >> 10 >> 6 >> 10 >> 12 >> 11 >> 9 >> 11 >> 13 >> 8 >> 7 >> 4 >> 5 >> 2 >> 5 >> 8 >> 9 >> 6 >> 3 >> 2 >> 1 >> 4 >> 7 >> 16 >> 17

VITA

VITA

Wubeshet Woldemariam was born on January 9, 1976, in Addis Ababa, Ethiopia. He attended elementary and high schools in Addis Ababa: 1st to 4th grade at Teramaj Elementary School and 4th to 8th grade at Ediget Besira Elementary and Medium High School where he received numerous awards for his academic achievements. He attended high school at Addis Ketema Comprehensive Secondary School in Addis Ababa. In 1997, he was admitted into Adama University in Ethiopia, to study construction technology. At Adama, he received numerous academic awards including the Dean's List award, and after completion of his studies in 2001, he accepted an offer to work as Graduate Faculty Assistant in Mekelle University in Ethiopia, where he taught civil engineering courses, assisted professors and participated in departmental activities. In 2002, he was admitted into the Indian Institute of Technology, Bombay (IIT Bombay) where he studied Transportation Systems Engineering and was awarded an M.Tech. degree at the completion of his studies. In 2004, Wubeshet Woldemariam returned to Mekelle University where he was promoted to a lecturer level and continued teaching and conducting research. In 2007, he was admitted, with assistantship, into Purdue University's School of Civil Engineering, where he pursued MS and PhD degrees and carried out various duties in research and teaching. His research work has been of national significance and was sponsored by the Federal Highway Administration (FHWA), through the Indiana Department of Transportation (INDOT), and the Joint Transportation Research Program (JTRP). Wubeshet Woldemariam has presented his research work at several research forums and also he has published his work in peer-reviewed archival journals and conference proceedings. His awards include the 33rd Harter Rupert Award for best paper on transportation noise presented by the transportation-related noise and vibration committee of the Transportation Research Board of the National Academies. After completing his studies at Purdue University's West Lafayette campus, Wubeshet Woldemariam will join Purdue University Calumet as a faculty to teach and conduct research in various areas of Civil Engineering.