Complex Networks Perspectives towards Accelerated Bridge Construction (ABC)

Quarterly Progress Report
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1. Background and Introduction

Accelerated Bridge Construction (ABC) employs precast bridge elements moved to the bridge location and installed in place. Although ABC advances the life cycle cost (while using new materials and methods), reduce construction time, and result in higher quality of elements, nevertheless many cast-in-place activities need to be undertaken. As such, despite the fact that ABC reduces many uncertainties associated with construction processes and performance during service life, ABC related activities can create impacts on the road network carrying regular traffic. The problem may get escalated during major natural extreme events (hurricane, wildfire). As such, network positions or credentials of bridges based on their topography or connectivity need to be assessed to prioritize or stage ABC activities. There have been limited investigations by many states to monitor the effects on traffic due to ABC related activities and to identify more efficient strategies to pursue such activities while reducing overall system-wide impact. ABC-UTC is planning to embark on a coordinated and extensive network experiments at different geographic scales to apply complex network science principles to the study of bridge networks and ABC related activities. The research will use GIS modeling along with FDOT bridge and road network data to run network experiments and prioritize certain bridges based on their network credentials. Essentially, it will be attempted to establish relationships between bridge topography with their functional behavior. The research will provide new insights into ABC activities and scheduling based on the topography of vulnerable bridges and monitoring system-wide cascading effects. The results will be compiled and published on ABC-UTC website and will become available to outside users and researchers. The study will develop an approach and tool that states, municipalities and other transportation authorities can use to select the proper actions for repair and replacement of exiting bridges by implementing ABC methods of choice and on a risk-based maintenance strategy.

2. Problem Statement

Conceptual and methodological developments in network analysis have furthered our understanding of the effects of individuals' interpersonal environment on normative social influence and social engagement. Network data offers better insights related to an individual's abilities, aspirations, attitudes, behaviors, and interpersonal environment. The complex topology of real networks allows its actors to change their functional behavior. Network models provide better understanding of the evolutionary mechanisms being accountable for the growth of such networks by capturing the dynamics in the ways network agents interact and change their behavior. Considerable amount of research efforts is required for developing novel network modeling techniques to understand the structural properties such networks, reproducing similar properties based on empirical evidence, and designing such networks efficiently.

ABC project applications are categorized in 6 tiers based on the project mobility/traffic impact time ranging from 1 day (Tier 1) to several months (Tier 6), with considerable reduction of time from the conventional option. For example, a project for which the entire superstructure has been assembled off-line and moved in place within just 24 hours will be specified as Tier 1 (Alipour and Shane 2018a). Tier 6 will include impacting for example a statewide bridge replacement program by months or years through implementing Tier 1 to 5 projects for individual bridges in the network. However, these options may translate to variable costs normally higher costs for shorter duration. Consequently, selection of the ABC method will impact the cost according to the advantage it offers for time. This trend is one of the factors to be considered on the network analysis for ABC options along with others.

Identifying the vulnerable sections and cascading effects in the bridge network system can be quite challenging. Potential failure in a bridge network system is often over-looked, but the consequence can be catastrophic as it can adversely affect the mobility of people. Therefore, addressing the vulnerabilities is very complicated in large cities. While there have been studies that discussed the necessity of developing framework for measuring resilience, a systematic approach to improving resiliency through vulnerability assessment is lacking. The objective of this study is to present method for assessing the vulnerability of a bridge network system and a strategy for improving its resiliency. With a growing attention to risk-based inspection and maintenance of infrastructure, an accurate knowledge of the vulnerabilities and importance, as well as consideration of interrelation among bridges in a network becomes crucial. The bridge network system in the state of Florida, USA will be used as a case study in this project.

The vulnerability and resilience of the Florida bridge network will be analyzed based on network science principles and graph theory. For example, a small portion (Miami-Dade) of the Florida road and bridge network is shown in Figure 1. The bridge connectivity will be treated as a network to assess the interdependence between the connectivity of the system components and their functional behavior (Newman 2003). In accordance with the network science literature, these network links and nodes can be analyzed with respect to the resilience metrics to determine the critical components of a bridge network system that are more susceptible to external shocks. Once the vulnerabilities have been identified, priorities will be set to improve the different vulnerable sections of the bridge network system. Furthermore, a plan will be developed, to improve the resiliency of all the different components of the bridge network systems. A preliminary literature review is provided in section 4.2 to motivate how network science principles can be applied to the study of bridge networks and Accelerated Bridge Construction (ABC) activities.

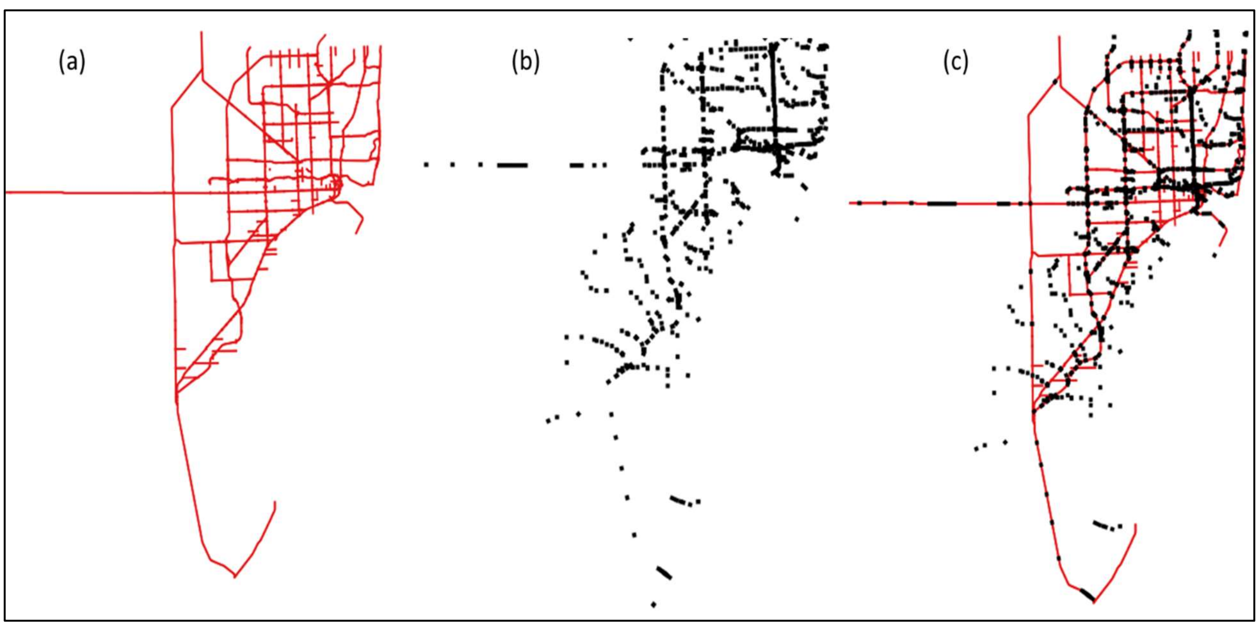


Figure 1 Examples of Miami-Dade County Road-bridge Network. (a) Road Network, (b) Bridge Network, (c) Superimposed Road-bridge Network.

3. Objectives and Research Approach

ABC-UTC is planning to embark on a coordinated and extensive network experiments at different geographic scales to apply complex network science principles to the study of bridge networks and ABC related activities. The research will use GIS modeling along with FDOT bridge and road network data to run network experiments and prioritize certain bridges based on their network credentials. Essentially, it will be attempted to establish relationships between bridge topography with their functional behavior. The specific objectives of the proposed project include *(a) investigation on the resiliency and vulnerability of road-bridge networked systems, (b) development of a framework for analysis of such networks and their topology with functional behavior, (c) incorporation of the analysis method in a user-friendly tool for use by bridge owners and consultants for decision making on maintenance of the infrastructure, and (d) incorporation of complex network analysis with ABC options and features*

The research will provide new insights into ABC activities and scheduling based on the topography of vulnerable bridges and monitoring system-wide cascading effects. By applying network science principles, most important (higher degree and more central) bridges among the bridge network will be identified. We can then suggest ABC to put more emphasize (maintenance, retrofitting) on those bridges, which can facilitate recovery of bridge networks after an extreme event, hence ensuring resiliency. Similar context can be applied to new ABC activities. The results will be compiled and published on ABC-UTC website and will become available to outside users and researchers. The study will develop an approach and tool that states, municipalities and other transportation authorities can use to select the proper actions for repair and replacement of exiting bridges by implementing ABC methods of choice and on a risk-based maintenance strategy.

4. Description of Research Project Tasks

The following is a description of tasks carried out to date.

Task 1 – Comprehensive Literature Review

A comprehensive literature review has been completed in this quarter which is detailed below:

Transportation infrastructure forms the mainstay of the economy and typically requires huge number of annual investments which are mainly for maintenance, rehabilitation, and replacement of the assets of the transportation infrastructure. The overall expenditures are expected to increase due to infrastructure aging, increased frequency and intensity of severe weather, and increasing traffic loads. More than 685,000 bridges in the United States are no exception to these conditions. The vitality of the bridge network to the transportation network and to economic development, the large investments in their repair and replacement, and the impact of their closures on the socio-economic prosperity of the society, inspires the implementation of new construction techniques, planning approaches, and policies for their management. One of the main challenges facing transportation asset managers is the need to cost-effectively prioritize the repair and replacement of the large inventory of deteriorating bridges considering the ever-increasing budgetary constraints. The indirect costs (such as traffic delay) associated with the closure times during these activities exacerbates the decision-making processes (Alipour, Gransberg et al. 2018b).

As an alternative to conventional construction, Accelerated Bridge Construction (ABC) techniques are gradually gaining acceptance to reduce construction duration and minimize the impact of closures at the network level. There are different types of ABC and each technique has its limitations and speed of completion. The choice of using a specific ABC depends on a host of different factors including its applicability to specific bridge site, criticality of the bridge to the network, and availability of capital funds for its implementation. Some of these factors tend to have contradicting affects, as a faster ABC technique often entails higher investment levels; on the other hand, a faster technique for a bridge with high criticality to the network may result in large savings in user costs (Alipour, Gransberg et al. 2018b).

Alice et al. aims to address the aspects through a review of the available literature and having interview with a few states that have implemented ABC at different levels. The results showed that the major aspects impacting the timelines for ABC projects are the impacts the closures might have on the socio- economic aspects of the community. Hence, most states acknowledge the importance of indirect costs, except for some, there is no mathematical formulation to account for them in the final decision making. Most of decisions are made based on the qualitative input from districts and through public discussions with the public. For the establishment of incentives, similar procedure as those for the conventional construction and following the FHWA guidelines is suggested by most of the states (Alipour and Shane 2018a).

To support resilience planning for roadway networks, Zhang et al. introduces a new stage-wise decision framework regarding pre-disaster mitigation (Stage I), post-disaster emergency response (Stage II) and long-term recovery (Stage III). These decision metrics are first defined, based on a derivation of the number of independent pathways (IPW) within a roadway system, to measure the performance of a network in term of its robustness, redundancy, and recoverability, respectively. In Phase I, a prioritization approach for temporary repairs to facilitate immediate post-disaster emergency responses in Phase II, and a methodology for scheduling network-wide repairs during the long-term recovery of the roadway system in Phase III. Using the three IPW-based decision metrics, a stage-wise decision process is then formulated as a stochastic multi-objective optimization problem, which includes a project ranking mechanism to identify pre-disaster network retrofit projects. Finally, this stage-wise decision framework is applied to the roadway network of Shelby County, TN, USA subjected to seismic hazards, to illustrate its implementation in supporting community network resilience planning (Zhang 2018).

Machado et al explains community resilience which depends on the resilience of the lifeline infrastructure and the performance of the disaster-related functions of local governments. This study summarizes the metrics used to assess the resilience of the transportation system and a categorization of the assessment approaches at three levels of analysis (the asset, network, and systems levels). State and federal resilience plans and guidelines acknowledge the importance of the transportation system as a critical lifeline in planning for community resilience and in helping local governments to set recovery goals. However, a widely accepted definition of the resilience of the transportation system and a structure for its measurement are not available. Furthermore, this paper ties these metrics to relevant dimensions of community resilience. This work addresses a key first step required to enhance the efficiency of planning related to transportation system resilience by providing (a) a standard terminology with which efforts to enhance the resilience of the transportation system can be developed, (b) an approach to organize planning and research efforts related to the resilience of the transportation system, and (c) identification of the gaps in measurement of the performance of the resilience of the transportation system (Machado-León 2017).

Sun et al states that the transportation infrastructure plays an important role in ensuring the well-being of its citizenry and for supporting the national economy. There is an increasing number of studies focusing on the resilience analysis of the transportation infrastructure to support planning and design and to optimize emergency management and restoration schedules. Extreme events (including both natural hazards and man-made disasters) have caused terrible physical damages to the transportation infrastructure, long-term socioeconomic impacts, and psychological damages. This study covers functionality metrics, functionality-based resilience metrics and socio-economic resilience metrics. The study also revealed that there are still fundamental challenges to comprehensively evaluate the resilience of the transportation infrastructure, especially due to two main sources of complexity: uncertainties and interdependencies. Besides, the validations of resilience assessments are limited due to the general scarcity of data, which may hinder the practical applications (Sun 2018).

4.1 Resiliency of Bridge Network

Alice et al develops a mixed-integer programming model that provides a balanced portfolio of construction techniques on bridge sites over a prioritization process for bridges at the network level. A project-level scheme accordingly is conducted to optimize the choice of accelerated construction techniques for this purpose, while a network-level scheme is used to select the bridges for rapid replacement based on their criticalities to the network, To account for the effects of different accelerated construction techniques, the costs associated with each replacement technique is calculated including direct costs from the actual replacement of bridges and indirect costs experienced by network users due to the bridge closure during the maintenance period (Alipour, Gransberg et al. 2018b).

Twumasi et al. explains hazard impacts on regional network infrastructures and identifying significantly affected areas are important for communicating the need for building resilient infrastructure by describing the comprehension of network-level consequences resulting from disruptive events is a main gray area in the evaluation of transportation network resilience at the regional level. High-impact-zone location identification metrics were developed and implemented in preliminarily identifying areas affected by bridge closures. This study presents a framework for assessing the regional network resilience by leveraging scenario-based traffic modeling and GIS techniques Resilience was estimated, and an index developed by utilizing practical functionality metrics based on vehicle distance and hours traveled. These are illustrated for the Tampa Bay, Florida, area. Findings for 10 bridge closure scenarios and recovery schemas indicated significant regional resilience losses. The I-275 bridge closure indicated the highest functional loss to the regional network: the aggregated resilience index below 0.5 reflects severe network performance deficit and mobility limitations (Twumasi-Boakye 2018).

Zhang et al. presents a methodology systematically incorporates network topology, redundancy, traffic flow, damage level and available resources into the stochastic processes of network post-hazard recovery strategy optimization. A novel resilience-based framework is developed here to optimize the scheduling of the post-disaster recovery actions for road-bridge transportation networks. Two metrics are proposed for measuring rapidity and efficiency of the network recovery: total recovery time (TRT) and the skew of the recovery trajectory (SRT). The TRT is the time required for the network to be restored to its pre-hazard functionality level, while the SRT is a metric defined for the first time in this study to capture the characteristics of the recovery trajectory that relates to the efficiency of those restoration strategies considered. To illustrate the proposed methodology, a genetic algorithm is used to solve the restoration schedule optimization problem for a hypothetical bridge network with 30 nodes and 37 bridges subjected to a scenario seismic event. Based on the two-dimensional metric, a restoration scheduling method is proposed for optimal post-disaster recovery planning for bridge-road transportation networks. A sensitivity study using this network illustrates the impact of the resourcefulness of a community and its time-dependent commitment of resources on the network recovery time and trajectory (Zhang 2017).

Frangopol et al. claims that the most earthquake damage prone components of a transportation network are certainly its bridges; therefore, the proposed approach focuses on bridge rehabilitation interventions. This study deals with the concept of “resilience” and proposes its use as optimization criterion for the rehabilitation of a transportation network subject to earthquake. The design variables of the optimization problem are the application times and durations of the interventions on bridges of the network. These durations are determined by the amount of funding invested on each bridge. Hence, the proposed methodology provides the optimal rehabilitation schedule and cost breakdown for all the bridges of the network. A numerical application is presented to illustrate the proposed approach and to show its capabilities (Frangopol 2011).

Bocchini et al. describes that the development of tools for the assisted decision making during the disaster management is the most promising fields where the concept of resilience is applied to engineering practice. The proposed technique involves a completely new formulation of the optimization problem, with new design variables, additional objectives, and constraints. This new technique for the optimal disaster management is presented here that provides bridge restoration sequences which maximize the network resilience and minimize the time to connect critical locations. The purpose of these modifications is to generate an automated procedure that mimics better the decision process currently used by disaster managers. Two numerical examples are presented: the first one is meant to validate and demonstrate the proposed approach, whereas the second proves its applicability to a network with a larger number of bridges. In this latter example the input data have been filtered by random factors to make the data more realistic (Bocchini 2013).

Karamlou et al. indicates transportation networks as necessary infrastructure elements to provide supports to impacted areas after the occurrence of a disaster. Recovering without functional roads, other damaged facilities and lifelines would be slow and difficult. Therefore, restoring the damages of transportation networks, specifically bridges as their most vulnerable elements, is among the first priorities of disaster management officials. This study develops a new methodology for the restoration of damaged bridges scheduling by developing an algorithm which is providing a practical restoration plan to be used by decision makers at the time of an event yet based on solid computations rather than mere engineering judgment. The problem is formulated as a multi-objective combinatorial optimization solved by Genetic Algorithms, which minimizes the time to connect the selected critical locations and maximizes the resilience of the transportation network. The algorithm is examined with a numerical example. The presented algorithm can be considered as the enhancement of previous work performed at Lehigh University. The results show that the new optimization setup improved the solution quality and efficiency compared to the previous techniques (Karamlou 2014).

Banerjee et al. provided an organized and wide-ranging review on bridge and bridge network resilience assessment under single hazard and multi-hazard conditions. Resilience assessment for engineered systems in recent years has attracted considerable attention from the engineering community. It has resulted in a large body of literature that focuses on relevant areas of resilience. Authors mentioned not that much work has yet been done on multi-hazard bridge resilience, relevant aspects are discussed, including combinations of multiple hazards for bridge performance assessment, loss assessment methods, and post-event recovery approaches. In addition, maintenance is a key component when a life-cycle framework evaluates resilience. Accessible maintenance plans and strategies are discussed as well as their likely applications for bridges and bridge networks. The article ends with a debate on the need for more work in the focus area and the challenges associated with it (Banerjee 2019).

Domaneschi et al. stated that structural management systems can make a significant contribution to reducing the impact of extreme events in areas affected by the earthquake, thus improving structural resilience. In addition, as structural conditions change due to local failures, the inherent advantage of some control systems, which can adjust to various loading rates, can be exploited. This happens by changing the control system's working parameters in real time or over the period between two seismic events, even if very short. This research deals with the durability of cable-stayed bridge seismic control solutions through a case study defined by a standard literature bridge control benchmark. Authors introduced a technique to restore the optimum bridge configuration after a damaging incident. Emphasis is placed on the time interval between the occurrence of damage and the recovery, which is the essential aspect of the resilient actions. Ultimately, in the sense of multiple hazards, the development of a robustness index and general procedures indicating how to measure durability for the cable-stayed bridge control system is discussed (Domaneschi 2015).

Bocchini et al. discussed an optimization method for the reconstruction activities associated with the bridges of an earthquake-seriously damaged transportation network. The development variables are (i) the time periods between the occurrence of the distress and the start of the interventions on each network bridge; and (ii) the rate of reconstruction of the interventions, which is a measure of the funding allocated to each bridge. The optimization goals were to optimize the efficiency of the network, reduce the time required to reach a target level of functionality, and minimize the total cost of restoration activities. Since the first two goals obviously clash with the last, the optimization approach does not provide a unique solution, but a whole array of Pareto solutions. The capabilities of the proposed methodology are illustrated by a numerical example involving a complex, existing transport network in Santa Barbara, California (Frangopol 2012).

Apostolopoulou et al. explained that sustainable monument conservation requires the use of performing materials that are at the same time compatible with the historical building materials of the monument to ensure structural integrity, sufficient structural quality in earthquake strain, and stability of both reconstruction and historical materials. It refers to cultural heritage properties that have suffered major damage, requiring extensive restoration. After a heavy rainfall in 2015, the Plaka Bridge in Epirus, Greece, partly collapsed. It was a supreme example and an important symbol of the region's typical stone bridge architecture. In this study, through a variety of laboratory techniques, a potential restoration stone from a nearby quarry was examined in terms of compatibility with the bridge's dominant historical building stone, as well as in terms of mechanical performance. Furthermore, criteria for the restoration of mortars were set, considering the characteristics of the historical materials as well as the bridge environment. The results of the study on restoration stone and mortars were presented and evaluated to select the most suitable restoration materials for Plaka Bridge in its upcoming reconstruction, with the goal of improving the structure's overall resilience (Apostolopoulou 2019).

Setunge et al. stated that the road networks and critical road systems such as bridges, culverts and floodways play a vital role in increasing the risk of the area being served before, during and after extreme events. The research presented a detailed analysis of the Lockyer Valley region of Australia's case study of 2013 floods to identify critical failure mechanisms of road bridge structures exposed to flood events. 43 out of 46 bridges in the region have been damaged as a result of the 2013 flood. Major bridge structure failure mechanisms are described as scouring of piers and abutments, damage to bridge decks due to impact of urban debris, and severe damage to bridge approach ramps. A methodology is proposed for vulnerability modeling of bridges for an extreme event, consisting of a combination of the definition of fault tree system and harm index (Setunge 2014).

Karamlou et al. presented a new scheduling methodology to restore damaged bridges. The problem is formulated as a multi-objective combinatorial optimization solved by Genetic Algorithms which minimizes the time to connect the critical locations selected and maximizes the transport network's resilience. The main purpose of designing the algorithm was to provide a restore strategy that is realistic to be used at the time of an incident by decision-makers but based on solid computations rather than pure judgment of technology. A statistical example explores the algorithm. The results show that, compared to previous approaches, the current optimization system improved the quality and efficiency of the solution (Karamlou 2014).

Zhang et al. proposed a new resilience-based framework for street-bridge transport networks to optimize the scheduling of post-disaster recovery actions. Systematically, the approach integrates network topology, reliability, traffic flow, damage level and available resources into the design of the post-hazard recovery strategy network stochastic processes. Two metrics were proposed to calculate network recovery speed and efficiency: total recovery time (TRT) and the skew of the recovery trajectory (SRT). The TRT is the time required to restore the network to its pre-hazard level of functionality, while the SRT is a metric established for the first time in this study to capture the characteristics of the recovery path that are linked to the efficiency of those strategies considered for restoration. A sensitivity study using this network illustrates the impact on the network recovery time and trajectory of a community's resourcefulness and its time-dependent resource commitment. A restore scheduling method for optimal post-disaster recovery planning for bridge-road transport networks is proposed based on this two-dimensional metric. A genetic algorithm is used to solve the problem of restore schedule optimization for a hypothetical bridge network with 30 nodes and 37 bridges subjected to a seismic scenario case to explain the suggested technique (Weili Zhang 2017).

Tao et al. described that bridge quality can deteriorate due to aging, traffic-induced fatigue, and environmental corrosion throughout their lifetime. Structural instability in earthquake-prone areas raises bridge seismic vulnerability, which means an increase in potential future economic and social losses. Therefore, determining the optimum maintenance strategies with regard to bridge deterioration is of critical importance. To this end, the present paper proposes an infinite-horizon hybrid Markov decision process model in which both the occurrence of earthquake and structural deterioration processes are integrated into a unified Markovian framework. A Markov chain is modeled on the structural deterioration process and a simplified earthquake-induced probability transition matrix is adopted. The proposed model is applied to a simple case study for demonstration purposes (Tao 2019).

Pritchard (2013) identified a range of issues that have been encountered as a result of the floods and cyclone events from 2011 to 2012 in Queensland, Australia. These included timber bridge destructions, pier settlement, abutment scouring, and the loss of road approaches to bridges. The AS 5100 Bridge Design Code is assumed to have been written primarily for traditional rural applications. In addition, this paper discusses the specific loads to which urban bridges are subject, including floating debris such as shipping containers, vehicles and rivercraft (e.g., 300 t vessels) to be included in future revisions of AS 5100. Bridge design codes were suggested to consider the context and location of bridges for accessibility and usability after catastrophe in the future. It is recommended that such training be considered and implemented in accordance with suggested changes to the AS 5100 Bridge Design Code for new bridges and remedial works (Pritchard 2013).

All the reviewed papers are associated with the resiliency of bridge network, which are providing meaningful insights for both response and recovery phases of a disaster. Single hazard and multi-hazard resiliency assessment for highway bridge network highlighted the importance of bridge maintenance work. For cable stayed bridges, a robustness index and general procedures are developed to measure durability during an earthquake event. Markovian framework is proposed for optimum maintenance of deteriorating bridges and a multi-criteria intervention optimization process is formulated for restoration of bridge networks in earthquake-prone areas. Besides, an evaluation of new building materials for its restoration is discussed for the Plaka bridge in Epirus. A framework for vulnerability bridge modeling for an extreme flood is proposed, consisting of a combination of the defect tree structure description and the harm list. As consequences for flood and cyclone events, timber bridge destruction, pier settlement, abutment scouring, and the loss of road approaches to bridges are identified. Then, a new scheduling methodology is introduced to restore damaged bridges to optimize bridge restoration sequence for resilient transportation networks. Two metrics are proposed to calculate network recovery speed and efficiency: total recovery time (TRT) and the skew of the recovery trajectory (SRT). These important metrics can influence the criterions for planning, evaluation and rebuilding guidelines of bridge network.

4.2 Review of Network Science Literature

Many new network concepts, properties and measures have been developed by running experiments on large-scale real networks. Several statistical properties and unifying principles of real networks have been identified from these studies. Significant amount of research efforts have helped to develop new network modeling tools, reproduce the structural properties observed from empirical network data, and design such networks efficiently with a view to obtaining more advanced knowledge of the evolutionary mechanisms of network growth (Hasan and Ukkusuri

2011). Many real networks possess interesting properties unlike random graphs indicative of possible mechanisms guiding network formation and ways to exploit network structure with specific objectives (Newman 2003). Some of these properties, common across many real networks, are described below:

Small-world Property

This property refers to the existence of relatively short paths between any pair of nodes in most networks despite their large size. The existence of this property is evident in many real networks (Milgram 1967, Travers and Milgram 1969, Watts and Strogatz 1998). The small-world effect has important implications in explaining dynamics of processes occurring on real networks. In case of spreading information or ideas through a network, the small-world property suggests that the propagation will be faster on most real world networks because of short average path lengths (Newman 2003). Three important measures to explain this property are eccentricity, radius and diameter. While the eccentricity of a node in a graph is the maximum distance (number of steps or hops) from that node to all other nodes; radius and diameter are the minimum and maximum eccentricity observed among all nodes, respectively.

Degree Distributions

The degree of a node (k) is the number of direct links to other nodes in a graph. The degree distribution $P(k)$ in real networks (probability that a randomly chosen node has degree k, issignificantly different from the Poisson distribution, typically assumed in the modeling of random graphs. In fact, real networks exhibit a power law (or scale-free) degree distribution characterized by higher densities of triangles (cliques in a social network, for example) (Barabási and Albert 1999). In addition, many real networks also exhibit significant correlations in terms of node degrees or attributes. This scale-free property validates the existence of hubs, or a few nodes that are highly connected to other nodes in the network. The presence of large hubs results in a degree distribution with long tail (highly right-skewed), indicating the presence of nodes with a much higher degree than most other nodes. For an undirected network, the degree distribution $P_{degree}(k)$ can be written as follows:

$$P_{degree}(k) \propto \; k^{-\gamma} \tag{1}$$

where γ is some exponent and $P_{degree}(k)$ decays slowly as the degree k increases, increasing the probability of obtaining a node with a very high degree. Networks with power-law distributions are called scale-free networks (Albert and Barabási 2002) that holds the same functional form (power laws) at all scales. The power law $P_{degree}(k)$ remains unchanged (other than a multiplicative factor) when rescaling the independent variable k by satisfying:

$$P_{degree}(xk) = \; x^{-\gamma}\, P_{degree}(k) \tag{2}$$

The presence of hubs that are orders of magnitude larger in degree than most other nodes is a characteristic of power law networks. In this study, we test the scale free property both for the activity frequency of all active nodes and the degree distribution of subgraphs being active at different activity levels.

Transitivity

This property is a distinctive deviation from the properties of random graphs. Network transitivity implies that two nodes are highly likely to be connected in a network, given each of the nodes are connected to some other node. This is indicative of heightened number of triangles that exist in real networks (sets of three nodes each of which is connected to each of the others) (Newman 2003). The existence of triangles can be quantified by *Clustering Coefficient. C:*

$$C = \frac{3 * Number\ of\ triangles\ in\ the\ network}{Number\ of\ connected\ triples\ of\ nodes} \quad (3)$$

A *connected triple* refers to a single node with links running to an unordered pair of others. In case of social networks, transitivity refers to the fact that the friend of one's friend is likely also to be the friend of that person. Another important notion is *Network Density*, frequently used in the sociological literature (Scott 2012). The density is 0 for a graph without any link between nodes and 1 for a completely connected graph.

Network Resilience

This property, related to degree distributions, refers to the resilience of networks as a result of removing random nodes in the network and the level of resilience to such vertex removal varies across networks depending on the network topology (Newman 2003). Networks in which most of the nodes have low degree have less disruption since these nodes lie on few paths between others; whereas removal of high degree nodes in a large real network can result in major disruption. The usual length of these paths will increase if nodes are removed from a network, resulting in disconnected pairs of nodes and making it more difficult for network agents to communicate.

Node-level Properties

Node Degree

The node degree is the number of edges adjacent to that node (deg_i). In-degree is the number of edges pointing in to the node (in_deg_i) and out-degree is the number of edges pointing out of the node (out_deg_i). Average neighbor degree refers average degree of the neighborhood ($z_{n,i}$) of each node i is:

$$z_{n,i} = \frac{1}{|N_i|} \sum_{j \in N_i} z_j \quad (4)$$

where, $N(i)$ are the neighbors of node i ; z_j is the degree of node j that belongs to N_i. In case of weighted graphs, weighted degree of each node can be used (Barrat, Barthelemy et al. 2004).

Clustering Coefficient

In case of an unweighted graph, the clustering coefficient (cc_i) of a node i refers to the fraction of possible triangles that exist through that node:

$$cc_i = \frac{2\,T_i}{deg_i * [deg_i - 1]} \quad (5)$$

where, T_i is the number of triangles that exist through node i and deg_i is the degree of node i. In case of weighted graphs, this clustering coefficient can be defined as the geometric average of the sub-graph edge weights (Saramäki, Kivelä et al. 2007). The eccentricity of node i is the maximum distance from node i to every other nodes in the graph G (ecc_i).

Betweenness Centrality

Out of a number centrality measures, betweenness centrality (BC_i) of node i is the sum of the fraction of all-pairs of shortest path that pass-through node i:

$$BC_i = \sum_{x,y \in V} \frac{\theta_{(x,y \mid j)}}{\theta_{(x,y)}} \tag{6}$$

where, V is the set of nodes in G, $\theta_{(x,y)}$ is the number of shortest (x, y) paths, and $\theta_{(x,y \mid j)}$ is the number of paths that pass through some node j other than (x, y). Please refer to (Brandes 2001, Brandes and Pich 2007, Brandes 2008) for more details.

Closeness Centrality

The closeness centrality (CC_i) of node i is the reciprocal of the sum of the shortest path distances from node i to all $(n-1)$ other nodes in the graph G:

$$CC_i = \frac{n-1}{\sum_{j=1}^{n-1} \theta_{(j,i)}} \tag{7}$$

where, $\theta_{(j,i)}$ is the shortest path distance between node j and node i and n is the number of total nodes in graph G. Closeness is normalized by the sum of minimum possible distances of $(n-1)$ since the sum of the distances depend on the number of nodes in the graph. Higher values of closeness imply higher centrality. Please refer to (Freeman 1978) for details.

Eigenvector Centrality

The eigenvector centrality (EC_i) computes the centrality for a node i based on the centrality of its neighbors. The eigenvector centrality for node i is:

$$A\, x = \lambda\, x \tag{8}$$

where A is the adjacency matrix of the graph G with eigenvalue λ. Perron–Frobenius theorem suggests that there is a unique and positive solution if λ is the largest eigenvalue associated with the eigenvector of the adjacency matrix A (Bonacich 1987, Newman 2010). Finally, degree centrality for a node is just the fraction of nodes it is connected to.

Other Network Properties

Some other common properties are observed in many real networks such as mixing patterns (selective linking), network homophily or similarity, degree correlations, preferential attachment, community structure, network navigation, size of giant components among others (Newman 2003).

Edge-level Properties

Edge Betweenness Centrality

Compute betweenness centrality for edges. Betweenness centrality of an edge e is the sum of the fraction of all-pairs shortest paths that pass through e:

$$c_B(e) = \sum_{s,t \in V} \frac{\sigma(s, t|e)}{\sigma(s, t)}$$

where V is the set of nodes, \`sigma(s, t)\` is the number of shortest (s, t)-paths, and $\sigma(s, t|e)$ is the number of those paths passing through edge e (Brandes 2008)

Edge Current-flow Betweenness Centrality

Compute current-flow betweenness centrality for edges. Current-flow betweenness centrality uses an electrical current model for information spreading in contrast to betweenness centrality which uses shortest paths. Current-flow betweenness centrality is also known as random-walk betweenness centrality (M. E. J. Newman 2005)

Edge Load Centrality

Compute load centrality for edges. The load centrality of a node is the fraction of all shortest paths that pass through that edge.

Task 2 – Obtain Accurate FDOT Road and Bridge Network Data

4.3 What is GIS Modeling?

Geographic Information System (GIS) is a software designed to capture, store, manipulate, analyze, manage, and present spatial or geographic data. It can convert statistical data, such as accident and geographic (road and bridge locations) data into meaningful information for spatial analysis and mapping (Ziari 2005). The GIS data model is a mathematical construct for the representation of geographic objects or surfaces as data. For example, the vector data model represents geography as a collection of dots, lines and polygons; the raster data model represents geography as a cell matrix that stores numeric values; and the TIN data model represents geography as a set of contiguous, non-overlapping triangles (Wade 2006). There is several software to perform GIS modeling, such as QGIS, ArcGIS among others. QGIS is a professional GIS application that is built as an open source software and supports numerous vector, raster, and database formats and functionalities (QGIS 2020). Besides, ArcGIS offers unique capabilities and flexible licensing for applying spatial analytics to gain greater insights using contextual tools to visualize and analyze big data by collaborating and sharing maps, apps, dashboards and reports (ArcGIS 2020). A data model in ArcGIS defines the thematic layers used in the applications (e.g. food court stands, highways, and counties); their spatial representation (e.g. point, line, or polygon); their attributes; their rules of fairness and relationships (e.g. counties must nest inside states); their cartographic representation; and their metadata specifications (Wade 2006). The data models are stored in a shape file format, which is compatible with all GIS software. In this report, the road shape file and the bridge location shape file of Miami-Dade County will be modeled to perform the combined road-bridge network analysis.

4.4 Challenges in GIS Modeling

Increasingly, GIS is used in many disciplines to provide valuable insights into problems from estimating the shortest path of a specific origin-destination to identifying the most influential link of the road network. GIS software helps professionals make better use of GIS modeling when evaluating locations or analyzing movement. Location analysis focuses on the common analysis of suitability, used to address questions such as where the next store will be located, as well as inadequacy analysis— analysis that determines places to be avoided as they have greater potential for danger from threats such as flooding or fire. Study of movement involves not only humans or animals, which requires a certain degree of decision-making, but also the movement of objects such as water, which follows the path of least resistance. In either case, travel is modeled as a cost surface and the analysis determines the least cost path, whether in terms of energy, time, distance or some other metric. The analytical method is complicated since the questions posed are of a subjective nature. It includes the concept of what the correct site is or which metric is most suitable for cost calculation. Such decisions may be based on the modeler's own professional knowledge of a particular topic, criteria or published work in that discipline, or on a consensus of experts in the area (Mitchell 2012).

Tansel et al. utilized ArcGIS to develop and visualize an integrated network methodology to identify the possible interactions between transportation infrastructure systems and pipeline systems for water and sewer services (Tansel 2014). The researchers reported that about 3.15 square miles in downtown Miami is considered vulnerable for service interruptions which will affect traffic flow significantly. Ziari and Khabiri developed a GIS model that generates contour maps and identifies hot spots of pedestrians and bicyclists crash occurrence. The study presents the development and findings of police reporting crash data and how they are used in the Geographic Information System (GIS). Authors analyzed the crash information in towns, provinces started with the Inner Ministry Traffic Organization considering access controls on functionally categorized roads. Safety is prioritized here as a driving factor in the management of access and crash reports are considered as the best indicator of the lack of safe routes (Ziari 2005).

4.5 Steps Involved in Obtaining Shape files

In this project, the Florida road and bridge network shape files are obtained from Florida Department of Transportation (FDOT) websites' Transportation Data and Analytics/GIS section (Figure 3). For the Florida road shape file, Florida Traffic Online is considered as the source of road shape file (FDOT 2019).

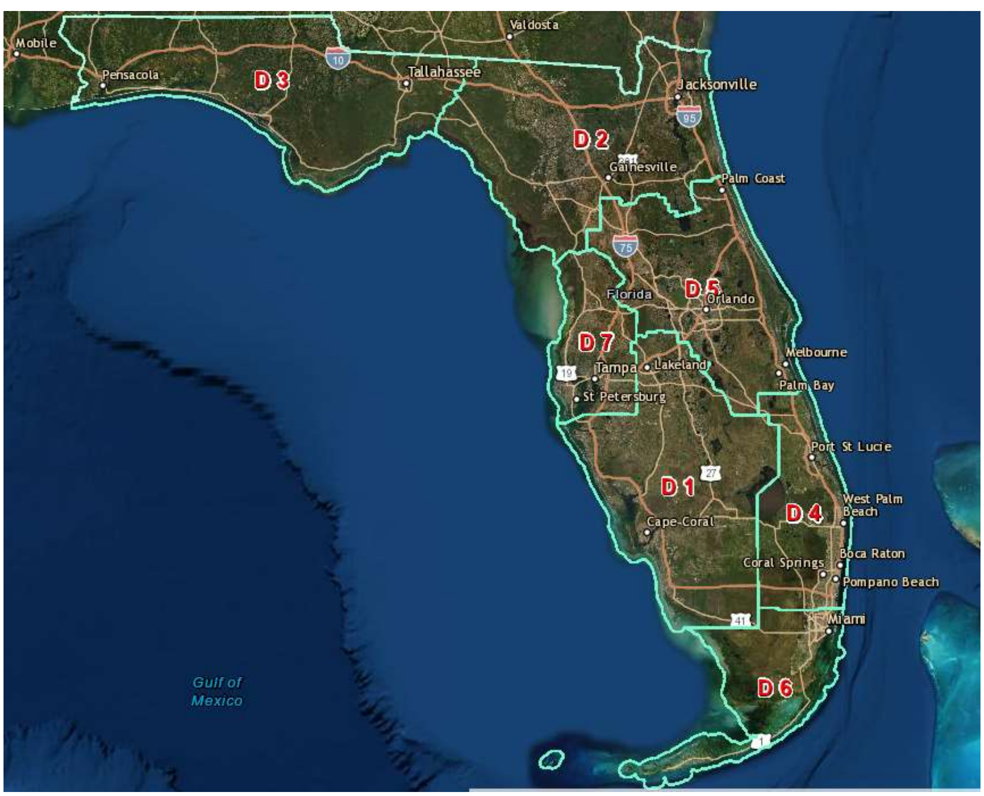


Figure 2 Florida Traffic Online- Source of Florida Road Network Shape File

Besides, the Florida bridge location shape file (Bridges) is obtained from the following FDOT website. Another road shape file (Roads with Local Names) for the Florida state can also be found in the same website which is used to match the roads and bridges name. Both the bridges and road shape files are marked with red box in Figure 4 (FDOT-GIS 2017).

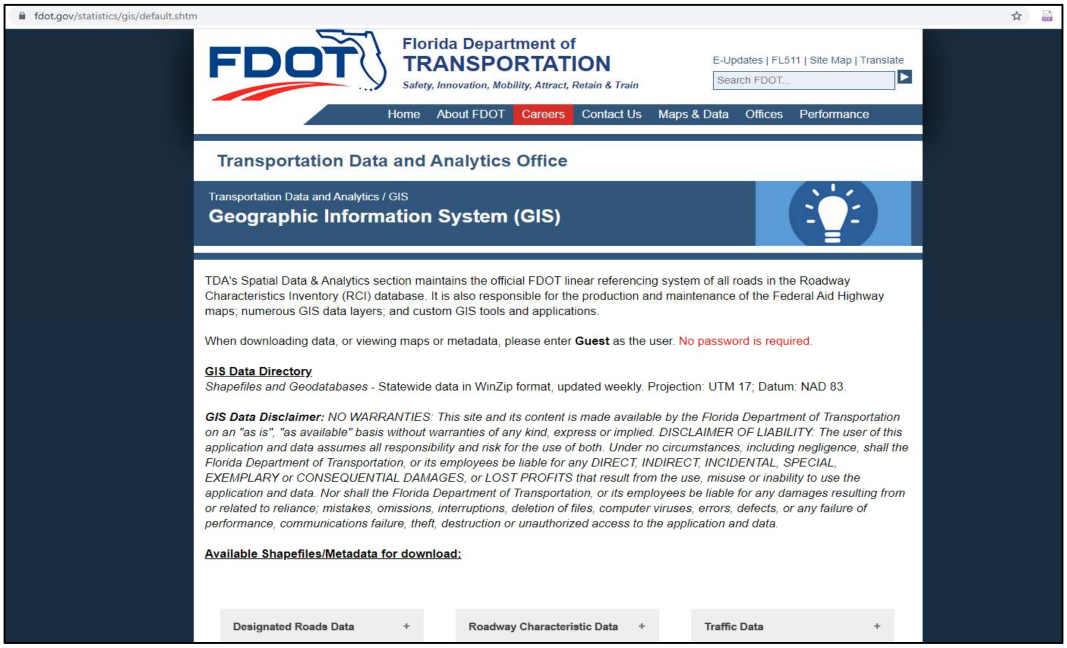


Figure 3 FDOT Transportation Data and Analytics/GIS Section

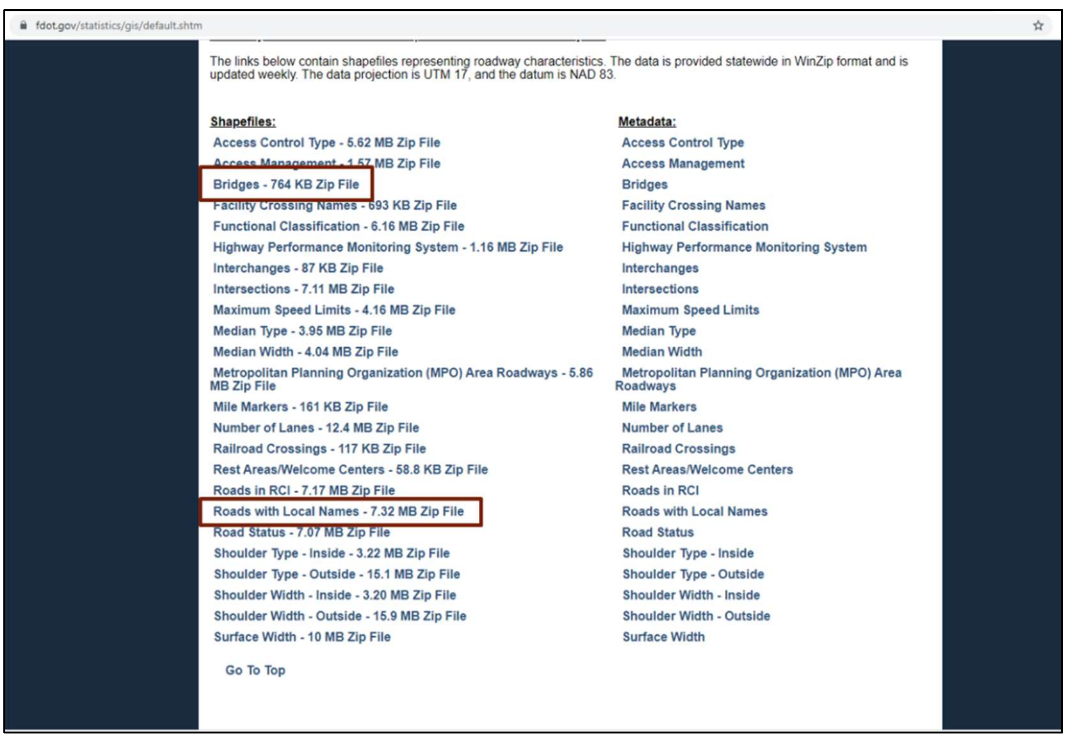


Figure 4 FDOT Transportation Data and Analytics/GIS Section *(*Florida Bridge Shape file)

4.6 Steps Involved in Converting Shape Files to Network Readable Files

The shapefile is converted to network readable file by using a library of python programming language named NetworkX. NetworkX is a python package for the creation, manipulation, and study of the structure, dynamics, and functions of complex networks (NetworkX 2019).
The key steps involved in converting shape files to network readable file are summarized below-

- At first, the road and bridge shape files of the State of Florida are superimposed to create the combined road-bridge network shape file.
- Then, python programming language is used to convert the shape file to network readable file for network analysis.
- NetworkX library in python language is used to convert the shape files.
- NetworkX library converts the geolocation information of the road-bridge network shapefile to a network graph, which contains the roads starting and end point information by specific labelling.
- This network graph is internally created within the python code; it is not necessary to import the network graph as NetworkX library can directly analyze the graph.

Task 3 – Identify the Scale and Scope of the Bridge Network to be Inspected

4.7 Data Description

The shape file for the road network of Florida consists of all the freeways, highways and state roads of the state. Besides, the Florida bridge location shape file covers all the bridges on these highways, state roads and local roads. The scaling of the road-bridge network analysis with these shape files will be done in four steps as following order-

1. Key West road-bridge network
2. Miami Beach bridge network
3. Miami-Dade County bridge network
4. State of Florida bridge network

Florida Road Network Shape file

The Florida road network shape file is a polyline shape file and contains very useful and authentic information about the roadways of the whole State of Florida. All the information is stored in a database which is accessible through the Attribute Table. From the Figure 5, it can be observed that the roadway names are available according to the road location and local place. Besides, the roadway numbers, assigned by FDOT are also available along with the county name, ZIP code and roadway direction (eastbound, westbound, southbound and northbound).

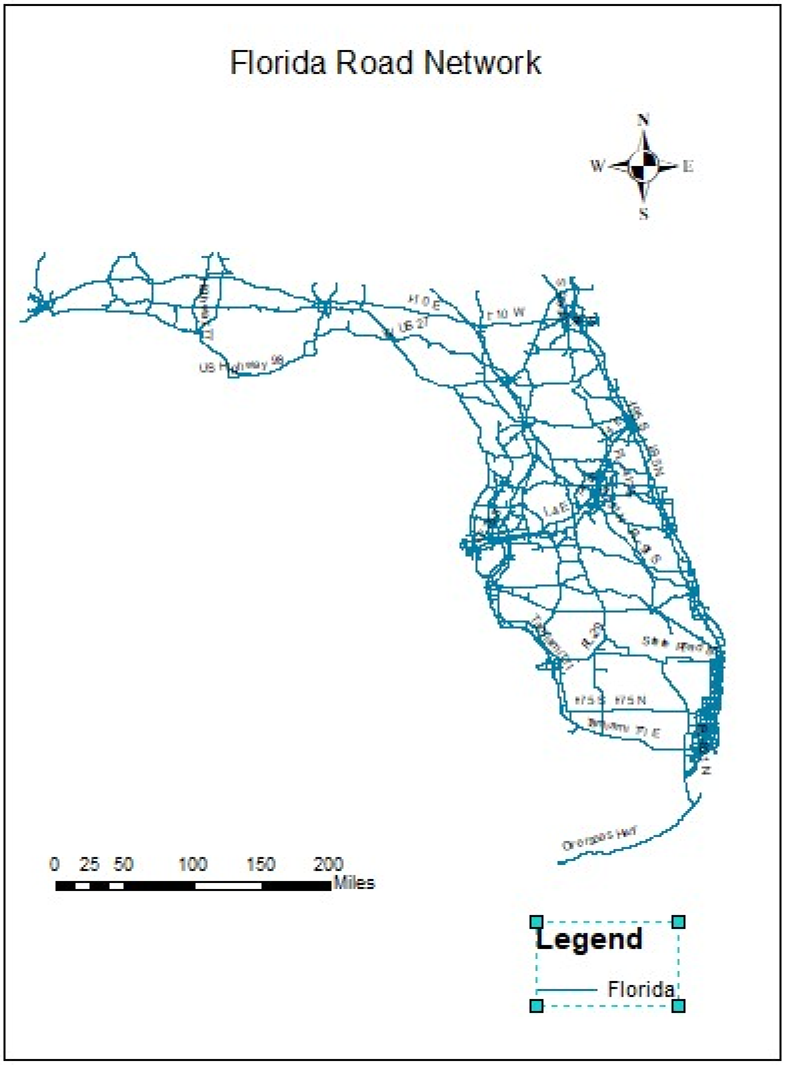
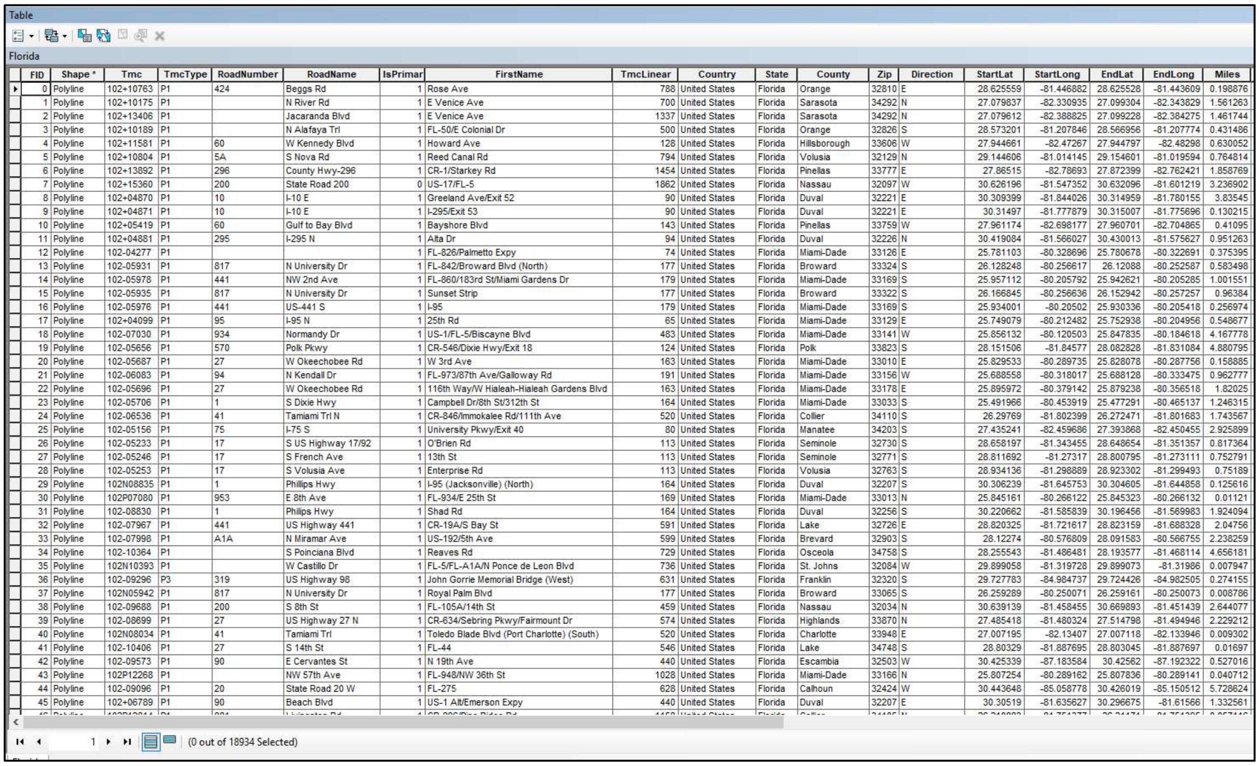


Figure 5 Florida Road Network

The most important information for the road and bridge network analysis is the specific geolocations (coordinates) of the starting point and end point of each roadway segment, which is available with the length of these segments. From the attribute tables (Figure 6 and Figure 7), it is found that there are approximately 18,550 roadway segment and 15,550 roadway segment intersection information are existing in the shape file. Then, the route number (for an example the name of the 8th street is US 41 according to the route number), number of lanes and Average Annual Daily Traffic (AADT) counts are also obtainable from the attribute tables of the shape file.



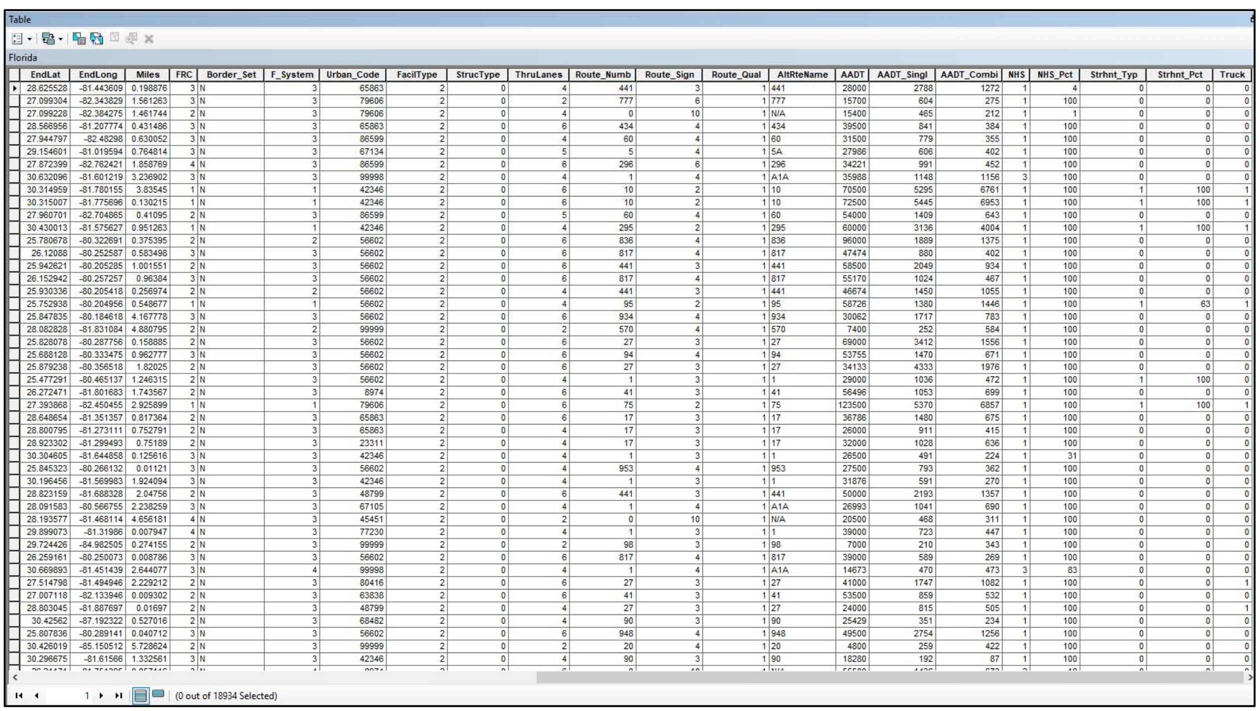
Table

Florida

FID	Shape *	Tmc	TmcType	RoadNumber	RoadName	IsPrimar	FirstName	TmcLinear	Country	State	County	Zip	Direction	StartLat	StartLong	EndLat	EndLong	Miles
0	Polyline	102+10763	P1	424	Beggs Rd	1	Rose Ave	788	United States	Florida	Orange	32810	E	28.625559	-81.446882	28.625528	-81.443609	0.198876
1	Polyline	102+10175	P1		N River Rd	1	E Venice Ave	700	United States	Florida	Sarasota	34292	N	27.079837	-82.330935	27.099304	-82.343829	1.561263
2	Polyline	102+13406	P1		Jacaranda Blvd	1	E Venice Ave	1337	United States	Florida	Sarasota	34292	N	27.079612	-82.388825	27.099228	-82.384275	1.461744
3	Polyline	102+10189	P1		N Alafaya Trl	1	FL-50/E Colonial Dr	500	United States	Florida	Orange	32826	S	28.573201	-81.207846	28.566956	-81.207774	0.431486
4	Polyline	102+11581	P1	60	W Kennedy Blvd	1	Howard Ave	128	United States	Florida	Hillsborough	33606	W	27.944661	-82.47267	27.944797	-82.48298	0.630052
5	Polyline	102+10804	P1	5A	S Nova Rd	1	Reed Canal Rd	794	United States	Florida	Volusia	32129	N	29.144606	-81.014145	29.154601	-81.019594	0.764814
6	Polyline	102+13892	P1	296	County Hwy-296	1	CR-1/Starkey Rd	1454	United States	Florida	Pinellas	33777	E	27.86515	-82.78693	27.872399	-82.762421	1.858769
7	Polyline	102+15360	P1	200	State Road 200	0	US-17/FL-5	1862	United States	Florida	Nassau	32097	W	30.626196	-81.547352	30.632096	-81.601219	3.236902
8	Polyline	102+04870	P1	10	I-10 E	1	Greeland Ave/Exit 52	90	United States	Florida	Duval	32221	E	30.309399	-81.844026	30.314959	-81.780155	3.83545
9	Polyline	102+04871	P1	10	I-10 E	1	I-295/Exit 53	90	United States	Florida	Duval	32221	E	30.31497	-81.777879	30.315007	-81.775696	0.130215
10	Polyline	102+05419	P1	60	Gulf to Bay Blvd	1	Bayshore Blvd	143	United States	Florida	Pinellas	33759	W	27.961174	-82.698177	27.960701	-82.704865	0.41095
11	Polyline	102+04881	P1	295	I-295 N	1	Alta Dr	94	United States	Florida	Duval	32226	N	30.419084	-81.566027	30.430013	-81.575627	0.951263
12	Polyline	102-04277	P1			1	FL-826/Palmetto Expy	74	United States	Florida	Miami-Dade	33126	E	25.781103	-80.328696	25.780678	-80.322691	0.375395
13	Polyline	102-05931	P1	817	N University Dr	1	FL-842/Broward Blvd (North)	177	United States	Florida	Broward	33324	S	26.128248	-80.256617	26.12088	-80.252587	0.583498
14	Polyline	102-05978	P1	441	NW 2nd Ave	1	FL-860/183rd St/Miami Gardens Dr	179	United States	Florida	Miami-Dade	33169	S	25.957112	-80.205792	25.942621	-80.205285	1.001551
15	Polyline	102-05935	P1	817	N University Dr	1	Sunset Strip	177	United States	Florida	Broward	33322	S	26.166845	-80.256636	26.152942	-80.257257	0.96384
16	Polyline	102-05976	P1	441	US-441 S	1	I-95	179	United States	Florida	Miami-Dade	33169	S	25.934001	-80.20502	25.930336	-80.205418	0.256974
17	Polyline	102+04099	P1	95	I-95 N	1	25th Rd	65	United States	Florida	Miami-Dade	33129	E	25.749079	-80.212482	25.752938	-80.204956	0.548677
18	Polyline	102-07030	P1	934	Normandy Dr	1	US-1/FL-5/Biscayne Blvd	483	United States	Florida	Miami-Dade	33141	W	25.856132	-80.120503	25.847835	-80.184618	4.167778
19	Polyline	102-05656	P1	570	Polk Pkwy	1	CR-546/Dixie Hwy/Exit 18	124	United States	Florida	Polk	33823	S	28.151506	-81.84577	28.082828	-81.831084	4.880795
20	Polyline	102-05687	P1	27	W Okeechobee Rd	1	W 3rd Ave	163	United States	Florida	Miami-Dade	33010	E	25.829533	-80.289735	25.828078	-80.287756	0.158885
21	Polyline	102-06083	P1	94	N Kendall Dr	1	FL-973/87th Ave/Galloway Rd	191	United States	Florida	Miami-Dade	33156	W	25.688558	-80.318017	25.688128	-80.333475	0.962777
22	Polyline	102-05696	P1	27	W Okeechobee Rd	1	116th Way/W Hialeah-Hialeah Gardens Blvd	163	United States	Florida	Miami-Dade	33178	E	25.895972	-80.379142	25.879238	-80.356518	1.82025
23	Polyline	102-05706	P1	1	S Dixie Hwy	1	Campbell Dr/8th St/312th St	164	United States	Florida	Miami-Dade	33033	S	25.491966	-80.453919	25.477291	-80.465137	1.246315
24	Polyline	102-06536	P1	41	Tamiami Trl N	1	CR-846/Immokalee Rd/111th Ave	520	United States	Florida	Collier	34110	S	26.29769	-81.802399	26.272471	-81.801683	1.743567
25	Polyline	102-05156	P1	75	I-75 S	1	University Pkwy/Exit 40	80	United States	Florida	Manatee	34203	S	27.435241	-82.459686	27.393868	-82.450455	2.925899
26	Polyline	102-05233	P1	17	S US Highway 17/92	1	O'Brien Rd	113	United States	Florida	Seminole	32730	S	28.658197	-81.343455	28.648654	-81.351357	0.817364
27	Polyline	102-05246	P1	17	S French Ave	1	13th St	113	United States	Florida	Seminole	32771	S	28.811692	-81.27317	28.800795	-81.273111	0.752791
28	Polyline	102-05253	P1	17	S Volusia Ave	1	Enterprise Rd	113	United States	Florida	Volusia	32763	S	28.934136	-81.298889	28.923302	-81.299493	0.75189
29	Polyline	102N08835	P1	1	Phillips Hwy	1	I-95 (Jacksonville) (North)	164	United States	Florida	Duval	32207	S	30.306239	-81.645753	30.304605	-81.644858	0.125616
30	Polyline	102P07080	P1	953	E 8th Ave	1	FL-934/E 25th St	169	United States	Florida	Miami-Dade	33013	N	25.845161	-80.266122	25.845323	-80.266132	0.01121
31	Polyline	102-08830	P1	1	Philips Hwy	1	Shad Rd	164	United States	Florida	Duval	32256	S	30.220662	-81.585839	30.196456	-81.569983	1.924094
32	Polyline	102-07967	P1	441	US Highway 441	1	CR-19A/S Bay St	591	United States	Florida	Lake	32726	E	28.820325	-81.721617	28.823159	-81.688328	2.04756
33	Polyline	102-07998	P1	A1A	N Miramar Ave	1	US-192/5th Ave	599	United States	Florida	Brevard	32903	S	28.12274	-80.576809	28.091583	-80.566755	2.238259
34	Polyline	102-10364	P1		S Poinciana Blvd	1	Reaves Rd	729	United States	Florida	Osceola	34758	S	28.255543	-81.486481	28.193577	-81.468114	4.656181
35	Polyline	102N10393	P1		W Castillo Dr	1	FL-5/FL-A1A/N Ponce de Leon Blvd	736	United States	Florida	St. Johns	32084	W	29.899058	-81.319728	29.899073	-81.31986	0.007947
36	Polyline	102-09296	P3	319	US Highway 98	1	John Gorrie Memorial Bridge (West)	631	United States	Florida	Franklin	32320	S	29.727783	-84.984737	29.724426	-84.982505	0.274155
37	Polyline	102N05942	P1	817	N University Dr	1	Royal Palm Blvd	177	United States	Florida	Broward	33065	S	26.259289	-80.250071	26.259161	-80.250073	0.008786
38	Polyline	102-09688	P1	200	S 8th St	1	FL-105A/14th St	459	United States	Florida	Nassau	32034	N	30.639139	-81.458455	30.669893	-81.451439	2.644077
39	Polyline	102-08699	P1	27	US Highway 27 N	1	CR-634/Sebring Pkwy/Fairmount Dr	574	United States	Florida	Highlands	33870	N	27.485418	-81.480324	27.514798	-81.494946	2.229212
40	Polyline	102N08034	P1	41	Tamiami Trl	1	Toledo Blade Blvd (Port Charlotte) (South)	520	United States	Florida	Charlotte	33948	E	27.007195	-82.13407	27.007118	-82.133946	0.009302
41	Polyline	102-10406	P1	27	S 14th St	1	FL-44	546	United States	Florida	Lake	34748	S	28.80329	-81.887695	28.803045	-81.887697	0.01697
42	Polyline	102-09573	P1	90	E Cervantes St	1	N 19th Ave	440	United States	Florida	Escambia	32503	W	30.425339	-87.183584	30.42562	-87.192322	0.527016
43	Polyline	102P12268	P1		NW 57th Ave	1	FL-948/NW 36th St	1028	United States	Florida	Miami-Dade	33166	N	25.807254	-80.289162	25.807836	-80.289141	0.040712
44	Polyline	102-09096	P1	20	State Road 20 W	1	FL-275	628	United States	Florida	Calhoun	32424	W	30.443648	-85.058778	30.426019	-85.150512	5.728624
45	Polyline	102+06789	P1	90	Beach Blvd	1	US-1 Alt/Emerson Expy	440	United States	Florida	Duval	32207	E	30.30519	-81.635627	30.296675	-81.61566	1.332561

1 (0 out of 18934 Selected)

Figure 6 Attribute Table (information from the shape file) of Florida Road Network



Table

Florida

EndLat	EndLong	Miles	FRC	Border_Set	F_System	Urban_Code	FacilType	StrucType	ThruLanes	Route_Numb	Route_Sign	Route_Qual	AltRteName	AADT	AADT_Singl	AADT_Combi	NHS	NHS_Pct	Strhnt_Typ	Strhnt_Pct	Truck
28.625528	-81.443609	0.198876	3	N	3	65863	2	0	4	441	3	1	441	28000	2788	1272	1	4	0	0	0
27.099304	-82.343829	1.561263	3	N	3	79606	2	0	2	777	6	1	777	15700	604	275	1	100	0	0	0
27.099228	-82.384275	1.461744	2	N	3	79606	2	0	4	0	10	1	N/A	15400	465	212	1	1	0	0	0
28.566956	-81.207774	0.431486	3	N	3	65863	2	0	6	434	4	1	434	39500	841	384	1	100	0	0	0
27.944797	-82.48298	0.630052	3	N	3	86599	2	0	4	60	4	1	60	31500	779	355	1	100	0	0	0
29.154601	-81.019594	0.764814	3	N	3	67134	2	0	5	5	4	1	5A	27986	606	402	1	100	0	0	0
27.872399	-82.762421	1.858769	4	N	3	86599	2	0	6	296	6	1	296	34221	991	452	1	100	0	0	0
30.632096	-81.601219	3.236902	3	N	3	99998	2	0	4	1	4	1	A1A	35988	1148	1156	3	100	0	0	0
30.314959	-81.780155	3.83545	1	N	1	42346	2	0	6	10	2	1	10	70500	5295	6761	1	100	1	100	1
30.315007	-81.775696	0.130215	1	N	1	42346	2	0	6	10	2	1	10	72500	5445	6953	1	100	1	100	1
27.960701	-82.704865	0.41095	2	N	3	86599	2	0	5	60	4	1	60	54000	1409	643	1	100	0	0	0
30.430013	-81.575627	0.951263	1	N	1	42346	2	0	4	295	2	1	295	60000	3136	4004	1	100	1	100	1
25.780678	-80.322691	0.375395	2	N	2	56602	2	0	6	836	4	1	836	96000	1889	1375	1	100	0	0	0
26.12088	-80.252587	0.583498	3	N	3	56602	2	0	6	817	4	1	817	47474	880	402	1	100	0	0	0
25.942621	-80.205285	1.001551	2	N	3	56602	2	0	6	441	3	1	441	58500	2049	934	1	100	0	0	0
26.152942	-80.257257	0.96384	3	N	3	56602	2	0	6	817	4	1	817	55170	1024	467	1	100	0	0	0
25.930336	-80.205418	0.256974	2	N	2	56602	2	0	4	441	3	1	441	46674	1450	1055	1	100	0	0	0
25.752938	-80.204956	0.548677	1	N	1	56602	2	0	4	95	2	1	95	58726	1380	1446	1	100	1	63	1
25.847835	-80.184618	4.167778	3	N	3	56602	2	0	6	934	4	1	934	30062	1717	783	1	100	0	0	0
28.082828	-81.831084	4.880795	2	N	2	99999	2	0	2	570	4	1	570	7400	252	584	1	100	0	0	0
25.828078	-80.287756	0.158885	2	N	3	56602	2	0	6	27	3	1	27	69000	3412	1556	1	100	0	0	0
25.688128	-80.333475	0.962777	3	N	3	56602	2	0	6	94	4	1	94	53755	1470	671	1	100	0	0	0
25.879238	-80.356518	1.82025	2	N	3	56602	2	0	6	27	3	1	27	34133	4333	1976	1	100	0	0	0
25.477291	-80.465137	1.246315	2	N	3	56602	2	0	4	1	3	1	1	29000	1036	472	1	100	1	100	0
26.272471	-81.801683	1.743567	2	N	3	8974	2	0	6	41	3	1	41	56496	1053	699	1	100	0	0	0
27.393868	-82.450455	2.925899	1	N	1	79606	2	0	6	75	2	1	75	123500	5370	6857	1	100	1	100	1
28.648654	-81.351357	0.817364	2	N	3	65863	2	0	6	17	3	1	17	36786	1480	675	1	100	0	0	0
28.800795	-81.273111	0.752791	2	N	3	65863	2	0	4	17	3	1	17	26000	911	415	1	100	0	0	0
28.923302	-81.299493	0.75189	2	N	3	23311	2	0	4	17	3	1	17	32000	1028	636	1	100	0	0	0
30.304605	-81.644858	0.125616	3	N	3	42346	2	0	4	1	3	1	1	26500	491	224	1	31	0	0	0
25.845323	-80.266132	0.01121	3	N	3	56602	2	0	4	953	4	1	953	27500	793	362	1	100	0	0	0
30.196456	-81.569983	1.924094	3	N	3	42346	2	0	4	1	3	1	1	31876	591	270	1	100	0	0	0
28.823159	-81.688328	2.04756	2	N	3	48799	2	0	6	441	3	1	441	50000	2193	1357	1	100	0	0	0
28.091583	-80.566755	2.238259	3	N	3	67105	2	0	4	1	4	1	A1A	26993	1041	690	1	100	0	0	0
28.193577	-81.468114	4.656181	4	N	3	45451	2	0	2	0	10	1	N/A	20500	468	311	1	100	0	0	0
29.899073	-81.31986	0.007947	4	N	3	77230	2	0	4	1	3	1	1	39000	723	447	1	100	0	0	0
29.724426	-84.982505	0.274155	2	N	3	99999	2	0	2	98	3	1	98	7000	210	343	1	100	0	0	0
26.259161	-80.250073	0.008786	3	N	3	56602	2	0	6	817	4	1	817	39000	589	269	1	100	0	0	0
30.669893	-81.451439	2.644077	3	N	4	99998	2	0	4	1	4	1	A1A	14673	470	473	3	83	0	0	0
27.514798	-81.494946	2.229212	2	N	3	80416	2	0	6	27	3	1	27	41000	1747	1082	1	100	0	0	1
27.007118	-82.133946	0.009302	2	N	3	63838	2	0	6	41	3	1	41	53500	859	532	1	100	0	0	0
28.803045	-81.887697	0.01697	2	N	3	48799	2	0	4	27	3	1	27	24000	815	505	1	100	0	0	1
30.42562	-87.192322	0.527016	2	N	3	68482	2	0	4	90	3	1	90	25429	351	234	1	100	0	0	0
25.807836	-80.289141	0.040712	3	N	3	56602	2	0	6	948	4	1	948	49500	2754	1256	1	100	0	0	0
30.426019	-85.150512	5.728624	2	N	3	99999	2	0	2	20	4	1	20	4800	259	422	1	100	0	0	0
30.296675	-81.61566	1.332561	3	N	3	42346	2	0	4	90	3	1	90	18280	192	87	1	100	0	0	0

1 (0 out of 18934 Selected)

Figure 7 Attribute Table (information from the shape file) of Florida Road Network

Florida Bridge Location Shape file

The bridge location shape file (Figure 8) for the State of Florida is also a polyline shape file which provides some essential information for the bridge network analysis. The attribute table (Figure 9) of the shape file consists of the specific roadway numbers, through which the bridges can be specified along with the roadways. Besides, the structure number of each bridges assigned by FDOT, information about FDOT districts, county names and the length of roadway segments are also available.

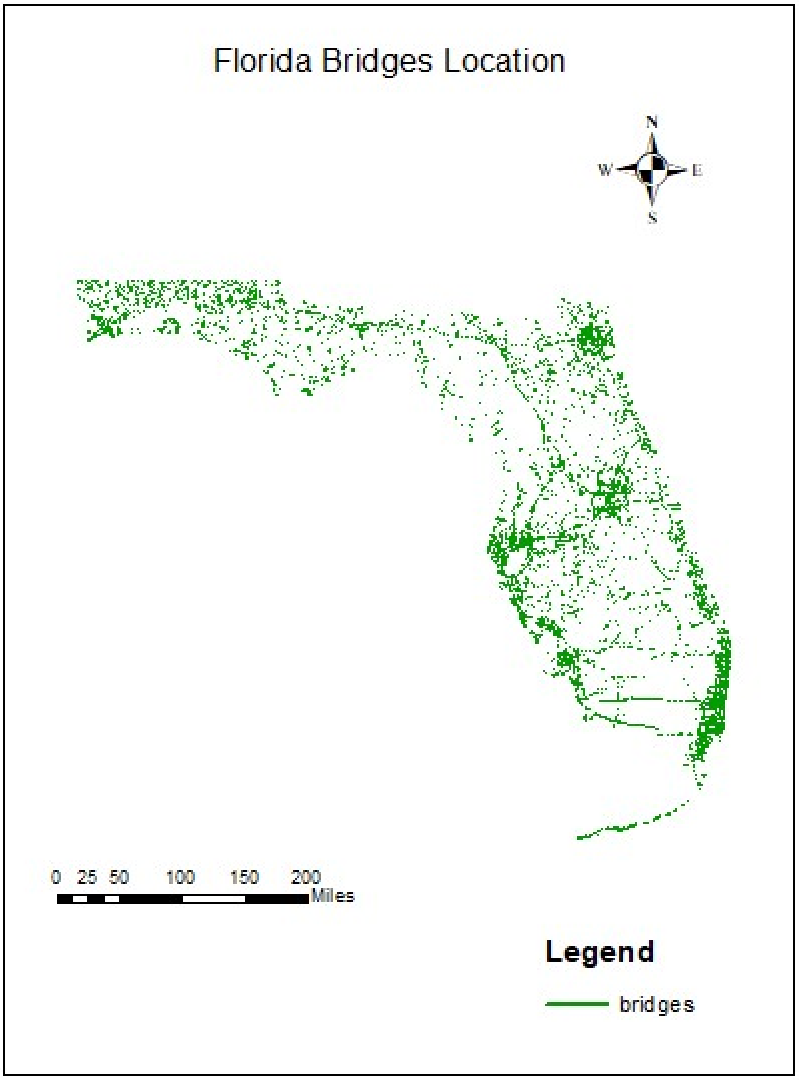


Figure 8 Florida Bridges Location

Table

bridges

FID	Shape *	ROADWAY	ROAD_SIDE	STRUCTURE_	DISTRICT	COUNTYDOT	COUNTY	MNG_DIST	BEGIN_POST	END_POST	Shape_Leng
0	Polyline	03020000	C	030136	1	03	Collier	1	0.477	0.484	11.1842
1	Polyline	94001000	R	940087	4	94	St. Lucie	4	24.107	24.16	85.3167
2	Polyline	87000068	C	874424	6	87	Miami-Dade	6	1.85	1.864	22.5843
3	Polyline	18000048	C	184109	5	18	Sumter	5	2.221	2.225	6.5039
4	Polyline	53000070	C	534164	3	53	Jackson	3	1.216	1.23	23.3464
5	Polyline	16580000	C	164176	1	16	Polk	1	9.168	9.172	6.4542
6	Polyline	52000012	C	524180	3	52	Holmes	3	0.935	0.954	30.6245
7	Polyline	75040002	L	754124	5	75	Orange	5	2.733	2.774	65.996
8	Polyline	57000030	C	574137	3	57	Okaloosa	3	3.613	3.626	20.9602
9	Polyline	94000008	C	944011	4	94	St. Lucie	4	1.399	1.453	87.1176
10	Polyline	03175000	L	030284	1	03	Collier	1	0.96	1.028	109.6008
11	Polyline	93862000	R	934946	4	93	Palm Beach	4	1.985	2.059	119.1984
12	Polyline	87075626	C	871111	6	87	Miami-Dade	6	0.326	0.388	99.6067
13	Polyline	15180503	C	157162	7	15	Pinellas	7	1.08	1.086	9.6514
14	Polyline	18000048	C	184069	5	18	Sumter	5	3.618	3.625	11.3017
15	Polyline	53002000	L	530055	3	53	Jackson	3	9.623	9.669	74.2365
16	Polyline	87000304	C	874440	6	87	Miami-Dade	6	1.258	1.266	12.8866
17	Polyline	87003000	R	870275	6	87	Miami-Dade	6	2.42	2.456	57.3882
18	Polyline	50001027	C	500075	3	50	Gadsden	3	0.399	0.434	58.7842
19	Polyline	87010000	C	871027	6	87	Miami-Dade	6	6.636	6.644	12.8657
20	Polyline	74030000	R	740029	2	74	Nassau	2	14.406	14.425	30.5766
21	Polyline	57000051	C	570802	3	57	Okaloosa	3	5.416	5.431	24.2487
22	Polyline	16000008	C	164344	1	16	Polk	1	8.357	8.361	6.4463
23	Polyline	87062000	C	870639	6	87	Miami-Dade	6	5.242	5.263	33.77
24	Polyline	75140000	R	750511	5	75	Orange	5	17.153	17.165	19.2351
25	Polyline	03000055	C	036001	1	03	Collier	1	2.69	2.716	41.7081
26	Polyline	74160000	C	740089	2	74	Nassau	2	11.989	12.226	380.9951
27	Polyline	52000016	C	524202	3	52	Holmes	3	1.18	1.188	12.8914
28	Polyline	16730500	C	164141	1	16	Polk	1	3.948	3.951	4.8118
29	Polyline	03175000	R	030239	1	03	Collier	1	27.05	27.072	35.4078
30	Polyline	87000081	C	874418	6	87	Miami-Dade	6	0.864	0.875	17.693
31	Polyline	87000021	C	874265	6	87	Miami-Dade	6	0.904	0.914	16.0279
32	Polyline	57000058	C	570811	3	57	Okaloosa	3	3.629	3.638	14.5629
33	Polyline	15190904	C	150182	7	15	Pinellas	7	0.296	0.338	67.6451
34	Polyline	94530000	C	940050	4	94	St. Lucie	4	6.337	6.369	51.4297
35	Polyline	87260475	C	871014	6	87	Miami-Dade	6	0.059	0.172	183.67
36	Polyline	75000230	C	750337	5	75	Orange	5	5.98	6.029	78.803
37	Polyline	87000157	C	876401	6	87	Miami-Dade	6	1.266	1.275	14.3736
38	Polyline	03175000	L	030028	1	03	Collier	1	5.9	5.93	48.2797

1 (0 out of 9768 Selected)

bridges

Figure 9 Attribute Table (information from the shape file) of Florida Bridge Location

4.8 Hypothetical Bridge Network Analysis

To understand the essence of bridge network analysis through different network parameters (degree, centrality) explained before, a hypothetical road-bridge network is considered here as shown in Figure 10. The road-bridge network is a 3x3 network with 9 nodes (roadway intersection), 12 links or roadways (L1-L12) and 4 bridges (B1-B4). The main objective of this sample analysis is to find the most influential bridge by analyzing node and link properties of this road network. The higher the values of node (degree) and link properties (edge betweenness centrality and edge current-flow betweenness centrality) of the bridge, the more influential it is for the whole network.

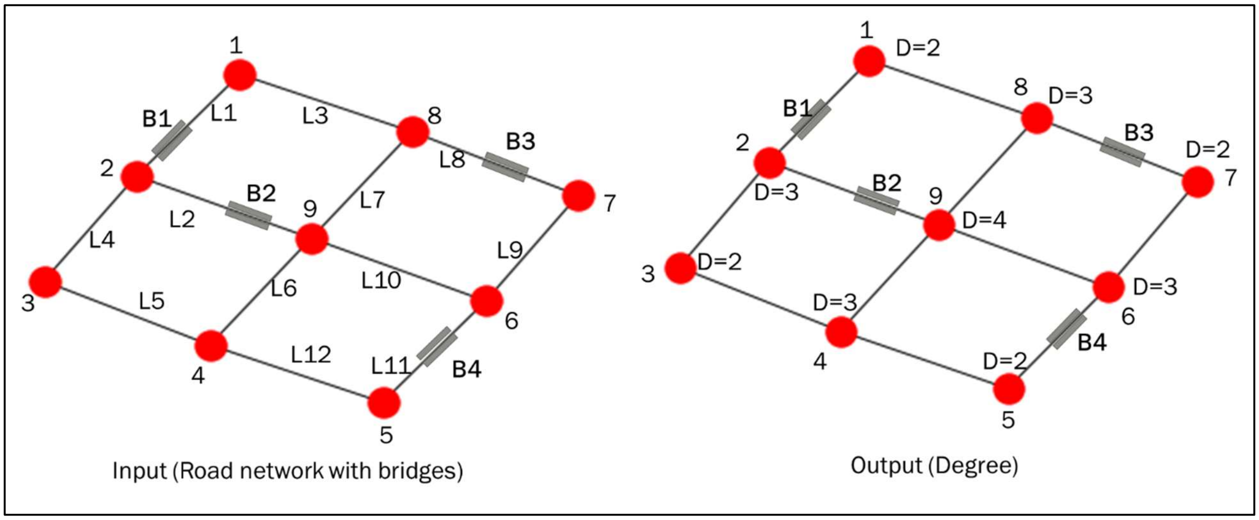


Figure 10 Hypothetical Bridge Network Analysis (Node Property)

The left road network of Figure 10 shows the position of the bridges along with the roads and intersections (nodes), which is considered as an input layer for the network analysis. The right figure shows the results for degree (no of roadway connections) of nodes which shows that node 9 possesses the highest degree value and it is connected with bridge B2 through link L2.

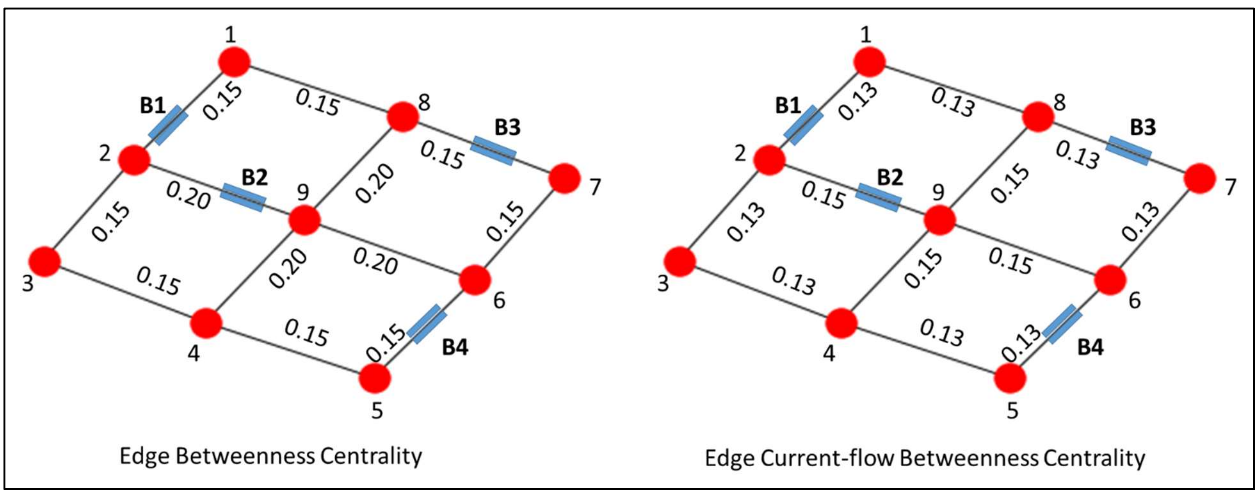


Figure 11 Hypothetical Bridge Network Analysis (Link Property)

From
Figure ***11***, the edge betweenness centrality (left network) and edge current-flow betweenness centrality (right network) results show that the link 2-9 (L2), where bridge B2 is situated has the highest values of 0.20 and 0.15 respectively. The results of the link property analysis are also listed in Table 1. These results indicate that the bridge B2 is the most influential bridge of the road network from network link property analysis, which is also true for network node property analysis as the bridge B2 is connected with the node of highest degree. Hence, it can be concluded that the bridge B2 is the most important bridge of this hypothetical road network.

Table 1 Results of Hypothetical Bridge Network Link Property Analysis

From Node	To Node	Bridge	Edge Betweenness Centrality (EBC)	Edge Current-flow Betweenness Centrality
1	2	B1	0.15	0.13
2	3		0.15	0.13
3	4		0.15	0.13
4	5		0.15	0.13
5	6	B4	0.15	0.13
6	7		0.15	0.13
7	8	B3	0.15	0.13
8	1		0.15	0.13
2	**9**	**B2**	**0.20**	**0.15**
4	9		0.20	0.15
6	9		0.20	0.15
8	9		0.20	0.15

Task 4 – Perform Road-Bridge Network Experiments and Analyses

The road-bridge network shape files used for the analyses have intermediate nodes (e.g., 2, 3; marked by red stripes) between the roadway intersections (e.g., 1, 4, 7; marked by red circle) as shown in Figure 12. The first reason of using these shape files is the data availability from the FDOT website and the second reason is that all the analyses are performed to identify the most central and vulnerable bridges, not roadways. As the bridges are not occupying the whole stretch of the roadway from one intersection to another, use of these type of shape files is ensuring more micro-level analysis for the bridge network.

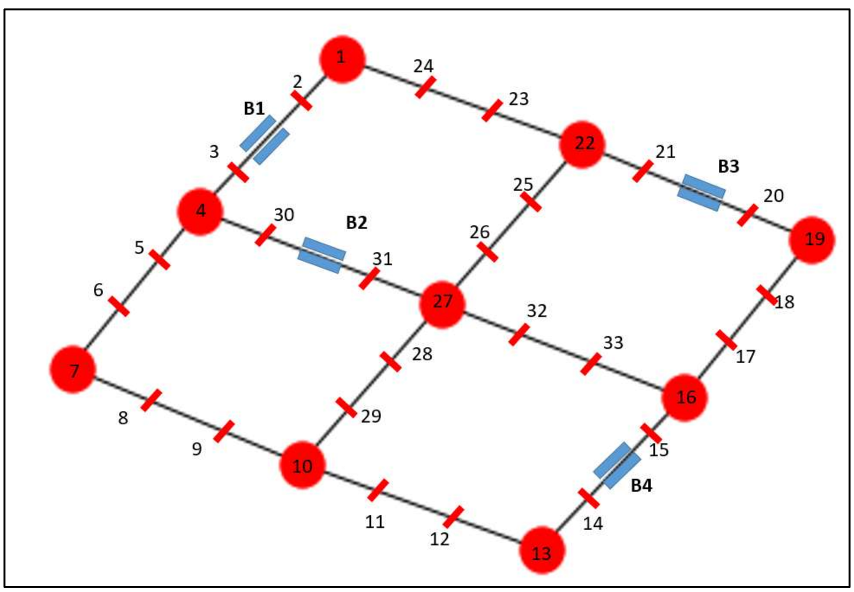


Figure 12 Hypothetical Representation of Road-Bridge (Shape file) Network Analysis

Besides, the centrality values of the bridges from Table 2 show that the bridge B2 is still the most central bridge with a minimal change in centrality value (EBC=0.1982) in compared with the value from Table 1 (EBC= 0.2).

Table 2 Results of Hypothetical Bridge Network (Shape file) Link Property Analysis

From Node	To Node	Bridge	Edge Betweenness Centrality
1	2		0.0960
1	24		0.0960
2	3	B1	0.1187
3	4		0.1452
4	5		0.1452
4	30		0.1755
5	6		0.1187
6	7		0.0960
7	8		0.0960
8	9		0.1187
9	10		0.1452
10	11		0.1452
10	29		0.1755
11	12		0.1187
12	13		0.0960
13	14		0.0960
14	15	B4	0.1187
15	16		0.1452
16	17		0.1452
16	33		0.1755
17	18		0.1187
18	19		0.0960
19	20		0.0960
20	21	B3	0.1187
21	22		0.1452
22	23		0.1452
22	25		0.1755
23	24		0.1187
25	26		0.1982
26	27		0.2247
27	28		0.2247
27	31		0.2247
27	32		0.2247
28	29		0.1982
30	**31**	**B2**	**0.1982**
32	33		0.1982

4.9 Key West Road-Bridge Network Analysis

Unweighted Analysis

Unweighted graph analysis only shows the effect of road-bridge network connectivity on different scale of the study area. As explained in previous section that the Florida road-bridge network is performed four scales, the Key West network is analyzed first. From key west road shape file, 50 roadway segments and 37 roadway segment intersection were found. After performing the Closeness Centrality analysis and mapping with bridges, 19 specific bridge location were found with centrality value.

Table 3 Closeness Centrality Values for Key West Road-bridge Network

Bridge Rank	Node Longitude	Node Latitude	Closeness Centrality	Roads	Bridges
1	-81.228329	24.6823346	0.118102797	Overseas Hwy	Overseas Hwy
2	-81.1246718	24.7068776	0.113471314	Overseas Hwy	Overseas Hwy
3	-81.6725094	24.5901406	0.107832988	Overseas Hwy	Overseas Hwy
4	-80.958729	24.756647	0.100353243	Overseas Hwy	Overseas Hwy
5	-81.6743332	24.589813	0.099206349	Overseas Hwy	Overseas Hwy
6	-81.047453	24.725695	0.099206349	Overseas Hwy	Overseas Hwy
7	-80.9235268	24.777144	0.092840166	Overseas Hwy	Overseas Hwy
8	-81.7427334	24.5729766	0.091857731	Overseas Hwy	Overseas Hwy
9	-81.047491	24.725827	0.089031339	Overseas Hwy	Overseas Hwy
10	-81.752044	24.5699624	0.088127468	Overseas Hwy	Overseas Hwy
11	-80.91951	24.7785898	0.085522715	Overseas Hwy	Overseas Hwy
12	-81.7432766	24.5728014	0.085522715	Overseas Hwy	Overseas Hwy
13	-81.7434696	24.5726258	0.082280147	Overseas Hwy	Overseas Hwy
14	-80.640942	24.9131724	0.078557064	Overseas Hwy	Overseas Hwy
15	-81.742596	24.572912	0.077160494	Overseas Hwy	Overseas Hwy
16	-81.6736356	24.5897558	0.072640632	Overseas Hwy	Overseas Hwy
17	-81.6733966	24.5897918	0.068620993	Overseas Hwy	Overseas Hwy
18	-80.374722	25.1707516	0.037037037	Overseas Hwy	Overseas Hwy
19	-80.3742914	25.17166	0.027777778	Overseas Hwy	Overseas Hwy

In Table 3, all the Key West bridge locations' Closeness Centrality values are orderly listed from highest to lowest. Then, the network analysis was performed for the link property by calculating Edge Betweenness Centrality. 25 roadway segments with bridges were found with centrality values after mapping with bridge shape file. In Table 4, all the Key West bridge segments Edge Betweenness Centrality values are orderly listed from highest to lowest.

Table 4 Edge Betweenness Centrality Values for Key West Road-bridge Network

Bridge Rank	Start Long.	Start Lat.	End Long.	End Lat.	Edge Betweenness Centrality	Roads	Bridges
1	-81.6734	24.58979	-81.2283	24.68233	0.217717718	Ovrs Hwy	Ovrs Hwy
2	-81.6736	24.58976	-81.6734	24.58979	0.216216216	Ovrs Hwy	Ovrs Hwy
3	-81.7426	24.57291	-81.6736	24.58976	0.214714715	Ovrs Hwy	Ovrs Hwy
4	-81.7435	24.57263	-81.7426	24.57291	0.213213213	Ovrs Hwy	Ovrs Hwy
5	-81.752	24.56996	-81.7435	24.57263	0.211711712	Ovrs Hwy	Ovrs Hwy
6	-81.7433	24.5728	-81.7522	24.57011	0.201201201	Ovrs Hwy	Ovrs Hwy
7	-81.7427	24.57298	-81.7433	24.5728	0.1996997	Ovrs Hwy	Ovrs Hwy
8	-81.6743	24.58981	-81.7427	24.57298	0.198198198	Ovrs Hwy	Ovrs Hwy
9	-81.6725	24.59014	-81.6743	24.58981	0.196696697	Ovrs Hwy	Ovrs Hwy
10	-81.2283	24.68233	-81.6725	24.59014	0.195195195	Ovrs Hwy	Ovrs Hwy
11	-81.0475	24.7257	-80.9587	24.75665	0.154654655	Ovrs Hwy	Ovrs Hwy
12	-81.1247	24.70688	-81.0475	24.7257	0.153153153	Ovrs Hwy	Ovrs Hwy
13	-81.2283	24.68233	-81.1247	24.70688	0.144144144	Ovrs Hwy	Ovrs Hwy
14	-81.0475	24.72583	-81.1247	24.70688	0.127627628	Ovrs Hwy	Ovrs Hwy
15	-80.9587	24.75665	-81.0475	24.72583	0.126126126	Ovrs Hwy	Ovrs Hwy
16	-80.9587	24.75665	-80.9235	24.77714	0.12012012	Ovrs Hwy	Ovrs Hwy
17	-81.1247	24.70688	-81.2283	24.68233	0.12012012	Ovrs Hwy	Ovrs Hwy
18	-80.9235	24.77714	-80.9195	24.77859	0.11036036	Ovrs Hwy	Ovrs Hwy
19	-80.9195	24.77859	-80.6409	24.91317	0.099099099	Ovrs Hwy	Ovrs Hwy
20	-80.6409	24.91317	-80.3748	25.17029	0.097597598	Ovrs Hwy	Ovrs Hwy
21	-80.9235	24.77714	-80.9587	24.75665	0.09009009	Ovrs Hwy	Ovrs Hwy
22	-80.9195	24.77859	-80.9235	24.77714	0.078828829	Ovrs Hwy	Ovrs Hwy
23	-80.6409	24.91317	-80.9195	24.77859	0.066066066	Ovrs Hwy	Ovrs Hwy
24	-80.3747	25.17075	-80.6409	24.91317	0.063063063	Ovrs Hwy	Ovrs Hwy
25	-80.3743	25.17166	-80.3747	25.17075	0.043543544	Ovrs Hwy	Ovrs Hwy

Weighted Analysis

Weighted graph analysis reflects the effect of different weights (e.g. traffic count, volume, delay etc.) applied on the nodes and links along with the connectivity of the network. In this study, weighted analysis is performed only for links or roadways as the network parameter for nodes (closeness centrality) does not consider weights. Average Annual Daily Traffic (AADT), which is calculated by counting the total volume of vehicles of a road for a year divided by 365 days, is considered as weight on the roadways. For the Key West road-bridge network, weighted analysis did not show any differences in Edge Betweenness Centrality values and the results show a similar output as shown in Table 4. The reason behind this is the network topology and characteristics of the Key West road-bridge network as it is actually a long stretch at the southernmost part of the State of Florida as shown in Figure 13. As such, networks with more complex topology (i.e. grids, triangles) are likely to show more convincing changes in network credentials, which is not applicable for the Key West network. Such effects are presented in the following sections that include analyses of Miami-Dade County and Florida networks.

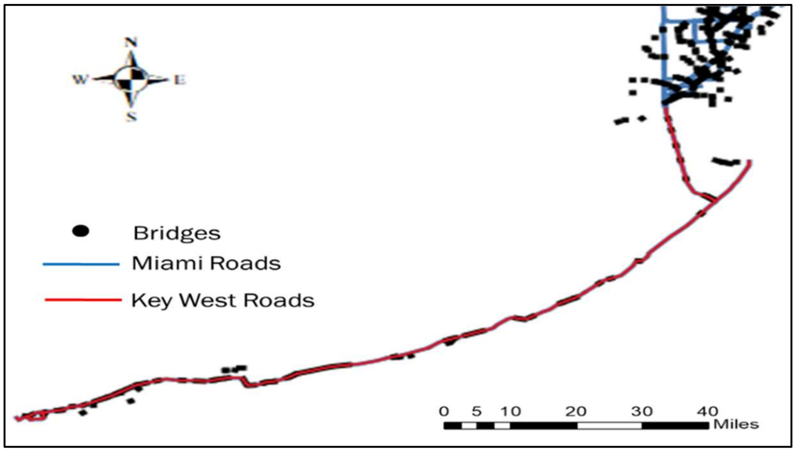


Figure 13 The Long Stretch of Key West Road-bridge Network

4.10 Miami-Dade County Road-Bridge Network Analysis

Unweighted Analysis

From Miami-Dade road shape file, 2199 roadway segments and 1960 roadway segment intersection were found. After performing the Closeness Centrality analysis and mapping with bridges, 137 specific bridge location were found with centrality value. The most 20 central bridges' specific location of Miami Dade county according to node property are listed in Table 5.

Table 5 Closeness Centrality Values for Miami-Dade Road-bridge Network

Bridge Rank	Node Long.	Node Lat.	Closeness Centrality	Roads	Bridges
1	-80.2637	25.7717	0.015244	W Flagler St	W FLAGLER ST
2	-80.2392	25.7723	0.014857	W Flagler St	W FLAGLER ST
3	-80.2735	25.7340	0.014087	Granada Blvd	GRANADA BLVD
4	-80.2727	25.8082	0.014011	East Dr	EAST DR
5	-80.2897	25.7043	0.013923	Sunset Dr	SUNSET DR
6	-80.2727	25.8081	0.013721	East Dr	EAST DR
7	-80.2899	25.7042	0.013622	Sunset Dr	SUNSET DR
8	-80.1886	25.7795	0.012464	Biscayne Blvd	BISCAYNE BLVD
9	-80.1893	25.7820	0.012332	Biscayne Blvd	BISCAYNE BLVD
10	-80.1889	25.7801	0.012222	Biscayne Blvd	BISCAYNE BLVD
11	-80.1893	25.7839	0.012096	Biscayne Blvd	BISCAYNE BLVD
12	-80.1892	25.7801	0.011950	Biscayne Blvd	BISCAYNE BLVD
13	-80.1891	25.7853	0.011868	Biscayne Blvd	BISCAYNE BLVD
14	-80.1889	25.7792	0.011735	Biscayne Blvd	BISCAYNE BLVD
15	-80.1890	25.7861	0.011649	Biscayne Blvd	BISCAYNE BLVD
16	-80.1891	25.7870	0.011632	Biscayne Blvd	BISCAYNE BLVD

17	-80.1891	25.7883	0.011492	Biscayne Blvd	BISCAYNE BLVD
18	-80.1890	25.7861	0.011438	Biscayne Blvd	BISCAYNE BLVD
19	-80.1891	25.7861	0.011421	Biscayne Blvd	BISCAYNE BLVD
20	-80.1891	25.7896	0.011355	Biscayne Blvd	BISCAYNE BLVD

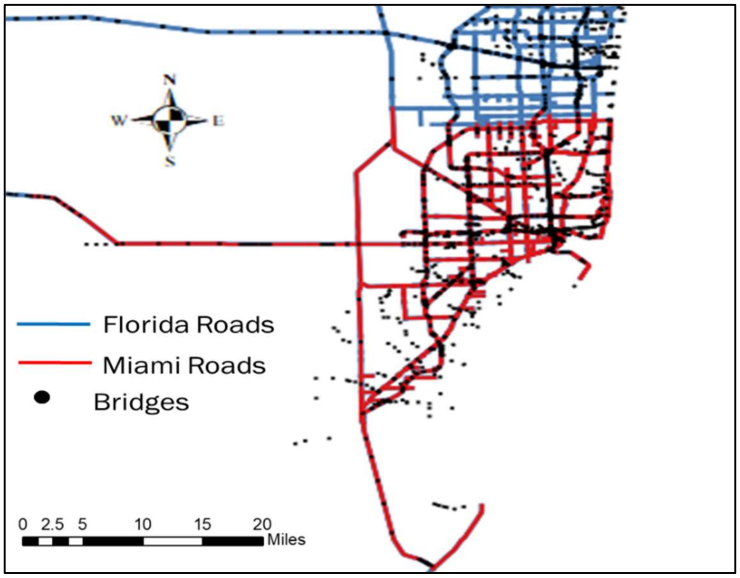


Figure 14 Miami-Dade County Road-bridge Network

Then, the network analysis was performed for the link property by calculating Edge Betweenness Centrality. 168 roadway segments with bridges were found with centrality values after mapping with bridge shape file. The most 50 central bridge segments of Miami Dade County according to link property are listed below in Table 6.

Table 6 Edge Betweenness Centrality Values for Miami-Dade Road-bridge Network

Unweighted Rank	Weighted Rank	Start Long.	Start Lat.	End Long.	End Lat.	Weight (AADT)	Unweighted Edge Betweenness Centrality	Weighted Edge Betweenness Centrality	Roads/Bridges
1	1	-80.1889	25.7801	-80.1893	25.7820	37297	0.079154	0.068973	Bscn Blvd
2	2	-80.1886	25.7795	-80.1889	25.7801	26070	0.079150	0.068970	Bscn Blvd
3	3	-80.1890	25.7861	-80.1891	25.7870	35988	0.077585	0.067270	Bscn Blvd
4	4	-80.1890	25.7861	-80.1890	25.7861	37500	0.077581	0.067268	Bscn Blvd
5	5	-80.1891	25.7853	-80.1890	25.7861	37500	0.077577	0.067265	Bscn Blvd
6	6	-80.1893	25.7839	-80.1891	25.7853	37930	0.077572	0.067262	Bscn Blvd
7	7	-80.1893	25.7820	-80.1893	25.7839	38000	0.077568	0.067260	Bscn Blvd
8	8	-80.1891	25.7870	-80.1891	25.7883	33500	0.075370	0.064964	Bscn Blvd
9	9	-80.1891	25.7883	-80.1891	25.7896	33500	0.075184	0.064762	Bscn Blvd
10	**19**	**-80.1220**	**25.9299**	**-80.1219**	**25.9304**	**54000**	**0.075149**	**0.062392**	**Clns Ave**
11	10	-80.1891	25.7896	-80.1890	25.7962	33500	0.074997	0.064560	Bscn Blvd
12	11	-80.1890	25.7962	-80.1894	25.8043	36018	0.074809	0.064358	Bscn Blvd
13	12	-80.1894	25.8043	-80.1894	25.8107	33067	0.074621	0.064155	Bscn Blvd
14	13	-80.1894	25.8107	-80.1894	25.8114	42500	0.074441	0.063951	Bscn Blvd
15	14	-80.1894	25.8114	-80.1894	25.8116	42500	0.074260	0.063747	Bscn Blvd
16	15	-80.1894	25.8116	-80.1893	25.8124	118000	0.074078	0.063543	Bscn Blvd
17	16	-80.1891	25.8134	-80.1869	25.8255	35768	0.074037	0.063459	Bscn Blvd
18	17	-80.1893	25.8124	-80.1891	25.8134	35500	0.074032	0.063457	Bscn Blvd
19	18	-80.1840	25.8327	-80.1841	25.8333	40000	0.073301	0.062631	Bscn Blvd
20	**22**	**-80.1227**	**25.8871**	**-80.1220**	**25.9299**	**49883**	**0.073270**	**0.060786**	**Clns Ave**
21	20	-80.1841	25.8333	-80.1841	25.8334	40000	0.072607	0.061886	Bscn Blvd
22	21	-80.1841	25.8334	-80.1846	25.8478	40000	0.072421	0.061677	Bscn Blvd
23	**51**	**-80.1539**	**25.9262**	**-80.1559**	**25.9262**	**51500**	**0.049956**	**0.034025**	**Bscn Blvd**
24	**57**	**-80.2637**	**25.7717**	**-80.2634**	**25.7644**	**44000**	**0.048500**	**0.026107**	**W Flglr St**
25	24	-80.1889	25.7792	-80.1878	25.7753	36000	0.046977	0.048211	Bscn Blvd
26	**45**	**-80.2897**	**25.7043**	**-80.2899**	**25.7042**	**41786**	**0.046962**	**0.036088**	**Sunset Dr**

27	26	-80.1892	25.7801	-80.1889	25.7792	26493	0.045677	0.046896	Bscn Blvd
28	27	-80.1896	25.7839	-80.1895	25.7820	38000	0.044392	0.045498	Bscn Blvd
29	28	-80.1893	25.7855	-80.1896	25.7839	37900	0.044388	0.045495	Bscn Blvd
30	29	-80.1892	25.7860	-80.1893	25.7855	37500	0.044384	0.045492	Bscn Blvd
31	30	-80.1891	25.7861	-80.1892	25.7860	37500	0.044379	0.045490	Bscn Blvd
32	31	-80.1891	25.7870	-80.1891	25.7861	33500	0.044375	0.064964	Bscn Blvd
33	**52**	**-80.2899**	**25.7042**	**-80.2909**	**25.7034**	**73000**	**0.044199**	**0.033205**	**Sunset Dr**
34	32	-80.1891	25.7883	-80.1891	25.7870	33500	0.042155	0.064762	Bscn Blvd
35	33	-80.1891	25.7896	-80.1891	25.7883	33500	0.041964	0.064560	Bscn Blvd
36	34	-80.1890	25.7962	-80.1891	25.7896	36018	0.041773	0.064358	Bscn Blvd
37	35	-80.1894	25.8043	-80.1890	25.7962	33067	0.041581	0.064155	Bscn Blvd
38	36	-80.1894	25.8107	-80.1894	25.8043	42500	0.041388	0.063951	Bscn Blvd
39	37	-80.1894	25.8114	-80.1894	25.8107	42500	0.041203	0.063747	Bscn Blvd
40	38	-80.1894	25.8116	-80.1894	25.8114	118000	0.041018	0.063543	Bscn Blvd
41	39	-80.1893	25.8124	-80.1894	25.8116	35500	0.040832	0.063457	Bscn Blvd
42	40	-80.1892	25.8134	-80.1893	25.8124	35500	0.040782	0.041649	Bscn Blvd
43	41	-80.1841	25.8327	-80.1870	25.8255	40000	0.040029	0.040811	Bscn Blvd
44	42	-80.1841	25.8333	-80.1841	25.8327	40000	0.040024	0.061886	Bscn Blvd
45	43	-80.1841	25.8334	-80.1841	25.8333	40000	0.039326	0.061677	Bscn Blvd
46	**23**	**-80.3684**	**25.5797**	**-80.3664**	**25.5818**	**53500**	**0.036177**	**0.048487**	**Carbn Blvd**
47	**25**	**-80.3595**	**25.5890**	**-80.3541**	**25.5986**	**53500**	**0.035879**	**0.048175**	**Marlin Rd**
48	44	-80.2392	25.7723	-80.2389	25.7652	38000	0.030916	0.039768	W Flagler St
49	46	-80.1234	25.8160	-80.1211	25.8420	42904	0.027048	0.036087	Clns Ave
50	47	-80.1229	25.8138	-80.1234	25.8160	15000	0.027043	0.036084	Clns Ave

***Unweighted road-bridge network is considered as the base network for comparison**

Weighted Analysis

As one of the prime objectives of this study is to examine the effect on traffic due to ABC related activities, hence Average Annual Daily Traffic (AADT) is considered as weight on the roadways of the Miami-Dade County. From the weighted Edge Betweenness Centrality results listed in **Table *6***, it can be said that traffic volume influences the network parameters significantly as the ranking of most central bridges changes after considering the impact of traffic on road-bridge network. For example, a bridge at Collins Avenue previously ranked as 10th most central bridge from unweighted analysis, but with the effect of traffic it's ranking as a central bridge changes to 19. From Table 6, this type of changes in ranking of central bridges are found multiple times where some of the bridges' ranking increased (marked in green) and some decreased (marked in red).

Previously (unweighted analysis) ranked as 24 (West Flagler Street) and 26 (Sunset Drive) central bridges' priority changes to 57 and 45 after considering the effect of traffic on the corresponding roadways. On the other hand, central bridges ranked as 46 (Caribbean Boulevard) and 47 (Marlin Road) from unweighted analysis are relocated in more central position of the Miami-Dade County road-bridge network with ranking of 23 and 25 respectively for weighted graph. Besides, the top 09 ranked bridges centrality values did not show any changes from unweighted analysis and the bridges ranked from 10 to 18 reflects minor changes in weighted analysis. The change in bridge ranking due to traffic is visualized in Figure 15, where the geolocation of bridge ranked as 22 from Table 6 (previously ranked as 20 in unweighted analysis) is highlighted.

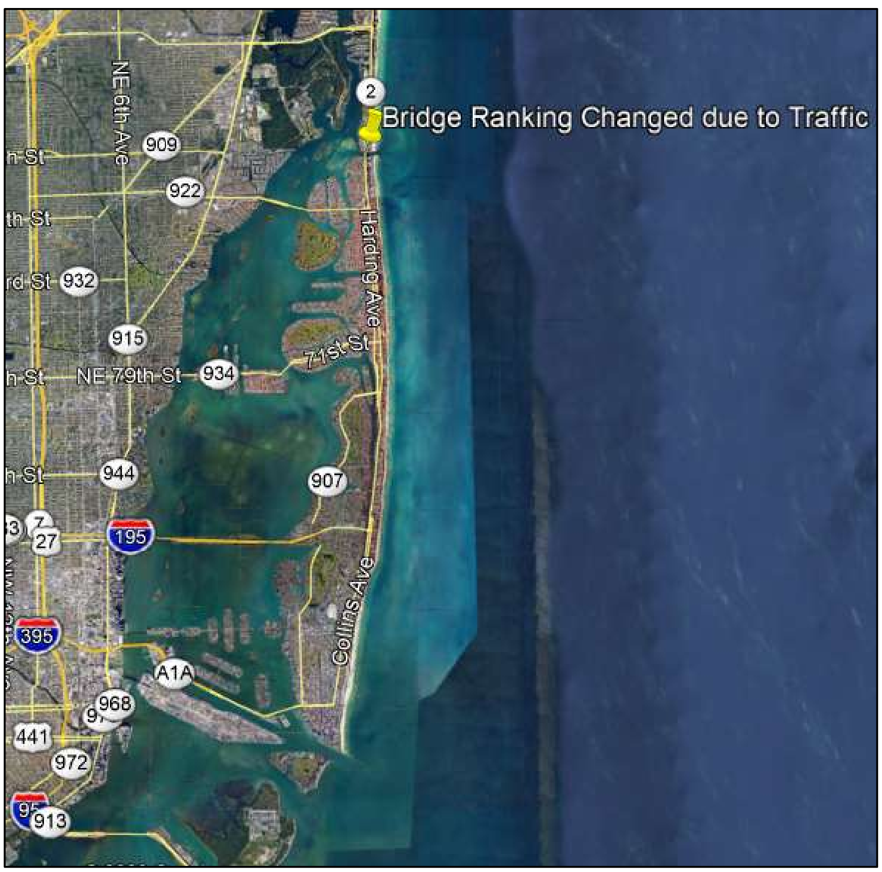


Figure 15 Change in Ranking of a Central Bridge of Miami-Dade County due to Traffic

4.11 Miami Beach Road-Bridge Network Analyses

The Miami Beach network shape file (which is a subset of Miami-Dade County shape file) consisted 745 roadway segments and 678 roadway segment intersection. After performing the Closeness Centrality analysis and mapping with bridges, 107 specific bridge location were found with centrality value. From Edge Betweenness Centrality analysis, 134 roadway segments with bridges were found with centrality values after mapping with bridge shape file. As the number of specific bridge locations and bridge segments of Miami Beach and Miami-Dade County are very close, hence the results of Miami Beach network are only considered for scaling effect discussion.

4.12 Florida Road-Bridge Network Analyses

Unweighted Analysis

From Florida road shape file, 18,462 roadway segments and 15,417 roadway segment intersection were found. After performing the Closeness Centrality analysis and mapping with bridges, 2,444 specific bridge location were found with centrality value. The most 20 central bridges' specific location of Florida according to node property are listed in Table 7. Then, the network analysis was performed for the link property by calculating Edge Betweenness Centrality. 3,252 roadway segments with bridges were found with centrality values after mapping with bridge shape file. The most 50 central bridge segments of Florida according to link property are listed in Table 8.

Table 7 Closeness Centrality Values of Florida Road-bridge Network

Bridge Rank	Node Long.	Node Lat.	Closeness Centrality	Roads	Bridges
1	-80.8036	27.6697	0.006676	State Road 60	STATE ROAD 60
2	-80.6435	27.6402	0.006616	State Road 60	STATE ROAD 60
3	-81.8435	27.9045	0.006615	Van Fleet Dr	VAN FLEET DR
4	-81.9575	28.0550	0.006588	N Florida Ave	N FLORIDA AVE
5	-81.9407	28.0441	0.006564	E Main St	E MAIN ST
6	-81.9409	28.0441	0.006561	E Main St	E MAIN ST
7	-80.6435	27.6405	0.006557	State Road 60	STATE ROAD 60
8	-81.9573	28.0555	0.006535	N Florida Ave	N FLORIDA AVE
9	-81.9469	28.0441	0.006532	E Main St	E MAIN ST
10	-81.9573	28.0548	0.006532	N Florida Ave	N FLORIDA AVE
11	-81.9575	28.0548	0.006532	N Florida Ave	N FLORIDA AVE
12	-81.9703	28.0549	0.006532	Kathleen Rd	KATHLEEN RD
13	-82.1703	28.5078	0.006517	Treiman Blvd	TREIMAN BLVD
14	-80.8034	27.6699	0.006497	State Road 60	STATE ROAD 60
15	-82.1953	28.5079	0.006487	Cortez Blvd	CORTEZ BLVD
16	-81.9574	28.0497	0.006473	George Jenkins Blvd	GEORGE JENKINS BLVD
17	-81.9705	28.0549	0.006473	Kathleen Rd	KATHLEEN RD
18	-82.204	28.3649	0.006469	Meridian Ave	MERIDIAN AVE
19	-82.1931	28.5079	0.006469	Cortez Blvd	CORTEZ BLVD
20	-81.9412	28.0550	0.006462	E Memorial Blvd	E MEMORIAL BLVD

Table 8 Edge Betweenness Centrality Values of Florida Road-bridge Network

Unweighted Rank	Weighted Rank	Start Long.	Start Lat.	End Long.	End Lat.	Weight (AADT)	Unweighted Edge Betweenness Centrality	Weighted Edge Betweenness Centrality	Roads/Bridges
1	1	-81.3583	27.2972	-81.3626	27.3174	17800	0.0612181	0.0855220	US-27 S
2	294	-81.9412	28.0550	-81.9569	28.0550	35888	0.0592377	0.0099064	E Mmrl Blvd
3	93	-81.8435	27.9045	-81.8433	27.9040	38000	0.0553112	0.0311746	Van Fleet Dr
4	2	-81.9573	28.0556	-81.9573	28.0624	35000	0.0550132	0.0838625	N Florida Ave
5	452	-81.9569	28.0550	-81.9573	28.0556	24500	0.0537450	0.0050895	Mmrl Blvd
6	1078	-81.9407	28.0442	-81.9408	28.0546	12800	0.0521861	0.0016348	E Main St
7	67	-81.9573	28.0549	-81.9412	28.0549	34253	0.0498294	0.0787735	N Florida Ave
8	80	-81.9575	28.0550	-81.9573	28.0549	24500	0.0478417	0.0446420	N Florida Ave
9	94	-81.9409	28.0442	-81.9408	28.0385	12800	0.0462698	0.0310316	E Main St
10	6	-81.9574	28.0624	-81.9575	28.0550	35000	0.0451576	0.0737822	N Florida Ave
11	427	-81.8014	27.7520	-81.8215	27.8202	16000	0.0393595	0.0059624	US-17 N
12	428	-81.8215	27.8202	-81.8216	27.8209	16000	0.0393594	0.0059619	US-17 N
13	36	-84.3875	30.0843	-84.3806	30.1042	8700	0.0367902	0.0456869	Coastal Hwy
14	55	-81.5145	27.5955	-81.4952	27.5148	30000	0.0353305	0.0425612	W Main St
15	12	-84.3804	30.1047	-84.3875	30.0843	8700	0.0349743	0.0601352	Coastal Hwy
16	20	-80.4400	26.1369	-80.4423	26.1473	10810	0.0342811	0.0515896	US-27 N
17	56	-81.3585	27.2972	-81.3585	27.2971	17800	0.0341818	0.0855220	US-27 S
18	10	-81.4174	26.4185	-81.4093	26.4180	6952	0.0335133	0.0623579	E Main St
19	11	-81.4093	26.4180	-81.4089	26.4179	6700	0.0335132	0.0623575	E Main St
20	57	-82.0455	28.8471	-82.0455	28.8387	14000	0.0329285	0.0418747	S Main St
21	58	-82.0455	28.8387	-82.0455	28.8361	12197	0.0329284	0.0418743	S Main St
22	40	-82.6120	28.9231	-82.6267	28.9526	16900	0.0327100	0.0446017	N Suncoast Blvd
23	41	-82.6267	28.9526	-82.6352	28.9696	16900	0.0327099	0.0446013	N Suncoast Blvd
24	42	-82.6352	28.9696	-82.6354	28.9700	16900	0.0327098	0.0446008	N Suncoast Blvd
25	43	-82.6354	28.9700	-82.6691	29.0304	8616	0.0327096	0.0446004	N Suncoast Blvd
26	21	-82.1953	28.5078	-82.1704	28.5078	16500	0.0327087	0.0563814	Cortez Blvd

27	22	-82.2381	28.5231	-82.2358	28.5231	16820	0.0326741	0.0511735	Cortez Blvd
28	23	-82.2358	28.5231	-82.1975	28.5078	16500	0.0326277	0.0511253	Cortez Blvd
29	3225	-82.1975	28.5078	-82.1953	28.5078	16500	0.0326275	0.0563814	Cortez Blvd
30	24	-82.3671	28.5428	-82.3031	28.5231	19100	0.0324811	0.0508994	Cortez Blvd
31	45	-82.8232	29.4170	-82.8596	29.4748	3400	0.0320685	0.0440034	S Main St
32	46	-82.8596	29.4748	-82.8600	29.4876	9153	0.0320684	0.0440030	S Main St
33	59	-82.0430	28.8583	-82.0455	28.8476	18144	0.0318837	0.0397539	S Main St
34	60	-82.0455	28.8476	-82.0455	28.8471	14000	0.0318836	0.0397535	S Main St
35	69	-80.5827	27.0963	-80.6773	27.1590	7100	0.0314177	0.0501940	SW Wrfld Blvd
36	70	-80.4824	27.0305	-80.5827	27.0963	10847	0.0313885	0.0501645	SW Wrfld Blvd
37	71	-80.4468	27.0065	-80.4495	27.0085	10900	0.0313709	0.0500852	SW Wrfld Blvd
38	72	-80.4495	27.0085	-80.4824	27.0305	10842	0.0313708	0.0346999	SW Wrfld Blvd
39	503	-82.4037	28.5402	-82.3691	28.5422	22132	0.0305668	0.0043342	Cortez Blvd
40	504	-82.3691	28.5422	-82.3671	28.5428	19356	0.0305667	0.0043338	Cortez Blvd
41	3247	-81.5145	27.5956	-81.5145	27.5955	9500	0.0302646	0.0321860	W Main St
42	14	-82.1953	28.5080	-82.2359	28.5232	16500	0.0301505	0.0577123	Cortez Blvd
43	3235	-82.2359	28.5232	-82.2382	28.5232	16900	0.0301504	0.0577119	Cortez Blvd
44	15	-82.2382	28.5232	-82.3031	28.5233	16900	0.0301502	0.0577119	Cortez Blvd
45	73	-84.2156	30.1906	-84.1836	30.1998	3497	0.0300947	0.0337856	Coastal Hwy
46	74	-84.2465	30.1737	-84.2156	30.1906	3497	0.0300550	0.0337449	Coastal Hwy
47	75	-84.3138	30.1409	-84.2465	30.1737	3500	0.0300154	0.0337042	Coastal Hwy
48	47	-82.4207	28.5525	-82.4208	28.5777	13900	0.0300098	0.0437691	W Jefferson St
49	76	-84.3806	30.1042	-84.3801	30.1050	10011	0.0299837	0.0336729	Coastal Hwy
50	77	-84.3801	30.1050	-84.3138	30.1409	4700	0.0299835	0.0336725	Coastal Hwy

***Unweighted road-bridge network is considered as the base network for comparison**

Weighted Analysis

As weighted analysis is not applicable for Closeness Centrality (node property) network parameter, hence Weighted Edge Betweenness Centrality values (link property) are calculated for Florida road-bridge network. Similar to Miami-Dade County network, noteworthy changes in bridge ranking due to traffic is also observed and reported in Table 8, where the increase in bridge ranking due to traffic is marked in green and the decrease in red. For example, bridges ranking 10, 19, 42, and 44 in unweighted network got improved to 6, 11, 14, and 15 after considering traffic as weight. Besides, some other bridges ranked as 2, 5, 6, 29, 41, and 43 experienced a huge decrease in ranking due to traffic in weighted network analysis. These results and changes in bridge ranking clearly shows the impact of traffic volume on the road-bridge network along with the network connectivity.

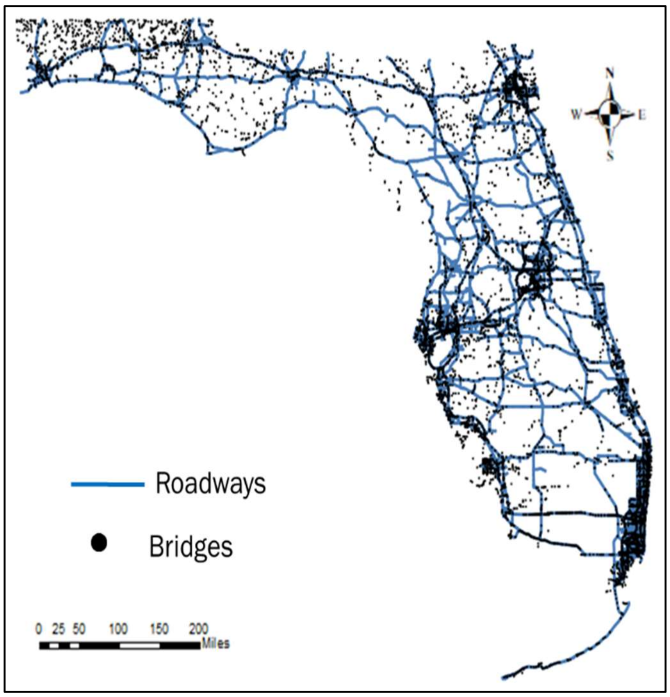


Figure 16 Florida Road-bridge Network

4.13 Scaling Effects

As Miami Beach and Miami-Dade County are a subset of Florida network, hence all the bridge points and bridge segments of Miami Beach and Miami-Dade County are found in the Florida network analysis, but with different centrality values. This happens because of the scaling effect of the networks. The same bridge shows different centrality value for different scale of the network. The smaller the network size, the higher the centrality values of bridges. In Table 9, network scaling effect is shown for the node property (Closeness Centrality) along with the respective bridge rankings of these networks, which clearly depicts higher centrality values for Miami Beach and Miami-Dade County network than the Florida network for the same bridge location.

Table 9 Scaling Effects Based on Node Property (Unweighted Closeness Centrality) of Network

Node Coordinates		Bridge Rank			Closeness Centrality			
Long.	Lat.	Florida	Miami-Dade	Miami Beach	Florida	Miami-Dade	Miami Beach	Roads/Bridges
-80.1220	25.9299	1199	37	1	0.004509	0.009720	0.020644	Collins Ave
-80.1204	25.9538	1252	45	2	0.004460	0.009349	0.019895	Collins Ave
-80.1469	25.9552	1279	56	3	0.004435	0.009043	0.019278	Biscayne Blvd
-80.1202	25.9556	1284	49	4	0.004432	0.009227	0.019172	S Ocean Dr
-80.1207	25.9501	1262	42	5	0.004453	0.009429	0.019137	Collins Ave
-80.1540	25.9260	1144	54	6	0.004563	0.009087	0.019049	Biscayne Blvd
-80.1539	25.9262	1288	51	7	0.004428	0.009170	0.018985	Biscayne Blvd
-80.1469	25.9601	1306	55	8	0.004414	0.009056	0.018747	Biscayne Blvd
-80.1537	25.9260	1172	58	9	0.004534	0.008971	0.018609	Biscayne Blvd
-80.1469	25.9550	1316	61	10	0.004408	0.008915	0.018579	Biscayne Blvd
-80.1193	25.9860	1319	53	11	0.004405	0.009108	0.018501	S Ocean Dr
-80.1423	25.9856	1317	64	12	0.004407	0.008830	0.018413	Federal Hwy
-80.1564	25.9168	1173	59	13	0.004534	0.008958	0.018380	Biscayne Blvd
-80.1847	25.8501	1404	36	14	0.004312	0.009857	0.018343	Biscayne Blvd
-80.1841	25.8334	1427	34	15	0.004281	0.010089	0.018297	Biscayne Blvd
-80.1841	25.8333	1435	32	16	0.004266	0.010192	0.018170	Biscayne Blvd
-80.1535	25.9266	1207	63	17	0.004505	0.008844	0.017965	Biscayne Blvd
-80.1468	25.9497	1348	65	18	0.004380	0.008790	0.017937	Biscayne Blvd
-80.1508	25.9347	1220	67	19	0.004492	0.008729	0.017911	Biscayne Blvd
-80.1849	25.8562	1424	39	20	0.004286	0.009706	0.017737	Biscayne Blvd

***Miami Beach road-bridge network is considered as the base network for comparison**

Similarly, for the link property (Edge Betweenness Centrality) of the network, scaling effect is also replicated in Table 10 where the centrality values of bridge segments for Florida network is smaller than the Miami Beach and Miami-Dade County network. In both cases, Miami Beach network is considered as the base network for the comparison of centrality values and bridge rankings among three different scales.

Table 10 Scaling Effects Based on Link Property (Unweighted Edge Betweenness Centrality) of Network

Link Coordinates				Bridge Rank			Edge Betweenness Centrality			
Start Long.	Start Lat.	End Long.	End Lat.	Florida	Miami-Dade	Miami Beach	Florida	Miami-Dade	Miami Beach	Roads/Bridges
-80.1220	25.9299	-80.1219	25.9304	258	10	1	0.01022	0.07515	0.08365	Collins Ave
-80.1227	25.8871	-80.1220	25.9299	355	20	2	0.00747	0.07327	0.07132	Collins Ave
-80.1840	25.8327	-80.1841	25.8333	494	19	3	0.00412	0.07330	0.06068	Biscayne Blvd
-80.1841	25.8334	-80.1846	25.8478	491	22	4	0.00418	0.07242	0.06039	Biscayne Blvd
-80.1841	25.8333	-80.1841	25.8334	493	21	5	0.00414	0.07261	0.06026	Biscayne Blvd
-80.1893	25.8124	-80.1891	25.8134	502	18	6	0.00400	0.07403	0.06015	Biscayne Blvd
-80.1891	25.8134	-80.1869	25.8255	503	17	7	0.00400	0.07404	0.06009	Biscayne Blvd
-80.1893	25.7820	-80.1893	25.7839	497	7	8	0.00406	0.07757	0.05974	Biscayne Blvd
-80.1893	25.7839	-80.1891	25.7853	498	6	9	0.00406	0.07757	0.05968	Biscayne Blvd
-80.1891	25.7853	-80.1890	25.7861	499	5	10	0.00406	0.07758	0.05962	Biscayne Blvd
-80.1890	25.7861	-80.1890	25.7861	500	4	11	0.00406	0.07758	0.05956	Biscayne Blvd
-80.1890	25.7861	-80.1891	25.7870	501	3	12	0.00406	0.07759	0.05950	Biscayne Blvd
-80.1894	25.8116	-80.1893	25.8124	520	16	13	0.00390	0.07408	0.05908	Biscayne Blvd
-80.1894	25.8114	-80.1894	25.8116	523	15	14	0.00387	0.07426	0.05891	Biscayne Blvd
-80.1894	25.8107	-80.1894	25.8114	531	14	15	0.00386	0.07444	0.05874	Biscayne Blvd
-80.1894	25.8043	-80.1894	25.8107	533	13	16	0.00384	0.07462	0.05856	Biscayne Blvd
-80.1890	25.7962	-80.1894	25.8043	536	12	17	0.00383	0.07481	0.05838	Biscayne Blvd
-80.1891	25.7896	-80.1890	25.7962	539	11	18	0.00382	0.07500	0.05820	Biscayne Blvd
-80.1891	25.7883	-80.1891	25.7896	540	9	19	0.00381	0.07518	0.05801	Biscayne Blvd
-80.1891	25.7870	-80.1891	25.7883	537	8	20	0.00382	0.07537	0.05781	Biscayne Blvd

***Miami Beach road-bridge network is considered as the base network for comparison**

Following Figure 17 shows all the different scales used for the network analyses to explain the scaling effect in this study.

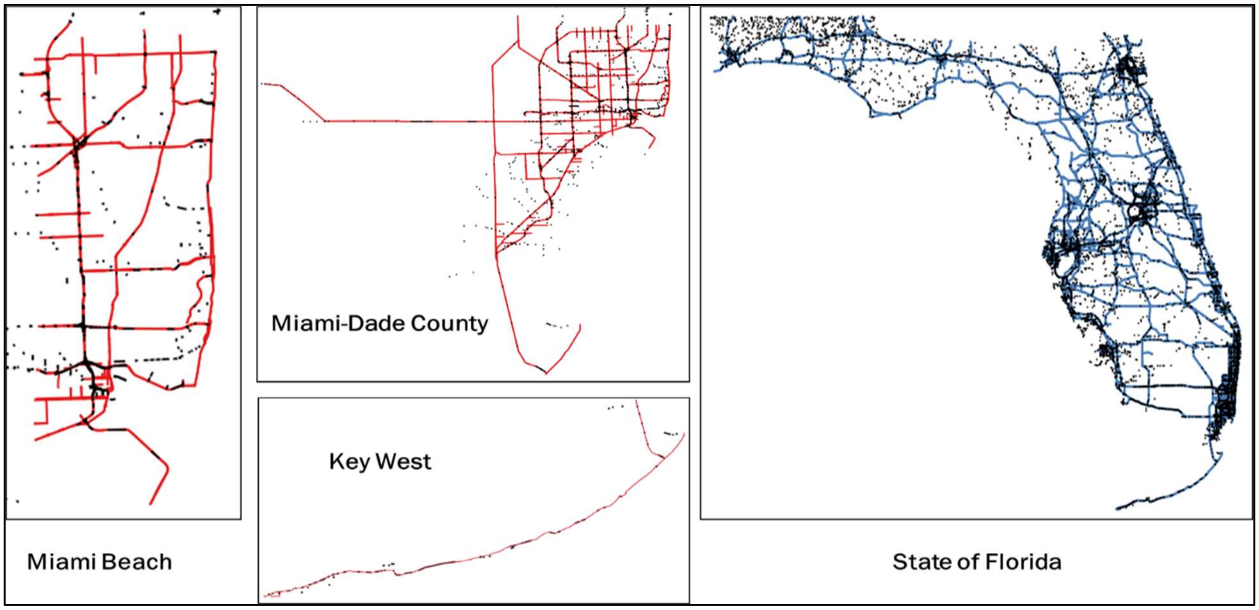


Figure 17 Key West, Miami Beach, Miami-Dade County and Florida Road-bridge Network

Task 5 – Compilation of Results and Reporting

The main objective of this project is to analyze the road-bridge network from a topographical or global point of view to identify the vulnerable bridges of the road network through network science principles to improve the network resiliency. Hence, the Florida road-bridge network is considered here and analyzed on four different scales. All the network analysis results listed in the previous section are representing the most influential, vulnerable and central bridges orderly for both weighted and unweighted network. To quantify this phenomena, node level property and link lever property of the network are measured by Closeness Centrality and Edge Betweenness Centrality. Table 3 to Table 8 are representing the ranking of most important bridges of the respective unweighted/weighted networks from high to low. Besides, Table 6 and Table 8 are showing the effect of traffic along with the network connectivity on bridge ranking as well as the changes in priority due to traffic volume which is visualized in Figure 15.

To prioritize (systematic sequencing) the new bridge construction or maintenance work by ABC method, Closeness Centrality values should be considered for specific bridge location (node) analysis, such as road-bridge intersecting point or bridge segment joints. Besides, Edge Betweenness Centrality should be considered while bridge segments are the point of interest for unweighted network. To consider the effect of traffic along with network credentials on bridge segments, ranking of bridges from Table 6 and Table 8 should be taken in consideration.

Normally every two years, the bridges of the United States are inspected for regular maintenance purposes. Sometimes due to time and budget constraints, inspection of all the bridges may not be possible in a timely manner, hence the maintenance work delays. As a result, the bridges which have more impact or influence on the road network remain undermined. This impact means if these bridges are removed from the road network, most of the routes of the network will be affected which will result in increased travel time and vehicle delay, hence deceasing the resiliency of road network. By having the list of influential bridges, Accelerated Bridge Construction (ABC) can approach systematically while performing the maintenance of the existing bridges. As an example, Roosevelt bridge in Florida has been shut down in June 2020 due to a major crack formation. In previous regular inspections this crack formation might have been overlooked. After the closure of the bridge, it hugely affected the surrounding traffic network which results in longer travel time, delay as well as higher repairing cost. As such, systematic sequencing of bridge maintenance activities can help traffic or emergency managers in a major crisis to prioritize action plans based on the relative importance of a given bridge to minimize the system wide impact.

The proposed methodology of identifying central or influential bridges could also be useful for new bridge construction according to ABC decision making guideline. As bridges are a part of road networks, the most influential road segments could also be found by following the similar network analysis. After identifying the central roadway segments which could be connected by bridges, the construction of these new bridges can be prioritized over the other new bridges' construction. By doing so, the bridges which connect most central roadways could reduce the surrounding roadways system travel time, vehicle delay for defined origin destination and the time-cost value of the construction, finally improve the resiliency of the road network.

Conclusions and Recommendations

Accelerated Bridge Construction (ABC) is an emerging alternative to traditional construction as ABC minimizes the life-cycle cost, construction time, several discrepancies related to construction methods and results in a better quality of work. This study proposed a framework for identifying network credentials of bridges (i.e., rank of relative importance) by combining traditional Geographic Information System (GIS) modeling with network science theories (centrality of bridges) to improve the road-bridge network resiliency. Resiliency of a system is defined as the ability to withstand external shocks (robustness) and recover from that perturbation to the full functionality (rapidity). For any external shocks, bridges may become inaccessible for neighboring traffic as well as undergo maintenance activities resulting in significant travel delays i.e. increased average travel time of vehicles. Systematic identification of the topological credentials of bridges as part of the road network may contribute to faster recovery of the system optimal travel time.

The outcome of the proposed approach is a list of bridges in the road network based on their centrality values (from most central to least central) that can be adopted at different scales i.e., network size. The study conducted extensive network experiments and demonstrated how such topological credentials can change at different scales as well as when weights are introduced to the topology such as traffic volumes to establish relative importance of bridges more in a global perspective rather than localized ones. This would allow practitioners and other stakeholders performing ABC activities to decide on which bridge should be inspected, maintained or constructed first based on the position of the bridges' in a network setting. Different agencies also engage in solving unprecedented problems observed on local roads or bridges, however, this study provides novel insights on how to go beyond local context and incorporate a broader perspective to avoid cascading effects in such networks. As such, prioritizing maintenance activities or new construction work can be done with a bigger picture into consideration.

The applications of this research can also be extended towards responding any emergency evacuation scenarios by ensuring more efficient route guidance to evacuees and avoid possible gridlocks due to ABC activities. For example, people in Miami Beach, USA tend to take Venetian and MacArthur Causeways as they evacuate inland. Such preferences can be diverted ahead of time if the vulnerability of these bridges is assessed ahead of time to ensure more credible system performance. Besides, the network metrics such as centrality changes based on the scale of the network as shown in Table 9 and Table 10. Hence, deciding an appropriate network scale should be the first step towards identifying the influential bridges in each road network. This study conducted network experiments at four different scales (i.e., Key West (US-1), Miami Beach, Miami-Dade County and Florida). For future studies, a larger road network (entire USA) could be considered which may capture larger scaling effect at the state or multi-state level. This study can also support traffic simulation-based studies to quantify the effects on travel time based on network credentials. Previous studies showed how to prioritize bridges based on mixed-integer programming, however, the network variables introduced in this study can add to such formulations to deduce more efficient solutions.

5. Expected Results and Specific Deliverables

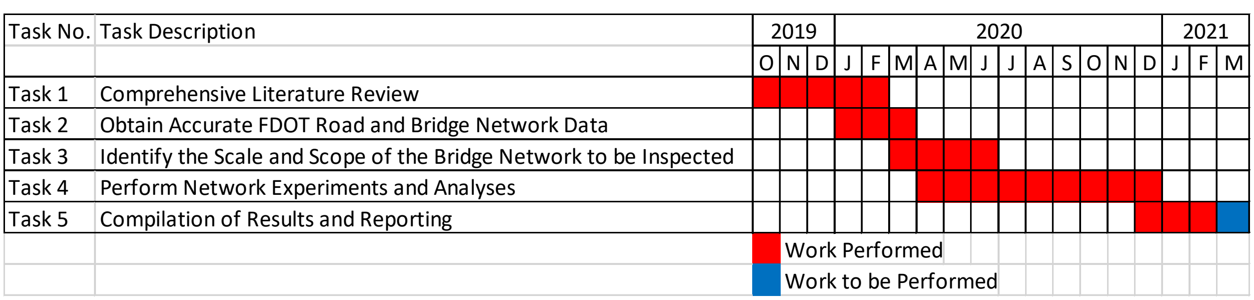
We plan to complete Task 5 to prepare the Final Report. The tasks breakdown of this project and the previous milestones are listed below:

Task 1 – Literature Review (completed)
Task 2 – Obtain Accurate FDOT Road and Bridge Network Data (completed)
Task 3 – Identify the Scale and Scope of the Bridge Network to be Inspected (completed)
Task 4 – Perform Network Experiments and Analyses (completed)
Task 5 – Compilation of Results and Reporting (to be completed)

6. Schedule

Progress of tasks in this project is shown in the table below.

Item	% Completed
Percentage of Completion of this project to Date	95



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