Dynamic Social Network Analysis for Infrastructure Transportation Systems

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ABSTRACT

It is essential to build, maintain, and use our transportation systems in a manner that meets our current needs while addressing the social and economic needs of future generations. In today’s world, transportation congestion causes serious negative impacts to our societies. To this end, researchers have been utilizing various statistical methods to better study the flow of traffic into the road networks. However, these valuable studies cannot realize their true potential without solid in-depth understanding of the connectivity between the various traffic intersections. This paper bridges the gap between the engineering and social science domains. To this end, the authors propose a dynamic social network analysis framework to study the centrality of the existing road networks. This approach utilizes the field of network analysis where: (1) visualization and modeling techniques allow capturing the relationships, interactions, and attributes of and between network constituents, and (2) mathematical measurements facilitate analyzing quantitative relationships within the network. Connectivity and the importance of each intersection within the network will be understood using this method. The authors conducted social network analysis (SNA) using a two studies in Louisiana. Results indicate intersection SNA modeling aligns with current congestion studies and transportation planning decisions.

INTRODUCTION

Traffic congestion is a major problem in the United States. In ASCE’s 2013 Roads Report Card, about 42% of major urban highways were congested (ASCE 2013). This congestion may be caused by a 39% increase in VMT with only a 4% increase in new construction road miles between 1990 and 2009 (ASCE 2013). Traffic congestion causes the following issues: reduced in travel speeds, restricted roadway capacity, unstable traffic conditions, increased fuel costs and length of travel times (ASCE 2013, Jun and Lim 2009, Pulugurtha and Pasupuleti 2010).

When delays occur, it is an indicator that a particular transportation network does not have a suitable design to meet the social and economic needs of current and future users. Increases in fuel consumption, engine emissions, vehicle wear and tear,
and wasted time are caused by traffic congestion (Zheng et al. 2010, Antipova and Wilmot 2012, GAO 1989). Traffic jams have also detrimental effects on the physical and psychological well-being of commuters (Levy et al. 2012, GAO 1989). In addition, high levels of speed reduction and travel time variability are dangerous to both the mental and physical safety of commuters. As a result, there are healthcare costs associated with bottlenecks and blockages. A study published by the National Institutes of Health (NIH) predicts the cost related to health impacts caused by congestion to be $13 billion by 2020 (Levy et al. 2010). Another negative cost effect of grid locked traffic is reduced economic productivity by limiting mobility of roadway users and commuters (Zheng et al. 2010). In total, all negative impacts caused by traffic congestion, cost the economy $101 billion a year (ASCE 2013).

Transportation system users experience many of these effects on a regular basis. For many people, traffic congestion is a daily fact of life. A commute that takes 30 minutes in normal conditions may take 45 minutes to more than 60 minutes in bottle necked traffic conditions. Many roadway users are forced to deal with extended and variable commute times in order to travel to and from work, medical appointments, social events, etc. They deal with the negative effects of travel time delays without giving much thought to what congestion really is. They simply take familiar routes to arrive at their planned destinations. For example, when commuters can accurately predict the travel time of a desired route, it is likely that they will travel on that route (Pulugurtha and Nagaswetha 2010). Transportation system users are hesitant to use untested travel networks to reach their planned destination because the travel time prediction of a new network can be less reliable than the time prediction of their regular travel network. They prefer to plan for extended and variable travel times than to plot different commute routes.

While it is known that commuters and the networks they use during their commute are relatively stable, developing a tool that utilizes social network analysis to examine the existing network and how to maximize its efficiency would be beneficial. This social network analysis tool can be used to analyze existing infrastructure to ensure that it is used efficiently and benefits individual commuters as well as the society as a whole. Specifically, individual commuters would benefit through reduced travel time and more reliable travel time predictions on a variety of transportation networks. Social network analysis of transportation networks could also be used to identify critical locations for new or additional infrastructure expansion and construction. In addition, this tool could create a sustainable solution by focusing infrastructure expenditures on precise locations, reducing capital expenditures and reducing the use of finite resources in unneeded construction.

The objective of this research is to help bridge the gap between engineering and social science disciplines. Specifically, two different transportation networks are studied and analyzed using social network analysis tools. This research uses traffic data from the case studies as the base data for entry and analysis within the social network analysis framework. The results of applying social network analysis tools to transportation network study and analysis are presented. Using the data presented in the case studies, new transportation network models are developed. These models consider the relationships and interactions of all intersections within the network. As
Transportation networks are groups of related intersections and roadways, this SNA model can provide guidance for improving these relationships.

**BACKGROUND**

The foundation of this research is focused on three main topics: traffic congestion, current and past applications of social network analysis, and applications of social network analysis in Civil Engineering and Construction.

**Traffic congestion**

Traffic congestion is identified by a reduction in travel speed and roadway capacity, increased variability and length of travel times, and unstable traffic conditions (Jun and Lim 2009, Pulugurtha and Pasupuleti 2010). Extended and variable travel times may be caused by poor roadway/network design, traffic demand fluctuations, work zones, weather, special events and accidents (Marchouk et al. 2011). Traffic congestion impacts the driver beyond added commute time or a delayed destination arrival. It impacts commuters through added travel and healthcare related costs. Beyond the individual user, through reduced mobility and safety, traffic jams have the potential to reduce the economic productivity of the users by increasing transportation and time related costs to the price of many consumer goods. Regardless of whether a bottleneck occurs in a dense urban area, a suburban neighborhood or a rural farming community, it has the potential to negatively impact drivers in many ways.

**Social network analysis**

Social network analysis has historically been used in social sciences. There are two major points of focus in social network analysis. One evaluates individual actors (intersections in the research) by determining how they are located or embedded in the overall network (Hanneman and Riddle 2005). The other point determines how the whole group of actor choices creates holistic patterns (Hanneman and Riddle 2005). Social network analysis has many relevant similarities to a roadway network. Much of the terminology used is similar or identical. This language includes short cuts, path redundancy, and bridges (Friedkin 2011, Sasovova et al. 2010). Additional analytical terms used in social network analysis with potential applicability to transportation planning are sparseness, inertia, asymmetry, skewness and alliance (Cowan and Jonard 2009). Similar to traffic congestion research, social network analysis has also determined that negative interactions tend to have a greater influence over decision making when perception and judgment main components of the decision making process (Labianca and Brass 2006). Social network analysis research has also determined that network characteristics tend to stay the same, indicating that prior behavior is a sound predictor of future actions and composition (Vaisey and Lizardo 2010), much the same way that travel time variability research has determined that once commuters select a route with predictable travel times, they will continue to use the same route for the indefinite future. Many studies in the social sciences have implemented the use of small world configurations in the study of networks (De Stefano et al. 2011). In traffic network analysis, a small network could be a specific neighborhood or region of a city’s
traffic network. For this research, the network will focus on relationships previously developed in a report on a continuous flow intersection and an existing transportation corridor.

Social Network Analysis in Civil Engineering and Construction

There is a somewhat limited research domain for utilizing social network analysis in the area of civil engineering and construction. One study used social network analysis to identify key trades including mechanical, electrical and drywall contractors (Wambeke et al. 2012). Another study focused on centrality to determine that project managers and construction managers are central to project communication between other project professionals (Chinowsky et al. 2008). A third study reviewed the interdependency of project participants to determine project effectiveness and collaborative ventures between various overseas companies (Park et al. 2011). Similarly to traditional social network analysis, it was determined that most related research in civil engineering and construction focused on the literal social interactions of individuals. As such, social network analysis has been applied to interactions between individual people and individual companies (in actor roles) in civil engineering and construction. However, no attempts were made in which the network’s main actors were not people or organizations controlled by people. Thus, applying this tool to transportation congestion where the actors are intersections is a new and innovative research focus worthy of more in depth study.

METHODOLOGY

Two case studies provided by the Louisiana Department of Transportation and Development (LADOTD) were utilized in this research. One case-study focused on a suburban intersection in Baton Rouge, LA. The second case-study focused on an urban street in New Orleans, LA. As such, this research focused on small world applications to simplify the social network analysis processes and calculations. Accordingly, the traffic network in a particular “neighborhood” area was studied instead of the entire city. In retrieving and analyzing related data, intersections within the networks under investigation were considered nodes and traffic flow between nodes was considered as flow or relation.

First case study

The first case study was based on a continuous flow intersection (CFI) in Baton Rouge, Louisiana. CFI’s maintain “continuous” flow by allowing left turn and through traffic movements of perpendicular streets to occur at the same time. CFI’s allow left turn traffic to cross over on-coming traffic while perpendicular traffic of a cross street is allowed to proceed through. Once left turn traffic has been given time to cross over to the left side of opposing traffic lanes, the signals are changed, allowing opposing traffic to proceed while also allowing left turns to take place unimpeded. This is because left turn traffic has already moved to the left of on-coming traffic. The data for this study is focused around the intersection of US 61 (Airline Highway) and LA 3246 (Siegen Lane). Data were obtained from a study that evaluated the change from a typical four leg signalized intersection where each approach consisted of two through lanes, two left turn lanes and a dedicated right turn
lane to a continuous flow intersection (CFI) (LADOTD 2007). Figure 1 details the location, intersections included and numbering system utilized in analyzing the first case study. This specific location was selected because of the abundance of traffic count data for intersections located within the “neighborhood” of this intersection.

Based on traffic congestion information provided in the LADOTD report, the model development process involved identifying 35 nodes or intersections, which would have traffic volumes studied. The associated traffic volumes between connected nodes were used to describe the strength of the connection. The higher the traffic count is between two nodes, the stronger is the connection. To evaluate the social makeup of the intersection network, traffic volume data were entered into a social network analysis program. The software selected for this research is Unicet 6.

Centrality was calculated using multiple functions within the Unicet 6 social network analysis software. Essentially, each type of centrality quantitatively measures the power or importance of a chosen node. Relative to transportation planning, a central intersection should be one that is given more focus to maintain consistent and non-extended travel time. Performance of central intersections drives the overall performance of the area roadway network. For instance, if an intersection that is central to the network is improved, the overall travel time will improve. However, if a non-central intersection is improved, the network will likely see little improvement in reducing travel time and travel time variability. To determine which intersections are most important for this research, four types of centrality were analyzed. They are defined below:

- Bonacich Power – a degree centrality measure that determines node centrality based on the degree centrality of adjacent nodes (Borgatti et al. 2002). For this study, degree centrality is determined based on the total traffic volume that each node receives.
- 2 Step Reach – determines centrality by summing the number of other nodes within 2 steps/links of a particular node (Borgatti et al. 2002).
• Eigenvector – a closeness centrality measure that determines node centrality based on the closeness centrality of adjacent nodes (Borgatti et al. 2002). Closeness centrality is calculated by determining how many connections are required to connect a selected node to all other nodes. In this study, closeness centrality is a function of how many intersections lie between any two selected intersections.

• Betweenness – a value to determine how central/between other nodes within the studied network a particular node is. Nodes with a value of zero are on the edge or periphery of the network (Borgatti et al. 2002).

Centrality analysis for each of the aforementioned attributes was calculated individually and compiled in a spreadsheet comparison chart. Analysis was also performed using images. Diagrams with node size scaled based on centrality, were analyzed to gain a better understanding of where the “power” nodes were located. Strength of nodes and clusters can be easily determined using network images. These details are provided in the results and analysis section of this paper.

Second case study

The second case study involved the Tulane Avenue Feasibility project in New Orleans, LA. This project represents a pre-construction/change study, and though does not have before and after information, it involved abundant data about the local network for the intersection as well as associated businesses and stakeholders. The related network map was plotted in a manner similar to case study 1. Similar analysis to the one described for the first case study was also conducted for the second case study.

RESULTS AND ANALYSIS

The analysis of the CFI in Baton Rouge was compiled in a spreadsheet and is detailed in Table 1. Each node was ranked for each category of centrality studied. Node 11 and node 19 each ranked number one in two of the centrality measures. Table 1 provides the details and rankings for each of these categories and nodes. As shown in Figure 1, Node 11 was the CFI intersection of US 61 (Airline Highway) and LA 3246 (Siegen Lane). Interestingly, the traffic volume reported in the case study increased after the completion of construction of the CFI. This result indicates that this intersection is central to the network studied, aligning with the general findings of the social network analyses. As such, this intersection is critical to the overall level of traffic congestion within its network. For instance, in a more restricted state, prior to constructing the CFI, the intersection was more congested with higher delay times and reduced traffic volume. As a result, the other intersections within the network had to carry higher traffic volumes and likely higher congestion. Upon construction completion, the CFI carried a higher traffic volume with reduced congestion delay times. The congestion of this intersection was reduced while also improving the traffic volume it can handle. This change likely reduced the traffic volume at other intersections within the network, reducing the overall congestion delays within the network. This ability makes node 11 central and very important to the congestion of the overall network.
The betweeness centrality is shown in Figure 2 where the top 10 most central (i.e., important and powerful) nodes as determined by four different measures are detailed. It is interesting to note that node 19 was highly ranked in two different measures - that based part of the centrality calculation on the centrality of each node connections - even though it was on the edge of the network. In addition, node 11 is shown as the largest node in the network. It clearly shows that node 11 has the highest betweeness centrality in the network. Reviewing the network betweeness centrality diagram also shows that node 11 is not in the center of the network. There are 15 nodes to the right of node 11 and 19 nodes to the left of node 11, yet using betweeness centrality (as well as two other measures) as the analytical factor, node 11 is the most central node in the network.

Table 1. Centrality values summary and rankings for first case study

<table>
<thead>
<tr>
<th>Rank</th>
<th>Bonacich Power Unicet Value</th>
<th>Node</th>
<th>2 Step Reach Unicet Value</th>
<th>Node</th>
<th>Eigenvector Unicet Value</th>
<th>Node</th>
<th>Betweeness Unicet Value</th>
<th>Node</th>
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</table>

Figure 2. Network betweenness centrality diagram for first case study

Table 2 details the analysis and findings of the Tulane Avenue network case study. The four major intersections within this study are represented by nodes 1, 2, 3 and 23. These nodes consistently appear in the top 10 most central intersections when the data was analyzed. Though not all of the intersections within the Tulane
Avenue study appeared in the top 10 under each centrality analysis category, all four intersections appeared in the top 10 at least twice, with three intersections appearing in the top 10 for three centrality measures.

Table 2. Centrality values summary and rankings for second case study

<table>
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<tr>
<th>Rank</th>
<th>Bonacich Power Unicet Value</th>
<th>2 Step Reach Unicet Value</th>
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It is interesting to note that the focus area of each study was ranked at the top or near the top of the centrality analysis. This indicates that centrality measures correlates with existing methods to determine critical intersections or corridors for improvement. As such, if an intersection is determined to have high centrality values within a network, it is an indicator that it is congested and that improving traffic volume capacity through it will have a high impact on mitigating congestion in the network as a whole. Interestingly, as indicated in the CFI study, traffic volume through an intersection may actually increase at a central intersection if its traffic volume capacity is improved, making the already central intersection, more central in its local network.

Using this model, design, construction and funding resources can be focused on the most critical intersections, getting more out of existing transportation infrastructure networks and pinpointing areas requiring modified infrastructure. Finite resources can be focused on the areas that need improvement and that which improvement will have the biggest positive impact on the entire network. Sustainability will be increased through maximizing the traffic flow capacity of already in place infrastructure and by minimizing monetary and natural resource use to modify or add infrastructure. Given that budgets for many individuals and organizations are limited do to current economic conditions, minimizing the money required to reduce traffic congestion is of utmost importance. Heightened awareness of environmental impacts of various aspects of life, including, traffic congestion and infrastructure modifications or additions, has also made maximizing the capabilities of existing infrastructure and minimizing the impacts of adding infrastructure critical. This social network analysis model has the ability to improve the lives of all individuals currently affected by traffic congestion. Based on this first study and analysis, this model can be used to reduce congestion, improving many congestion
related individual and society based factors. It has the potential to improve the lives of anyone who uses a transportation network.

CONCLUSION

Based on the results of this study, it is shown that using social network analysis is a viable traffic congestion management tool, worth further and more in depth study. Proven successful, using social network analysis will create a new perspective for evaluating traffic congestion and making related infrastructure network decisions. It will help decision makers determine critical intersections to focus research and decision making on.

In the CFI study, the model helped determine the exact areas for infrastructure improvement. It zeroed in on node 11 as one of the most critical and important intersection for congestion improvement. In the Tulane Avenue study, the four intersections within the study area frequently earned high levels of centrality and power when analyzing the data. They ranked high in four different centrality measures. Combined, this indicates that the Tulane Avenue area studied is important to maximizing the traffic performance within the downtown New Orleans area. Improving this section of the network should be among the top priorities for improving the surface street transportation network in downtown New Orleans.

Future work related this study should address O-D distribution. The inherent nature of O-D distribution could have a large impact on network dynamics. It is hypothesized that areas with a high O-D distribution would also have a high centrality value. Future work should analyze networks in locations other than the southern United States. Population density, number of transportation options and the culture of the study area could change the results of the SNA analysis.

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