ASSESSING THE IMPACT OF POTENTIAL BRIDGE COLLAPSE ON ROAD NETWORK VULNERABILITY:

A CASE STUDY IN OKLAHOMA

By

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CHAPTER I

INTRODUCTION

Transportation networks are indispensable parts of society. As a critical component of transportation networks, the road network has been providing us critical services since the beginning of the 20th Century. Platt (1991) even considered road network and other physical and virtual networks (such as pipelines, transmission lines, and Internet cables) as lifelines to our lives. Disruptions of road network will highly decrease the quality of the living standard of a normal society, and sometimes even threaten our lives in disaster scenarios. The 2011 Tōhoku earthquake and tsunami that hit Japan on March 11, 2011 provides a recent and rather tragic proof of this point. The main expressway connecting Tokyo and the tsunami-devastated region was shut down for 13 days. With the expressway out of service, the delivery of rescue and relief effort to the devastated area was tremendously hindered. According to an Iwate government spokesman, the road was eventually reopened on March 24 and finally allowed "supplies to be delivered" to the devastated areas (Chu and Sakamaki 2011). A robust and functioning road network under this disastrous situation would be critical for effective and efficient emergency management operations. Therefore, understanding the consequences of an interruption in a road network presents a significant research task in the field of transportation. A number of recent efforts have been dedicated to the study of network vulnerability analyses, which focus on assessing the probability of network link disruptions as well as the societal and economic consequences (Jenelius 2009). A similar study of vulnerability analysis can help people understand the potential consequences of an interrupted link in a road network. Various vulnerability analyses concerning road network have been performed by scholars all over the world. Those vulnerability studies of road network in general will provide insights for better “road management, prioritization for road maintenance and repair, contingency planning, and for the assessing of regional disparities” (Jenelius et al. 2006, 538). For example, Chang and Nojima (2001) developed post-disaster system performance measures for the urban rail and highway transportation system in Kobe, Japan where the 1995 Hyogoken-Nanbu earthquake took place. The measures of transportation system performance suggested by Chang and Nojima helped people to better understand “the effects of historic disasters and preparing for future hazard events” (Chang and Nojima 2001, 475). Sohn (2006) introduced an accessibility method to evaluate the highway network degradation of Maryland under a hypothetical flooding scenario. The study identified critical links under such a scenario. Results were used to suggest the retrofit priority of the transportation network under a flooding situation.

Even though different methods have been proposed and many case studies have been carried out, limited studies have focused on the vulnerability of the road network in Oklahoma. Because network vulnerability analysis is highly site-dependent due to the variation of different network structures, such studies on the Oklahoma road network need to be accomplished before any major disasters actually strike. This presents an urgent issue due to the high risk of severe weather in the State of Oklahoma. Huddleston (2011) used “Tornado Alley” as the key word to describe the disaster threats to Oklahoma and mentioned that “severe storms and twisters are so much part of the state’s weather that the National Severe Storms Laboratory and Storm Prediction Center are located here” (Huddleston 2011, 7). Provided that Oklahoma ranks as the sixth most likely state to be at risk of a disaster by Kiplinger.com recently (Canfield 2011), a network vulnerability analysis becomes critical for people to pinpoint the weakest links and maintain a robust road network to support normal daily functions of the society and effective and efficient disaster management operations under disaster scenarios in Oklahoma.

While road network in general are subject to degraded performance due to both natural and man-made disasters, bridges in road network are even more fragile when facing adverse scenarios. According to one report by *Transportation for America* in March 2011, "one out of every nine bridges that U.S. motorists cross each day is likely to be deteriorating to some degree", which means that 11.5 percent, or nearly 70,000, of the total 599,996 bridges nationwide are rated "structurally deficient" (Transportation for America 2011, 5). Oklahoma is even worse at the state-level: it ranks as *the second worst* state with 22 percent of its bridges are rated structurally deficient, which doubled the average rate of the whole United States. (Transportation for America 2011, 6). That means *one out of every five bridges* motorists cross is deteriorated in Oklahoma. Based on the above facts, this study chooses to evaluate the significance of highway network links with unsafe bridges in Oklahoma rather than assessing all the road links in Oklahoma. A bridge is considered an unsafe bridge if its deck condition is extremely poor based on the Federal Highway Administration (FHWA) deck condition ranking. The unsafe bridges on major highways are chosen because: 1) while bridges in general have a higher probability to fail than links that sit on a solid surface, bridges with worse deck conditions have an even higher probability to fail; and 2) their location on major highways makes their failure even more disastrous, as major highways provide more significant services than local roads. Also, there are usually more bridges in a highway network as it becomes common for roads to surpass rivers, local roads, creeks, etc.

In recent years, more than often funds are very limited and far from covering all the maintenance costs of all the road network (AASHTO 2009). While $27 billion has been provided for highway maintenance through the American Reinvestment and Recovery Act of 2009, the actual need is around $166 billion for highways and bridges each year (AASHTO 2009). Figure 1.1 from *Transportation for America* also gives a comparison of the Federal Estimates Versus FHWA Needs on bridge repair funding levels. On October 16, 2009, the Champlain/Crown Point Bridge which connected New York and Vermont and carried 3,500 cars per day was closed without warning due to the deficiency of the bridge's two support piers (Transportation for America 2011, 12). Jim Bonnie, with the New York Department of Transportation, said through the National Public Radio that "We set aside about $30 million a year for our bridge program, but we need on the order of $100 million to maintain our 830 bridges. So, it's just an epidemic" (Transportation for America 2011, 12).

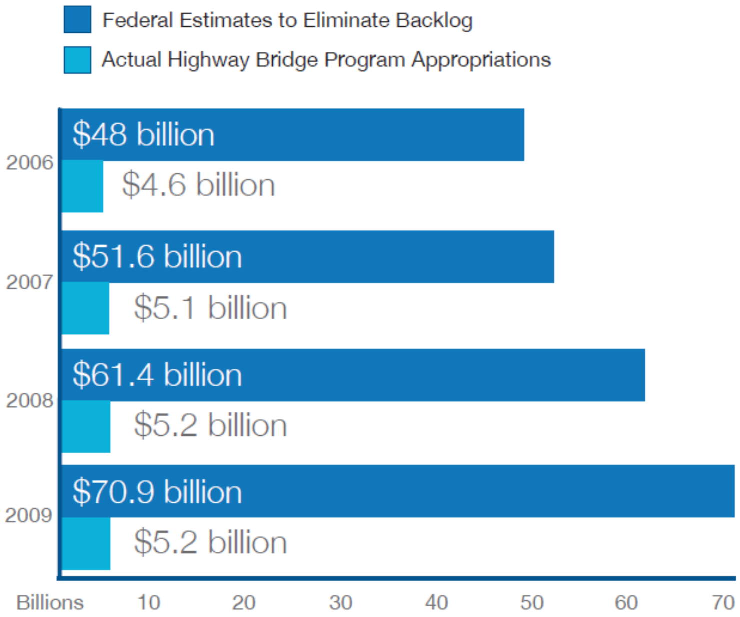

Fig 1.1 Bridge repair funding levels versus FHWA Needs Estimate. From *Transportation For America* (2011).

As no intentions to "fix them now" are presented, it seems inevitable for us to "pay for it later" (AASHTO 2009, 1). The worst scenario will be a sudden collapse of defective bridges. And it has happened in recent years. On August 1, 2007, the I-35W Bridge in Minneapolis, Minnesota suddenly failed, killing 13 and injuring 145 people (Transportation for America, 12). Because the I-35W Mississippi River Bridge also provided direct access to downtown Minneapolis and carried 140,000 vehicles each day, its collapse significantly affected the Minnesota economy. A daily net economic impact of an $113,000 reduction in the state's economic output was estimated.

Also, a daily loss of $247,000 of vehicle travel time through longer commutes was also a significant cost to individuals (Minnesota DEED 2009).

The above facts indeed demonstrate an urgent need for more studies concerning the structure conditions of the bridges and the resulting consequences a failed bridge will lead to. While recommended guidelines for highway bridge structures are documented (Rojahn et al. 1997), no guidelines for the overall transportation system performance exist (Chang and Nojima 2001). This study aims to provide a way to assess bridge importance from a system-wide perspective. The results from this study can provide insights for the prioritization of highway bridge maintenance under limited funds. By a better protection of more critical bridges, major losses may be prevented.

Objectives and Research Questions

The failure of highway links with bridges will lead to a degraded network and a reduced performance compared to that of the original network. Highway links are considered critical if their losses will significantly decrease the performance of the whole highway network. Bridges are considered critical if they sit on critical links and their failure will disable the corresponding critical links. The goal of this study is to identify the critical bridges among the unsafe bridges. The consequence of a failed link is measured by the change of highway network performance before and after the removal of that link. For example, if the removal of link *a* degrades the network performance more than link *b*, link *a* is considered more critical.

The first objective of this study is to use the increased travel cost measure to identify the critical unsafe bridges. A travel cost could be measured by the distance, time, or monetary cost of a trip. There specific research questions related to this objective are listed as follow:

1) **At the individual level, what is the influence of a failed bridge in terms of the increased travel cost on a single traveler?** An unweighted total travel cost assumes there is only one trip that is generated between each origin-destination (OD) pair.

Thus it does not take the traffic volume information between OD pairs into consideration. The unweighted total travel cost increase will be used to measure the influence at the individual level. It provides an assessment in terms of the increased travel cost when there is only one traveler who departs from each origin to each destination. The unweighted total increased travel cost offers an effective indicator for the impact of a failed bridge on travelers at the individual level. What is the unweighted total travel cost increase for the removal of each unsafe bridge in the highway network of Oklahoma? Which bridges are considered critical under this measure? By measuring the unweighted total travel cost, this study shows how each bridge's removal will affect individuals traveling among a set of origin-destination (OD) pairs under an uncongested network environment.

2) **At the system-wide level, what is the influence of a failed bridge on the performance of the road network?** In this case, the traffic volume of the road network will be considered when evaluating the total travel cost increase. What is the total weighted travel cost increase by the traffic flow among all OD pairs for the removal of each unsafe bridge in the highway network of Oklahoma? How do we derive the traffic flow information for each pair of cities? Which bridges are considered critical under this measure? The weighted increased travel cost considers the traffic flow information for each OD pair and heavily traveled roads will have higher weights. Thus the weighted increased travel cost is a better global indicator to measure the overall social and economic impact of a bridge failure.

3) **Are there any particular cities that will be affected enormously due to the failure of unsafe bridges under each of the indicators (i.e., unweighted and weighted increased travel cost)?** A huge travel cost increase between any pair of cities is not desirable and needs to be noticed. This question intends to detect whether such a situation exists in the examined road network system.

The second objective of this study is to determine how the cities will be affected from the removal of unsafe bridges based on an accessibility measure. Similar to the increased travel cost approaches, this study aims to answer the following questions:

1) What are the accessibility changes of the cities with each unsafe bridge's removal?
2) What is the total accessibility loss for each bridge's removal? Which bridges will cause the highest accessibility losses?
3) Are there huge accessibility losses for any particular cities with the removal of particular bridges?

This study will tackle the above questions and evaluate how potential bridge collapse will affect the performance of the road network.

Thesis Organization

This thesis is organized as follows. Chapter I has provided a general introduction of the importance of network vulnerability analyses and the objectives and research questions that will be tackled in this thesis. Chapter II offers a literature review on the topic of network vulnerability analyses. Chapter III introduces the study area, methodology, data collection, and data preparation for the analysis. Chapter IV focuses on the analysis and interpretation of the results. Finally, Chapter V contains conclusions as well as discussions on the limitations of this study and potential further research directions.

CHAPTER II

REVIEW OF LITERATURE

Spurred by the earthquake in Kobe, Japan in 1995 and the terrorist attacks in the United States on September 11, 2001, vulnerability analysis of road network is attracting increasing attention at an international scale in recent years (Chang and Nojima 2001, Jenelius et al. 2006, Taylor et al. 2006). The recent Tōhoku earthquake and tsunami that hit Japan on March 11, 2011 is likely to draw more attention on this topic worldwide. In this section, a selection of previous works on road network vulnerability analysis is reviewed.

Berdica (2002) provided a review on recent works and developments on road network vulnerability. In her paper, Berdica outlined a conceptual framework and definition of vulnerability, which is widely accepted and cited by other scholars (See Taylor et al. 2006, Chen et al. 2007). She argued that accessibility measure of road vulnerability only offers a demand side perspective. In addition to accessibility, Berdica mentioned serviceability of a network should be included as a supply side measure. She also suggested that vulnerability should include both probability and consequence, which is similar to the study of risk analysis. Meanwhile, Berdica admitted that vulnerability itself may be hard to measure, while reliability of a network could be a sufficient substitute concept and is more manageable to capture. She further concluded that reliability has been studied mainly in three aspects, which are 1) reliability of connectivity, 2) reliability of travel time, and 3) capacity reliability. A selection of performance measures for transportation systems, including travel time, total delay, accessibility, and congested level, etc. were summarized. In Berdica's opinion, however, the results of the above methods are only static mean values and may not be adequate to explain traffic, which is a highly dynamic process. Overall, this paper provided a clear review of current development and the changing conception of road vulnerability.

Connectivity Measures

Connectivity measures of highway network provide a simple and fundamental tool. Grubesic et al. (2008) performed a comprehensive comparison of various approaches for assessing network vulnerability. Graph theoretic measures, including Beta index, Alpha index, Gamma index and others were introduced; the T matrix and D matrix were also explained. While these methods are all relatively easy to perform, they yield single values that only give rough estimates of network performance. Also, they do not take the actual condition of the network into consideration. Moreover, real world road network systems are often too complicated to apply simple connectivity measures. The realistic road network always has numerous intersections, which makes it difficult to determine if two cities are directly connected or not. Thus classic connectivity measures are more appropriate when analyzing simple networks, telecommunication networks, and human social networks, in which it is easy to determine whether two nodes are directly connected or not.

Additionally, connectivity measures are sometimes not adequate to properly reflect the degradation of a road network. D’Este and Taylor (2001) performed a system-wide network performance evaluation concerning certain connections in the Australian transport system. The result showed that even though the network had a high probability of remaining connected under flood or other natural causes, disruptions of certain segments could lead to detours as long as 5,000 km (see Figure 2.1). Under this scenario, though Perth and Adelaide are still connected to each other, few people will actually be willing to travel an additional 5,000 km to reach the other end. This study provides a perfect example of showing that remaining connected is far from being reachable. The limitation of this paper is that only a limited number of disruptions in certain transport connections were considered and no well-established methods of assessing vulnerability were provided.

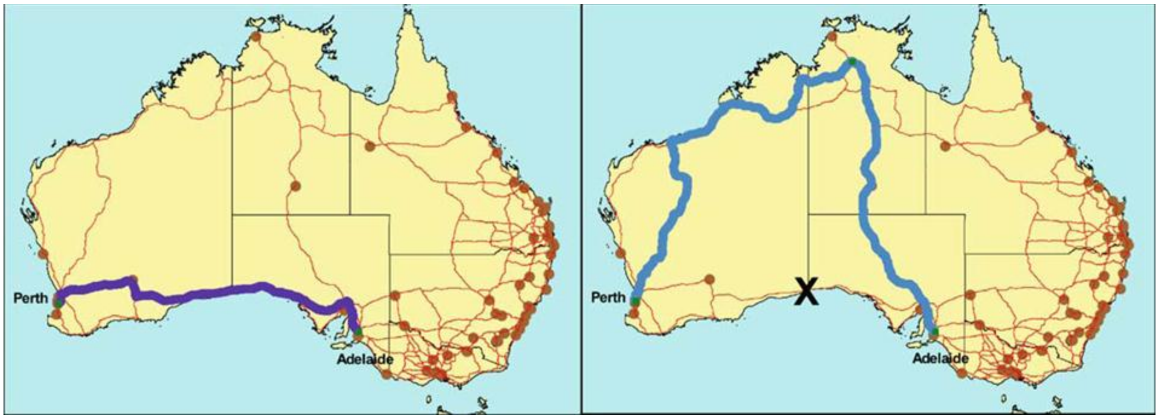

Fig 2.1 Effect of a loss of connectivity in the Australian road network. A cut of Eyre Highway gives an extra 5000km increase to the shortest path from Perth to Adelaide. From D'Este and Taylor (2001).

Accessibility Measures

Accessibility is a fundamental concept in transportation study and is widely used to assess highway performance (Miller 1999). Based on the network of Australia, Taylor et al. (2006) made a more comprehensive analysis by employing an accessibility-based method to evaluate the network vulnerability. A network scan was performed first to determine critical links based on travel time increase. Then two accessibility measures, Hansen integral accessibility index (Hansen 1959) and Accessibility/Remoteness Index of Australia (ARIA) (DHAC 2001), were used separately to evaluate how the removal of critical links would affect the major cities in Australia. Though Hansen integral accessibility index (Hansen 1959) was first brought out by Hansen in 1959 and has a long history, it is still widely used by recent scholars (Taylor, et al. 2006, Grubesic et al. 2008, Miller 2009). While Hansen's accessibility index "is useful in assessing accessibility between major population or activity centers" (Taylor et al. 2006, 273), ARIA is a better tool to assess "level of government and private sector services available to residents of regional and remote areas" (Taylor et al. 2006, 273). ARIA is an index that is designed especially for cities in Australia, and its change can adequately reflect the socio-economic impact for the cities. Results in Taylor's paper were presented in graphs and tables, which clearly illustrated the changes of accessibility for each major city. The drawback of this paper, however, is that it used a gravity model to weight the travel time without specifying the methodology on how they determined the scale factor α and distance impedance index β in the gravity model.

Sohn (2006) used an accessibility approach to evaluate the significance of highway network links in Maryland under a hypothetical flooding scenario. Sohn's study did a better job by using a well-estimated distance-decay parameter, as well as including traffic flow information as a second part of the accessibility score. He assessed the impact of flooding scenario based on the 100-year floodplain data at the county level. It is reasonable to study the impact at the county level, as counties/county commissioners are the basic units to act against natural disasters. Thus, an evaluation of the county level damage could help the county commissioners allocate their resources so that they could calculate the estimated damage and then ask for funds from the state government. Traffic flow data were also included in the calculation of accessibility. Sohn used the annual average daily traffic (AADT) weighted by the length of each segment to represent the traffic volume between each pair of cities. One advantage of including the traffic flow data is that it brings through traffic into account when calculating accessibility. Different from Australia, Maryland is not an island state and through traffic cannot be ignored. This helped to generate more realistic results that take through traffic into account.

Jenelius et al. (2006) employed a more complex road vulnerability analysis by dividing the concept of vulnerability into importance of links and exposure of nodes. The methodology of their study is also based on accessibility concepts. Two perspectives, namely the "equal opportunities perspective," which gives people equal opportunities everywhere and the "social efficiency perspective," which gives more credits to the roads that have higher traffic flow, were taken into consideration by adopting different weighting factors. Using the road network of northern Sweden, they visualized their results in a GIS environment. Results showed that critical links and the most exposed regions were different under different perspective and scenarios. However, this study requires extensive, detailed national-wide data as input to the Swedish national travel demand model system (SAMPERS). Thus, it is difficult to apply this model to other areas due to the lack of complete datasets. This method did not take congestion into consideration either, assuming all the links are uncongested.

Capacity Measures

Scott et al. (2006) included congestion into vulnerability analysis by proposing a new index named “Network Robustness Index” to evaluate network performance. This new index incorporated gamma index and volume/capacity (V/C) ratio factors. It provides both a global measure of the connectivity of the network and a local measure of single link by the V/C ratio. By considering volume/capacity of a link, this method is able to deal with congestion in a road network, which occurs frequently in real world. In the real world, however, the volume and capacity data of road segments are missing due to the difficulty of capture. The research of Dheenadayalu et al. (2004) provided some useful information by examining the relationships between the amount of information that was necessary to reasonably estimate capacity and the accuracy of the capacity data captured. Their results may provide some insight on how to properly and efficiently capture the capacity data of real world road segments when necessary.

Travelers’ Behavior Response Consideration

While all of the above studies provided well-established case studies and results, none of them took travelers’ behavior into account: they simply assume travelers will continue to make their trips to the same destinations using the shortest paths even under the proposed scenarios. The fact is that travelers may change their plans or even cancel their trips. Thus travelers’ behaviors need to be included for better analysis. Chen et al. (2007) adopted a combined travel demand model (CTDM) to include travelers’ behavioral responses to a certain disruption in road network. The users have a probability of canceling their trips, or choosing other destinations, modes, and routes under certain situations. At each stage, travelers' responses are determined by logit-based probability expressions. The expressions are based on the concept that "a traveler is a consumer of urban trips, reflecting the traveler's utility maximization and budget constraint choices" (Chen et al. 2007, 245). While the assumption of travelers as a consumer of urban trips may be appropriate when analyzing travel patterns and highway performance within city limits, it is not suitable if the study area is a whole state and cities are only considered as nodes of the transportation network. The lack of existing models and empirical data of the state of Oklahoma also makes it almost impossible to conduct a study that could accurately predict travelers' behaviors under certain disruptions of network. The lack of existing real world data may also be a main reason why Chen et al. (2007) used a hypothetical network in their study.

Further Discussions on Reviewed Literature

Based on the above literature review, an accessibility approach is selected to measure the highway network performance for multiple reasons. A detailed discussion about this decision is provided as follow.

1) Connectivity measures are not effective because their calculation requires a simplified and generalized representation of an original network. Given the complex structures of the highway network of Oklahoma, it is difficult to tell if two cities are directly connected or not. It is often the case in Oklahoma that two major highways intersect each other without a city at the intersection. No junctions could be added at the intersection in this case, as junctions represent cities in the connectivity measures. Cities are always connected through a series of intersections, and it is hard to tell if the cities are directly connected to each other, or they are only directly connected to the nearby intersections of highways. Connectivity measures also give only a fundamental assessment and may not be adequate to give detailed evaluation of the degradation for a road network.

2) Data limitation is a major problem for the employment of capacity-related methods. When a bridge on an Interstate highway fails, congestion will occur as the traffic is rerouted from

the Interstate highways to the secondary highways, since the latter are designed for less traffic volume. However, the lack of data concerning the volume and capacity of highway segments prevents a further step to take congestion into account to make this study more realistic. Fortunately, due to the relatively low population density in most part of the State of Oklahoma, congestion is not a major problem for most of the secondary highway segments, which are major components of this study. Congestion is more likely to happen only within urbanized areas, which are defined as geographic entities that have at least 50,000 people and a population density larger than 1,000 people per square mile, according to the US Census Bureau (FHWA 2003). According to this definition, Oklahoma has only four urbanized areas, which are Oklahoma City, Tulsa, Lawton, and Norman. Due to limited resources and time constraints, capacity-related methods are not presented in this study. Future studies may emphasize volume/capacity issues for more realistic results.

3) Users' responses are not considered either, as it is mostly used for assessing urban traffic analysis. For traffic within a city, the users of the urban transportation system may have multiple route choices for one destination. Moreover, the travel time of all the route choices may be close to each other because of the high density of the road system within a city. Thus, the final path a user eventually chooses is uncertain and a probability system to determine the user's responses is necessary for urban transportation analysis. For traffic among city pairs, however, there will be more likely only one clear choice, which is the shortest path, for the users. Due to a more sparsely distributed highway system, alternative routes other than the shortest path tend to significantly increase the travel time. Thus, the shortest path will be the primary choice for most of the users due to its exceptional time efficiency. Hence, users' responses are not considered in this inter-city transportation study.

The accessibility method is chosen as an easy-to-apply and yet effective approach. Also, this method is not data-demanding. It requires only a measure of attractiveness of places and a measure of separation between places. More specifically, the Hansen accessibility index is chosen as a useful method in “assessing accessibilities between major population or activity centers” (Taylor et al. 2006, 273). A gravity model will be employed to estimate the traffic flow volume between OD pairs. Different from Sohn’s approach, major cities with higher population are selected as the study unit rather than county seats in my study. This is because 1) this study focuses more on the performance of highway network, and how well major cities with higher population are served by the highway system reflects a higher performance level of the highway; and 2) no emergency reactions are needed from the counties. The responsibility to repair the failed highway bridges will be either the State Department of Transportation or the Federal Department of Transportation: the counties are only responsible for the maintenance of the county property and they are not responsible for any maintenance of and along the highway system. A detailed discussion of the methodology this study adopted is provided in the following chapter.

CHAPTER III

METHODOLOGY AND DATA PREPARATION

This chapter provides an introduction to the study area, the methods for the assessment of bridge importance, data collection, and data preparation. The study area section gives an overview of the highway network and city distribution of the selected study area; the methodology section discusses the different methods used in this study to assess the bridge importance; the data collection section provides a list of obtained and their source; and the data preparation section discusses the preparation process of the collected data.

The Study Area

The state of Oklahoma is chosen as the study area in this research. Based on the 2010 census data, there are 3,751,351 residents in Oklahoma, which makes it the 28st most populous state in the United States. According to the 2002 data of the US Census Bureau, Oklahoma has four urbanized areas: Oklahoma City, Tulsa, Lawton, and Norman. The residents in Oklahoma City and Tulsa account for 35% of the total population in Oklahoma, which means the distribution of the population in Oklahoma is greatly concentrated in Oklahoma City and Tulsa. According to the U.S. Department of Transportation Federal Highway Administration, Oklahoma has 933 miles of Interstate highway, 3,365 miles of other Principal Arterial roads, 4,835 miles of Minor Arterial, 25,301 miles of Collectors, and 78,698 miles of local roads (FHWA 2011). Among all the public roads, 85.8% of the roads are in the rural area, while the rest are in the urban area (FHWA 2011). Figure 3.1 shows the distributions of Oklahoma highway network and Oklahoma cities and towns.

Fig 3.1 Highway systems and major cities and towns in Oklahoma. Obtained from geology.com.

From Figure 3.1, we can see that Interstate 35 connects the northern and southern part of Oklahoma. Interstate 44 serves as the major connector between the Northeast and Southwest Oklahoma. Additionally, I-44 is the major road to connect the two most populous cities in Oklahoma—Oklahoma City and Tulsa. Interstate 40 also runs through Oklahoma from the east to the west and functions as a major connector of the state.

In this study, Interstate highways, U.S. highways, and state highways are selected to form the highway network; 24 major urbanized areas (UAs) and urban clusters (UC) are selected and how well the highway networks serve the UAs are used to evaluate the network performance. The definition of UAs and UCs are discussed in detail in the data preparation section of this chapter. Highway bridges with a serious or critical condition on decks are selected as links that have a high probability of collapse.

Methods of Assessing Bridge Importance

The importance of a bridge is determined by the change of the road network performance before and after the bridge link is removed. In this study, two measures are used to capture the highway performance: 1) increased travel cost, and 2) decreased node accessibility.

This study assumes that a broken link will stay unavailable long enough for a new equilibrium to form, and people are well informed of failed bridges. Travelers may then choose to use a new different route to avoid the unavailable link. Having a new traffic pattern formed, the performance of the network can be assessed by incorporating the following methods.

1) Increased travel cost

Increased travel cost is an indirect way to assess accessibility, because an increase in travel cost will reduce the capability of people to travel and make a place less accessible to potential visitors due to people's decreased mobility. Travel cost can be measured from different aspects such as distance, time, money, etc. In this case, travel time is chosen as the measure unit, provided that 1) time efficiency is usually valued more by travelers than travel distance, 2) monetary measures depend on too many other factors (e.g., vehicle's fuel economy, cargo value, passengers on board, etc.) and may not be a universal indicator for all traffic. Therefore, this study adopts the unweighted travel time change and weighted travel time change to evaluate the increase travel cost. The unweighted travel time change approach assumes only one trip is generated from one origin and thus gives more demonstrative results for individual users; the weighted travel time change approach, however, weights the travel time change by traffic flow amount and is a better indicator for system-wide performance of the highway system.

a) Unweighted travel time change approach

In the unweighted travel time change approach, the travel time between a pair of cities is derived from the time spent by a single traveler to finish the trip under the free flow condition of a road network. For the entire road system, the total travel time is the summation of such a single-traveler-based travel time for every pair of cities in the road system. Therefore, this approach treats the travel time changes between any pair of cities with the same weight (i.e., one single trip). In this case, a 10 minutes travel time increase between Stillwater and Tulsa is considered more significant than a 5 minutes travel time increase between Oklahoma City and Tulsa, even though the traffic flow between the later pair of cities might be much higher. The unweighted travel time change measure can be represented by the following formula

$$T_N = \sum_i \sum_j t'_{Nij} - \sum_i \sum_j t_{ij} \quad (3\text{-}1)$$

where T_N means the total increased travel time when Bridge N is out of service; t_{ij} means the travel time by a single traveler under free flow condition from city i to city j before bridge N is removed; t'_{Nij} means the travel time after Bridge N is out of service.

b) Weighted travel time change by travel flow approach

This approach considers the travel flow between a pair of cities as the weight factor when the travel time increase is calculated. Results generated using this method take into the travel flow information and gives a more appropriate judgment of the total travel time increase. Travel flow data among cities in Oklahoma is estimated by the gravity model. This could be represented by the formula below

$$T_{WN} = \sum_i \sum_j w_{ij} t'_{Nij} - \sum_i \sum_j w_{ij} t_{ij} \quad (3\text{-}2)$$

$$\text{where } w_{ij} = {P_i P_j}/{t_{ij}^2} \quad (3\text{-}3)$$

where T_{WN} represents the total weighted increased travel time between all city pairs when Bridge N is out of service; w_{ij} represents the weighting factor for the travel time between city i and city j; t_{ij} means the travel time by a single traveler under free flow condition from city i to city j before bridge N is removed; t'_{Nij} means the travel time after Bridge N is out of service. $P_{i/j}$ represents the population of city i/j.

While both of these two measures are based on the increased travel time among all the city pairs after one bridge is removed from the highway network, the weighted travel time increase measure complicates the unweighted travel time increase measure by introducing the weighting factor w_{ij}, which in this case is the traffic flow information simulated by the gravity model. This makes the weighted travel time increase measure a more appropriate method as a system-wide indicator. For example, a 20 minute delay between Stillwater and Oklahoma City will have more significance for single travelers than a 10 minute delay between Oklahoma City and Tulsa in the unweighted travel time measure, as it only assumes one trip between both Stillwater to Oklahoma City and Oklahoma City to Tulsa. However, the weighted travel time change measure will indicate that the 10 minute delay between Oklahoma City and Tulsa are actually more significant, because this 10 minute delay will have a much higher weight due to the high traffic flow that is generated by the gravity model.

2) Decreased node accessibility

This study uses Hansen (1959) accessibility index to evaluate the impact of a failed link. The Hansen accessibility considers attractiveness and distance between locations. While attractiveness is usually represented by population size, it has a positive relationship with Hansen accessibility; distance in this case will be represented using the shortest path based on free flow travel time and it has a negative relationship with Hansen accessibility. Through the numeric changes of the Hansen (1959) accessibility index, this study will be able to evaluate the accessibility changes at every node in the road network system. The Hansen (1959) accessibility index for a location i could be specified as

$$A_i = \sum_j B_j f(c_{ij}) \qquad (3\text{-}4)$$

where A_i represents the accessibility score of place i, B_j represents the attractiveness of location j, and $f(c_{ij})$ is an impedance function between place i and j that represents the separation between the two places. This study chooses the reciprocal of travel time to represent the separation of two cities using formula 3-5:

$$f(c_{ij}) = \frac{1}{t_{ij}} \qquad (3\text{-}5)$$

where t_{ij} is the travel time between place i and j.

As a gravity model is used to estimate the traffic flow between city pairs, this study does not take through traffic into consideration. Only traffic flows that are generated, traveled, and finally absorbed within the state of Oklahoma are considered. It is because this study only aims to evaluate the importance of bridges by their function of connecting major cities within Oklahoma. Thus, the state of Oklahoma is considered as a closed study area, which leads to the exclusion of through traffic, which includes 1) the traffic generated outside Oklahoma, 2) the traffic absorbed outside Oklahoma, and 3) the traffic going through Oklahoma. In other words, only traffic flow with a path that is totally within the state of Oklahoma is considered in this study. This certainly will cause limitations, which are discussed in detail in Chapter V under the section of Limitation and Future Directions.

Data Collection

This section offers a list of the data sets used in this study with their sources.

1) Oklahoma highway shapefiles

   Two road shapefiles were used in this study. One was based on TIGER road data and was obtained from the Oklahoma Center for Geospatial Information (OCGI) website, and the other was from the Oklahoma Department of Transportation (ODOT) website. The TIGER dataset contains both highways and local roads with a well-maintained topology of the road network. It was last updated in 2003 and thus does not contain roads built after 2003. The up-to-date ODOT dataset contains all the highway segments and Annual Average Daily Traffic count of each highway link. However, the topology of the ODOT dataset is somehow not accurate. Therefore, no adequate network analysis layers could be generated based on it.

2) Oklahoma bridges shapefile

   The Oklahoma Bridges shapefile was acquired from the 2010 National Transportation Atlas Database (NTAD). It contains all the bridges on major highways with many other attributes of the bridges, including year built, deck condition ranking, length, the type and name of the road the bridge sits on, etc.

3) Major urbanized areas and urban clusters shapefile for Oklahoma

   The shapefile of major urbanized areas and urban clusters for Oklahoma was obtained from the Geography Division of U.S. Census Bureau. It was last modified by the Census Bureau on May 20, 2002. It could be accessed online through http://www.census.gov/geo/www/ua/ua_bdfile.html. UAs (urbanized areas) and UCs (urban clusters) are chosen as better representations of where the people are than municipal areas of cities. A detailed comparison of UA and municipal areas for the major cities in Oklahoma is shown at the major city selection part in data preparation.

4) Municipal boundaries shapefile for Oklahoma

   The municipal boundaries shapefile for Oklahoma was obtained from the OCGI website that is maintained by the Department of Geography at Oklahoma State University. It represents cities as polygons, and the shape of the polygon corresponds to the city limit. It is used to determine the speed limit on each type of road.

5) Oklahoma county shapefile

   A shapefile of Oklahoma counties was obtained from the OCGI webpage. It contains all counties in Oklahoma with their names and FIPS codes. It is used as a background layer.

6) One Microsoft Excel file containing the 2002 population counts of the urbanized areas and urban clusters in Oklahoma.

   The Population Excel file was obtained from the U.S. Census website at the URL http://www.census.gov/geo/www/ua/uaucinfo.html#lists. It was accessed and downloaded on March, 2011.

Data Preparation

Three types of data, namely highway network dataset, UAs and UCs in Oklahoma, and unsafe bridges, were extracted from the original datasets separately. A detailed description on the data preparation is provided for each type of data in the following section.

1) Highway network correction

Because the topology of the ODOT dataset is poorly maintained and hard to improve after digitization, the TIGER dataset is chosen for the construction of the network dataset. The problem with TIGER dataset, however, is that 1) it contains both highways and local roads; 2) it is only current through 2003. Fortunately, road type information is stored in the attribute table in the format of U.S. Census Bureau's Census Feature Class Codes (CFCC). Table 3.1 gives an illustration of the meaning of commonly used CFCC codes for road system. Highways were extracted based on the CFCC code. However, a significant number of highway links were missing when the extracted dataset from TIGER was compared to the ODOT dataset. After a further examination, it turned out that the CFCC code information of the TIGER dataset was sometimes mislabeled. For example, some US Highways and State Highways are assigned a CFCC code of ‘A4’, ‘A6’, and ‘A7’. The ODOT dataset were then used as a reference layer to correct the mislabeled CFCC codes. Mislabeled highway segments in the TIGER dataset were visually identified and then merged into the original TIGER highways dataset. Figure 3.2 shows the comparison before and after the correction. It shows that the highway system in the TIGER dataset is more complete after the correction.

Table 3.1 An illustration of commonly used CFCC codes. Provided by the U.S. Census Bureau.

CFCC	Definition	Description
A0	Road with Category Unknown	Classification unknown or not elsewhere classified
A1	Primary Highway With Limited Access	Interstate highways and some toll highways
A2	Primary Road Without Limited Access	It contains mainly US highways, but include some state highways
A3	Secondary and Connecting Road	This category includes mostly state highways
A4	Local, Neighborhood, and Rural Road	A road in this category is used for local traffic and usually has a single lane of traffic
A5	Vehicular Trail	A road in this category is usable only by four-wheel drive vehicles
A6	Road with special characteristics	This category includes roads…that are parts of the vehicular highway system and have separately identifiable characteristics
A7	Road as Other Thoroughfare	A road in this category is not part of the vehicular highway system

After the correction, there were still two highway segments near Oklahoma City and one highway segment near Tulsa that are not present. This may be due to the reason that those road segments are newly constructed and the 2003 TIGER dataset does not contain them at all. These three highways were then digitized into the TIGER dataset based on their locations provide by the ODOT data.

The TIGER dataset also simplified the highway network by representing two-way highway segments by only one line in the dataset. As bridges will be present on both lanes, this simplification may cause inaccurate results in some scenarios. Detailed discussions are provided under the Limitations and Future Directions section in Chapter V.

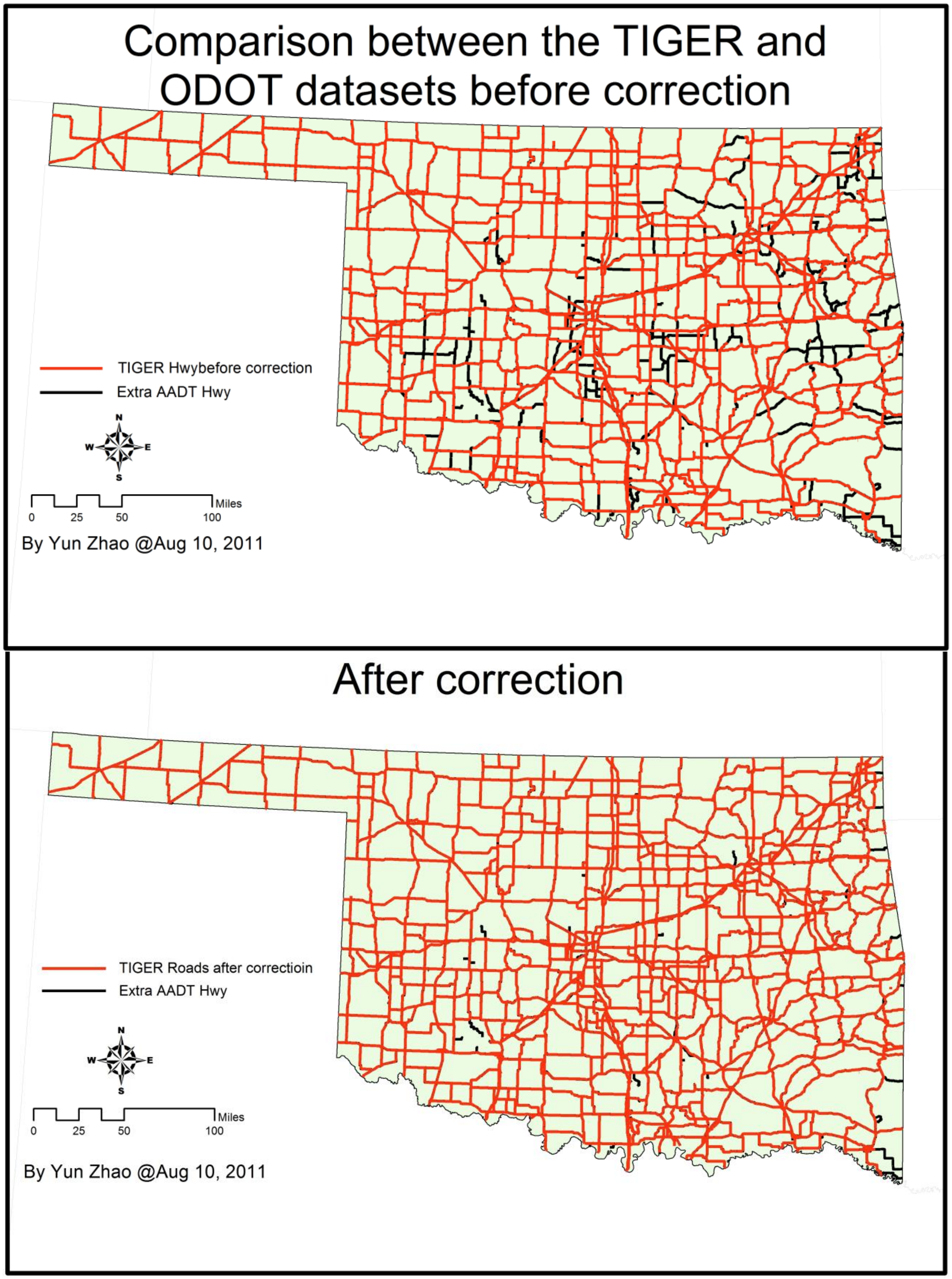

Fig 3.2 The TIGER road dataset before and after correction. The black lines indicate the missing highways comparing to the AADT highway reference dataset. TIGER dataset is more complete after correction.

Moreover, both the TIGER and ODOT road network datasets only maintain the distance of highway segments. Travel time needs to be calculated for each segment for further analysis. To calculate the travel time for each segment, this study starts from the simplest situation, assuming traffic flow will travel at the designated speed limit of each type of road. Without speed limit information on the dataset, the rules in Table 3.2 are used to determine the speed limit for each segment.

Table 3.2 Rules to specify highway speed limit.

Road Type	**Within City Boundaries**	**Outside City Boundaries**
Turnpike	75mph	75mph
Interstate	60 mph	70 mph
US Hwy and State Hwy	45 mph	60 mph

With travel time attribute of each road segment integrated to the original dataset, the change of highway network performance based on travel time increase could then be evaluated. Based on the accumulated travel time of all the segments included in a path, the total travel time could be derived.

2) Major cities selection

One polygon shapefile that contains the urbanized areas (UAs) and urban clusters (UCs) in Oklahoma was obtained. There are 5 UAs and 84 UCs in Oklahoma. An urbanized area is a place that “a statistical geographic entity designated by the Census Bureau, consisting of a central core and adjacent densely settled territory that together contain at least 50,000 people, generally with an overall population density of at least 1,000 people per square mile” (FHWA 2003); an urban cluster is “a new statistical geographic entity designated by the Census Bureau for the 2000 Census, consisting of a central core and adjacent densely settled territory that together contains between 2,500 and 49,999 people. Typically, the overall population density is at least 1,000 people per square mile. Urban clusters are based on Census block and block group density and do not coincide with official municipal boundaries” (FHWA 2003).

UAs and UCs rather than municipal areas are selected to represent cities in Oklahoma. This is because UAs and UCs are defined by population density, while municipal areas in this study are provided by Oklahoma Tax Commission for the purpose of capturing data related to municipal boundaries. By definition, it is clear that UAs and UCs are more precise representations of where people are around the city. Figure 3.3 gives a comparison of what Oklahoma City UA and Oklahoma Municipal boundaries look like on a Google Earth satellite Image. As buildings have a higher reflection rate than vegetation and bare soil because of their roofs, they appear lighter in satellite images. It is then easy to see that the areas from the UA layer have a high correlation to the areas where buildings are denser, which is an indicator of central business districts and residential houses where there are more people. The municipal boundary of Oklahoma City, however, does not show clear relationships with the distribution of population density.

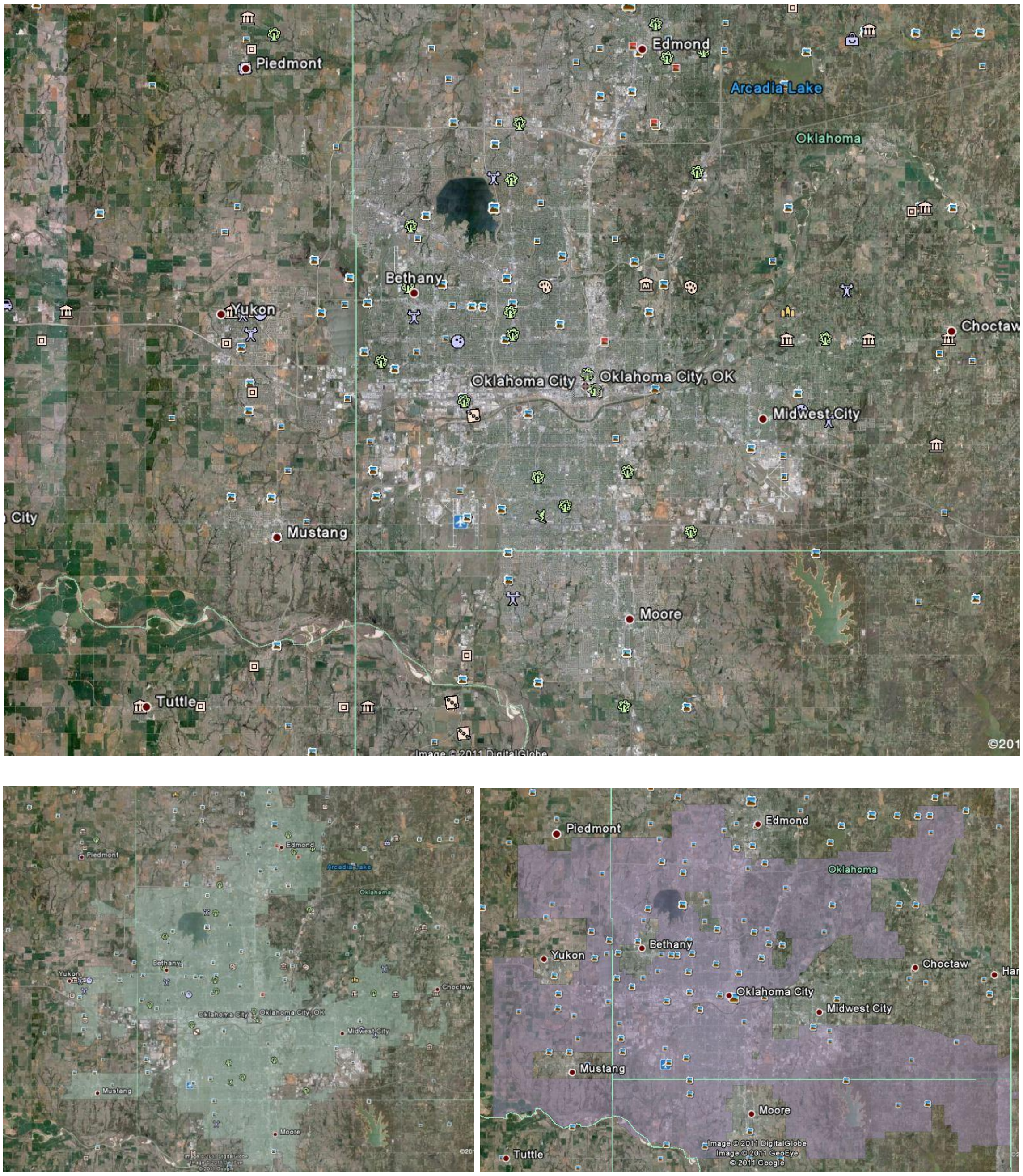

Fig 3.3 Comparison of OKC UA and OKC municipal boundary. The above image is what OKC looks like on Google Earth. The left bottom one shows OKC with UA lying above it; the right bottom image shows OKC with Municipal boundary lying above it.

The five UAs are Fort Smith AR-OK, Lawton, Norman, Oklahoma City, and Tulsa. Because this study only focuses on Oklahoma, Fort Smith is filtered out because of its cross-border location with Arkansas. The other four UAs are included as major cities in this study.

There are 84 UCs with various populations. For example, Enid as a UC has a population of 45,654, while Chandler has a population of 2,502. I set the population threshold at 10,000 to include all major cities in Oklahoma as well as to keep this study within a manageable calculation load. Because this study is interested in where people are, UAs and UCs are selected to represent city locations. As only points and lines are accepted for analysis in the ESRI ArcGIS Network Analyst Extension, all the urbanized areas are converted to points by the Feature to Point tool in ESRI ArcGIS Toolbox. Each point is located at the centroid of each urbanized area. Finally, 24 UAs and UCs are selected. Table 3.3 provides a list of the selected UAs and UCs with their area information, population density, and population.

Table 3.3 A list of selected UAs and UCs in this study.

NAME	**UATYPE**	**Area (meter^2)**	**Pop Density (per mile^2)**	**Pop2002**
Oklahoma City	UA	834888045	2317	747003
Tulsa	UA	677032189	2136	558329
Lawton	UA	142951216	1623	89556
Norman	UA	78316520	2860	86478
Enid	UC	62283466	1899	45654
Muskogee	UC	70541108	1419	38637
Bartlesville	UC	65490585	1524	38541
Stillwater	UC	53588628	1851	38288
Shawnee	UC	42004781	1954	31696
Owasso	UC	73456140	1090	30910
Ponca City	UC	34271162	1994	26382
Altus	UC	27289460	2011	21188
Ardmore	UC	24614912	2161	20539
Duncan	UC	32295497	1610	20075
McAlester	UC	38412871	1311	19443
Claremore	UC	37412364	1312	18957
Miami	UC	23281432	1875	16852
Tahlequah	UC	29610404	1453	16614
Ada	UC	28382357	1502	16463
Chickasha	UC	24660209	1629	15510
El Reno	UC	17701594	2137	14602
Durant	UC	22208496	1553	13313
Okmulgee	UC	22223493	1549	13290
Woodward	UC	20462475	1403	11088

Even though the city of Guymon has a population of 10,461, it was not selected. This is because trips between Guymon and most of other major cities in Oklahoma use the road network of Northern Texas, as Guymon is located in the panhandle of Oklahoma. Because this study focuses on the vulnerability of road network of Oklahoma, Guymon is excluded from the selected cities. Future studies may address this problem when road network data of Northern Texas is included. Figure 3.4 shows the selected UAs and UCs in proportional circles based on their population.

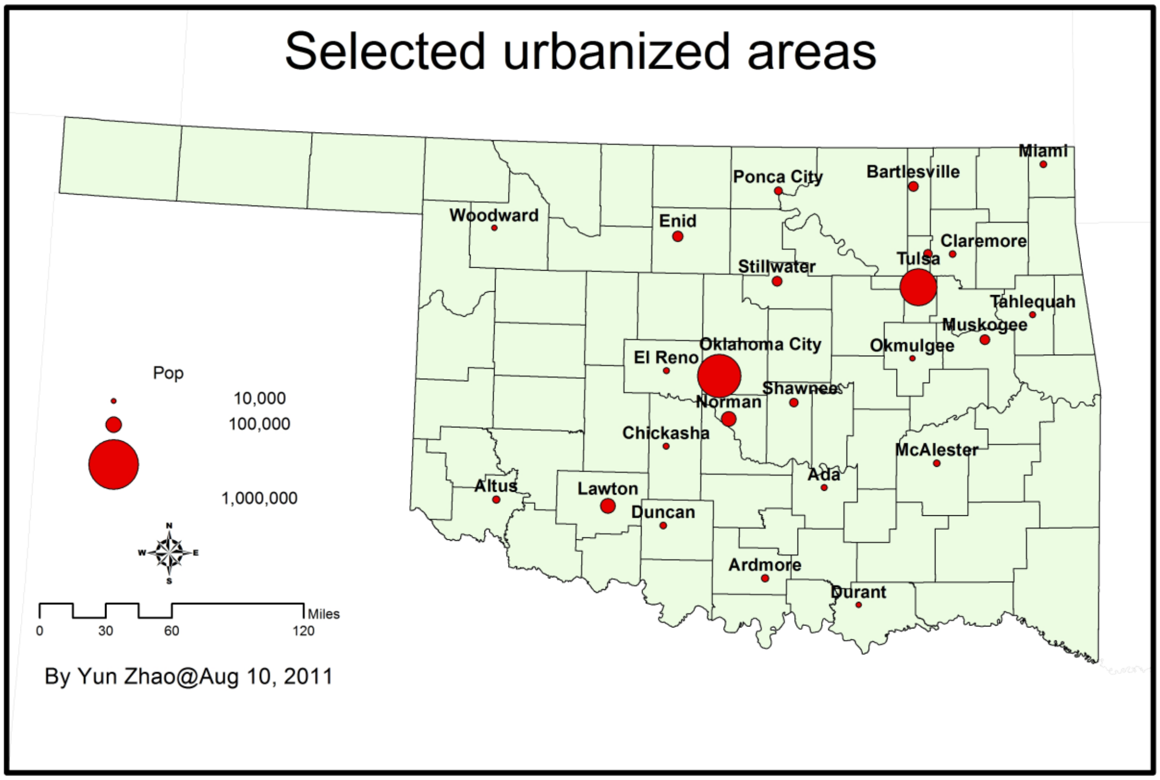

Fig 3.4 Locations of selected UAs/UCs.

3) Unsafe bridges selection

In this study, unsafe bridges are defined as bridges that have an extremely poor deck condition, and yet are still open to public traffic without any restrictions. Specifically, unsafe bridges that meet all the following criteria were chosen for this study:

a. It is located on the Base Highway Network, which includes "the through lane (mainline) portions of the NHS, rural/urban principal arterial system" and "ramps, frontage roads and other roadways are not included" (National Bridge Inventory Data Dictionary). Bridges on the Base Highway Network tend to have a more significant role than those not on the Base Highway Network.
b. It is open to the public with no restriction. Bridges that are closed to the public and open to public with certain restrictions tend to already have a decreased level of service and are thus not included in this analysis.
c. Bridges are on the highways rather than overpass the highways. While both conditions will have an impact on the performance of the highway system, the failure of bridges on the highway system will need a longer period to repair, which usually involves rebuilding of a new bridge. The failure of bridges that overpass highways, however, could be cleaned away from the highway in several days and would only cause a limited impact on the performance of highway networks. This study only considered the situation when a bridge will be closed for a longer period of time. For this reason, only bridges that are actually on the highways are considered.
d. Bridge deck conditions are classified as "3-SERIOUS CONDITION" or "2-CRITICAL CONDITION". Bridges are classified into 10 categories by FHWA, ranging from "9-EXCELLENT CONDITION" to "0-FAILED CONDITON". Bridges in Category"0-FAILED CONDITON" and "1-IMMINENT FAILURE CONDITION" are already closed so these two categories are not taken into consideration. Category 2 and 3 are recognized as the most dangerous bridges in this study.

e. Bridges on the US and State Highways must sit on the shortest paths that connect any pair of the 24 major cities. Otherwise, it might not affect the travel time and accessibility of selected cities.

When a bridge meets all of the above criteria, it is considered as an unsafe bridge in this study. Figure 3.5 shows the selected unsafe bridges in Oklahoma.

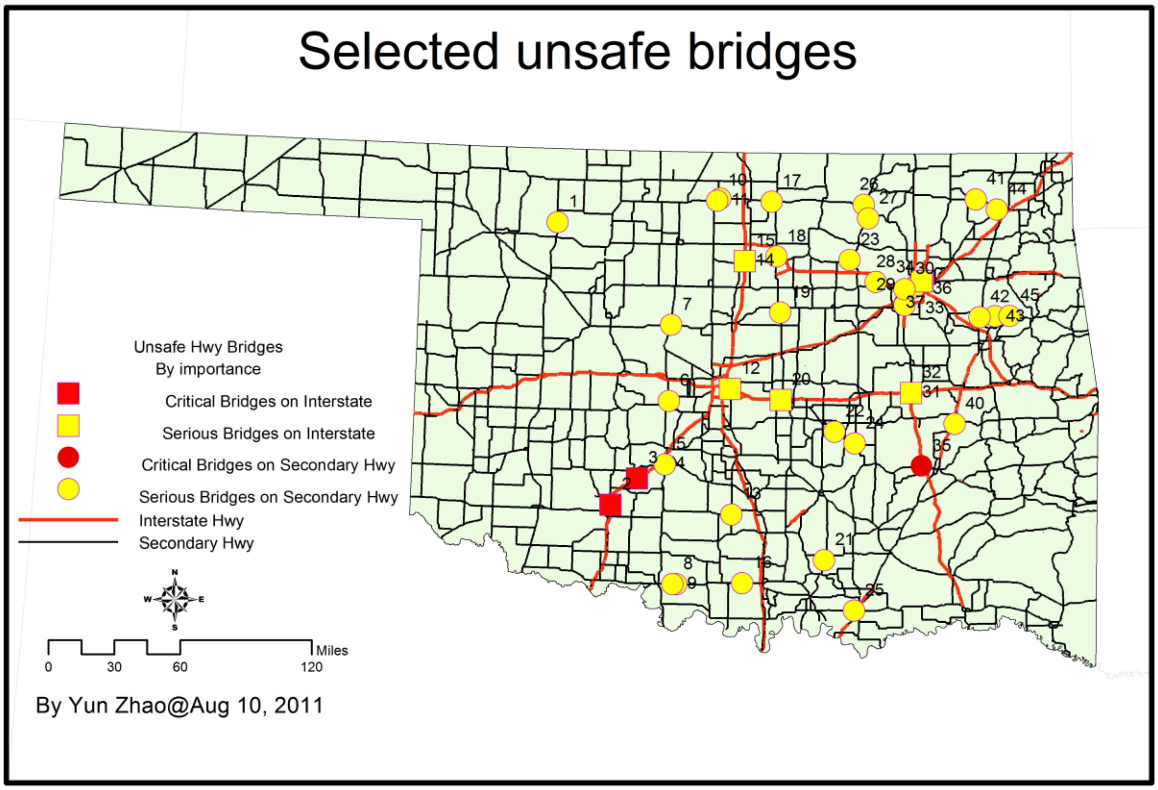

Fig 3.5 The locations and conditions of unsafe highway bridges in Oklahoma

There are 45 unsafe highway bridges selected in this study. Some of the bridges are close to each other and will generate the same results when either one of them is out of service. In this study, I refer to bridges that are close to each other and will cause the same degradation of the highway performance as one entity. For example, if Bridge A and Bridge B are close to each other and will have exactly the same impact on the performance of the highway system when failed, they two are considered as one entity in this study and are referred as Bridge A /B. In this study, there are 7 pairs of bridges that are considered as one entity to simplify the calculation of the analysis. These bridge pairs are Bridge 4/5, Bridge 8/9, Bridge 14/15, Bridge 31/32, Bridge 33/34, Bridge 36/37, and Bridge 38/39 in this study. Appendix I at the end of this paper provides detailed information for every bridge.

In conclusion, this chapter discussed the selected study area, the methods for assessing bridge importance, the collected data and the preparation of data for final analysis. A series of analyses then are carried out by applying the proposed methods to the prepared data. The analysis results and their interpretations are given in the following chapter.

CHAPTER IV

RESULTS AND FINDINGS

Starting with a detailed description of the calculation procedure, this chapter focuses on the demonstration of the final results and comprehensive interpretation of the results. Detailed information (e.g., their locations, year built, carried structure, etc.) of the unsafe bridges with a higher significance is also provided to help the readers to understand the results. Two ways of showing the results, which are table views and map views, are included and discussed in detail.

Calculation Procedure

As stated in Chapter III, two different measures, the increased travel cost measure and the decreased accessibility measure, will be used to evaluate the importance of bridges. The calculation of both measures requires travel time as a basic input. Hence, calculating the travel time before and after the failure of a bridge between each pair of the cities in the road network becomes the first step of the analysis.

The Network Analyst extension of ESRI's ArcGIS software package functions to calculate the shortest travel time path between a given set of origins and destinations in a network. The extension also reports the travel cost (e.g., distance, travel time) of each route in the resulting route attribute table. Therefore, this study uses the ArcGIS Network Analyst extension to derive the shortest travel time path between each pair of the selected cities in the Oklahoma highway network.

First, the original routes that connect all the OD pairs based on the original highway network are derived. Then, a point barrier is placed at one unsafe bridge at a time in the network to disable the use of that bridge in the following shortest path analysis. If necessary, detours will be automatically generated to avoid the disabled bridge. This step is repeated until all the unsafe bridges have been disabled once. After all the routes are derived, their travel time information is then exported from ArcGIS to Microsoft Office Excel for further manipulations. For the original network and each selected unsafe bridge, there is a corresponding 24 by 24 matrix which reveals the travel time between all the OD pairs, with one row/column representing one of the 24 selected cities. The travel time change for each OD pair before and after the failure of each bridge then can be derived by taking a matrix subtraction operation between the matrix corresponding to that bridge and to the original matrix. Having all the travel time changes information for all the bridges, further calculations to derive the measures can be carried out in Microsoft Office Excel directly following the formula 3-1 to 3-5 in Chapter III. All of the selected unsafe bridges are ranked by using unweighted travel time, weighted travel time, and accessibility decrease measures. The complete lists for each measure are included in Appendix III. Both table views and map views of the results are presented and interpreted, followed by a brief overview of the bridge locations.

All the 45 bridges are evaluated based on the methodology mentioned in Chapter III. Due to the pairing issue discussed at the very end of Chapter III, those 45 bridges are represented as only 38 points. Most of the bridges only show limited impact on the performance of the Oklahoma highway system. This chapter focuses only on the most significant bridges recognized by the three methods. More specifically, the top five most important bridges identified by each of the unweighted/weighted travel time increase measure and accessibility measure are discussed. Because some of the bridges are repeatedly identified by different methods, instead of 15, there are only a total of 9 bridges included in the three lists of the top five most important bridges. Moreover, there are two pairs of bridges involved in the 9 bridges, which reduced the 9 bridges into 7 “choke” points.

An Overview of Bridges Locations

It is necessary to provide the reader some basic information about the unsafe bridges. For complete information of all the unsafe bridges included in this study, please refer to Appendix I in the Appendices section. In this section, only the 9 bridges/7 “choke” points that are considered as the most significant bridges by the unweighted/weighted travel time increase measure and accessibility measure are included. Figure 4.1 and Table 4.1 shows the locations and detailed information for the bridges that are mentioned.

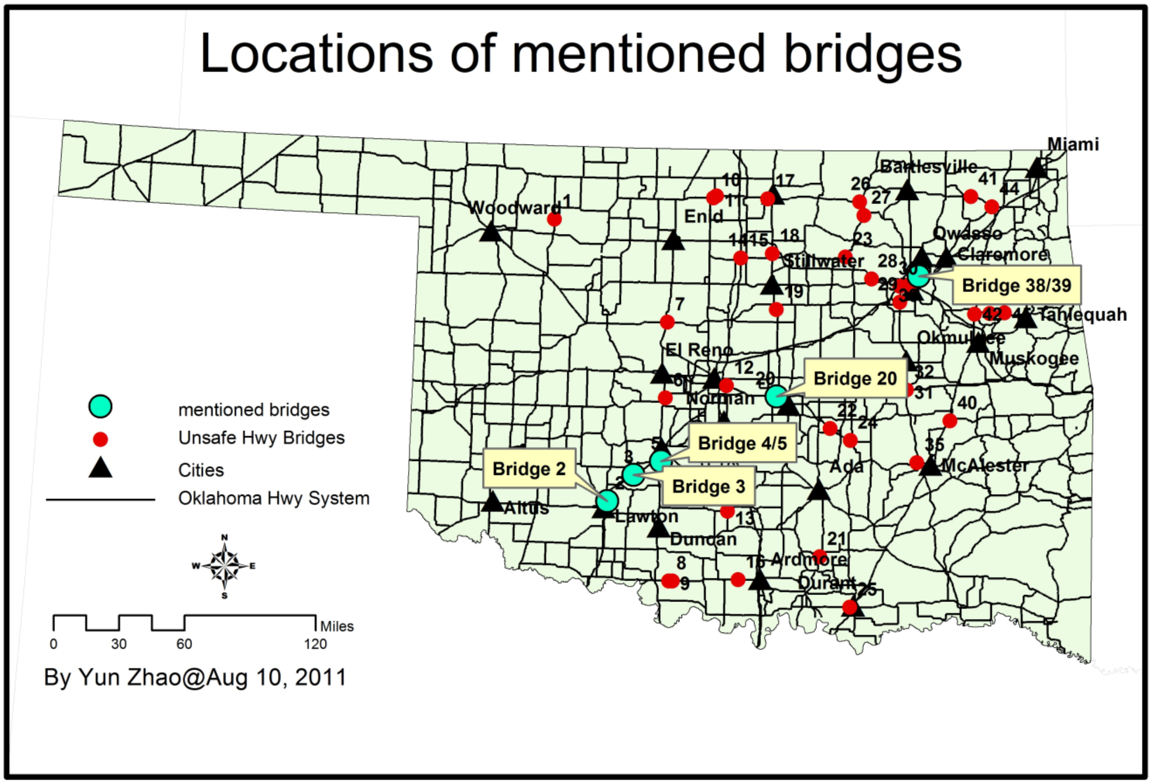

Fig 4.1 The locations of the selected unsafe bridges in Oklahoma

Table 4.1 Detailed information of the selected bridges discussed

Bridge Number	Carried by Structure	Narrative Description of Location	Features (River or Street) Intersected	Rank under Unweighted Travel Time Measure	Rank under Unweighted Travel Time Measure	Rank under Unweighted Travel Time Measure
Bridge 2	I-44 SB	12.4 miles north of State Highway 36	Medicine Creek & RD. UND	2nd	2nd	2nd
Bridge 3	BAILEY A TP (I-44)	T/P.BR.NO.45.47	LITTLE WASHITA RIVER	4th	3rd	6th
Bridge 4/5	U.S. 81	18.4 miles north of Stephens C/L (Closed Loop)	LITTLE WASHITA RIVER	3rd	5th	3rd
Bridge 20	I-40	7.6 miles east of OK C/L (Closed Loop)	CO. RD. UNDER	7th	4th	4th
Bridge 26	U.S. 60	WEST EDGE OF PAWHUSKA	BIRD CREEK	5th	12th	11th
Bridge 29	U.S. 75	5.2 miles north of JCT SH-67	NICKLE CREEK	10th	7th	5th
Bridge 38/39	U.S. 169	2.8 miles north of JCT I-44	PINE ST UNDER	1st	1st	1st

Results and Interpretation by Table View

Table views of the results have the advantage of being concise and comparable. The results from unweighted increased travel time measure, weighted increased travel time measure, and accessibility measure are presented in the table view and followed by interpretation.

1) Results of unweighted increased travel time measure

Unweighted increased travel time measure captures the increased travel time in minutes when one bridge is out of service. The unweighted measure assumes only one traveler will travel from each origin. It thus is an effective indicator for individual travelers. The five most important bridges under this measure are Bridge 38/39, Bridge 2, Bridge 4/5, Bridge 3, and Bridge 26. When one bridge fails, not all the city pairs are affected. For example, the failure of Bridge 3 that is located on the H.E. Bailey Turnpike between Lawton and Chickasha will increase the travel time between Lawton and Chickasha/Oklahoma City, while the travel time from Stillwater to Tulsa remains the same under Bridge 3's failure. That is the reason why a column "Numbers of city pairs affected", which indicates the city pairs that will be influenced because of the given bridge's failure, is listed in the table. Considering that there are a total of 276 different combinations of city pairs in this study, the numbers in this column provide an overview of the impact extent for each given failed bridge.

Table 4.2 The five most important bridges under the unweighted measure

Unweighted Travel Time Change	**Total Travel Time (in minutes)**	**Total Increased Travel Time (in minutes)**	**Numbers of city pairs affected**	**Average affected time per pair (in minutes)**
Original Network	39447.66	0	0	0
After B38/39 removed	40039.24	591.58	98	6.04
After B2 removed	39978.68	531.03	68	7.81
After B4/5 removed	39768.83	321.17	34	9.45
After B3 removed	39665.90	218.245	68	3.21
After B26 removed	39569.46	121.805	14	8.70

As stated above, the unweighted measure assumes only one traveler will travel from each origin. In Table 4.2, the column of "Total Travel Time" means the sum of travel time of each individual traveler from each origin to each destination. The "Total Increased Travel Time" is an aggregated measure that means the sum of the increased travel time of every single pair of trips.

Table 4.2 shows that Bridge 38/39 can cause the highest increased travel time to the whole highway network system, which is 591.58 minutes. Moreover, the failure of Bridge 38/39 will affect 98 pairs of cities, which is the highest number in the given bridges. While this means the failure of Bridge 38/39 will influence a wide range of city pairs, it also means that the impact will be distributed to a large group of cities. This will actually decrease the average impact to each single pair of cities. Contrary to the large amount of city pairs that will be affected by the failure of Bridge 38/39, the failure of Bridge 4/5 or Bridge 26 will affect a relatively small group of city pairs and yield a higher impact to each single pair of cities. A small value in "Average affected time per pair" column indicates that it is relatively easy for people to find similar alternative routes to avoid the failure of the corresponding bridge, while a large value indicates that it will be more difficult for people to find an alternative route. As shown in Table 4.2, it is difficult for travelers to find comparable alternative routes when Bridge 4/5 fails, while it is relatively easy for people to find similar substitute routes when Bridge 3 fails.

2) Results of weighted increased travel time measure

The weighted increased travel time measure takes account of traffic flow information between each city pair and provides a measure at the system-wide level. The traffic flow between a given pair of cities is estimated based on formula 3.3, which is $w_{ij} = {P_i P_j}/{t_{ij}^2}$. In this formula, w_{ij} represents the traffic flow simulation between city i and j; t_{ij} means the travel time by a single traveler under free flow condition from city i to city j, and $P_{i/j}$ represents the population of city i/j. A complete matrix which contains the traffic flow estimations for all city pairs is included in Appendix II. For the purpose of demonstration, Table 4.3 only shows the estimated traffic flow of a small selected group of cities. This study only cares about inter-city traffic. The traffic flow is arbitrarily set to zero for the same city, like Ada to Ada or Chickasha to Chickasha in Table 4.3. According to this gravity model, city pairs with higher populations and shorter travel time to each other tend to have higher volume of traffic flow. This is the reason why OKC and Tulsa have the highest traffic flow of 48888884 under this formula, which is because of the high populations of these two cities and their relatively short travel time by using Interstate 44. The traffic flow between OKC and Shawnee is also relatively high at 9866864, because these two cities are relatively close to each other and the travel time is short. The smallest travel flow in this demonstration is between Chickasha and Durant, which is 9470. This is because those two cities both have a relatively small population, and they are not close to each other.

Table 4.3 A demonstration of traffic flow information simulated by gravity model.

Traffic Flow	Ada	Chickasha	Lawton	OKC	Shawnee	Stillwater	Tulsa
Ada	0	32300	86577	1161860	134922	43938	608033
Chickasha	32300	0	803222	4995098	73161	47485	454885
Durant	32776	9470	43850	376729	21327	13069	246725
OKC	1161860	4995098	8305935	0	9866864	6522504	48888884
Stillwater	43938	47485	145686	6522504	301306	0	3268496
Tulsa	608033	454885	1550838	48888884	2203918	3268496	0

Using estimated traffic flow information as the weighting factors, the five most important bridges under the weighted increased travel time measure are Bridge 38/39, Bridge 2, Bridge 3, Bridge 4/5, and Bridge 20. Table 4.4 gives more complete information for the top five most important bridges based on this measure.

Table 4.4 The five most important bridges under the weighted measure

Weighted Travel time Change	Total Travel Time	Total Increased Travel Time	Percentage Change
Original network	35018205480	0	0.00%
After B38/39 removed	37136995278	2118789798	6.05%
After B2 removed	35530114297	511908816.6	1.46%
After B3 removed	35202409825	184204345.1	0.53%
After B20 removed	35166560530	148355049.7	0.42%
After B4/5 removed	35145550582	127345101.9	0.36%

It is easy to see that the results from the weighted methods and the unweighted methods give similar rankings. Bridge 38/39 is still considered as the most important bridge under this measure, followed by Bridge 2. Bridge 4/5 and Bridge 3 both ranked at the top five most important bridges under these two measures. Bridge 20 is included as the fourth significant bridge under the weighted measures, while Bridge 26 dropped out. With a close examination of those two results, however, it shows the most obvious difference is that Bridge 38/39 becomes much more critical under the weighted measures than in the unweighted measures. In the unweighted measure, B38/39 ranks No.1 with a total of 591 minutes delay. It is 60 minutes more than that of Bridge 2, which has a delay of 531 minutes. The gap between Bridge 38/39 and Bridge 2 is relatively small. Under the weighted measure, however, the removal of Bridge 38/39 will cause a 6.05% increase of travel time system-wide, while the removal of Bridge 2 will only cause a 1.46% increase to the travel time of the whole system. While Bridge 2 still ranks No.2 under the weighted measure, it is actually far less significant than Bridge 38/39.

The reason for the huge increase of the importance of Bridge 38/39 under the weighted measure will certainly have connections with the traffic flow. When referring to Figure 4.1 and Table 4.1 for bridge locations, it is easy to notice that Bridge 38/39 is located on I-44 between Owasso/Claremore and Tulsa, while Bridge 2 is located on I-44 between Lawton and Chickasha. While Table 4.3 shows the traffic flow between Lawton and Chickasha is 803,222, the traffic flow between Owasso/Claremore to Tulsa are 36,465,185 and 11,424,575 respectively (see the complete traffic flow matrix in Appendix II). The high volume of estimated traffic flow on Bridge 38/39 gives the increased time a much higher weight and makes it much more critical under the weighted measure.

3) Result of accessibility measure

Accessibility measures reflect the importance of bridges by capturing the total accessibility decrease for all the cities. The table below gives the five most important bridges determined by the accessibility measure.

Table 4.5 The five most important bridges under the accessibility measure

Accessibility Changes	Original Accessibility	Changed Accessibility	Absolute Accessibility Change	Percentage Accessibility Change
B38/39	502412	477046	25366	5.05%
B2	502412	497454	4958	0.99%
B4/5	502412	499454	2958	0.59%
B20	502412	499932	2480	0.49%
B29	502412	500320	2092	0.42%

Under the accessibility measures, Bridge 38/39 is still considered as the most important bridge. Failure of this bridge will cause a system-wide 5.05% accessibility decrease. Bridge 2 remains the second most important bridges by decreasing the accessibility by 0.99%. Bridge 4/5, Bridge 20, and Bridge 29 complete the third to fifth places in the list. Based on this analysis, Bridge 38/39 can cause an exceptional high system-wide decrease in accessibility, which is more than five times comparing that of Bridge 2 that is in the second place.

While the system-wide accessibility decrease gives a general idea of how significant a bridge is to the whole system, it gives no information on how the impact is distributed to each affected cities. For example, the 0.99% decrease in system-wide accessibility caused by Bridge 2 could be distributed only a few cities, which might cause the decrease of accessibility for each city. On the other hand, the 0.99% decrease could as well be distributed to a large amount of cities, which will only generate a moderate decrease for each pair of the cities. Because no huge accessibility changes for any particular cities are desired, this information needs to be captured as well. This could be achieved by inspecting the accessibility changes for each city at the local scale. Table 4.6 shows the five highest accessibility changes of a single city that could be caused by one particular bridge's failure.

Table 4.6 Particular city and bridge combinations.

City and Bridge Combination	Percentage Accessibility Decrease
Owasso and B38/39	32.72%
Claremore and B38/39	29.96%
Duncan and B4/5	14.32%
Lawton and B2	13.66%
Miami and B38/39	11.98%

It is obvious that Bridge 38/39's failure will cause a considerable accessibility decrease to both Owasso and Claremore. Owasso has a higher accessibility decrease with the failure of Bridge 38/39, which is 32.72%; Claremore has a 29.96% decrease in accessibility. Duncan, Lawton, and Miami also will suffer a more than 10% decrease in accessibility due to the failure of particular bridges.

Results and Interpretations by Map View

While a table view of the results will demonstrate a general idea of the impact of a failed bridge by each measure, it gives only numbers and thus a limited ability to show the reasons behind the numbers. A map view, however, is a better way to demonstrate the reasons that leads to the numeric changes in the table view.

Here I choose the four bridges that are brought up frequently by the table view. Those bridges, in sequence of their importance revealed by the table view, are Bridge 38/39, Bridge 2, Bridge 4/5, and Bridge 3. The maps for each bridge will focus on how the routes have changed before and after the given bridge is removed.

1) Map view of route changes if Bridge 38/39 collapsed

The removal of Bridge 38/39 will highly influence the accessibility of Claremore, Owasso, and Miami (Figure 4.2). From Figure 4.2 and Figure 4.3, we can see that Miami, Owasso, and Claremore all depend heavily on Mingo Valley Expressway (also known as US Highway 169) to reach other major cities. The failure of Bridge 38/39, which is located right on Mingo Valley Expressway, will force those three cities to change their routes to many other cities. The red route is used as the major substitute, which will lead to a delay in travel time ranging from 5.59 minutes to as long as 25.70 minutes. The failure of Bridge 38/39 will severely increase the travel time from those three cities to Tulsa. The increased travel time is 25.70 minutes for Claremore, 23.22 minutes for Owasso, and 18.69 minutes for Miami. This will lead to serious consequence. Owasso and Clare more are close to Tulsa, and the traffic flow between those two cities and Tulsa tends to be high according to the gravity model. The accumulated increased travel time will be tremendously high when the weight of traffic count is applied. Thus, Bridge 38/39 will be the last bridge that we can afford to lose.

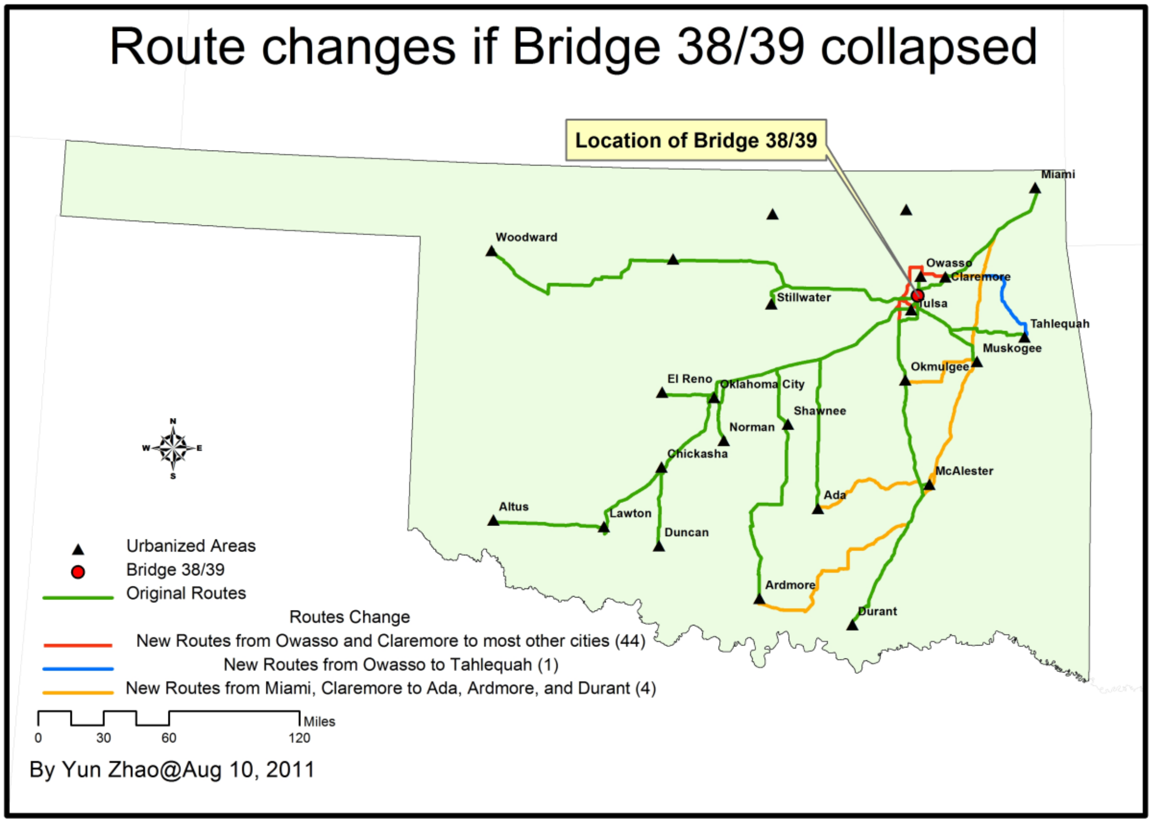

Fig 4.2 Route changes comparison before and after Bridge 38/39 is removed

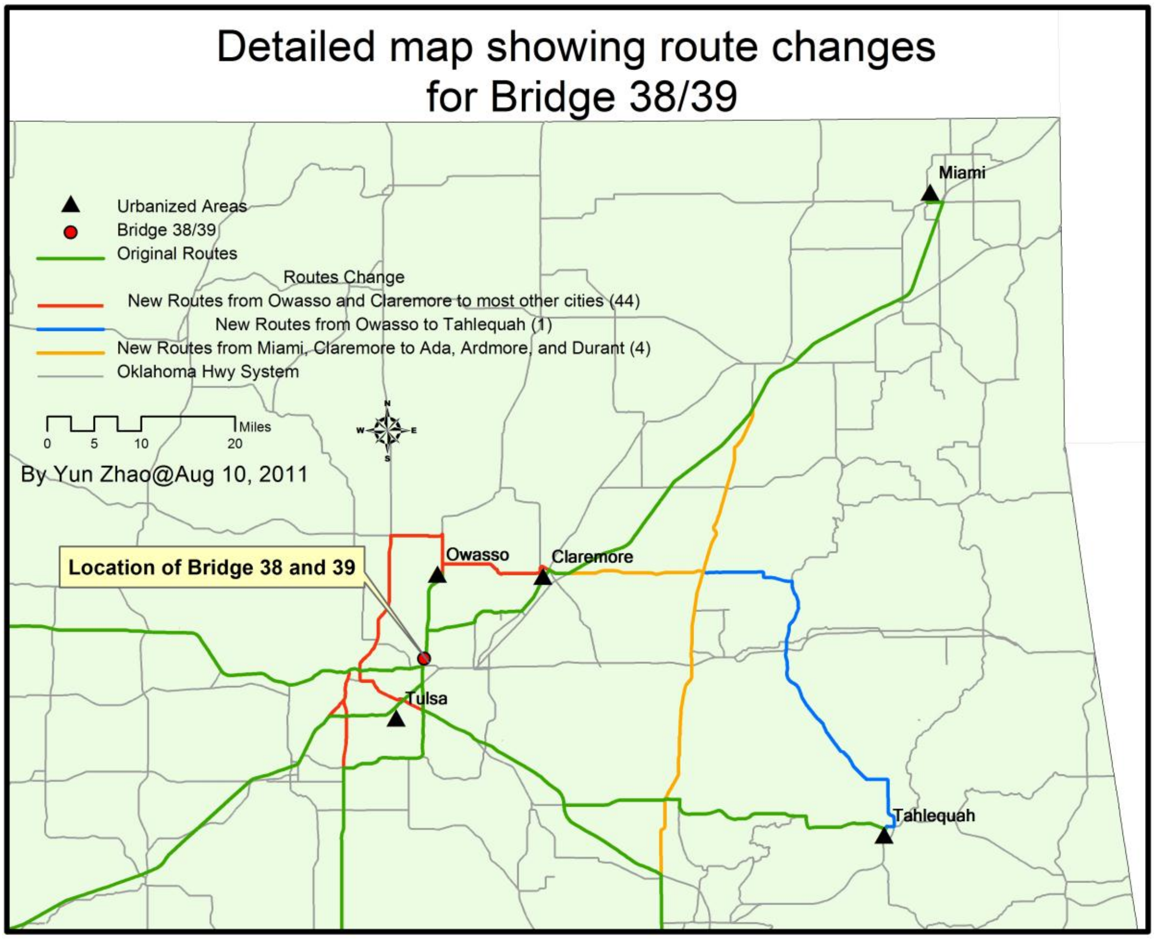

Fig 4.3 A detailed map view of route changes of Bridge 38/39.

2) Map view of route changes if Bridge 2 collapsed

Bridge 2 is located on Interstate 44 and is 12.4 miles north of the intersection of State Highway 36. As it is located near Lawton, the shortest routes connecting Lawton and many other cities will go through Bridge 2. Also, as Altus is west of Lawton, many of the shortest paths to Altus use this bridge as well. Figure 4.4 shows the location of Bridge 2 and the routes before and after Bridge 2 is removed among major cities. Before Bridge 2 is removed, there are 34 shortest paths (SP) for 34 OD pairs that use Bridge 2 (see the green lines in the map). 18 SPs are related to Lawton, while the other 16 are related to Altus. It is then obvious that if Bridge 2 is out of service, the impact will mainly be distributed to Lawton and Altus. Other cities will suffer a little for longer routes to Lawton and Altus, while Lawton and Altus will suffer a lot for longer routes to 18 and 16 other cities respectively.

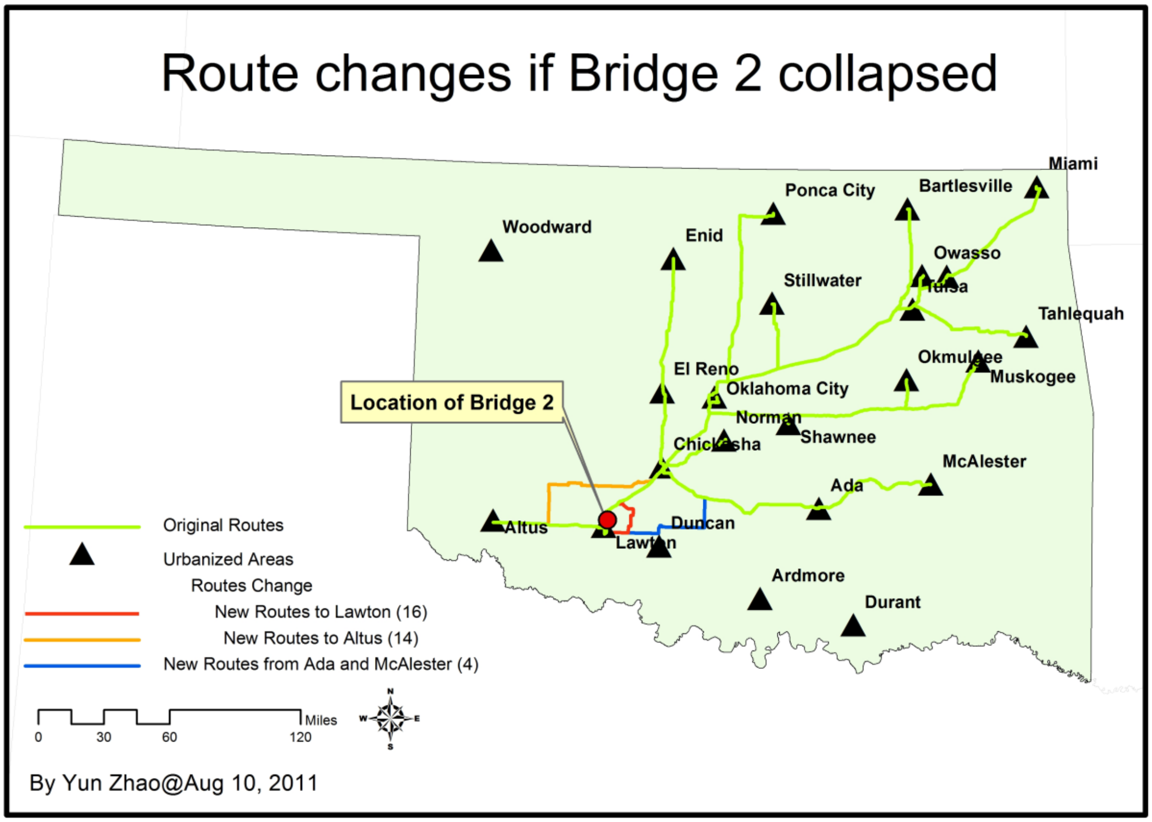

Fig 4.4 Route changes comparison before and after Bridge 2 is removed

After Bridge 2 is removed, three new routes emerge as substitutes for the original routes. The red route represents the new routes for 16 cities to Lawton, which has an increased travel time of 18.33 minutes. The yellow route represents substitute routes to Altus, which has an increased travel time of 14.12 minutes. The blue route represents the substitute routes from Ada/McAlester to Altus/Lawton, which has an increased travel time of 11.92 minutes to Altus and 8.06 minutes to Lawton.

While the red route represents a typical detour to avoid the failure of Bridge 2 from most cities to Lawton, the yellow route becomes a faster route to reach Altus rather than the red route that takes Lawton as a via point. Travelers from the 14 affected original cities will save 4 minutes if they choose the yellow route rather than the red route to Altus. Ada and McAlester are different from the majority: their original routes to Lawton and Altus are different from other cities and their new detours to Altus and Lawton increased a small amount of travel time, which are 11.93 minutes to Altus and 8.06 minutes to Lawton. This is determined by their relative geographic locations to Lawton and Altus, as well as the distribution of Oklahoma highway network.

Figure 4.4 suggests that locations of origin and destination do matter when determining the detours. Suppose that Bridge 2 fails, the red route will more likely to be chosen as the detour to avoid Bridge 2. However, Figure 4.4 indicates the fact that the yellow route is actually a better alternative route to avoid Bridge 2 for traffic from the 14 cities that consider Altus as their destination. The yellow route could save them more than 4 minutes in travel time than the red route does.

3) Map view of route changes if Bridge 4/5 collapsed

Bridge 4/5 is heavily used to connect Duncan to other cities in Oklahoma. The failure of Bridge 4/5 will severely influence the accessibility of Duncan from other cities in Oklahoma, as shown in Table 4.6 earlier in this chapter. Four new detours emerge as the alternatives to the original routes (Figure 4.5). The red route is used by 11 out of the 17 cities that are affected. It takes an extra 23.88 minutes. The yellow one is used only by the traffic from Norman to substitute the original route, which takes an extra time of 10.14 minutes. The blue route is used by Muskogee, Okmulgee, Shawnee, and Tahlequah, and it increases the travel time by 10.93 minutes for Muskogee and Okmulgee, 6.80 minutes for Shawnee, and 13.01 minutes for Tahlequah. The increased time for those four cities is not all the same because their original routes to Duncan are different.

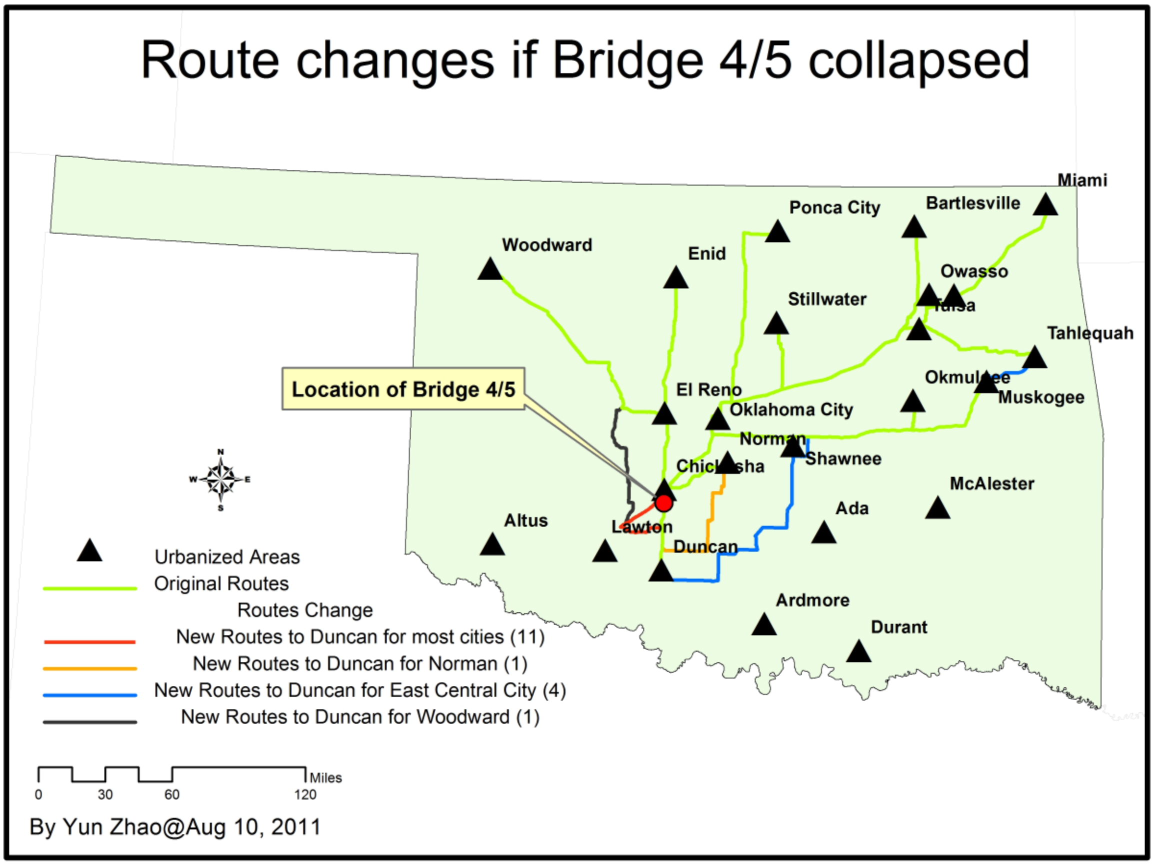

Fig 4.5 Route changes comparison before and after Bridge 4/5 is removed

4) Map view of route changes if Bridge 3 collapsed

A detour for Bridge 3 is obvious through the map view. It is clear that people from the 17 cities located at the northeast of Bridge 3 can simply choose a short detour to reach Lawton and Altus (Figure 4.6). The traffic simply shifts from Interstate 44 to US Highway 277 to avoid the failure of Bridge 3. The detour takes an extra time of 6.42 minutes.

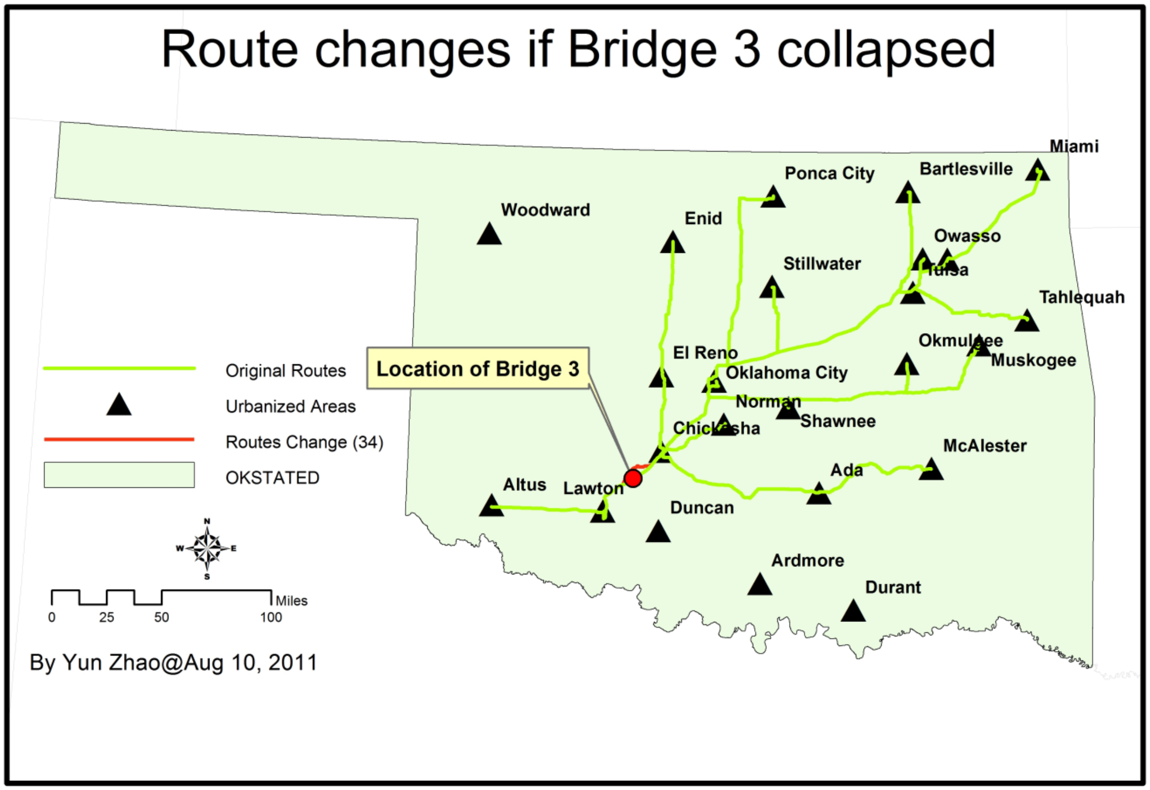

Fig 4.6 Route changes comparison before and after Bridge 3 is removed

In conclusion, this study applied two methods, which are the increased travel time and decreased accessibility, to assess the importance of unsafe highway bridges in Oklahoma. In the increased travel time method, this study further divided the method into unweighted travel time increase and weighted travel time increase. Each method has a different focus on the importance of bridges. This chapter demonstrates the calculation procedure and provides a thorough interpretation of the results. This chapter shows that even though these methods can capture different aspects of the highway bridge importance, they actually give similar results in the end. All the methods recognize Bridge 38/39 as the most critical bridges, followed by Bridge 2. Bridge 4/5 is always included as the top five most important bridges with different rankings from the 3rd place to the 5th place. Bridge 3, Bridge 20, Bridge 26, and Bridge 29 are also mentioned at least once as the top five most important bridges by different methods.

While the results point out the critical unsafe bridges that need to be given high priority for repair and maintenance, this paper further demonstrates that increased travel time measures and accessibility measures are simple and effective tools to identify the critical network links. While the table view of the results provides concise and comparable numbers to describe the importance of the bridges, the map view of the results gives more detailed intuitive presentation on the actual route changes that eventually lead to the changes of the numbers in the table view. The map view also demonstrates that origin and destination of the traffic can significantly affect the choices of detours to bypass a failed bridge.

CHAPTER V

CONCLUSION

This study uses three measures, namely the unweighted travel cost increase measure, the weighted travel cost increase measure, and the decreased city accessibility measure, to evaluate how a failed bridge may affect the highway network in Oklahoma. These three measures are used to rank the importance of a selected set of unsafe bridges on the Oklahoma highway network. Based on the analysis results, critical bridges that may cause relatively high impact to the highway performance are identified and discussed in more detail. Both table views and map views of the analysis results are presented to facilitate the understanding of the importance of the critical bridges and the potential consequences of their failure to the highway network.

Each of the measures focuses on different aspects of the performance of the highway network. The unweighted travel time increase measure evaluates the scenario when there is only one traveler traveling between each pair of origin and destination. Thus it offers a straightforward indicator of the bridge importance for individual travelers. The weighted travel time increase measure, however, takes the traffic flow information into consideration. The results based on this measure are useful to the state transportation planners, who consider the system performance of the transportation network more significant. The accessibility measure can reveal how cities will be affected by the failure of each unsafe bridge. Therefore, the accessibility measures will provide useful information for city planners. Finally, as all three measures provide an evaluation on the potential consequences caused by the failure of any given unsafe bridge, they present a useful tool to suggest the maintenance prioritization of the unsafe highway bridges under limited funds.

Overall, the three methods offer simple but rather effective approaches to the evaluation of bridge importance. The amount of data required to perform the analysis based on the three measures are relatively small: only travel time information for all the Origin-Destination (OD) pairs before and after the removal of each unsafe bridge, the population of the OD pairs, the distribution of the highway network of the study area with speed limit information, bridge deck condition, etc. are needed to perform the analysis. The results are demonstrative and relatively consistent: all three methods identify Bridge 38/39 as the most important unsafe bridge, followed by Bridge 2. The consistent results indicate the critical role of these bridges in the Oklahoma highway network. The results could be used by ODOT for a better decision making on the prioritization of bridge maintenance. It may be especially useful provided that funds for highway bridge maintenance are always limited.

Limitations and Future Directions

Given the constraints of resources and time, this research has certain limitations and shortcomings. Some major limitations are introduced by the predetermined settings of the selected study scenarios and the methodology used in this study.

Limitation 1. This study did not take through traffic into consideration. Considering Oklahoma is located in the South Central region of the United States and constitutes a great portion of the Historic Route 66, which connects the East and West Coasts, the absence of through traffic will not provide a complete picture of the traffic patterns in the state.

Limitation 2. An uncongested condition is assumed through the study. This is also not the case in reality. To consider congestion, road capacity data, real-time road volume data, and the relationship between the actual speed and the ratio of volume/capacity should be obtained for each segment of the highway system. Such data may not always be available and collecting the data is an extremely time-consuming and expensive task. Due to the limited resources, the congestion scenario was not included in this study. However, with the necessary data available, an evaluation under the congested network will be more realistic and can provide improved suggestions for road/bridge maintenance prioritization decisions.

Limitation 3. A simplified version of the transportation network was assumed in this study. First, no “divided highway” information was presented. The dataset in this study represents all the highway segments as one single line. In the real world, however, highways could be divided, which requires a more accurate representation of two separate lines, one for each direction. This simplification may exaggerate the impact of the failure of a bridge if the bridge is located on one direction of the divided highways. In this case, the failure of the bridge should only affect the traffic flow in one direction. In this study, however, any bridge’s failure will affect traffic on both directions. Actually, Bridges 4 and 5, Bridges 14 and 15, Bridges 31 and 32, and Bridges 38 and 39 are all pairs of bridges that are located on different directions of the same divided highways segments. Second, no real traffic count information is considered. This may decrease the credibility of the traffic count generated by the gravity model, because real-world traffic count data could be used to better calibrate the gravity model used in this study. Moreover, no information on the separation of trucks and passenger vehicles are available in this study. Given that 1) trucks wear out the road much more heavily, and 2) the delay of business trucks will usually generate a higher economic loss, it would be desirable to separate trucks from other traffic when evaluating the vulnerability of a road network.

The incorporation of through traffic will make this study more realistic, provided that the highway system in Oklahoma does support a high volume of through traffic. There are two possible ways to estimate through traffic and take it into consideration. The first way is to use the Annual Average Daily Traffic data, which is included in the road shapefile provided by the Oklahoma Department of Transportation. However, certain methods and assumptions need to be established to separate in-state traffic and through traffic. More research needs to be done to derive such methods in future studies. The second way of doing this is to keep using the gravity model for the estimation of traffic flow information while adding several hypothetical origins and destinations (ODs) at the border of Oklahoma as ODs of through traffic. The problem then will become how large those ODs should be. Those two problems will provide two major directions for future studies.

Congested scenarios need to be taken into consideration to make this study more practical. The congested scenarios will more likely happen on 1) highways around and within the urban and suburban areas, 2) detours that will need to handle more traffic flow than they are originally assigned. The workload of gathering relevant information related to congestion could be greatly reduced if the focus areas for congestion could be successfully reduced.

Real traffic flow data between OD pairs need to be obtained to calibrate the gravity model for more precise scale factor α and distance impedance index β. Future studies may include real-world data collection of traffic flow among OD pairs.

A comprehensive gathering of business truck information should be carried out to separate trucks from other passenger cars. This will require information about the locations of warehouses, store locations, truck schedules and routes, etc.

Extrapolation

The highway system of the United States was mainly built several decades ago when there was generally less traffic. While the condition of the highway deteriorates as time goes by, the traffic amount shows no sign of decrease and is even increasing. According to the AASHTO, “every mile of the Interstate highway sees 10,500 trucks a day” (AASHTO 2009, vii). While the bridges at that time were designed to have a lifespan of roughly 50 years, a number of bridges have exceeded their expected lifespan (Transportation for America 2011, 4). And the American bridges already have an average age of 42 years (Transportation for America 2011, 4). Urgent needs are present for a higher budget to improve the condition of the aging American highway system. The ultimate goal of this study is to draw more attention on the worn infrastructure from both the public and the government. On the one hand, more funds on maintenance need to be scheduled; on the other hand, regulations should encourage other modes of ground transportation of goods and people to reduce the stress on the old and fragile highway network system.

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APPPENDICES

Appendix I. Detailed Information of selected unsafe highway bridges in this study

Bridge Identifier	Structure Number (Unique)	Features Intersected	Facility Carried by Structure	Location	Year Built
1	136900000000000	CIMARRON RIVER	U.S. 281	0.9 MI N MAJOR C/L	1956
2	144650000000000	MEDICINE CREEK & RD. UND	I-44 SB	12.4 MI N OF SH 36	1959
3	161470000000000	LITTLE WASHITA RIVER	BAILEY A TP (I-44)	T/P.BR.NO.45.47	1964
4	139270000000000	LITTLE WASHITA RIVER	U.S. 81	18.4 MI N STEPHENS C/L	1957
5	139280000000000	LITTLE WASHITA RIVER	U.S. 81	18.4 MI N STEPHENS C/L	1957
6	135370000000000	S. CANADIAN RIVER	U.S. 81	21.5 MI N US62	1955
7	045910000000000	UNCLE JOHN'S CREEK	S.H. 33	.5 MI E JCT US 81	1935
8	037690000000000	WEST MUD CREEK	U.S. 70	6.3 mi E jct US81	1932
9	037540000000000	CREEK	U.S. 70	8.0 mi E jct US81	1932
10	042330000000000	POND CREEK	U.S. 60	1.5 MI E OF JCT SH 74	1934
11	040010000000000	BOGGEY CREEK	U.S. 60	4.2 MI W KAY C/L	1933
12	151790000000000	FAU 9440 (SE 15 ST) UND	I-40 EB	2.6 MI E OF JCT I35	1960
13	130650000000000	WEST ROCK CREEK	S.H. 29	8.8 MI E STEPHENS CO	1953
14	153340000000000	U.S. 64 (FIR ST.) UND	I-35	1.0 MI N JCT US 77	1961
15	153350000000000	U.S. 64 (FIR ST.) UND	I-35	1.0 MI N JCT US 77	1961
16	034350000000000	COTTONWOOD CREEK	U.S. 70	14.0 mi E Jefferson C/L	1931
17	126220000000000	BOIS D'ARC CREEK	U.S. 60	12.9 MI E JCT I 35	1951
18	055010000000000	BLACK BEAR CREEK O'FLOW	U.S. 177	2.1 MI N JCT US64	1937
19	045820000000000	DUGOUT CREEK	U.S. 177	1.1 MI N LINCOLN C/L	1935
20	151150000000000	CO. RD. UNDER	I-40	7.6 MI E OK C/L	1960

Bridge Identifier	Structure Number (Unique)	Features Intersected	Facility Carried by Structure	Location	Year Built
21	033600000000000	BIG SANDY CREEK	S.H. 99	1.8 MI S JCT SH7	1931
22	136530000000000	CRI & P R.R. UNDER	U.S. 270	6.6 MI SE SH 3	1956
23	155340000000000	PEDESTRIAN UNDER	U.S. 64	US 64; 0.2 MI S JCT SH 99	1962
24	155330000000000	CRI & P R.R. UNDER	U.S. 270	3.4 MI SE SEMINOLE CL	1962
25	065860000000000	BLUE RIVER	U.S. 70	7.7 MI E JCT US 69 BUS	1938
26	141990000000000	BIRD CREEK	U.S. 60	WEST EDGE OF PAWHUSKA	1958
27	050190000000000	ABANDONED R.R. UNDER	S.H. 99	11.6 MI N SH 20	1936
28	157670000000000	S.H. 151 UNDER	U.S. 64	0.3 MI SE OSAGE C/L	1963
29	136570000000000	NICKLE CREEK	U.S. 75	5.2 MI N JCT SH-67	1956
30	183420000000000	S.W.BLVRD.&R.R.UNDER	U.S. 75	2.2 MI N JCT I-44	1972
31	157720000000000	COAL CREEK	I-40	5.9 MI E OKFUSKEE CO	1963
32	157730000000000	COAL CREEK	I-40	5.9 MI E OKFUSKEE CO	1963
33	164320000000000	PITTSBURG AVE. UNDER	S.H. 51	1.3 MI SE 21 ST	1965
34	164330000000000	PITTSBURG AVE. UNDER	S.H. 51	1.3 MI SE 21 ST	1965
35	050330000000000	COAL CREEK	U.S. 270	13.2 MI E HUGHES C/L	1936
36	169750000000000	MINGO ROAD UNDER	I-244	6.26 MI E JCT I 444	1967
37	167790000000000	U.S. 169 UNDER	I-244	6.69 MI E JCT I 444	1966
38	157780000000000	PINE ST UNDER	U.S. 169	2.8 MI N JCT I-44	1963
39	157770000000000	PINE ST UNDER	U.S. 169	2.8 MI N JCT I-44	1963
40	155850000000000	N. CANADIAN RIVER(EUFALA	U.S. 69	8.6 MI N PITTSBURG CO	1962
41	049650000000000	MADDEN CREEK	U.S. 60	0.6 MI E NOWATA C/L	1936
42	179150000000000	COAL CREEK	U.S. 69	6.4 MI N MUSKOGEE CO	1970

Bridge Identifier	**Structure Number (Unique)**	**Features Intersected**	**Facility Carried by Structure**	**Location**	**Year Built**
43	111240000000000	FOURTEEN MILE CREEK	S.H. 51	5.0 MI E WAGONER C/L	1949
44	073180000000000	S.L. & S.F. R.R. UNDER	U.S. 60	0.6 MI W JCT SH 66	1939
45	124710000000000	DOUBLE SPRING CREEK	S.H. 51	SH 51; 0.3 MI W JCT SH 80	1950

Appendix II. Traffic flow information derived by gravity model

Traffic Flow	**Ada**	**Altus**	**Ardmore**	**Bartlesville**	**Chickasha**	**Claremore**	**Duncan**	**Durant**
Ada	0	11115	54118	22628	32300	13264	30092	32776
Altus	11115	0	16420	11143	42206	6098	50052	5928
Ardmore	54118	16420	0	14569	37731	8116	77096	84266
Bartlesville	22628	11143	14569	0	17952	226418	15376	10631
Chickasha	32300	42206	37731	17952	0	10367	171832	9470
Claremore	13264	6098	8116	226418	10367	0	8608	6226
Duncan	30092	50052	77096	15376	171832	8608	0	16082
Durant	32776	5928	84266	10631	9470	6226	16082	0
El Reno	13634	17804	16272	20037	113882	11744	39231	5299
Enid	22157	25384	23947	90938	53411	40137	37188	9446
Lawton	86577	621181	153279	68752	803222	38498	1035294	43850
McAlester	74684	6998	23400	36609	12653	23715	13464	36425
Miami	6430	3692	4632	101229	5268	108238	4832	3979
Muskogee	39209	11940	21697	161369	19884	168292	16710	24496
Norman	240954	109241	252710	125848	787483	74165	251295	59062
OKC	1161860	850701	1347781	1536951	4995098	939045	1851063	376729
Okmulgee	22538	5279	9474	57852	10121	43921	7833	11215
Owasso	24301	10651	14348	699313	18791	1708389	15271	11087
Ponca City	13187	9909	12513	186654	18363	29316	14499	5272
Shawnee	134922	23180	59203	67921	73161	41694	41504	21327
Stillwater	43938	20267	29800	142239	47485	64724	32546	13069
Tahlequah	10708	4123	6819	47133	6194	72985	5519	7032
Tulsa	608033	231173	322419	7011105	454885	11424575	346627	246725
Woodward	2937	11677	3578	8812	6624	3240	5403	1555

Traffic Flow	El Reno	Enid	Lawton	McAlester	Miami	Muskogee	Norman	OKC
Ada	13634	22157	86577	74684	6430	39209	240954	1161860
Altus	17804	25384	621181	6998	3692	11940	109241	850701
Ardmore	16272	23947	153279	23400	4632	21697	252710	1347781
Bartlesville	20037	90938	68752	36609	101229	161369	125848	1536951
Chickasha	113882	53411	803222	12653	5268	19884	787483	4995098
Claremore	11744	40137	38498	23715	108238	168292	74165	939045
Duncan	39231	37188	1035294	13464	4832	16710	251295	1851063
Durant	5299	9446	43850	36425	3979	24496	59062	376729
El Reno	0	133952	176075	10977	5696	22114	355431	8082559
Enid	133952	0	166454	22999	19011	63174	277288	4101420
Lawton	176075	166454	0	45343	21601	74724	1128134	8305935
McAlester	10977	22999	45343	0	13601	191401	86351	877388
Miami	5696	19011	21601	13601	0	69903	35363	401231
Muskogee	22114	63174	74724	191401	69903	0	145579	1734362
Norman	355431	277288	1128134	86351	35363	145579	0	81599219
OKC	8082559	4101420	8305935	877388	401231	1734362	81599219	0
Okmulgee	11244	26977	35041	107729	13239	233999	79009	980047
Owasso	21513	73930	68303	44640	105188	337878	136395	1773002
Ponca City	22657	241472	64858	13663	18769	38208	135960	1833840
Shawnee	70291	85391	185936	69150	17567	108257	764798	9866864
Stillwater	63648	364359	145686	36334	25134	92954	390405	6522504
Tahlequah	6785	21554	24675	35718	33300	609586	42461	494876
Tulsa	538099	1594500	1550838	1155047	1309502	10418277	3453725	48888884
Woodward	11480	41449	29864	2802	2072	5995	30904	348723

Traffic Flow	**Okmulgee**	**Owasso**	**Ponca City**	**Shawnee**	**Stillwater**	**Tahlequah**	**Tulsa**	**Woodward**
Ada	22538	24301	13187	134922	43938	10708	608033	2937
Altus	5279	10651	9909	23180	20267	4123	231173	11677
Ardmore	9474	14348	12513	59203	29800	6819	322419	3578
Bartlesville	57852	699313	186654	67921	142239	47133	7011105	8812
Chickasha	10121	18791	18363	73161	47485	6194	454885	6624
Claremore	43921	1708389	29316	41694	64724	72985	11424575	3240
Duncan	7833	15271	14499	41504	32546	5519	346627	5403
Durant	11215	11087	5272	21327	13069	7032	246725	1555
El Reno	11244	21513	22657	70291	63648	6785	538099	11480
Enid	26977	73930	241472	85391	364359	21554	1594500	41449
Lawton	35041	68303	64858	185936	145686	24675	1550838	29864
McAlester	107729	44640	13663	69150	36334	35718	1155047	2802
Miami	13239	105188	18769	17567	25134	33300	1309502	2072
Muskogee	233999	337878	38208	108257	92954	609586	10418277	5995
Norman	79009	136395	135960	764798	390405	42461	3453725	30904
OKC	980047	1773002	1833840	9866864	6522504	494876	48888884	348723
Okmulgee	0	91362	16165	73956	53185	35932	3224605	2581
Owasso	91362	0	61575	78998	125227	80347	36465185	5663
Ponca City	16165	61575	0	51454	227891	12970	978816	12704
Shawnee	73956	78998	51454	0	301306	27330	2203918	8993
Stillwater	53185	125227	227891	301306	0	29579	3268496	16293
Tahlequah	35932	80347	12970	27330	29579	0	2129625	2110
Tulsa	3224605	36465185	978816	2203918	3268496	2129625	0	116340
Woodward	2581	5663	12704	8993	16293	2110	116340	0

Appendix III. Complete list of bridge ranking for unweighted and weighted increased travel cost measure, and accessibility measure.

Bridge Identifier	Unweighted Travel Time Increase	Ranking based on Unweighted Increase	Percentage Increase by Weighted Measures	Ranking based on Weighted Increased	Decreased Accessibility Percentage	Ranking based on Accessibility Measures
1	34	18	0.00%	30	-0.01%	30
2	531	2	1.46%	2	-0.99%	2
3	218	4	0.53%	3	-0.41%	6
4	321	3	0.36%	5	-0.59%	3
5	321	3	0.36%	5	-0.59%	3
6	120	6	0.06%	10	-0.14%	9
7	24	22	0.00%	28	-0.01%	25
8	9	30	0.00%	29	-0.01%	29
9	9	30	0.00%	29	-0.01%	29
10	34	19	0.00%	31	-0.01%	31
11	34	20	0.00%	32	-0.01%	32
12	22	26	0.34%	6	-0.37%	7
13	2	37	0.00%	37	0.00%	37
14	19	27	0.03%	15	-0.04%	16
15	19	27	0.03%	15	-0.04%	16
16	11	28	0.01%	26	-0.01%	26
17	6	34	0.00%	33	0.00%	35
18	5	35	0.00%	27	-0.01%	27
19	43	11	0.06%	11	-0.08%	13
20	88	7	0.42%	4	-0.49%	4
21	7	33	0.00%	36	0.00%	36
22	8	31	0.00%	34	0.00%	33
23	3	36	0.01%	25	-0.01%	28
24	8	32	0.00%	35	0.00%	34
25	88	8	0.03%	16	-0.08%	12
26	122	5	0.05%	12	-0.08%	11
27	10	29	0.01%	22	-0.01%	24
28	80	9	0.08%	9	-0.10%	10
29	60	10	0.18%	7	-0.42%	5
30	0	38	0.00%	38	0.00%	38
31	22	25	0.01%	18	-0.02%	23
32	22	25	0.01%	18	-0.02%	23
33	27	21	0.17%	8	-0.16%	8
34	27	21	0.17%	8	-0.16%	8

Bridge Identifier	**Unweighted Travel Time Increase**	**Ranking based on Unweighted Increase**	**Percentage Increase by Weighted Measures**	**Ranking based on Weighted Increased**	**Decreased Accessibility Percentage**	**Ranking based on Accessibility Measures**
35	36	15	0.01%	24	-0.02%	22
36	42	12	0.01%	17	-0.02%	19
37	42	12	0.01%	17	-0.02%	19
38	592	1	6.05%	1	-5.05%	1
39	592	1	6.05%	1	-5.05%	1
40	39	14	0.01%	23	-0.02%	20
41	35	16	0.01%	19	-0.02%	17
42	40	13	0.01%	21	-0.02%	21
43	23	23	0.03%	13	-0.07%	14
44	35	17	0.01%	20	-0.02%	18
45	23	24	0.03%	14	-0.07%	15

VITA

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Thesis: ASSESSING THE IMPACT OF POTENTIAL BRIDGE COLLAPSE ON ROAD NETOWRK VULNERABILITY: A CASE STUDY IN OKLAHOMA

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Major Field: Geography

Scope and Method of Study: This study applied three different measures, which are unweighted increased travel time, increased travel time weighted by traffic flow, and decreased accessibility of cities, to assess the importance of unsafe highway bridges in Oklahoma, United States. The aim of this study is to rank the unsafe highway bridges in Oklahoma using all of the three methods. The results of this study may be suggestive for the determination of periodization of highway bridge maintenance.

Findings and Conclusions: This study ranked the unsafe highway bridges in Oklahoma using three different methods, which are unweighted increased travel time, increased travel time weighted by traffic flow, and decreased accessibility of cities. Each method focuses on different perspectives of the highway performance. The results can provide useful information for the state and city transportation planners by pointing out the critical bridges that may have the highest negative impact to the state and cities if fail.

ADVISER’S APPROVAL: Dr. Hongbo Yu