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BRIDGING THE GAP: PROVIDING TRANSPORTATION LEADERS WITH A STRATEGIC AND RISK-BASED INVESTMENT METHODOLOGY THROUGH THE APPLICATION OF NETWORK THEORY

by

Brittany N. Miller

March 2020

Co-Advisors: Rudolph P. Darken
Thomas J. Mackin (contractor)

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A nationally accepted and adopted methodology for state departments of transportation to assess the importance of roads, bridges, and other transportation assets does not exist. Instead, transportation agencies must prioritize the projects to invest in, without having a complete picture of the makeup of their network and the risk posed from a loss or disruption of a component of the network. To make informed transportation investment decisions, transportation leaders need to have the tools necessary to determine the risk to the infrastructure based on the possible consequences if a segment of the transportation infrastructure network were disrupted. This thesis provides a methodology for network modeling of surface transportation infrastructure and analyzing the risk of a disruption to that network based on the consequence of population and economic impacts. By applying the methodology herein, transportation leaders can make informed decisions about their transportation investments based on the investments that provide the greatest return on investment.

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BRIDGING THE GAP: PROVIDING TRANSPORTATION LEADERS WITH A STRATEGIC AND RISK-BASED INVESTMENT METHODOLOGY THROUGH THE APPLICATION OF NETWORK THEORY

Brittany N. Miller
Deputy Emergency Preparedness Coordinator, Santa Rosa Fire Department,
Santa Rosa, California
BS, Arizona State University, 2009
BA, Arizona State University, 2009

Submitted in partial fulfillment of the
requirements for the degree of

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from the

NAVAL POSTGRADUATE SCHOOL
March 2020

Approved by: Rudolph P. Darken
Co-Advisor

Thomas J. Mackin
Co-Advisor

Erik J. Dahl
Associate Professor, Department of National Security Affairs

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ABSTRACT

A nationally accepted and adopted methodology for state departments of transportation to assess the importance of roads, bridges, and other transportation assets does not exist. Instead, transportation agencies must prioritize the projects to invest in, without having a complete picture of the makeup of their network and the risk posed from a loss or disruption of a component of the network. To make informed transportation investment decisions, transportation leaders need to have the tools necessary to determine the risk to the infrastructure based on the possible consequences if a segment of the transportation infrastructure network were disrupted. This thesis provides a methodology for network modeling of surface transportation infrastructure and analyzing the risk of a disruption to that network based on the consequence of population and economic impacts. By applying the methodology herein, transportation leaders can make informed decisions about their transportation investments based on the investments that provide the greatest return on investment.

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EXECUTIVE SUMMARY

A nationally accepted and adopted methodology for state departments of transportation to assess the importance of roads, bridges, and other transportation assets does not exist. Instead, transportation agencies must prioritize the projects to invest in, without having a complete picture of the makeup of their network and the risk posed from a loss or disruption of a component of the network. To make informed transportation investment decisions, transportation leaders need to have the tools necessary to determine the risk to the infrastructure based on the possible consequences if a segment of the transportation infrastructure network were disrupted.

This thesis provides a methodology for developing a network model of surface transportation infrastructure using the Network Theory of Green et al.,[1] and analyzing the risk of a disruption to that network based on the consequence of population and economic impacts. Population impacts are derived from the number of vehicles that will no longer be able to utilize the network, based on Annual Average Daily Traffic (AADT) numbers. Economic impacts are calculated from the tonnage of commodities that travel throughout the network, and calculating the dollar value per ton of those commodities.

The methodology is presented in two ways: first, by explaining the steps of the methodology using LeBlanc's Sioux Falls North Dakota data set;[2] and second, by applying those same steps to the real-world data available for Pierce County in Washington State.[3]

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[1] David G. Green, Jing Liu, and Hussein A. Abbass, "Network Theory," in *Dual Phase Evolution*, ed. David G. Green, Jing Liu, and Hussein A. Abbass (New York, NY: Springer New York, 2014), 43–67, https://doi.org/10.1007/978-1-4419-8423-4_2.

[2] Larry Leblanc, "An Algorithm for the Discrete Network Design Problem," Transportation Science 9, no. 3 (1967): 17, https://doi.org/10.1287/trsc.9.3.183.

[3] Pierce County, "About Pierce County | Pierce County, WA - Official Website," accessed October 13, 2019, https://www.co.pierce.wa.us/193/About-Pierce-County.

The outcome of the network-based risk assessment is then applied to Tundrea et. al.'s risk management theory,[4] in order to demonstrate to transportation leaders what the data is telling them, and how to apply that information toward the reduction of risk to their respective transportation networks.

The methodology outlined in this thesis is simple in nature, can be applied to multiple levels of government, and fills a notable gap in the transportation community. By analyzing the surface transportation system as a network, and then analyzing the risk to that network based on the consequence of a disruption, transportation leaders can make better informed decisions about how to prioritize their investments based on mitigating the risk to the network.

[4] Adrian-Costin Tundrea, Celestin Draganescu, and Cosmin Popa, "Integrating Intelligent Transport Systems in a Risk Management System of Systems," in 2017 21st International Conference on Control Systems and Computer Science (CSCS), 2017, 385–91, https://doi.org/10.1109/CSCS.2017.60.

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I. INTRODUCTION

A. PROBLEM STATEMENT

As the leader of a transportation agency, you receive a set amount of funding to reduce the risk to only one component of the surface transportation in your jurisdiction. How do you choose? If one segment is critical to the supply chain, would it have a higher priority than others? If another section is a critical route for a neighboring jurisdiction, would that factor into your decision? These are all important questions that need to be answered in order to make an informed decision on the investment you will ultimately decide to make.

The challenge for transportation agencies is the lack of an accepted methodology to address these questions collectively. Similarly, a nationally accepted and adopted procedure for state departments of transportation to assess the importance of roads, bridges, and other transportation assets does not exist.[1] Instead, transportation agencies must prioritize the projects to invest in without having a complete picture of the makeup of their network and the risk posed from a loss or disruption of a component of the network. To make informed transportation investment decisions, transportation leaders need to have the tools necessary to determine the risk to the infrastructure based on the possible consequences if a segment of the transportation infrastructure were disrupted.

The challenge with quantifying risk in this context is the difficulty in determining the consequences of a disruption of a component of the transportation infrastructure network. Without a clear methodology to determine the consequence of a disruption of that network, decision makers may not have a complete understanding of the level of impact that would result. Through the development of a comprehensive network model, looking at the effects of disruption from a network perspective based on supply chain disruption, the method proposed herein can address a notable gap.

[1] Department of Transportation Federal Highway Administration, Bridge Security Design Manual, FHWA-HIF-17-032 (Washington, DC: Federal Highway Administration, 2017), 13, https://www.fhwa.dot.gov/bridge/security/hif17032.pdf.

This thesis incorporates a concept from an existing risk based prioritization framework called the National Cooperative Highway Research Program's (NCHRP's) *Costing Asset Protection: An All-Hazards Guide for Transportation Agencies (CAPTA).* The *CAPTA* is an all-hazards approach to analyzing the risk to transportation infrastructure based on subjectively-determined consequence thresholds set by the jurisdiction running the model.[2] Applying a quantitative approach to the *CAPTA* risk methodology, based on the cost associated with a disruption to that jurisdiction's network, narrows the investment decisions to the most critical need. This thesis analyzes the impact to surface transportation infrastructure, roads more specifically, critical to the network in that jurisdiction rather than to every mode of transportation, as in the *CAPTA* model. The analysis provides decision-makers a scoped methodology to apply limited funds to where they get the greatest return on investment, based on the assets most critical to the transportation network in that jurisdiction. By providing a methodology for network modeling of surface transportation infrastructure, and analyzing the risk of a disruption to that network based on the consequence of population and economic impacts; transportation leaders can make informed decisions about their transportation investments.

1. Status of Transportation Infrastructure

It is no secret that the United States transportation system is in poor shape. As explained by the National Conference of State Legislatures, "transportation funding has been in a near constant state of crisis for more than a decade."[3] In a 2017 report, the American Society of Civil Engineers graded the country's infrastructure at a D+ (C+ for Bridges and D for roads specifically),[4] demonstrating the "desperate need for an infusion

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[2] National Cooperative Highway Research Program; Transportation Research Board; and National Academies of Sciences, Engineering, and Medicine, *Costing Asset Protection: An All-Hazards Guide for Transportation Agencies (CAPTA)*, vol. 15, Surface Transportation Security 525 (Washington, DC: The National Academies Press, 2009), https://www.nap.edu/catalog/14183/costing-asset-protection-an-all-hazards-guide-for-transportation-agencies-capta.

[3] National Conference of State Legislatures, "Deep Dive Transportation Funding | State Policy Trends," accessed August 22, 2019, http://www.ncsl.org/bookstore/state-legislatures-magazine/deep-dive-transportation-funding.aspx.

[4] American Society of Civil Engineers, "2017 Infrastructure Report Card - A Comprehensive Assessment of America's Infrastructure," Annual Report (American Society of Civil Engineers, 2017), https://www.infrastructurereportcard.org/.

of funding."[5] A " C" grade is defined as showing general signs of deterioration that requires attention due to increased vulnerability, while a "D" grade is defined as being in poor condition, below standard, at the end of their service life; and, adding that its condition presents a "strong risk of failure."[6] More specifically, 47,052 of America's 616,087 bridges are rated "structurally deficient" and need urgent repairs according to the American Road and Transportation Builders Association, which campaigns for a greater investment in transportation infrastructure by analyzing data from the Federal Highway Administration and releasing an annual deficient bridge report.[7] This report adds to the bridge data by stating that "Americans cross these deficient bridges 178 million times a day" and that while the data may show that the number of structurally deficient bridges is down since 2017, the "pace of improvement has slowed compared to the last five years."[8] The numbers of structurally deficient bridges is still quite alarming when you consider that this means that four out of every ten U.S. bridges need to be replaced or repaired, to include one in every three bridges on the Interstate network.[9]

In 2015, Congress passed a long-term transportation funding program called the Fixing America's Surface Transportation (FAST) Act. The FAST Act "authorizes $305 billion over fiscal years 2016 through 2020 for highway, highway and motor vehicle safety, public transportation, motor carrier safety, hazardous materials safety, rail, and research, technology, and statistics programs."[10] However, these federal funds typically go towards

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[5] Simone Del Rosario, "Trump's Infrastructure Talks Crumble Like Washington's Bridges, Roads," *Q13 Fox*, May 27, 2019.

[6] American Society of Civil Engineers, "2017 Infrastructure Report Card - A Comprehensive Assessment of America's Infrastructure."

[7] Michelle Lou and Brandon Griggs, "Bridge Safety: It'll Take More than 80 Years to Repair the 47,000 Structurally Deficient Bridges in America, Report Finds.," CNN, April 3, 2019, https://www.cnn.com/2019/04/02/us/deficient-bridge-report-2019-trnd/index.html.

[8] American Road & Transportation Builders Association, "2019 Bridge Report" (American Road & Transportation Builders Association, 2019), https://artbabridgereport.org/reports/2019-ARTBA-Bridge-Report.pdf.

[9] American Road & Transportation Builders Association, "ARTBA Bridge Report," ARTBA Bridge Report, 2018, https://artbabridgereport.org/.

[10] Federal Highway Administration, "Fixing America's Surface Transportation Act or the FAST Act - FHWA | Federal Highway Administration," accessed August 22, 2019, https://www.fhwa.dot.gov/fastact/.

new projects, and "cannot close the growing maintenance backlog."[11] Another concern is what will happen with this revenue stream past 2020, when the FAST Act expires. States are having to balance this revenue stream potentially disappearing along with issues such as declining assistance from the federal government, changing trends in transportation use, and increased costs of road construction and maintenance.[12] The biggest hurdles that states are facing is related to the maintenance of transportation infrastructure such as "repairing faulty bridges, maintaining roads, building new transit lines, and simply maintaining the existing infrastructure so it remains safe and efficient."[13] And that does not account for other emergent and largely unfunded issues such as culvert failures, potholes and other wear and tear issues, and human-caused issues such as litter clean up, homeless encampment issues, and graffiti removal.[14] Transportation agencies have been doing more with less for years, with the problem only increasing each passing year. For this reason, there is a desperate need to reevaluate the methodologies used to determine investment priorities with limited funds and increasing demand.

State Departments of Transportation are not the only entities that are struggling to finance their transportation infrastructure needs. In the report *Rural Connections: Challenges and Opportunities in America's Heartland*, a safety evaluation of the condition of rural roads and bridges finds that "the nation's rural transportation system is in need of immediate improvements to address deficient roads and bridges, high crash rates, and inadequate connectivity and capacity."[15] The report addresses the critical role transportation infrastructure plays in the economy, highlighting the rural transportation system specifically as providing "the first and last link in the supply chain from farm to market, connects manufacturers to their customers, supports the tourism industry, and

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[11] National Conference of State Legislatures, "Deep Dive Transportation Funding | State Policy Trends."

[12] National Conference of State Legislatures.

[13] National Conference of State Legislatures.

[14] This observation comes from my direct professional experience while employed in the Maintenance and Operations Division at the Washington State Department of Transportation.

[15] Rocky Moretti and Carolyn Bonifas Kelly, "U.S. Rural Roads & Bridges Have Signficant Deficiencies & High Fatality Rates; Repairs & Modernization Needed to Improve Conditions, Boost Safety & Support Growth & Connectivity," Press Release (Washington, DC, May 22, 2019), 1, tripnet.org.

enables the production of energy, food and fiber."[16] Surface transportation infrastructure is a critical link in the country's supply chain accounting for approximately 78.6% of goods via rail and truck, and 63.3% via truck specifically.[17] There is a direct impact on the economy and the public when the supply chain is disrupted, along with the more visible disturbance from a disruption, such as increased congestion on secondary routes from a primary route closure.

2. Current Investment Methodologies

The most common transportation revenue source at the State level is gas tax; meaning that for every dollar spent on fuel, a percentage of that dollar is provided to the State. Due to changes in the way Americans drive, 28 states and D.C. increased the gas tax rate between 2013 and 2018 due to a decline in revenue. For example, according to the National Conference of State Legislatures report, "fuel economy standards were 27.5 miles per gallon in 1985, 30.2 mpg in 2011, and rose to 36.5 mpg in 2016."[18] An even more challenging issue for state transportation revenue is the significant increase in hybrid and electric vehicles, which "use gas only part of the time—or not at all."[19] The National Conference of State Legislatures provides alarming data on this trend for future transportation revenue projections. They claim that "American electric and plug-in hybrid vehicle sales are projected to near 1.6 million units in 2018, up from just 122,000 in 2012. Experts predict by 2040, 55 percent of all new car sales and 33 percent of the global fleet will be electric."[20] Many states are exploring ways of creating "new transportation user funds by investigating the feasibility of road use charges for drivers, tolling, and fees and taxes for alternative vehicles that do not use gasoline."[21] States are investing significant

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[16] Rocky Moretti and Carolyn Bonifas Kelly, 2.

[17] Bureau of Transportation Statistics, "2017 North American Freight Numbers | Bureau of Transportation Statistics," 2017, https://www.bts.gov/newsroom/2017-north-american-freight-numbers.

[18] National Conference of State Legislatures, "Deep Dive Transportation Funding | State Policy Trends," 2017, http://www.ncsl.org/bookstore/state-legislatures-magazine/deep-dive-transportation-funding.aspx.

[19] National Conference of State Legislatures.

[20] National Conference of State Legislatures.

[21] National Conference of State Legislatures.

time and energy into determining the feasibility of these ideas, as the gas tax continues to decline as a reliable source of revenue.[22]

It is clear that the ways in which transportation agencies determine what investments take priority need to be reevaluated based on dire budget projections. The maintenance and preservation needs are only going to continue to increase, as is the risk for failure of our aging infrastructure. This thesis will provide a methodology for determining investment priorities based on a comprehensive risk-based approach using Network Theory to determine where the greatest need is, and what segments are the most critical to the surface transportation network.

B. RESEARCH QUESTION

How can transportation leaders apply a risk-based approach using Network Theory in order to better inform investment decisions?

C. LITERATURE REVIEW

The two categories that existing literature on transportation risk assessments fall into are national guidance doctrine, and technical risk assessments of the individual infrastructure performance based on specific hazards. Each aspect of the literature has merit, and contributes to the ability of stakeholders to understand a component of the risk to individual segments of transportation infrastructure's network; though none of them provides a comprehensive risk assessment of the transportation infrastructure, or the impact of a disruption of a specific piece of infrastructure on the collective surface transportation network. This thesis will address the gap identified in the existing literature, by combining elements of current assessments into a methodology that accounts for the surface transportation network as a whole, based on the projected population impacts and economic losses from a disruption within the network.

[22] National Conference of State Legislatures.

1. National Guidance Doctrine

National guidance for transportation infrastructure protection provides a baseline of mitigation and preparedness activities for infrastructure owners to strive to achieve. However, the national guidance lacks specific direction or incentives to achieve those steps. Furthermore, none of the national guidance provides comprehensive infrastructure protection information, instead focusing on very specific threats and/or hazards. The *National Strategy for the Physical Protection of Critical Infrastructures and Key Assets* very broadly outlines the challenges to protecting critical infrastructure from a terrorist attack, but neglects to provide anything tangible that could resolve them.[23] Similarly, the USDOT Federal Highway Administration's *Bridge Security Design Manual* provides a detailed overview of how to design bridges to be able to better withstand a terrorist attack, but does not address other hazards that could be mitigated through bridge design.[24] Conversely, the U.S. Department of Homeland Security's *National Infrastructure Protection Plan* and its *Transportation Systems Sector-Specific Plan* both provide all-hazards guidance for managing risk to critical infrastructure; however, both are very general in nature, and only provide a high-level overview rather than concrete steps that should be taken to address the risks to critical infrastructure.[25] Likewise, the American Society of Civil Engineers offers four guiding principles for critical infrastructure that are "intended to inform the planning, funding, design, construction, and operation of critical infrastructure systems," but the recommendations do not provide specific enough recommendations for application by infrastructure owners and operators.[26] Finally, the National Cooperative Highway Research Program's (NCHRP's) *Costing Asset Protection: An All-Hazards Guide for Transportation Agencies (CAPTA)* provides the start to national

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[23] Barack Obama, *The National Strategy for the Physical Protection of Critical Infrastructures and Key Assets* (Washington, DC: White House, 2003), https://www.dhs.gov/xlibrary/assets/Physical_Strategy.pdf.

[24] Department of Transportation Federal Highway Administration, *Bridge Security Design Manual*.

[25] Department of Homeland Security, *National Infrastructure Protection Plan* (Washington, DC: Department of Homeland Security, 2006), https://www.dhs.gov/xlibrary/assets/nipp_consolidated_snapshot.pdf.

[26] American Society of Civil Engineers Critical Infrastructure Guidance Task Committee, *Guiding Principles for the Nation's Critical Infrastructure* (Reston, VA: American Society of Civil Engineers, 2009), https://doi.org/10.1061/9780784410639.

guidance on prioritizing transportation investments, but it is too broad and too subjective for it to be applied consistently and nationally.[27]

2. Technical Risk Assessments of the Individual Infrastructure Performance Based on Specific Hazards

A variety of methods exist to determine risks to transportation infrastructure; but none of them enables comprehensive assessment of the impact that a disruption of transportation infrastructure poses on an existing network. Existing literature on transportation risk assessments falls into two very specific categories: critical link vulnerability analysis based on network reliability, and the impact of specific hazards on individual components of the transportation infrastructure network. The concept of critical link analysis is described by Bagloee et al. as the "Achilles-heel" of a road network.[28] They assess critical road links and the impact a disruption of that critical link will have on the transportation network. Balijepalli and Oppong, Tundrea et al., and Khademi et al., among many others conducted similar studies assessing the interoperability of the transportation network and its ability to accommodate traffic loads when there is a critical link disruption.[29] Decò and Frangopol provide the most comprehensive approach to determining risk to transportation infrastructure in their article, "Risk Assessment of Highway Bridges Under Multiple Hazards."[30] Their article provides a quantitative, time-based assessment of risk from common hazards to bridges such as traffic loads,

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[27] National Cooperative Highway Research Program; Transportation Research Board; and National Academies of Sciences, Engineering, and Medicine, *Costing Asset Protection: An All-Hazards Guide for Transportation Agencies (CAPTA)*.

[28] Saeed Asadi Bagloee et al., "Identifying Achilles-Heel Roads in Real-Sized Networks," *Journal of Modern Transportation* 25, no. 1 (March 1, 2017): 1–11, https://doi.org/10.1007/s40534-016-0121-7.

[29] Chandra Balijepalli and Olivia Oppong, "Measuring Vulnerability of Road Network Considering the Extent of Serviceability of Critical Road Links in Urban Areas," *Journal of Transport Geography* 39 (July 2014): 145–55, https://doi.org/10.1016/j.jtrangeo.2014.06.025; Adrian-Costin Tundrea, Celestin Draganescu, and Cosmin Popa, "Integrating Intelligent Transport Systems in a Risk Management System of Systems," in *2017 21st International Conference on Control Systems and Computer Science (CSCS)*, 2017, 385–91, https://doi.org/10.1109/CSCS.2017.60; Navid Khademi et al., "Transportation Network Vulnerability Analysis for the Case of a Catastrophic Earthquake," *International Journal of Disaster Risk Reduction* 12 (June 2015): 234–54, https://doi.org/10.1016/j.ijdrr.2015.01.009.

[30] Alberto Decò and Dan M. Frangopol, "Risk Assessment of Highway Bridges under Multiple Hazards," *Journal of Risk Research* 14, no. 9 (October 2011): 1057–89, https://doi.org/10.1080/13669877.2011.571789.

environmental attacks, scour, and earthquakes, based on probabilities of occurrence. Dong and Frangopol take this assessment one step further by considering also the effects of deterioration of the transportation infrastructure against seismic risk.[31] Utilizing the concepts of critical link analysis derived from this technical research, and applying it quantitatively to a network model will provide a comprehensive assessment of the risk posed by the disruption of a component of the surface transportation infrastructure network.

D. SCOPE AND DESIGN

Research on transportation infrastructure risk assessments has increased significantly over the last several years, but in order to achieve a risk assessment that can inform investment decisions, a critical gap will be addressed in this thesis.[32] Rather than assessing the criticality of a single segment of surface transportation infrastructure (road, bridge, etc.) and/or the capacity of alternate routes to accommodate the traffic flow posed by the disruption, this thesis applies risk assessment methodology to a local jurisdiction's transportation network based on the community and economic consequence of a network disruption.

This thesis does not discuss the specific maintenance, design, or construction considerations necessary to reduce the risk to a road or bridge; but it does provide a methodology for how to determine the significance of the road or bridge to the network, and the consequences of a disruption to the network.

Two important factors figure into risk evaluation—the impact of the risk, and the likelihood of that risk scenario occurring. This thesis is focused on the impact, and more specifically the community and economic consequences of the risk scenario, or disruption to the network. While the likelihood or probability of occurrence is an important factor for consideration, it is not in the scope of the proposed methodology.

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[31] You Dong, Dan M. Frangopol, and Duygu Saydam, "Time-Variant Sustainability Assessment of Seismically Vulnerable Bridges Subjected to Multiple Hazards: Time-Variant Sustainability of Seismically Vulnerable Bridges," *Earthquake Engineering & Structural Dynamics* 42, no. 10 (August 2013): 1451–67, https://doi.org/10.1002/eqe.2281.

[32] Lars-Göran Mattsson and Erik Jenelius, "Vulnerability and Resilience of Transport Systems—A Discussion of Recent Research," *Transportation Research Part A: Policy and Practice* 81 (November 2015): 16–34, https://doi.org/10.1016/j.tra.2015.06.002.

This approach provides transportation leaders with a more complete perspective by accounting for a road or bridge's role in the larger transportation network, rather than an individual component that is often constrained by geographical and political boundaries. By determining the criticality of routes on that network, based on population impact and economic losses, decision makers can make more informed decisions on where to invest limited transportation funding to reduce the risk to their surface transportation network.

II. METHODOLOGY

Funding for surface transportation infrastructure (roads and bridges) is inadequate to maintain it to acceptable standards, let alone to make improvements or upgrades to the infrastructure by investing in necessary mitigation strategies. As a result, it is necessary to prioritize limited funding in order to ensure that investments are made in the areas where they provide the greatest benefit to the surface transportation network. In the first chapter, the National Cooperative Highway Research Program's (NCHRP's) *Costing Asset Protection: An All-Hazards Guide for Transportation Agencies (CAPTA)* was introduced as the only available methodology for prioritizing investments in a consistent manner, but it comes with some limitations. This chapter outlines a proposed methodology for addressing those limitations, by combining concepts from the *CAPTA* and other risk reduction research, with Network Theory in order to provide a comprehensive prioritization method based on reducing risk to the threats that pose the greatest risk to the network.

A. NETWORK MODELING

In order to be able to prioritize transportation investments, it is important to first determine the criticality of the components within a given area of focus or network. This can be accomplished by analyzing a road or bridge in relation to the network it belongs to, in order to determine how a disruption of an individual piece of infrastructure impacts the larger network. In the article "Identifying Achilles-Heel Roads in Real-Sized Networks," Bagloee et al. explain this by analyzing how a road can become an "Achilles-heel" for an entire network during a disruption.[33] This concept is applied using a theory called Link Analysis, where roads in the network are prioritized based on highest travel demand.[34] Link Analysis is discussed in research by Balijepalli and Oppong, where they examined the importance of road links in a network and how a broken link can disrupt the functionality

[33] Bagloee et al., "Identifying Achilles-Heel Roads in Real-Sized Networks," 1.

[34] Bagloee et al., 2.

of the network.[35] Utilizing aspects of on the above research, this thesis provides a methodology to determine the importance of a piece of infrastructure to the larger network by modeling the system using Network Theory.

1. Network Theory

In Network Theory, infrastructure pieces are represented by nodes and links, which are also known as vertices and edges.[36] For this methodology, the analysis is restricted to surface transportation infrastructure, and more specifically roads and bridges (links) that connect cities (nodes).

Roads and bridges have specific load capacities, speed limits, and numbers of lanes that, in turn, affect the flow of people and commodities throughout these surface transportation networks. By mapping the network and applying data on the aforementioned categories, a complete picture is developed that can then be analyzed against risk posed if a disruption were to occur.

2. Overview of Network Modeling

The ultimate goal of network modeling is to understand how many separate components act together through quantitative analysis of the data makeup of the network.[37] To accomplish this, a graphical representation of the roadways (links) that incorporates Annual Average Daily Traffic (AADT) numbers and economic data must be developed. With this information, the link between any two points (nodes) can be quantified based on population impacts as well as mathematically determining the economic impact when parts of the network are disrupted, regardless of the cause of the disruption.

Many programs can be used to analyze networks; rather than focusing on one particular program, this thesis will instead walk step by step through the process for

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[35] Balijepalli and Oppong, "Measuring Vulnerability of Road Network Considering the Extent of Serviceability of Critical Road Links in Urban Areas," 145.

[36] David G. Green, Jing Liu, and Hussein A. Abbass, "Network Theory," in *Dual Phase Evolution*, ed. David G. Green, Jing Liu, and Hussein A. Abbass (New York, NY: Springer New York, 2014), 43–67, https://doi.org/10.1007/978-1-4419-8423-4_2.

[37] Stephen Wolfram, "Wolfram Mathematica: Modern Technical Computing," Wolfram: Computation Meets Knowledge, accessed October 10, 2019, https://www.wolfram.com/mathematica/.

network modeling, utilizing test network data from Leblanc's article "An Algorithm for the Discrete Network Design Problem." [38] The same methodology will then be applied to a county in Washington State in the subsequent chapter.

a. Data Sample: Sioux Falls, South Dakota

In his research on the discrete network design problem in transportation networks, Larry Leblanc developed an aggregation of a network used to model the city of Sioux Falls, South Dakota, where each node was considered both a destination and an origin.[39] The underlying concept of his research is to "determine the best improvements to an existing transportation system," which lays the foundation of this methodology.[40] As discussed in Chapter I, most transportation agencies struggle to maintain the infrastructure in their respective jurisdictions, so a methodology that proposes any new construction or replacement is highly unlikely to be feasible as a risk management solution. Instead, using Leblanc's data set and network model for Sioux Falls, this methodology will demonstrate how to build a network model for a surface transportation system with data to support risk management solutions.

In Leblanc's test network, depicted in Figure 1, the network is made up of 24 nodes represented as both an origin and a destination, which could be considered individual cities within Sioux Falls and the routes to and from those cities.[41] The table that contains the full matrix of trips between each node pair is available as an Appendix.

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[38] Larry Leblanc, "An Algorithm for the Discrete Network Design Problem," *Transportation Science* 9, no. 3 (1967): 17, https://doi.org/10.1287/trsc.9.3.183.

[39] Larry Leblanc, 193–94.

[40] Larry Leblanc, 185.

[41] Ziyou Gao, Jianjun Wu, and Huijun Sun, "Solution Algorithm for the Bi-Level Discrete Network Design Problem," *Transportation Research Part B* 39, no. 6 (2005): 493, https://doi.org/10.1016/j.trb.2004.06.004.

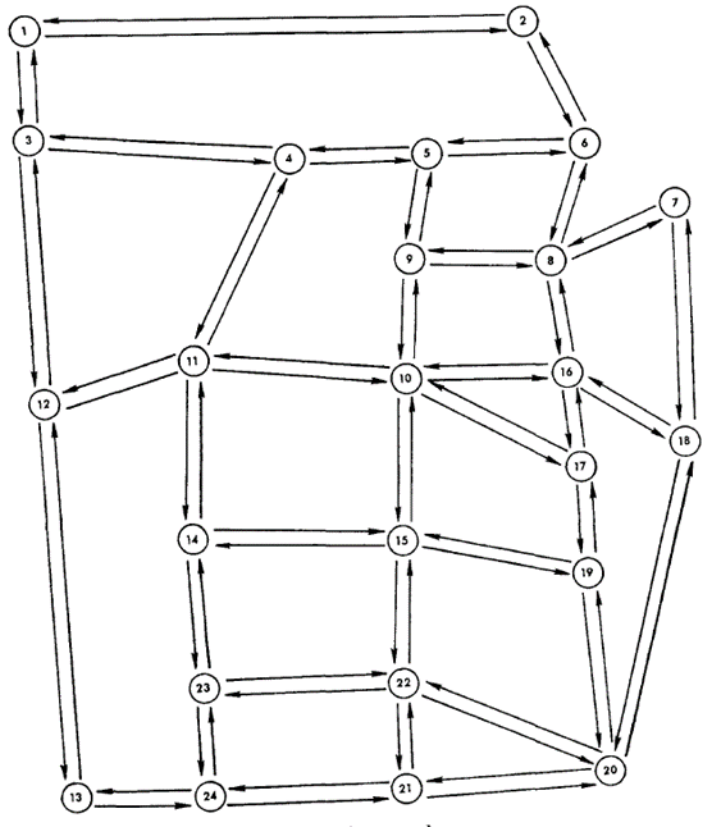

Figure 1. Leblanc Test Network[42]

3. Network Modeling, One Step at a Time

For the purpose of this example, the Leblanc data and network model are used to demonstrate the steps that should be applied to a real-world transportation system. When this network model does not exist, the first step is to build one. Network modeling can feel complex if you are not comfortable with the steps involved in the methodology. Putting the methodology into a step-by-step process provides a user-friendly process that can be modeled in any jurisdiction. The steps to build a network model are as follows:

1. **Identify and Model a Transportation Network**. Modeling a network begins with identifying all the nodes and links of the network. The nodes are cities, towns, or intersections between roadways (links). Each node

[42] Larry Leblanc, "An Algorithm for the Discrete Network Design Problem," 194.

must be labeled, and the connections between nodes, or links, must be clearly identified, as shown in Table 1. In order to simplify this example, Leblanc's data set was narrowed to only Destination and Origin routes 10 through 17.

Table 1. Example of How to Identify Nodes and Links[43]

Destination	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**
Origin								
10								
11								
12								
13								
14								
15								
16								
17								

In this example, the Destination and Origin represents both the Node and the Link. In a real-world example, this would be differentiated based on cities and the routes to/from those cities.

2. **Create a Master List of All Nodal Connections by Assigning Node Labels**. This is determined based on the link(s) used to travel from one node to another. In Table 1, Node 10 is connected to nodes 10, 11, 12, etc. in the test example.

3. **Identify and Assign a Measure of Performance for Each Link in the Network**. The measure of performance is chosen based on the desire to measure the effectiveness or functionality of a given measure, and could include speed, capacity, congestion, etc. In this example, the measure of performance is based on population and economic impacts if a specific link were disrupted. Population impacts are based on the impact to the

[43] Adapted from Larry Leblanc, 195.

Average Annual Daily Traffic (AADT) numbers, and economic impacts are based on calculating a dollar value per ton, per hour.

4. **Assign Flow Capacities to Each Link Using the Measure of Performance Selected**. For this step, gather the data that supports the measure of performance. In this methodology, the Average Annual Daily Traffic (AADT) and economic value for commodities are assessed for each link. In LeBlanc's model, this data is actually thousands of trips per day, rather than road capacities or the number of vehicles using the roads. However, we use them to illustrate how a matrix of data can be read directly into the spreadsheet and used to calculate flow within a network.

Table 2. Example for Assigning Flow Capacities to Each Link in the Network[44]

Destination	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**
Origin								
10	0	40	20	19	21	40	44	39
11	39	0	14	10	16	14	14	10
12	20	14	0	13	7	7	7	6
13	19	10	13	0	6	7	6	5
14	21	16	7	6	0	13	7	7
15	40	14	7	7	13	0	12	15
16	44	14	7	6	7	12	0	28
17	39	10	6	5	7	15	28	0

The flow capacities in this example are based on the measure of performance of the number of vehicles that travel on each link from Destination to Origin. In a real-world example, this will be your Average Annual Daily Traffic (AADT).

Now that the network model has been built for an area of interest, a measure of performance has been assigned, and capacities for each measure of performance has been

[44] Adapted from Larry Leblanc, 195.

determined; the next step in the methodology is to determine the level of risk posed from a disruption in the network based on the measure of performance assigned.

B. CONDUCTING A RISK ANALYSIS

In *Costing Asset Protection: An All Hazards Guide for Transportation Agencies (CAPTA)* a "consequence-driven approach" is used, the concept of which is applied to this methodology.[45] The *CAPTA* focuses on exposed population, population loss and mission disruption. This methodology takes a deeper dive into their concept of loss by examining economic loss more specifically. This approach also broadens their concept of human impact by focusing on the impact from the network disruption rather than focusing on injury and fatality numbers.[46] Impact in this context is defined as the numbers of commuters who will no longer be able to use the link in the network based on Annual Average Daily Traffic (AADT) numbers for that link.

Once the network model has been developed for the area of analysis, the next step is to determine the risk posed to the critical links of that network. Douglas Hubbard, author of *The Failure of Risk Management* defines risk as "the probability and magnitude of a loss, disaster, or other undesirable event."[47] The theoretical framework used by Tundrea et al. in *Integrating Intelligent Transport Systems in a Risk Management System of Systems* expands on this definition by describing disaster risk management as "a complex process of disaster identification, risk assessment, risk treatment, and the systematic process of decision-making."[48] They describe Network Theory as Systems of Systems (SoS), which examines the interactions of the individual components or parts of the whole system.[49] For

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[45] National Cooperative Highway Research Program; Transportation Research Board; and National Academies of Sciences, Engineering, and Medicine, *Costing Asset Protection: An All-Hazards Guide for Transportation Agencies (CAPTA)*, 15:12.

[46] National Cooperative Highway Research Program; Transportation Research Board; and National Academies of Sciences, Engineering, and Medicine, 15:20.

[47] Douglas W. Hubbard, The Failure of Risk Management: Why It's Broken and How to Fix It (Hoboken, NJ: Wiley, 2009), 10.

[48] Tundrea, Draganescu, and Popa, "Integrating Intelligent Transport Systems in a Risk Management System of Systems," 386.

[49] Tundrea, Draganescu, and Popa, 386.

this method, risk will be assessed based on the impact to the population and economy that a disruption to the network will cause, using Leblanc's dataset as the foundation of the analysis for this example.

C. RISK ANALYSIS

Understanding the risk posed from the consequence of a disruption to the network in the network model is an important step in the methodology because doing so informs the impact of potential disruption scenarios that could occur. In order to get a more comprehensive perspective on the impact of a disruption, the next step is to conduct a consequence analysis of a disruption scenario on the network. In this methodology, the consequence is determined based on:

- ***Population Impact***: The number of people who would be impacted by a disruption. This is calculated according to the Annual Average Daily Traffic (AADT) traveling through the impacted link within the network, based on the timeframe being assessed.[50] The AADT would then be multiplied by the duration of the closure.

- ***Economic Impact***: The financial loss to the local, state, and federal communities based on the movement of commodities in the supply chain. Similar to the AADT, there is a financial impact if a critical link in the supply chain is disrupted. This is calculated by the total number of commodities traveling through the impacted link, multiplied by the value of the commodity, and the duration of the closure.

Utilizing Leblanc's network and data, and a fictitious economic data set, the following sections demonstrate how risk can be calculated based on population and economic impact.

[50] "Annual Average Daily Traffic (ADT)," Wikipedia, September 12, 2019, https://en.wikipedia.org/w/index.php?title=Annual_average_daily_traffic&oldid=915234038.

1. Population Impact

In order to simplify the sample data, this example focused on a subset of the most used routes in Leblanc's data set. Displaying the number of vehicles per day that travel a particular link, also known as Annual Average Daily Traffic (AADT), is a quick way of assessing risk based on the impact to the population. For example, in this data set, if the "10" Origin and Destination route were disrupted, and assuming the calculations were based on a daily (24 hour) timeframe, it would impact 445,000 people daily (assuming equal flow in each direction). This is calculated by adding together all of the ADT numbers for the Origin and Destination "10" route in the data set as shown in yellow in Table 3.

Table 3. Population Impact (in thousands) Demonstrated with Annual Average Daily Traffic (AADT) Numbers for Origin and Destination Route 10[51]

Destination	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**
Origin								
10	0	40	20	19	21	40	44	39
11	39	0	14	10	16	14	14	10
12	20	14	0	13	7	7	7	6
13	19	10	13	0	6	7	6	5
14	21	16	7	6	0	13	7	7
15	40	14	7	7	13	0	12	15
16	44	14	7	6	7	12	0	28
17	39	10	6	5	7	15	28	0
Total: 445								

This is important data for transportation leaders because it illustrates which links would cause the greatest impact to the population if disrupted, which can in turn be used to inform investment decisions.

[51] Adapted from Larry Leblanc, "An Algorithm for the Discrete Network Design Problem," 195.

2. Economic Impact

Using the same data set and determining that 10% of vehicle traffic was made up of commercial vehicles, we can also calculate the economic impact associate with the transport of goods.[52] By discovering that every commercial vehicle held a value of one million dollars in commodities, calculate the loss if the "10" Origin and Destination links were disrupted, which would result in $445 billion in economic losses daily.[53]

10 % of 445,000 = 44,500 commercial vehicles

44,500 X $1 Million = $44.5 billion per day

This calculation is important because it provides a financial impact data set that demonstrates where the greatest economic impact would be from a disruption in that network. This, separately or in conjunction with population impact, can be used to inform investment decisions.

The next and final step in the methodology is to prioritize investments based on severity of consequence provided by these calculations, and to use that information to inform how to reduce the risk or consequence of a disruption through risk management, which is discussed in Chapter IV. In Chapter III, the methodology for determining the consequence of a disruption in the network will be applied to a county in Washington State, in order to demonstrate the real-world applicability of the aforementioned methodology.

[52] This calculation was fabricated for the purpose of the example. To apply this methodology, real data would need to be gathered in advance for the network being analyzed.

[53] This calculation was fabricated for the purpose of the example. To apply this methodology, actual data would need to be gathered in advance for the network being analyzed.

III. APPLICATION OF THE METHODOLOGY

A. PIERCE COUNTY, WASHINGTON

In this chapter, the methodology outlined in Chapter II is applied to a county in Washington State. This county was selected in order to provide a demonstration for how to apply the methodology a local communities' state route and interstate surface transportation networks.

Pierce County is the second-most populous county in Washington State, with just over 800,000 residents, nestled in the beautiful Pacific Northwest. To the west is the Port of Tacoma, the largest exporting port in the state and the Puget Sound connecting up to the Pacific Ocean. To the east is the iconic 14,000-ft Mount Rainier, which is not only the backdrop of residents' skyline, but also one of five active volcanoes in the state.[54] Pierce County is host to 238 state-owned and -operated bridges and multiple state owned and operated highways connecting cities throughout the county that will be the focus of the remainder of this chapter.[55]

B. NETWORK MODEL

As discussed in Chapter II, the first step in the methodology is developing a network model for the area to be analyzed. The network model for Pierce County was developed using the same steps as outlined in Chapter II:

1. **Identify and Model a Transportation Network.** Pierce County was selected as the jurisdiction to develop a network model because of its population density and role in the supply chain for Washington State. This step is completed by locating a map with chosen nodes and links displayed on it; in this case it is the major cities (nodes) and state route and interstate

[54] Pierce County, "About Pierce County | Pierce County, WA - Official Website," accessed October 13, 2019, https://www.co.pierce.wa.us/193/About-Pierce-County.

[55] Department of Homeland Security, "Region Resiliency Assessment Program (RRAP) Bridge Seismic Screening Tool (BSST)" (Cybersecurity and Infrastructure Security Agency (CISA), August 2019).

highways connecting them (links) as demonstrated in Figure 2. To support the analysis in future steps, it is encouraged to also document the nodes and links in a table, and include the geographic information related to the actual distance between each node, as shown in Table 4.

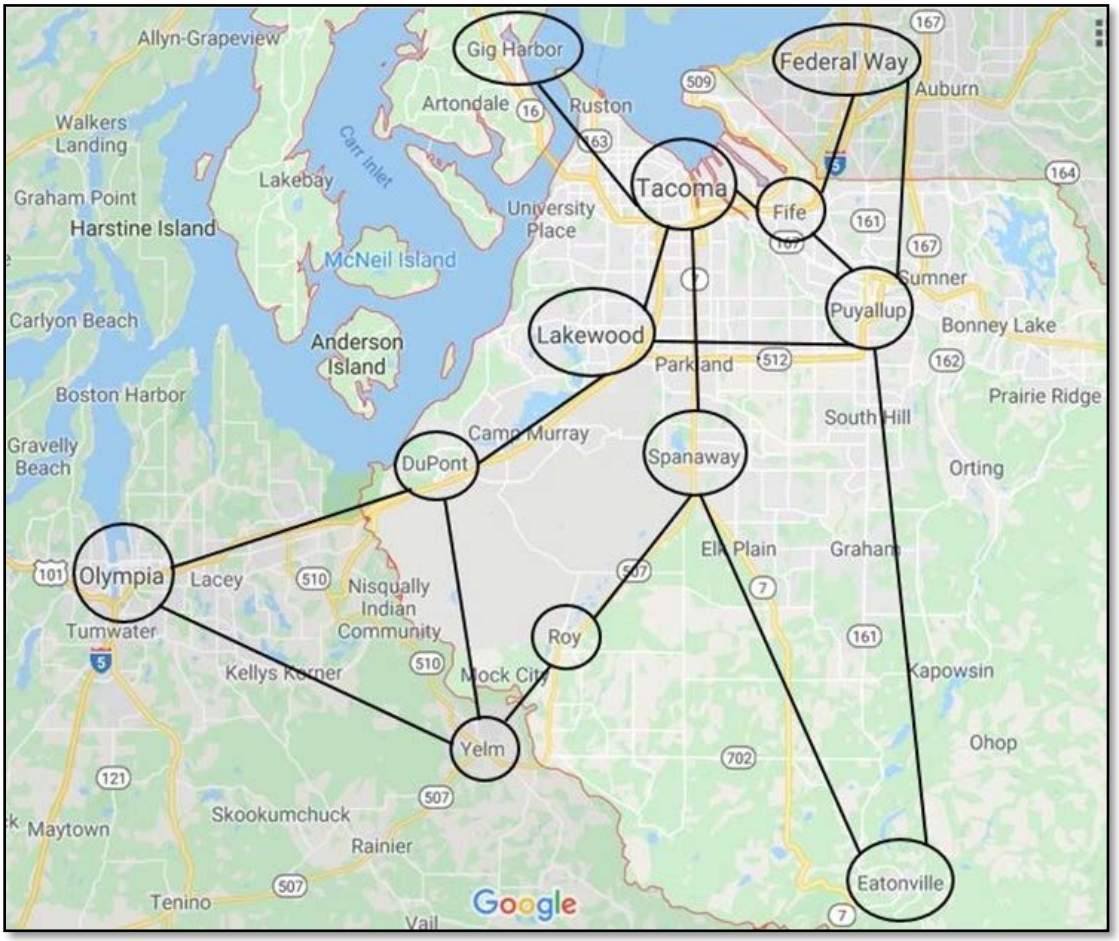

Figure 2. Pierce County Network Model[56]

[56] Adapted from Google, "Google Maps," Google Maps, 2019, https://www.google.com/maps/place/Pierce+County,+WA/@47.0646342,-122.6736829,9z/data=!3m1!4b1!4m5!3m4!1s0x54910358f2c86d29:0xdca97ba3811c01f!8m2!3d47.0675877!4d-122.1295269?hl=en.

Table 4. Example of Documenting Distance between Nodes[57]

City from	City to	Distance (Miles)	Route	Mileposts
Olympia	DuPont	14	I-5	105-119
Olympia	Yelm	8	I-5	105-113
		30	SR-510	0-30
DuPont	Yelm	6	I-5	119-113
		30	SR-510	0-30
DuPont	Lakewood	8.5	I-5	119-127.5
Roy	Yelm	20	SR-507	35-28
Roy	Spanaway	8	SR-507	35-43
Eatonville	Spanaway	3	SR-161	3-0
		20	SR-7	27-47
Eatonville	Puyallup	20	SR-161	5-25
		2	SR-512	9-11
Lakewood	Puyallup	11	SR-512	0-11
Tacoma	Fife	1.5	SR-705	1.5-0
		4	I-5	134-138
Tacoma	Gig Harbor	1.5	SR-705	1.5-0
		1	I-5	133
		10	SR-16	0-10
Tacoma	Lakewood	1.5	SR-705	1.5-0
		8	I-5	134-126
Fife	Federal Way	6	I-5	138-144
Federal Way	Puyallup	3	SR-18	0-3
		8.5	SR-167	14.5-6

2. **Create a Master List of All Nodal Connections by Assigning Labels.** In Excel, each of the major cities (nodes) was listed along with the cities (nodes) they connect to, and they were given a link label number to easily distinguish them from one another as shown in Table 5. The state routes and

[57] Adapted from Washington State Department of Transportation, "Traffic GeoPortal," Interactive Map, accessed January 15, 2020, https://www.wsdot.wa.gov/data/tools/geoportal/?config=traffic.

highways that connect the nodes were listed for each respective link, including the mileposts for each. In order to show an accurate representation of the Pierce County network, the network model in Figure 2 includes nodes (cities) that are outside of the county boundaries, but are included as an endpoint node because they are vital to the movement of people and commodities throughout the network.

Table 5. Example of How to Assign Link Labels to a Network[58]

Link #	City from	City to	Distance (Miles)	Route	Mileposts
1	Olympia	DuPont	14	I-5	105-119
2	Olympia	Yelm	8	I-5	105-113
			30	SR-510	0-30
3	DuPont	Yelm	6	I-5	119-113
			30	SR-510	0-30
4	DuPont	Lakewood	8.5	I-5	119-127.5
5	Roy	Yelm	20	SR-507	35-28
6	Roy	Spanaway	8	SR-507	35-43
7	Eatonville	Spanaway	3	SR-161	3-0
			20	SR-7	27-47
8	Eatonville	Puyallup	20	SR-161	5-25
			2	SR-512	9-11
9	Lakewood	Puyallup	11	SR-512	0-11
10	Tacoma	Fife	1.5	SR-705	1.5-0
			4	I-5	134-138
11	Tacoma	Gig Harbor	1.5	SR-705	1.5-0
			1	I-5	133
11	Tacoma	Gig Harbor	10	SR-16	0-10
12	Tacoma	Lakewood	1.5	SR-705	1.5-0
			8	I-5	134-126
13	Fife	Federal Way	6	I-5	138-144
14	Federal Way	Puyallup	3	SR-18	0-3
			8.5	SR-167	14.5-6

[58] Adapted from Washington State Department of Transportation.

3. **Identify and Assign a Measure of Performance for the Network.** The measure of performance assigned for this example is the population and economic impacts from a disruption to a link in the network. Population impacts are based on the impact to the annual average of daily traffic numbers, and economic impacts are based on a tonnage per hour calculation of the value of commodities disrupted in the supply chain.

4. **Assign Flow Capacities to each Link Using the Measure of Performance Selected.** The measure of performance is calculating the impact to the Annual Average Daily Traffic (AADT) and economic value of commodities for each link. The AADT numbers came directly from the Washington State Department of Transportation's *Traffic Geoportal*, which contains the AADT numbers for each state route and interstate in Washington State as shown in Table 6.[59] The annual tonnage data that supports the economic value of the commodities calculation was provided by the Washington State Department of Transportation's *State Route T-1 Through T-5 Classifications* for the respective state routes and interstates that make the link as shown in Table 7.

C. RISK ANALYSIS

Building the network model and being able to determine what links are critical to the network based on population and economic impact are the foundation of this method. network modeling provides the framework for further analysis of potential impacts to the network and the starting point for determining where to focus limited funds toward the reduction of risk to the network. Conducting a risk analysis of the links of the network is accomplished through the examination of the impacts to the population and the economy.

[59] Adapted from Washington State Department of Transportation.

1. Population

Once the network has been constructed and key links have been identified, determining the population impact is relatively simple. Most State Departments of Transportation capture a wealth of data that can be used, such as the Annual Average Daily Traffic (AADT) numbers for this example. The AADT is the average number of vehicles that on average, travel a given route annually.[60] This figure compared with the network links, provides a clear picture of how much of the population would be disrupted by a disruption to an individual link, as demonstrated in Table 2 for the Pierce County network model.

Table 6. Population Impact Demonstrated with Annual Average Daily traffic (AADT) for Pierce County Network in 2018[61]

Link #	City from	City to	Distance (Miles)	Route	Mileposts	Annual Average Daily Traffic on Route (2018)
1	Olympia	DuPont	14	I-5	105-119	105,000-146,000
2	Olympia	Yelm	8	I-5	105-113	9,900-146,000
			30	SR-510	0-30	5,800-25,000
3	DuPont	Yelm	6	I-5	119-113	108,000-132,000
			30	SR-510	0-30	5,800-25,000
4	DuPont	Lakewood	8.5	I-5	119-127.5	128,000-156,000
5	Roy	Yelm	20	SR-507	35-28	10,000-23,000
6	Roy	Spanaway	8	SR-507	35-43	11,000-16,000
7	Eatonville	Spanaway	3	SR-161	3-0	1,000
			20	SR-7	27-47	2,000-27,000
8	Eatonville	Puyallup	20	SR-161	5-25	6,000-43,000
			2	SR-512	9-11	93,000-104,000
9	Lakewood	Puyallup	11	SR-512	0-11	64,000-112,000
10	Tacoma	Fife	1.5	SR-705	1.5-0	40,000-75,000
			4	I-5	134-138	174,000-231,000
11	Tacoma	Gig Harbor	1.5	SR-705	1.5-0	40,000-75,000

[60] "Annual Average Daily Traffic (ADT)."

[61] Adapted From Washington State Department of Transportation, "Traffic GeoPortal."

Link #	City from	City to	Distance (Miles)	Route	Mileposts	Annual Average Daily Traffic on Route (2018)
11	Tacoma	Gig Harbor	1	I-5	133	166,000
			10	SR-16	0-10	68,000-133,000
12	Tacoma	Lakewood	1.5	SR-705	1.5-0	40,000-75,000
			8	I-5	134-126	135,000-231,000
13	Fife	Federal Way	6	I-5	138-144	170,000-195,000
14	Federal Way	Puyallup	3	SR-18	0-3	66,000-106,000
			8.5	SR-167	14.5-6	89,000-114,000

By reviewing the data, it becomes clear to transportation leaders that the routes that could cause the greatest population impact are links #4, 10, 12, 13, and 14, respectively.

2. Economy

In order to identify the economic impact that could occur with a disruption to the network model, it is important to first determine how it should be measured. For this example, the economic impact is measured by first calculating the maximum flow rate of each link in the network model in tonnage, or weight of commodities on the route, then doing a basic calculation to determine how a disruption of that link is represented in economic losses.

In order to calculate the financial value of the tonnage in the flowrate, data needs to be gathered that supports the dollar value per ton of cargo. This exact dollar value per ton was not readily available, so some basic calculations were made to provide a rough estimate of the dollar value per ton. According to the Washington State Department of Transportation, $132,567 million dollars, and 6,807,155 tons of goods of import and export trade traveled throughout the state in 2017.[62] Those figures can then be compared to the Bureau of Transportation Statistics calculation that trucks, or highway-based transport of

[62] Washington State Department of Transportation, "2017 Waybill Analysis GNB," 2017; Washington State Department of Transportation, "WA Trade Data 2018," 2018.

trade, make up 63.3% of all of the nation's trade. This provides an estimated dollar amount per ton figure of $51.35 million per ton, as demonstrated below.[63]

- 63.3% truck trade of 6,807,155 total tons = 4,308,929 tons of truck trade
- 63.3% truck trade of $132,567 million total in WA = $83,915 million in truck trade annually
- $83,915 / 4,308,929 tons of truck trade = **$19,475 per ton**

Using the network model shown in Figure 2, a network flow table was created to find the minimum and maximum tonnage that can be delivered from one node (city) to another, for each link. This was done by calculating the annual tonnage along a given route and multiplying that by the value per ton ($19,475). To calculate the economic value per day, one would divide those values by 365 for the amount of days per year, as shown in the last column.

The application of this data to the network model is demonstrated in Table 7, displaying the minimum and maximum tonnage that can be delivered from each link in Pierce County Washington, assuming the roadways are operating at maximum possible capacity. The far right columns, labeled $/ton, demonstrate the minimum and maximum rates in annual dollars per ton and daily dollars per ton. This provides a demonstration of the potential economic consequence of a disruption to a given link, based on the value of commodities that travel along that link on an annual and daily basis.

[63] Bureau of Transportation Statistics, "2017 North American Freight Numbers | Bureau of Transportation Statistics."

Table 7. Annual and Daily Economic Losses Demonstrated with the Tonnage Per Year and Per Day Loss during a Disruption to the Links in the Pierce County Network Model[64]

Link #	City from	City to	Distance (Miles)	Route	Mileposts	Annual Tonnage (Min)	Annual Tonnage (Max)	Annual $/Ton Value (Min)	Annual $/Ton Value (Max)	Daily $/Ton Value (Min)	Daily $/Ton (Max)
1	Olympia	DuPont	14	I-5	105-119	62,990,000	72,360,000	$1,226,730,250,000	$1,409,211,000,000	$3,360,904,794.52	$3,860,852,054.79
2	Olympia	Yelm	8	I-5	105-113	62,990,000	72,360,000	$1,226,730,250,000	$1,409,211,000,000	$3,360,904,794.52	$3,860,852,054.79
			30	SR-510	0-30	2,410,000	2,730,000	$46,934,750,000	$53,166,750,000	$128,588,356.16	$145,662,328.77
3	DuPont	Yelm	6	I-5	119-113	72,360,000	72,360,000	$1,409,211,000,000	$1,409,211,000,000	$3,860,852,054.79	$3,860,852,054.79
			30	SR-510	0-30	2,410,000	2,730,000	$46,934,750,000	$53,166,750,000	$128,588,356.16	$145,662,328.77
4	DuPont	Lakewood	8.5	I-5	119-127.5	72,360,000	72,360,000	$1,409,211,000,000	$1,409,211,000,000	$3,860,852,054.79	$3,860,852,054.79
5	Roy	Yelm	20	SR-507	35-28	2,280,000	2,280,000	$44,403,000,000	$44,403,000,000	$121,652,054.79	$121,652,054.79
6	Roy	Spanaway	8	SR-507	35-43	2,280,000	2,280,000	$44,403,000,000	$44,403,000,000	$121,652,054.79	$121,652,054.79
7	Eatonville	Spanaway	3	SR-161	3-0	150,000	150,000	$2,921,250,000	$2,921,250,000	$8,003,424.66	$8,003,424.66
			20	SR-7	27-47	1,130,000	4,900,000	$22,006,750,000	$95,427,500,000	$60,292,465.75	$261,445,205.48
8	Eatonville	Puyallup	20	SR-161	5-25	2,020,000	5,490,000	$39,339,500,000	$106,917,750,000	$107,779,452.05	$292,925,342.47
			2	SR-512	9-11	28,120,000	28,120,000	$547,637,000,000	$547,637,000,000	$1,500,375,342.47	$1,500,375,342.47
9	Lakewood	Puyallup	11	SR-512	0-11	28,120,000	28,120,000	$547,637,000,000	$547,637,000,000	$1,500,375,342.47	$1,500,375,342.47
10	Tacoma	Fife	1.5	SR-705	1.5-0	4,770,000	4,770,000	$92,895,750,000	$92,895,750,000	$254,508,904.11	$254,508,904.11
			4	I-5	134-138	74,110,000	74,110,000	$1,443,292,250,000	$1,443,292,250,000	$3,954,225,342.47	$3,954,225,342.47

[64] Adapted from Washington State Department of Transportation, "State Route T-1 through T-5 Classifications," accessed January 15, 2020, https://www.wsdot.wa.gov/NR/rdonlyres/0DACF477-0EAC-4C0B-BD58-6E5F3C66C05F/0/ClassificationsTableStateRouteT1throughT5.pdf.

Link #	City from	City to	Distance (Miles)	Route	Mileposts	Annual Tonnage (Min)	Annual Tonnage (Max)	Annual $/Ton Value (Min)	Annual $/Ton Value (Max)	Daily $/Ton Value (Min)	Daily $/Ton (Max)
11	Tacoma	Gig Harbor	1.5	SR-705	1.5-0	4,770,000	4,770,000	$92,895,750,000	$92,895,750,000	$254,508,904.11	$254,508,904.11
			1	I-5	133	72,360,000	74,110,000	$1,409,211,000,000	$1,443,292,250,000	$3,860,852,054.79	$3,954,225,342.47
11	Tacoma	Gig Harbor	10	SR-16	0-10	11,370,000	17,100,000	$221,430,750,000	$333,022,500,000	$606,659,589.04	$912,390,410.96
12	Tacoma	Lakewood	1.5	SR-705	1.5-0	4,770,000	4,770,000	$92,895,750,000	$92,895,750,000	$254,508,904.11	$254,508,904.11
			8	I-5	134-126	72,360,000	74,110,000	$1,409,211,000,000	$1,443,292,250,000	$3,860,852,054.79	$3,954,225,342.47
13	Fife	Federal Way	6	I-5	138-144	74,110,000	74,110,000	$1,443,292,250,000	$1,443,292,250,000	$3,954,225,342.47	$3,954,225,342.47
14	Federal Way	Puyallup	3	SR-18	0-3	33,260,000	33,260,000	$647,738,500,000	$647,738,500,000	$1,774,626,027.40	$1,774,626,027.40
			8.5	SR-167	14.5-6	7,960,000	43,030,000	$155,021,000,000	$838,009,250,000	$424,715,068.49	$2,295,915,753.42

Analyzing the economic impact in the network, it becomes clear that a disruption to links 2, 3 and 11 would cause the greatest economic impact to the Pierce County network.

In the risk analysis, the population and economic impacts can be factored independently or together to further analyze the consequences of the risk to the network. Determining how to use this data to support the decision of where to mitigate the risk identified for the network is addressed in Chapter IV.

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IV. USING THE METHODOLOGY IN PRACTICE

A. RISK MANAGEMENT

Having a greater understanding of the potential consequences of the various risk scenarios through network modeling and the calculation measures of performance, are a critical step in the methodology. The final step, as Tundrea et al. describe, is to determine what to do with the risk, which they group into four primary categories:

5. "Risk Avoidance: Taking measures to avoid risk directly or avoid actions that may cause risks like building weak structures in known seismic zones.

6. Risk Restraining: Taking measures to prevent and control risk. It means decreasing the condition of risk occurrence and lowering the probability of risk occurrence, taking useful measures to lower the loss that risk may bring.

7. Risk Sharing and Transferring: Collectively raising individual risk capability based on the type of risk.

8. Risk Adapting: Accepting the potential loss incurred by the risk."[65]

In their article "Integrating Intelligent Transport Systems in a Risk Management System of Systems," Tundra et al. demonstrate the decision-making process for the four primary categories of disaster risk management, as demonstrated in Figure 3. The concepts from their research, combined with the application of the Network Theory methodology outlined in chapters II and III, is the final phase of this methodology.[66]

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[65] Tundrea, Draganescu, and Popa, "Integrating Intelligent Transport Systems in a Risk Management System of Systems," 389.

[66] Tundrea, Draganescu, and Popa, 388.

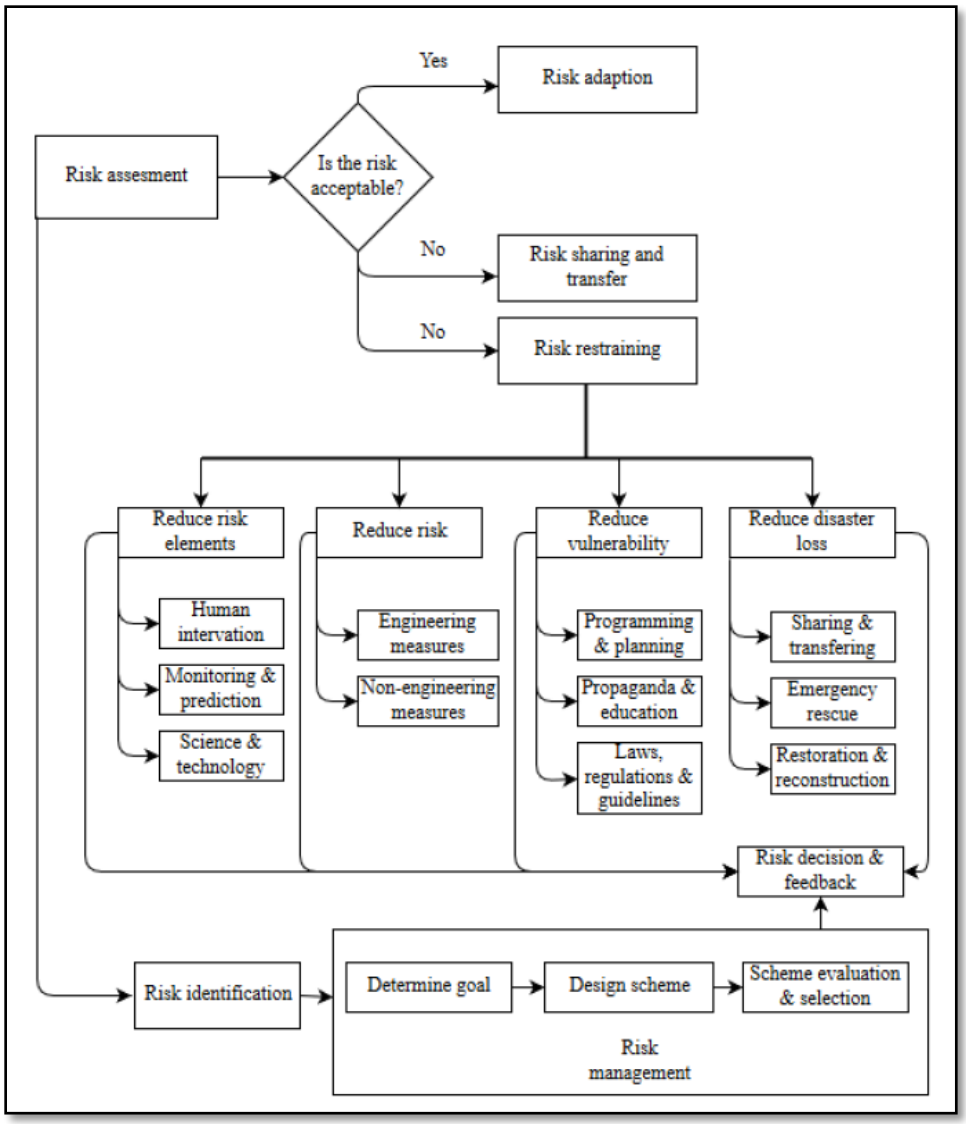

Figure 3. Implementation of Disaster Risk Management Process[67]

Given the current state of transportation infrastructure funding covered in chapter I, avoiding risk altogether is likely the least realistic option Tundrea et. al. expand on this by explaining that most risk management approaches attempt to eliminate the risk all together, which may not always be the most practical or financially feasible option.[68] In

[67] Tundrea, Draganescu, and Popa, 388.

[68] Tundrea, Draganescu, and Popa, 388.

situations where risk cannot be eliminated, it may make more sense to reduce the consequence of the risk, through risk restraint.

Transportation leaders who fall into the risk restraining group will have to go through an iterative process of determining how to reduce the risk of a disruption occurring. While this methodology will not provide specific technical recommendations for any of these strategies, there are several key considerations for each that transportation leaders can use to assess their next steps in the prioritization of their investments. As Tundrea et. al. explain, this can be accomplished by reducing risk elements, vulnerabilities, or disaster loses. It is important that transportation leaders ensure that the investments they make provide the greatest return on investment.

B. RETURN ON INVESTMENT

The concept of Return on Investment (ROI) is described by Andrew Beattie on Investopedia.com as "a simple ratio of the gain from an investment relative to its cost."[69] The formula for calculating ROI is to take the overall net return from the investment (profit, savings, etc.), divide it by the original cost of the investment, and multiply that figure by 100%.[70] For example, using the Pierce County data - if link #12 had a potential project that would cost the county $12 million dollars, but the project is expected to reduce the economic loss by $80 million annually during a disruption; the ROI for this project would be 6.67%.

$$\$80 \text{ million} / \$12 \text{ million} = 6.67 \times 100\% = 6.67\%$$

This link project provides an example of a positive ROI, which should be a factor that transportation leaders use to determine where to invest limited transportation funds.

In some circumstances, it may be better to share or transfer the risk throughout the network in order to reduce the consequence of a single impact. As discussed in the Literature Review in Chapter I, assessing the interoperability of the transportation network

[69] Andrew Beattie, "How to Calculate Return on Investment—ROI," Investopedia, July 1, 2019, https://www.investopedia.com/articles/basics/10/guide-to-calculating-roi.asp.

[70] Andrew Beattie.

and its ability to accommodate traffic loads when there is a critical link disruption is where the most research has been conducted for the transportation industry. Transportation leaders can apply concepts from this research for how to transfer risk, the specifics of which are outside the scope of this thesis.

The risk adapting category is where most transportation leaders find themselves when determining risk management strategies, due to the lack of funds to adequately restrain or transfer the risk. In some cases, the duration of the disruption may exceed the level of risk considered acceptable for a jurisdiction, or a less-than-ideal fix will have to suffice until funds become available to fully address the issue.[71] The purpose of the methodology outlined in this thesis is to provide transportation leaders caught in this situation with a means of determining how to apply those limited funds to the projects of greatest consequence based on those projects that provide the greatest return on investment.

C. LEVELS OF APPLICATION

The methodology outlined in this thesis provides an easy to follow process that can be replicated across multiple cities, counties, and states. The most critical factor for implementation at multiple levels, is developing a network model that represents the important nodes and links in the area being analyzed. These nodes and links can fall outside of geographic boundaries, as the Pierce County network model demonstrated. One of the noted gaps in current transportation investment methodologies, is that they are often constrained by political or geographic boundaries; which the methodology proposed herein provides a solution for overcoming those constraints. For example, the Pierce County network model could be expanded into two different levels: First, include locally-owned and -operated roads as links; and second, include neighboring counties into the network model for a regional network model analysis. Analyzing a network model, regardless of the political or geopolitical boundaries that fall within, provides a robust methodology for determining the consequence that would result from of a disruption to a link in the network.

[71] This observation comes from my direct professional experience in dealing with the consequences of a disruption while employed at the Washington State Department of Transportation.

This is an important factor for making a determination of where to apply limited funds to address the risk of the consequence of the disruption occurring.

D. CONCLUSION

In his book The Failure of Risk Management, Douglas Hubbard notes that one of the most important questions we should ask when conducting risk management strategies is "how do we know it works?"[72] A tried-and-true method for determining if something works, is to take out the subjectivity in the analysis of effectiveness, and apply quantitative calculations to answer the question. The impact calculations derived from the quantitative analysis discussed herein clearly demonstrate how a methodology for choosing risk management strategies should be based on where the greatest return on investment exists for reducing the consequence of a disruption. Doing so will in turn reduce the risk to the critical links in the network model. Identifying mitigation strategies to reduce the risk to the network can demonstrate the effectiveness of the investment, or a positive return on investment, if the calculations verify that less of the population is impacted, or that there is a reduction in economic impacts as a result of the mitigation strategy.

[72] Hubbard, The Failure of Risk Management, 15.

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APPENDIX. LEBLANC MATRIX OF TRIPS

TABLE I

Matrix of Trips Between Each Node Pair (Thousands of Vehicles/Day)

Origin Nodes	Destination Nodes 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	0	1	1	5	2	3	5	8	5	13	5	2	5	3	5	5	4	1	3	3	1	4	3	1
2	1	0	1	2	1	4	2	4	2	6	2	1	3	1	1	4	2	0	1	1	0	1	0	0
3	1	1	0	2	1	3	1	2	1	3	3	2	1	1	1	2	1	0	0	0	0	1	1	0
4	5	2	2	0	5	4	4	7	7	12	14	6	6	5	5	8	5	1	2	3	2	4	5	2
5	2	1	1	5	0	2	2	5	8	10	5	2	2	1	2	5	2	0	1	1	1	2	1	0
6	3	4	3	4	2	0	4	8	4	8	4	2	2	1	2	9	5	1	2	3	1	2	1	1
7	5	2	1	4	2	4	0	10	6	19	5	7	4	2	5	14	10	2	4	5	2	5	2	1
8	8	4	2	7	5	8	10	0	8	16	8	6	6	4	6	22	14	3	7	9	4	5	3	2
9	5	2	1	7	8	4	6	8	0	28	14	6	6	6	9	14	9	2	4	6	3	7	5	2
10	13	6	3	12	10	8	19	16	28	0	40	20	19	21	40	44	39	7	18	25	12	26	18	8
11	5	2	3	15	5	4	5	8	14	39	0	14	10	16	14	14	10	1	4	6	4	11	13	6
12	2	1	2	6	2	2	7	6	6	20	14	0	13	7	7	7	6	2	3	4	3	7	7	5
13	5	3	1	6	2	2	4	6	6	19	10	13	0	6	7	6	5	1	3	6	6	13	8	8
14	3	1	1	5	1	1	2	4	6	21	16	7	6	0	13	7	7	1	3	5	4	12	11	4
15	5	1	1	5	2	2	5	6	10	40	14	7	7	13	0	12	15	2	8	11	8	26	10	4
16	5	4	2	8	5	9	14	22	14	44	14	7	6	7	12	0	28	5	13	16	6	12	5	3
17	4	2	1	5	2	5	10	14	9	39	10	6	5	7	15	28	0	6	17	17	6	17	6	3
18	1	0	0	1	0	1	2	3	2	7	2	2	1	1	2	5	6	0	3	4	1	3	1	0
19	3	1	0	2	1	2	4	7	4	18	4	3	3	3	8	13	17	3	0	12	4	12	3	1
20	3	1	0	3	1	3	5	9	6	25	6	5	6	5	11	16	17	4	12	0	12	24	7	4
21	1	0	0	2	1	1	2	4	3	12	4	3	6	4	8	6	6	1	4	12	0	18	7	5
22	4	1	1	4	2	2	5	5	7	26	11	7	13	12	26	12	17	3	12	24	18	0	21	11
23	3	0	1	5	1	1	2	3	5	18	13	7	8	11	10	5	6	1	3	7	7	21	0	7
24	1	0	0	2	0	1	1	2	2	8	6	5	7	4	4	3	3	0	1	4	5	11	7	0

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