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THESIS

YOUR BRIDGES ARE FAILING, WHICH ONE SHOULD YOU FIX FIRST? AN OBJECTIVE YET SIMPLE METHOD TO RATE BRIDGES

by

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March 2020

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ABSTRACT

There is no simple and objective method for rating the criticality of bridges that conveys multi-sector components. This thesis addresses this problem using a multi-sector approach that accounts for sector-specific disruptions that can arise from damage to a single bridge. Methods for rating bridges are drawn from the existing academic, industrial, and international communities' efforts to quantify criticality. Using this sector-specific information, a novel solution is proposed for rating the criticality of a bridge, or other structure, that conveys co-linear links or nodes associated with multiple infrastructure networks.

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LIST OF ACRONYMS AND ABBREVIATIONS

AUS	Australia
CAN	Canada
CAT	category
cf	cubic feet
CI	critical infrastructure
CIP	critical infrastructure protection
CIR	critical infrastructure rating
CNI	critical national infrastructure
CP	Critical Process
DHS	Department of Homeland Security
ECI	European Critical Infrastructure
EU	European Union
F	failure
FHWA	Federal Highway Administration
GBR	United Kingdom
GER	Germany
KCMO	Kansas City, MO
KCMO OEM	Kansas City, MO Office of Emergency Management
KWH	kilowatt hour
MoDOT	Missouri Department of Transportation
MOP	measure of performance
NI	national infrastructure
NPS	Naval Postgraduate School
ns	nanoseconds
O/D	origin and destination
PDD	Presidential Decision Directive

PPD	Presidential Policy Directive
RRW	resilience reduction worth
S	success
SUI	Switzerland
T^{OPT}	optimal recovery time
USA	United States of America
W	warning

EXECUTIVE SUMMARY

Though bridges are vital for surface transportation, they also serve as structural supports for a broad variety of communication cables, power conduits, and gas or liquid pipelines, serving as vital links for multiple infrastructure sectors. Despite their importance across multiple sectors, an objective and simple rating system does not exist to account for their multi-sector criticality. Knowing the true criticality of a bridge across sectors is vital to determine which bridges are more in need of funds to repair or protect.

To solve this problem, this thesis asked what methodology can evaluate the criticality of bridges that convey multiple critical infrastructure networks or, if none exist, can one be created. Examining existing methods for rating individual critical infrastructures, this thesis proposed a process to rate bridges that convey multiple critical infrastructures. The formula retains objectivity and simplicity for those that are not mathematicians.

Governmental agencies, academic groups, private industry, and other countries all participate, at some level, in infrastructure protection. DHS provided a starting point for my investigation into current methods, but their methodology was too subjective. DHS relies heavily on other organizations to rate their own infrastructure. Other countries are very similar to DHS in how they defined and rated critical infrastructure. Academic groups provide much more precision and objectivity to their rating system but require complex mathematical processes. Private industry and governmental agencies (other than DHS) use much more specific rating systems for their transmission lines. This thesis incorporated some portion of each of these groups rating methods into my final formula/process.

My process begins with using measure of performance (MOP) to determine an individual critical infrastructure rating (CIR) for each CI transmission line conveyed by the bridge. The formula $CIR_n = 100(MOP_n \div MOP_{max})$ generates a percentage number that can be compared to other types of CI. CIR_n is the criticality rating for the CI network transmission line conveyed by the bridge, MOP_n represents the MOP of the transmission line conveyed by the bridge, and MOP_{max} represents the maximum MOP of the greatest line in the network. Once the individual CIRs are calculated, the bridge's rating can be computed from a simple summation of the individual CIRs: $CIR_t = \sum CIR_n$.

However, the formula demonstrated that under certain conditions a bridge conveying just a couple of CI networks could rate higher than a bridge with many networks. Realizing the equation needed a coefficient, this thesis attempted to use a simple coefficient (ranging from 0.2 for the least important CI and 1.0 for the most) for the CIR calculation. However, this process injected a subjectivity bias of the user. For example, one person might rate electricity as the most important CI while another might rate water as the most important.

Discarding the subjective coefficient method, this thesis next proposed using a coefficient based on revenue generated or lost by the failure of the bridge. The formula expanded to $CIR_n = (CI_c \div CI_{ctot})(MOP_n \div MOP_{max})$ where CI_c is the loss of revenue from failure of the bridge and CI_{ctot} is the total revenue generated by the network. This modification to the formula adjusted the final rating score in favor of bridges that conveyed more CI networks (more networks equals a greater monetary loss resulting from bridge failure). However, the formula weighted more critically higher revenue generating CIs.

To account for bridges conveying more CI networks, this thesis created a divisor that would divide the formula by a greater factor for bridges that conveyed fewer CI networks. The adjustment would be represented by N-n+1, where N equals the maximum number of CI network lines a bridge could carry and n equals the number the rated bridge carries. The factor +1 ensures that the divisor is not 0 if a bridge conveys the maximum number of CI networks. The new formula provides a weighted rating where: $CIR_t = \sum CIR_n/(N-n+1)$. However, this proposed formula could result in a bridge conveying multiple CIs of low importance rates higher than a bridge conveying only a couple CIs of higher importance.

The formula provided contains both the elements of objectivity and relative precision. However, the process contains some shortcomings. The first is determining the base MOP_{max} that provides the basis for the CIR. The maximum MOP will vary depending on the basis for the calculation, whether local, state, or national figures. Adjusting the CIR based on the importance of the CI creates another difficulty. Using a subjective coefficient counters the objective requirements. However, using a more objective monetary based coefficient weighs the formula in favor of the higher revenue generating/cost CI. Dividing the calculation by a factor based on the number of CI networks conveyed weighs the rating more heavily for bridges that convey a greater number of CI networks.

The proposed method proffers a starting point for addressing the problem of rating the criticality of bridges. It is not intended to be the final solution to the problem. Further research should be conducted to improve and standardize the process. Future efforts should focus on refining the CIRs of each CI, possibly even dividing certain CIs into separate categories for more accuracy (pipelines could be divided into the individual petroleum products, for example). The CIs also need a ranking determination so that less important CIs to the communities' life and safety do not rate higher than more important CIs. Once the above steps are refined, the basic formula presented in this thesis will become more accurate. Any enhancements must not increase accuracy at the total expense of simplicity, however.

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I. INTRODUCTION

The following sections outline the rationale for developing a new criticality rating for bridges that convey infrastructure components from multiple sectors. The need and importance to Homeland Security is justified through Presidential Directives and my personal experience as an emergency planner for the Kansas City Office of Emergency Management (KCMO OEM).

A. PURPOSE

Bridges throughout the country can be important lifelines for communities, cities, counties, states, and even the nation.[1] Bridges, however, can convey more than traffic. Bridges provide structural support that links the nation via local and regional telecommunication systems, energy supply chains, water distribution, transportation, and other critical infrastructure (CI). Their role makes bridges critical infrastructure that impacts security and health, not just transportation. These other types of CI (e.g., water, electricity, natural gas, communications), through channels attached to the structure, can traverse obstacles using bridges.[2] So, if a bridge is destroyed through natural or man-made means, the impact to the community may be greater than just the loss of vehicular traffic. The community can suffer loss of communication and even access to vital resources such as water and electricity.

During a meeting, February 4, 2016, with Verizon and other telecommunication agencies of Kansas City, MO (KCMO) and the Office of Emergency Management (KCMO OEM), an attendee pointed out that a seriously damaged or collapsed bridge would severely affect telecommunications because of several tubes (links) attached under a particular

[1] Caroline McDonald, "A Bridge Too Far: Repairing America's Aging Infrastructure," *Risk Management;* 61, no. 1 (February 2014): 16, http://www.rmmagazine.com/2014/02/01/a-bridge-too-far-repairing-americas-aging-infrastructure/.

[2] Department of Homeland Security, *Transportation Systems Sector-Specific Plan - 2015* (Washington, DC: Department of Homeland Security, 2016), 15, https://www.dhs.gov/publication/nipp-ssp-transportation-systems-2015.

riverine bridge. Because trusted subject matter experts relayed this information to KCMO OEM, KCMO dedicated additional resources to monitoring and protecting this bridge.

The Pfeiffer Canyon Bridge collapse in Big Sur, California, provided a micro example of the importance that bridges can play in a community beyond vehicular traffic. From February to March of 2017, the Pfeiffer Canyon Bridge, which services Big Sur from the south, collapsed. Travelers from the south added over 66 miles since they were required to journey north and head back south.[3] Aside from cutting off the southern travel route to Big Sur, the bridge collapse affected power and telecommunications.[4] Cutting those resources effectively isolated businesses and residents, affecting their safety.[5]

From research, I discovered three bridges that crossed the Missouri River in the Kansas City Region (the Liberty Bridge between Jackson County and Clay County, Missouri; the Fairfax Bridge between Wyandotte County, Kansas, and Platte County, Missouri; and the Centennial Bridge between Leavenworth, Kansas, and Platte County, Missouri) carried major pipelines that convey natural gas or hazardous liquids.[6] Aside from the vehicular traffic, which can be rerouted to other nearby bridges, natural gas, water, and other critical resources flow in conduits under bridges, and the impact of their loss could have national implications.

This thesis examined the current literature regarding rating CI, either singly or as part of a multi network system. The goal is to propose parameters to develop an objective rating system for bridges, or other links/nodes that convey CI from multiple networks. Any system developed should be simple enough to be used by emergency managers or others

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[3] Google Maps, accessed October 12, 2019, https://www.google.com/maps/place/Pfeiffer+Canyon+Bridge/@36.0328061,-121.4234343,9.25z/data=!4m5!3m4!1s0x8092825622a88867:0x3d6d20bf51adc068!8m2!3d36.2392825!4d-121.775067?hl=en.

[4] Tom Wright, "Highway 1: Pfeiffer Canyon Bridge Deterioration Continues," *Mercury News*, February 23, 2017, https://www.mercurynews.com/2017/02/23/highway-1-pfeiffer-canyon-bridge-deterioration-continues/.

[5] Wright, "Highway 1."

[6] "National Pipeline Mapping System Public Viewer," Pipeline and Hazardous Materials Safety Administration, 2019, https://pvnpms.phmsa.dot.gov/PublicViewer/.

involved in CI protection (CIP). The simplicity, however, should not sacrifice the objectivity of the criticality rating.

B. SCOPE

The question and problem this thesis addressed is how to quantify the impact of the loss of a bridge that carries more than just traffic (i.e., it conveys multiple CI sector resources): or its criticality. With an objective rating system, decisions to protect bridge infrastructures can be based on a complete data set that includes all critical infrastructure networks served by a bridge, not just transportation. Because a bridge could serve as either a link (a conduit that connects two points) or a node (an intersection of multiple links), this thesis explored and evaluated current methodologies for rating links and nodes that cover multiple critical infrastructure sectors.[7] Not finding such a method, this thesis examined current ways that individual CIs are rated and synthesized a possible process for determining the criticality of those links and nodes, such as bridges.

As this process is new, it provides a foundation for further research and development to improve its accuracy and objectivity. Not all information was readily available, policy must be implemented to ensure uniform usage of the process, and other shortcomings (described in Chapter V.A.) result in additional refinement to the process. The formulas and methodology, however, capture the necessary elements to provide an objective rating system for bridges and other links/nodes that convey multiple CI networks.

C. SIGNIFICANCE

Under Presidential Policy Directive 21 (PPD-21) Critical Infrastructure Security and Resilience, the Secretary of Homeland Security has a responsibility “promote the security and resilience of the Nation’s critical infrastructure.”[8] Critical infrastructure is

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[7] *Merriam-Webster*, s.v. “Link,” accessed February 28, 2019, https://www.merriam-webster.com/dictionary/link; *Merriam-Webster*, s.v. “Node,” accessed February 28, 2019, https://www.merriam-webster.com/dictionary/node.

[8] Barack Obama, *Critical Infrastructure Security and Resilience,* Presidential Policy Directive, PPD-21 (Washington, DC: White House, 2013), https://fas.org/irp/offdocs/ppd/ppd-21.pdf.

categorized into 16 sectors, including transportation.[9] According to the Transportations Systems Sector Specific Plan, bridges fall under the Department of Homeland Security's (DHS) Highway and Motor Carrier subsector of the Transportations Sector.[10] This plan states that "the impact of a loss of a key node or asset, such as a bridge, poses an immediate threat to users and can have cascading impacts to passenger and freight movement, as well as potentially large-scale impacts (such as supply chain disruption)."[11] Supply chains include pipelines, freight, mass transit, railroads, and cyber systems.[12] The impact of bridge failure can jeopardize public safety, imperil the quality of life, and place a hardship on the U.S. economy.[13]

However, no objective rating system currently exists to determine the criticality of one link or node, such as a bridge, that conveys critical infrastructure from multiple networks. A few academic papers propose systems to rate the criticality of traffic network links and nodes, which will be examined in more detail later. These methods, however, only examine one aspect, traffic flow or repair need, of a bridge to determine its criticality. Neither of these methods study other CI that might be conveyed by the bridge. Nor do these studies compare the criticality of one bridge to another.

Implementing an objective rating system is necessary to determine the criticality of bridges and other links and nodes that convey critical infrastructure from multiple networks. Knowing which bridges are the most critical ensures the efficient use of resources to protect the more important ones. By committing more resources to the more critical bridges, the return on investment for civic institutions like state and local governments will increase.

[9] "Critical Infrastructure Sectors," Department of Homeland Security, March 5, 2013, https://www.dhs.gov/cisa/critical-infrastructure-sectors.

[10] Department of Homeland Security, *Transportation Systems Sector-Specific Plan - 2015*, 5.

[11] Department of Homeland Security, 6.

[12] Department of Homeland Security, 15.

[13] McDonald, "A Bridge Too Far," 16.

II. INFORMATION PROVIDING A BACKGROUND TO THE PURPOSE OF DESIGNING A METHOD TO RATE THE CRITICALITY OF BRIDGES

This section provides background for classifying bridges as part of the CI complex. The information includes DHS's role in protecting CI (and thus, bridges) and the significance of bridges.

A. THE DEPARTMENT OF HOMELAND SECURITY AND CRITICAL INFRASTRUCTURE

From reviewing various literature, three main viewpoints prevail in DHS's mission to protect the nation's critical infrastructure: DHS should have the mission of protecting the nation's critical infrastructure; DHS should protect but modify its stance of protecting the nation's critical infrastructure; and DHS should not commit resources to protecting the nation's critical infrastructure.

Many writings support the proposition of DHS protecting critical infrastructure as part of its mission. The most influential are the presidential directives. Even prior to the creation of DHS, President Clinton authored Presidential Decision Directive 63 that recognized the vulnerability of critical infrastructure and the need to protect it from attack.[14] President Obama followed and refined President Clinton's directive by charging DHS with tasks associated with critical infrastructure protection.[15] DHS has produced resources to guide critical infrastructure protection, which DHS recognizes as part of the its mission.[16] Although some in the private sector disagree whether critical infrastructure protection is the primary responsibility of DHS or private industry, most generally agree

[14] William J. Clinton, *Critical Infrastructure Protection*, Presidential Decision Directive/NSC PDD-63 (Washington, DC: White House, 1998), https://fas.org/irp/offdocs/pdd/pdd-63.htm.

[15] Obama, *Critical Infrastructure Security and Resilience*, 2–12.

[16] Department of Homeland Security, *A Guide to Critical Infrastructure and Key Resources Protection at the State, Regional, Local, Tribal, and Territorial Level* (Washington, DC: Department of Homeland Security, 2008), https://www.dhs.gov/xlibrary/assets/nipp_srtltt_guide.pdf.

that critical infrastructure should be protected and DHS owns that mission.[17] Therefore, DHS should take a lead role in CIP.

Although much of the consensus is that DHS should provide protection for critical infrastructure, there are those that express that the list of critical infrastructures is too broad. These spokespersons contend that DHS should modify its scope of protection to focus more clearly on infrastructure that is essential. Riedman, in his thesis for the Naval Postgraduate School (NPS), proposes that DHS is misusing its resources on too many non-critical resources.[18] Eric Lipton, writing in the *New York Times*, echoes this view, noting that such places as petting zoos are listed as critical resources.[19] Both recommend that the CI list needs to be revised with improved criteria. In addition, the Office of the Inspector General criticizes the list of critical assets because states could rely on opinion-based criticality when interpreting DHS's definition of a critical assets.[20]

Although there is broad consensus that CIP should be a DHS mission, some critics believe that DHS's scope of responsibility should be reduced. In a survey conducted for Bradford C. Mason's NPS thesis, responses from local, state, federal, and tribal governmental personnel indicated that 85% of the CI was privately owned and that more engagement was needed between government and private sector.[21] Sue Eckert shares this sentiment in her report regarding a need for a partnership between public and private sectors to protect markets and finances concluding "the government and private sector both

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[17] Chris Koski, "Committed to Protection? Partnerships in Critical Infrastructure Protection," *Journal of Homeland Security and Emergency Management* 8, no. 1 (May 2011): 20, https://doi.org/10.2202/1547-7355.1860; Larry M. Wortzel, ~~"~~*Securing America's Critical Infrastructure: A Top Priority for the Department of Homeland Security*,~~"~~ (Washington, DC: Heritage Foundation, 2003) https://www.heritage.org/homeland-security/report/securing-americas-critical-infrastructures-top-priority-the-department.

[18] David A. Riedman, "How Critical Is Critical Infrastructure?" (master's thesis, Naval Postgraduate School, 2015), 111–13, https://www.hsdl.org/?view&did=788375.

[19] Eric Lipton, "Come One, Come All, Join the Terror Target List," *New York Times*, July 12, 2006, https://www.nytimes.com/2006/07/12/washington/12assets.html.

[20] Office of the Inspector General, *Progress in Developing the National Asset Database*, OIG-06-40 (Washington DC: Department of Homeland Security, 2006), 9–15, https://www.oig.dhs.gov/sites/default/files/assets/Mgmt/OIG_06-40_Jun06.pdf.

[21] Bradford C. Mason, "Putting the Critical Back in Critical Infrastructure" (master's thesis, Naval Postgraduate School, 2015), 14–72, https://doi.org/10.21236/AD1009160.

need to work together more effectively."[22] Furthering the notion of private sector involvement in CIP, Larry Wortzel proposes in his article for The Heritage Foundation that more responsibility should be placed on the private sector instead of DHS stating, "Permitted enough flexibility, the private sector can respond much more quickly and effectively to many homeland security threats than government agencies can."[23] The important commonality in these writings is that none suggest that DHS should be completely removed from CIP.

B. THE SIGNIFICANCE OF RATING BRIDGES' CRITICALITY

PPD-21 Critical Infrastructure Security and Resilience mandates that the DHS has a responsibility regarding the nation's critical infrastructure.[24] Bridges need protection as part of the transportation sector of CI.[25] Bridge failure has a wide-reaching impact. The collapse of a bridge endangers public safety, disrupts the quality of life, and negatively affects the U.S. economy through loss of transportation.[26]

The Federal Highway Administration (FHWA) reported that the percentage of large bridges that were structurally deficient dropped from 10.2 percent to 6.4 percent from 2007 to 2016 despite the federal funds allocated for highway bridges remaining stable.[27] Although the lower percentage of structurally deficient bridges seems a significant improvement, more than 39,000 bridges remain structurally deficient.[28] Shifting allocation from building new bridges to preserving the existing bridges accounts for the improvement,

[22] Sue Eckert, "Protecting Critical Infrastructure: The Role of the Private Sector," in *Guns and Butter: The Political Economy of International Security*, ed. Peter J. Dombrowski (Boulder, CO: Lynne Rienner Publishers, 2005), 198.

[23] Wortzel, "*Securing America's Critical Infrastructure*"

[24] Obama, *Critical Infrastructure Security and Resilience*.

[25] Department of Homeland Security, Transportation Systems Sector-Specific Plan–2015.

[26] McDonald, "A Bridge Too Far," 16.

[27] Mark Goldstein, *Highway Bridges: Major Projects Present Challenges for States, but Strategies Exist to Overcome Them*, GAO-17-707 (Washington, DC: Government Accountability Office, 2017), 10–11, https://www.gao.gov/products/GAO-17-707; Mark Goldstein, *Highway Bridges: Linking Funding to Conditions May Help Demonstrate Impact of Federal Investment*, GAO-16-779 (Washington, DC: Government Accountability Office, 2016), 15–16, https://www.gao.gov/products/GAO-16-779.

[28] Goldstein, *Highway Bridges*, 38–39.

but an increase in state and local funding has also contributed to the reduction of structurally deficient bridges.[29] However, FHWA, which focused on repair and replacement due to age, implemented these resiliency measures and not DHS. The funds also provide for monitoring bridges only on a regular basis and not constantly, although bridge inspections are required not less than every 24 months.[30]

FHWA allocated funds to repair and reinforce aged bridges, not to protect them from attack. Globally, terrorist attacks on bridges have been on the rise since 1998 (only a couple of bridge attacks occurred before then in the years from 1970 to 1998), with 87 percent of those, or 465, attacks within the last decade (2007 to 2017).[31] The rise of attacks on bridges is important as bridges have specific points at which they are vulnerable to shelling or explosives.[32] The FHWA recommended in a 2003 report that "Bridge and tunnel security is important enough to be a matter of national security policy."[33] The same report outlines countermeasure options to safeguard bridges and tunnels.[34]

However, in looking at past terrorism activity from 1970 to 2017, only 534 out of the 1,816,920 attacks in the world targeted bridges. Of those attacks, only two, one in 1970 by the Black Panthers and one in 2011 by unknown persons, occurred in the United States (both attacks failed).[35] In a list of ten common reasons that bridges collapse, terrorism is

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[29] *Highway Bridges*, 16–18.

[30] "Bridges, Structures, and Hydraulics," U.S. Congress, *Code of Federal Regulations,* title 23 (2004 comp): 650.311 https://www.ecfr.gov/cgi-bin/text-idx?c=ecfr&sid=370f47191998a86077876bcde37e49c3&rgn=div6&view=text&node=23:1.0.1.7.28.3&idno=23.

[31] "GTD Search Results," GTD Global Terrorism Database, accessed July 20, 2018, http://www.start.umd.edu/gtd/search/Results.aspx?expanded=no&casualties_type=&casualties_max=&start_year=2006&start_month=1&start_day=1&end_year=2006&end_month=12&end_day=31&success=yes&ob=GTDID&od=desc&page=1&count=100#results-table.

[32] P. S. Bulson, *Explosive Loading of Engineering Structures*, (London: Chapman & Hall, 2002), 218–34, https://doi.org/10.4324/9780203473863.

[33] Blue Ribbon Panel on Bridge and Tunnel Security, *Recommendations for Bridge and Tunnel Security* (Washington, DC: Federal Highway Administration, 2003), 33, https://www.hsdl.org/?view&did=439975.

[34] Blue Ribbon Panel on Bridge and Tunnel Security, 35–39.

[35] "GTD Search Results."

not listed as a consideration.[36] The more likely causes of bridge failure or collapse are natural (including aging from the elements), crashes, and poor construction/engineering. The lack of terrorist attacks does not lessen the need to protect bridges but shifts the focus to other causes.

With the importance of bridges and the number needing repair, an objective rating system would assist with determining which bridges should take priority. The rating system would examine more than just the age of the bridge, as FHWA does, in order to ensure efficient allocation of funds to repair and protect bridges from natural or man-made failure. It should take into account the impact due to the failing bridge.

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[36] Ed Grabianowski, "10 Reasons Why Bridges Collapse," How Stuff Works, September 13, 2011, https://science.howstuffworks.com/engineering/structural/10-reasons-why-bridges-collapse.htm.

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III. CURRENT METHODOLOGIES TO RATE CRITICAL INFRASTRUCTURE

Various institutions involved in CIP have used differing methods to rate the importance, or criticality, of CI elements. In order to synthesize a method to rate bridges, this thesis examined different fields and how they classify and rate individual CIs. Through researching governmental (including other countries), academic, and subject matter experts (in private industry and governmental agencies), this thesis determined factors needed to synthesize a process to rate bridges.

A. THE CURRENT DHS SYSTEM TO RATE CRITICAL INFRASTRUCTURE

Based on the "National Infrastructure Protection Plan 2013: Partnering for Critical Infrastructure Security and Resilience" taken from the USA Patriot Act of 2001, DHS defines critical infrastructure as systems or assets whose incapacity or destruction would have a "debilitating impact on security, national economic security, national public health and safety, or any combination of those matters."[37] This definition, however, lacks any objective or quantitative measure for the level of criticality for the asset. Instructions on identifying critical infrastructure are no less subjective as partners (including the states and private companies) determine what infrastructure is "essential to their continued operation, considering associated dependencies and interdependencies."[38] A lack of an objective definition results in great subjectivity as to what is critical and its criticality.

DHS provides some guidance in its rating for critical infrastructure on vulnerability and risk assessments. For example, DHS's *A Guide to Critical Infrastructure and Key Resources Protection at the State, Regional, Local, Tribal, and Territorial Level* instructs

[37] Department of Homeland Security, *National Infrastructure Protection Plan 2013: Partnering for Critical Infrastructure Security and Resilience* (Washington, DC: Department of Homeland Security, January 2014), https://www.dhs.gov/publication/nipp-2013-partnering-critical-infrastructure-security-and-resilience; U.S. Congress, Uniting and Strengthening America by Providing Appropriate Tools Required to Intercept and Obstruct Terrorism (USA Patriot Act) Act of 2001, Public Law 107-56, *U.S. Statutes at Large* 115 (2001): 272 , https://www.congress.gov/bill/107th-congress/house-bill/3162/text/enr.

[38] Department of Homeland Security, *National Infrastructure Protection Plan 2013*, 16.

that a risk-based approach in prioritizing critical assets should be used but leaves the rating criteria up to the agency.[39] The United Kingdom also utilizes a method of risk assessment with criticality to determine prioritization, which this thesis will examine more closely in the next section.[40]

The lack of quantitative rating criteria has resulted in inconsistency when measuring the criticality of assets to prioritize them. As a study conducted by DHS showed, ten of their vulnerability assessment tools, used by different agencies "varied greatly in their length and the detail of information to be collected."[41] Without objective assessments/ratings, those involved in CIP cannot objectively determine which assets should be protected more than other assets.

B. CURRENT SYSTEMS TO RATE CI CRITICALITY

Aside from the DHS method, several different systems exist to rate the criticality of critical infrastructure. To determine what processes can best determine criticality, this thesis examined methodologies proposed by the academic community, methods used by other countries, and then methods used by CI companies.

1. An Academic Approach to Determining CI Criticality

Members of the academic community propose multiple methods for determining the criticality of a CI network component. Some examine only the links and their importance to the network as a whole. Others examine the links and nodes of a network to determine their relative importance. In academic approaches, the impact on the network due to failure of that link or node determines its criticality.

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[39] Department of Homeland Security, *A Guide to Critical Infrastructure,* 36–37.

[40] Cabinet Office, *Strategic Framework and Policy Statement on Improving the Resilience of Critical Infrastructure to Disruption from Natural Hazards* (London: Cabinet Office, 2010), 19–20, https://www.gov.uk/government/publications/strategic-framework-and-policy-statement-on-improving-the-resilience-of-critical-infrastructure-to-disruption-from-natural-hazards.

[41] Stephen Caldwell, *Critical Infrastructure Protection: DHS Action Needed to Enhance Integration and Coordination of Vulnerability Assessment Efforts* (Washington, DC: Government Accountability Office, 2014), 13–17, https://www.gao.gov/products/GAO-14-507.

Jenelius, Petersen, and Mattsson examine the importance of just the links in a CI network. Jenelius, Petersen, and Mattsson define the criticality of a particular link through its contribution to the system as a whole and the consequences of complete failure.[42] Using the example of transportation networks, they calculate the cost of increased travel as the measure of criticality. Jenelius, Petersen, and Mattsson state "We have defined the importance of a link or group of links in a road network to be the increased generalised cost of travel when that link or group of links is closed."[43] More specifically, the measure of performance is the increased travel cost if failure of the link or links causes rerouting.

Jenelius, Petersen, and Mattsson present a collection of formulas that compare costs of travel on damaged versus undamaged stretch of road (link). The cost from unsatisfied demand (travel demand not met for a particular link) increased by the exposure to risk factors determines importance. The calculation determines the importance of a link or group of links in a traffic network.[44] The number of links that must be used to travel from one node to another and the demand, or "number of vehicles on an annual daily average," figure into the calculation and increase the cost.[45] They state "Further, we have defined a collection of operational measures of these concepts, based on an increase in travel cost, weighted and averaged in different ways."[46] Through these calculations, Jenelius, Petersen, and Mattsson provide an objective method to determine the criticality of a link. By comparing the criticality, a rating system can be devised to rank the various links in the network.

Although manipulating the factors through their formula is complex, Jenelius, Petersen, and Mattsson simplify the network through three steps. First, the formula assumes that travel on the links is in two directions. Where there are two one-way links between

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[42] Erik Jenelius, Tom Petersen, and Lars-Göran Mattsson, "Importance and Exposure in Road Network Vulnerability Analysis," *Transportation Research Part A: Policy and Practice* 40, no. 7 (August 2006): 541–42, https://doi.org/10.1016/j.tra.2005.11.003.

[43] Jenelius, Petersen, and Mattsson, 554.

[44] Jenelius, Petersen, and Mattsson, 558–59.

[45] Jenelius, Petersen, and Mattsson, 545–49.

[46] Jenelius, Petersen, and Mattsson, 554.

nodes, Jenelius, Petersen, and Mattsson view them as one link in both directions. The second step entails removing all centroids and connectors. Centroids are points in the network where links intersect without being a point of origin or destination. For the purposes of calculation, the nearest demand node (point of origin or a destination for the traveler) replaces the centroid. The authors' third step is to "remove a few nodes that are not connected to the rest of the network."[47] This process leaves a single, main network consisting of only links and nodes pertinent to this network.[48]

Another category for determining CI criticality is the performance and efficiency of the link or node to the network. Rather than using an increase in cost, the method uses the effect on the performance of the link or node on the network. The greater the impact to the system of the loss of the link or node, then the more critical that component rates.

Nagurney and Qiang equate criticality to the effect of a drop in efficiency of the link or node on the overall system to determine its importance (criticality).[49] Through a complex series of equations, Nagurney and Qiang assign a measure to the network equilibrium, the N-Q measure.[50] The equations determine factors such as demand, flow, behavior of users, and incurred costs.[51] The importance of the network component is also assigned an N-Q measure and then rated according to its effect on the network equilibrium.[52] All components are then rated and compared to determine their criticality.[53]

Nagurney and Qiang distinguish their method from Jenelius, Petersen, and Mattsson by examining the nodes as well as the links.[54] They do not separate the

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[47] Jenelius, Petersen, and Mattsson, 546.

[48] Jenelius, Petersen, and Mattsson, 545–46.

[49] Anna Nagurney and Qiang Qiang, "A Network Efficiency Measure with Application to Critical Infrastructure Networks," *Journal of Global Optimization* 40, no. 1–3 (March 2008): 261, http://dx.doi.org /10.1007/s10898-007-9198-1.

[50] Nagurney and Qiang, 263–66.

[51] Nagurney and Qiang, 273–74.

[52] Nagurney and Qiang, 266–68.

[53] Nagurney and Qiang273–74.

[54] Nagurney and Qiang, 262.

components into links as nodes specifically but combine them as origin and destination pairs (O/D pairs).[55] The O/D pair looks at the node where the CI traversing the system (vehicles, electricity, internet, etc.) begins, the node where it ends, and the link in between. By creating O/D pairs, Nagurney and Qiang's method essentially examines the links' efficiency, thereby simplifying the process without considering the nodes separately.

Eldosouky, Saad, and Mandayam approach the problem of rating CI from the aspect of resiliency, importance to the CI network, and cost to allocate resources to the component (link or node). A multi-stage method determines the individual steps of the process with each building on the prior step. To begin the process, Eldosouky, Saad, and Mandayam's method uses reliability, the frequency or likelihood of failure, and resilience. Resilience is defined as the "ability to reduce the magnitude and/or duration of disruptive events… its ability to anticipate, absorb, adapt to, and/or rapidly recover."[56] With these definitions of reliability and resilience, their method advances with the next stages of the process.

Focusing on resilience as the method of determining resource allocation, and thus criticality, Eldosouky, Saad, and Mandayam's process assigns three values to "represent the three CI states: success (S), warning (W) and failure (F)."[57] S represents normal service, W indicates a partial failure but still providing service, and F represents complete failure to provide service.[58] The method then determines the probability that a link or node will transition from one state to another (e.g., from a success to warning state) using a Markov chain (a mathematical system that transitions from one state to another) and a probability matrix.[59] Using a Bayesian network model, the method examines the relationship of the CI network's components to determine the resiliency of the network and

[55] Nagurney and Qiang, 263.

[56] AbdelRahman Eldosouky, Walid Saad, and Narayan Mandayam, *Resilient Critical Infrastructure: Bayesian Network Analysis and Contract-Based Optimization* (Ithaca, NY: Cornell University Library, ArXiv.org, 2017), 1, http://arxiv.org/abs/1709.00303; National Infrastructure Advisory Council, *Critical Infrastructure Resilience: Final Report and Recommendations* (Washington DC: Department of Homeland Security, 2009), 3, https://itlaw.wikia.org/wiki/Critical_Infrastructure_Resilience:_Final_Report_and_Recommendations.

[57] Eldosouky, Saad, and Mandayam, 3.

[58] Eldosouky, Saad, and Mandayam, 3.

[59] Eldosouky, Saad, and Mandayam, 3–5.

the importance of those componence to the overall resiliency.[60] A Bayesian network model "describes the causality and relationship between independent random variables under incomplete information."[61] Use of the Markov chain, probability matrix, and Bayesian network model, Eldosouky, Saad, and Mandayam initiate the process to objectively rate the criticality of links and nodes.

Once the interdependency is determined, Eldosouky, Saad, and Mandayam's approach uses a Bayesian algorithm to "capture the effect of each component on the infrastructure's probability of failure."[62] The Bayesian algorithm assigns a probability CI failure and importance to the component based on the greatest need to increase resilience.[63] A cost/benefit analysis then establishes the amount of resources needed to improve resiliency of the rated components.[64] The results of the analysis inform the decision to allocate resources to improve the resiliency of the particular components.

Fang, Pedroni, and Zio examine the repair priority of a CI component, the component's resiliency, and the impact of the component's (link or node) failure on the system as its measure of importance (criticality).[65] To accomplish the overall rating, their system begins with calculating the optimal recovery time (T^{OPT}) for a particular link or node of the network.[66] The method uses a complex formula, calculating a value that measures the time from failure to the time where the link or node is halfway back to full functioning.[67] The value obtained becomes the resilience of the system or the individual link or node.[68]

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[60] Eldosouky, Saad, and Mandayam, 5–6.

[61] Eldosouky, Saad, and Mandayam, 5.

[62] Eldosouky, Saad, and Mandayam, 14.

[63] Eldosouky, Saad, and Mandayam, 14.

[64] Eldosouky, Saad, and Mandayam, 8–14.

[65] Yi-Ping Fang, Nicola Pedroni, and Enrico Zio, "Resilience-Based Component Importance Measures for Critical Infrastructure Network Systems," *IEEE Transactions on Reliability* 65, no. 2 (June 2016): 502, https://doi.org/10.1109/TR.2016.2521761.

[66] Fang, Pedroni, and Zio, 504.

[67] Fang, Pedroni, and Zio503–6.

[68] Fang, Pedroni, and Zio, 510–11.

Fang, Pedroni, and Zio next obtain a value for the resilience reduction worth (RRW). The RRW–or more specifically, the *$RRW_{ij}(\Delta t_0)$*: the reduction of arc *ij* over time *Δt_0* - is defined as that which "quantifies potential loss in optimal system resilience"[69] To determine the RRW, Fang, Pedroni, and Zio examine the system's reduction effect from each component's failure.[70] With RRW, components with higher values should be given higher priority.

Fang, Pedroni, and Zio's method then uses two mathematical systems to calculate the final rating. To generate distributions of T^{OPT} and RRW, their process uses the Monte Carlo method to calculate the values of T^{OPT} and RRW.[71] The Monte Carlo method (or simulation, as it is better known) models the chance of different outcomes that cannot be easily predicted.[72]

Fang, Pedroni, and Zio then use the Copeland Method to rank the values generated from the Monte Carlo simulation to obtain the importance (criticality) of each component.[73] The Copeland Method is a comparison technique that rates all components of the network by comparing two components at a time and valuing the better of the two points; a score of 1 is given to the higher value and 0.5 if the scores were even. The components' points are then added to create a final score for the component.[74] Once all of the components are valuated, the component with the highest score is most important (critical).[75]

Each of these methods for determining criticality has a commonality: multi-step processes involving complex algebra or calculus equations. Having spent years in the

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[69] Fang, Pedroni, and Zio, 511.

[70] Fang, Pedroni, and Zio, 506–7.

[71] Fang, Pedroni, and Zio, 506–7.

[72] Will Kenton, "Monte Carlo Simulation," Investopedia, June 10, 2019, https://www.investopedia.com/terms/m/montecarlosimulation.asp.

[73] Fang, Pedroni, and Zio, "Resilience-Based Component Importance Measures," 506–507.

[74] "Copeland's Method," Lumen: Mathematics for the Liberal Arts, accessed October 10, 2019, https://courses.lumenlearning.com/waymakermath4libarts/chapter/copelands-method/.

[75] Fang, Pedroni, and Zio, "Resilience-Based Component Importance Measures," 511.

emergency management community, my experience has been that emergency managers will not use complex systems when rating the criticality of CI components such as bridges. Emergency managers, especially those who must convince their superiors to spend money, need a simple, easy-to-explain method for rating criticality. A simpler method must be examined for rating the criticality of a bridge.

2. Methods Used by CI Agencies within the United States to Determine CI Criticality

To obtain a different and more practical perspective on rating CI, I next conducted a survey with various agencies and utility companies around the United States. Through face-to-face, telephonic, and email conversations, various experts in the industry provided me with their companies' methods of measuring performance of their lines and nodes. I then analyzed the responses to determine whether a common rating system could be synthesized from the diverse means companies and other agencies use to determine a measure of performance (MOP).

My research began with the simple question: How do you quantify the importance of your transmission lines or nodes (amount of product, number of customers served, other)? What I wanted to obtain was not necessarily a precise rating system but commonalities that could be applied to a rating system. In communicating with various agencies, I was able to obtain useable information, although my data pool was limited due to lack of response. For more details of the responses obtained, see the Appendix—INTERVIEW RESULTS.

Utility companies generally rate electrical transmission lines using a four-tiered system based on state guidelines. Companies prioritize lines based on what they supply. Top-rated lines power critical infrastructure: hospitals, first responder facilities, water pumps, water treatment plants, etc. The second level are lines designated as a "primary backbone" (feeder lines to power distribution stations). The third level lines provide power to entire neighborhoods. Finally, the lines that provide power to individual customers are on the bottom tier. Within these tiers, priority is based on the number of customers served. For example, a third level line supplying 500 households would be rated over one supplying only 250 households. Neither would be given priority over a line providing electricity to a hospital, emergency responder facility, or water pumping station. Both would be given priority over lines powering an individual residence.

Water companies rate their lines based on the flow of water or capacity (size) of the pipe. Companies use different means to measure water flow. Cubic feet per second is a measure of water flow. Acre feet of water in the line determines its capacity. An acre foot of water is the volume necessary to cover one acre of water to a depth of one foot, or 325,851 gallons.[76] Another consideration when determining the criticality of a pipe is the size of the "pressure zone" for that particular link or node. A pressure zone, in simple terms, is the area that would be affected if the valve on the pipe would be closed. The size of this zone relates to how much of the rest of the system would need to absorb due to the increase in pressure.

Telecommunications fall into two areas: communication and data transmission. Communication is speaking, such as a phone call. Data transmission is any other form of communication that consists of sending and receiving data packets (e.g., texting, emails, streaming). For communication, the number of customers served determines the line's priority. Communication components separate into links (lines) and nodes (either taps or nodes; nodes service ≤ 500 modems/receivers, taps service more). Data transmission lines receive ratings based on the lag time of the data, should the pathway need to be rerouted. For example, if a particular line, say *a-b*, is down (represented by the red circle with line in Figure 1), the added time needed for the data to reach its recipient using lines *a-c, c-d*, and *d-b* factors into its rating. The greater the time to send/receive the data (measured in milliseconds) if the line is down, the higher the priority/criticality. For the example, the new path would transmit the data 0.2 nanoseconds (ns) slower, as demonstrated by the lines' transmission rates in Figure 1.

[76] Tim Boucher, "What Is an Acre-Foot of Water?," *Tim Boucher* (blog), October 18, 2016, https://medium.com/@timboucher/what-is-an-acre-foot-of-water-8b04613ac346.

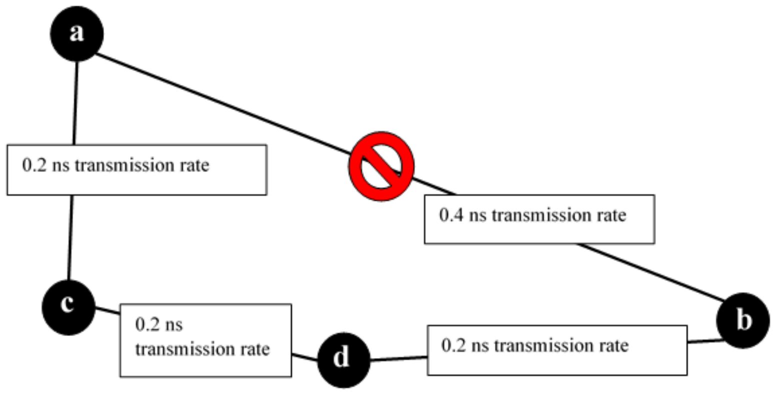

Figure 1. Example of a Telecommunications Data Transmission Network Segment with a Broken Line

Traffic/vehicular pathways score ratings according to category and condition. Transportation agencies, such as the Missouri Department of Transportation (MoDOT), use three specific categories to classify a stretch of road or bridge: Interstate, Major, and Minor. Definitions for Major and Minor are subjective based on the level of traffic flow. Within the categories, bridges and roads are rated by their condition: good, fair, or poor. The FHWA rates bridges by deficiency: either structurally deficient (one or more structural components in need of repair) or functionally obsolete (bridge can no longer support the amount of traffic to be served).[77] Transportation departments also calculate the amount of traffic for a given link of road.

For each of the examples above, a common MOP can be determined for the CI type (electricity, water, telecommunications, and traffic). The challenge is to determine a method to equate the MOPs for a common rating system.

3. Methods Used by Other Countries to Determine CI Criticality

This thesis also compared international CI criticality rating systems. Through examining other, specifically chosen, countries, this thesis wanted to ascertain if any of them had created an objective system for rating CI either as an individual network or a multi-network system.

[77] Goldstein, *Highway Bridges*, 6.

For this section, this thesis examined the critical infrastructure identification and critical rating of six countries (or, in the case of the European Union, entities): Australia, Canada, the European Union, Germany, United Kingdom, and Switzerland. Beyond being open with their critical infrastructure protection (CIP) plans, each was chosen for specific reasons. Australia has a similar government to the United States. Canada shares a border and an action plan for CIP with the United States. The European Union provides a unique situation with being an alliance of sovereign countries. Germany, which belongs to the European Union, only recently began privatization of its critical infrastructure. The United Kingdom has more elements for identifying and prioritizing CI in its CIP than many other plans. Switzerland divides its CI into numerous subsections similar to the United States

a. Australia

Australia uses a similar plan for CI as the United States Australia defines CI as "those physical facilities, supply chains, information technologies and communications networks which, if destroyed, degraded or rendered unavailable for an extended period, would significantly impact the social or economic wellbeing of the nation or affect Australia's ability to conduct national defence and ensure national security."[78] Their definition is similar to the United States' in that it looks at how significant the impact of losing the CI would be to the nation. Australia divides CI into only 10 sectors, instead of 16 as with the United States, for classification purposes but, like the United States, assigns a government agency to be the lead for each sector.[79]

The Australian Government takes a stronger role in CI identification and prioritization, however. State and territory governments are responsible for identifying CI within their jurisdictions, but the federal government identifies CI "which are federally regulated, support national security and defence, the continuity of government, the delivery

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[78] Commercial and Administrative Law Branch, *Critical Infrastructure Resiliency Strategy: Policy Statement* (Barton, Australian : Attorney General's Department, 2015), 3, https://www.tisn.gov.au/Documents/CriticalInfrastructureResilienceStrategyPolicyStatement.PDF.

[79] Commercial and Administrative Law Branch, *Critical Infrastructure Resiliency Strategy: Plan* (Barton, Australia: Attorney General's Department, 2015), 3, https://www.tisn.gov.au/Documents/CriticalInfrastructureResilienceStrategyPlan.PDF.

of its services and any infrastructure of additional national importance.”[80] The *Critical Infrastructure Protection Risk Management Framework for the Prioritisation of Critical Infrastructure*, produced by the Australian Government, identifies and prioritizes CI and can be used as a guide by state and territory governments.[81] The Australian government collaborates with the state and territory governments, but the collaboration focuses more on information sharing than CI identification and prioritization.[82] Focusing away from identification and prioritization inhibits the creation of an objective criticality rating system.

The Australian Government provides levels of criticality to prioritize its CI. The rating consists of four levels: low, significant, major, and vital, plus a category of “unknown” for CI that does not have enough information to rate.[83] The system ranks CI from low, the CI can be replaced with no functionality loss, to vital, the CI is not replaceable and “will result in long term cessation of the asset.”[84] Australia’s rating system still contains a high degree of subjectivity.

b. Canada

Canada defines CI as “processes, systems, facilities, technologies, networks, assets and services essential to the health, security or economic well-being of Canadians and the effective functioning of government,” and, like Australia, divides CI into 10 sectors.[85] Similar to the United States, however, Canada places much of the responsibility for identifying and prioritizing CI on the Province and Territory governments and the private

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[80] Australia-New Zealand Counter-Terrorism Committee, *National Guidelines for Protecting Critical Infrastructure from Terrorism* (Barton, Australian Capital Territory: Attorney-General’s Department, 2015), 4, https://www.nationalsecurity.gov.au/Media-and-publications/Publications/Documents/national-guidelines-protection-critical-infrastructure-from-terrorism.pdf.

[81] Australia-New Zealand Counter-Terrorism Committee, *National Guidelines for Protecting Critical Infrastructure from Terrorism*, 4.

[82] Commercial and Administrative Law Branch, *Critical Infrastructure Resiliency Strategy: Plan*, 4.

[83] Australia-New Zealand Counter-Terrorism Committee, *National Guidelines for Protecting Critical Infrastructure from Terrorism*, 4.

[84] Australia-New Zealand Counter-Terrorism Committee, 4.

[85] Public Safety Canada, *National Strategy for Critical Infrastructure* (Canada: Public Safety Canada, 2009), 2, https://www.publicsafety.gc.ca/cnt/rsrcs/pblctns/srtg-crtcl-nfrstrctr/srtg-crtcl-nfrstrctr-eng.pdf.

owner/operators, which must be based on the 10 sectors outlined.[86] The Canadian Government provides owner/operators with CI information, guidance on how to remain engaged in CIP, and works with owner/operators to develop and prioritize key CIP activities within each of the 10 sectors.[87] However, as with the United States, what is rated critical results in a highly subjective process.

Canada participates with the United States in a joint action plan for CIP. The plan recognizes the interconnectivity between the United States and Canada, particularly with respect to energy and transportation.[88] In the plan, CI "refers to the assets, systems and networks that are essentials to the security, public health and safety, economic vitality, and way of life of citizens."[89] Although the plan does not provide guidance for identifying or prioritizing CI, it does promote "cross-border collaboration" and information sharing between the United States and Canada.[90]

c. European Union

The European Union consists of sovereign nations collaborating on many aspects including CIP. As a collective, the European Union defines CI as "an asset, system or part thereof located in Member States which is essential for the maintenance of vital societal functions, health, safety, security, economic or social well-being of people, and the disruption or destruction of which would have a significant impact in a Member State as a result of the failure to maintain those functions."[91] However, a second, higher level of CI

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[86] Public Safety Canada, *2018-2020 Action Plan for Critical Infrastructure* (Ottawa, Canada: Public Safety Canada, 2018), 16, https://www.securitepublique.gc.ca/cnt/rsrcs/pblctns/pln-crtcl-nfrstrctr-2018-20/index-en.aspx.

[87] Public Safety Canada, National Strategy for Critical Infrastructure, 3.

[88] Department of Homeland Security and Public Safety Canada, *Canada-United States Action Plan for Critical Infrastructure*, (Washington, DC: Department of Homeland Security, 2010), 3, https://www.dhs.gov/xlibrary/assets/ip_canada_us_action_plan.pdf.

[89] Department of Homeland Security and Public Safety Canada, 4.

[90] Department of Homeland Security and Public Safety Canada, 3.

[91] Council of the European Union, *Identification and Designation of European Critical Infrastructures and the Assessment of the Need to Improve Their Protection*, Council Directive 2008/114/EC (Luxembourg: Publications Office of the European Union, 2008), 3, https://publications.europa.eu/en/publication-detail/-/publication/ba51b03f-66f4-4807-bf7d-c66244414b10/language-en.

classification exists, the European Critical Infrastructure (ECI), which is defined as "critical infrastructure located in Member states the disruption or destruction of which would have a significant impact on at least two Member States."[92] This definition refines the criticality of ECI in that it needs to severely affect two "Member States," rather than the union as a whole. The Council Directive 2008/114/EC also provides definite criteria for rating CI as ECI. CI must meet four conditions to be considered as ECI:

1. The CI must belong to the electricity or transportation sector and;
2. Must meet the definition of critical infrastructure and;
3. Must impact two or more Member States and;
4. Must meet cross-cutting criteria (affect CI in another sector).[93]

The European Union plan, or program, provides guidance for member nations to identify National Critical Infrastructure (NCI). Council Directive 2008/114/EC defines NCI through criteria such as scope and severity.[94] The guidelines do not provide specificity for the Member States and, like the United States' plan, leaves much of the responsibility for identification and rating to the Member States.

d. Germany

Germany provides an interesting study as its reunification was less than 30 years ago.[95] Many of their CI industries have only recently become privatized.[96] The definition of CI is similar to others being stated as "organizational and physical structures and facilities of such vital importance to a nation's society and economy that their failure or

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[92] Council of the European Union, 3.

[93] Council of the European Union, 3–4, 8.

[94] Commission of European Communities, *Communication from the Commission on a European Programme for Critical Infrastructure Protection*, (Luxembourg: European Commission, 2006), 7, https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2006:0786:FIN:EN:PDF.

[95] *Encyclopaedia Britannica, Inc.*, s.v. "Germany—The Reunification of Germany," May 29, 2019, https://www.britannica.com/place/Germany.

[96] Federal Ministry of the Interior, *National Strategy for Critical Infrastructure Protection (CIP Strategy)* (Berlin, Germany: Federal Republic of Germany, 2009), 8, https://www.kritis.bund.de/SharedDocs/Downloads/BBK/EN/CIP-Strategy.pdf?__blob=publicationFile.

degradation would result in sustained supply shortages, significant disruption of public safety and security, or other dramatic consequences."[97]

Germany's strategy possesses several notable differences from other plans. Their CIP strategy calls for more than just coordination between government and private industry but includes the general public as a partner.[98] Germany, like the European Union, further subdivides criticality into two classifications. One classification defines systemic criticality as "it is highly relevant as regards interdependencies." The other defines symbolic criticality "its loss might, on account of its cultural significance or its important role in creating a sense of identity, emotionally unsettle a nation's society and psychologically have a lasting unbalancing effect on it."[99] These subdivisions allow for the further classification of the nine sectors into two types: Technical Basic Infrastructure and Socio-economic Services Infrastructure.[100] While not providing specific criteria for criticality, the organization provides some structure for determining if a resource should be classified as critical.

e. Switzerland

Switzerland defines both CI and criticality. CI is defined as "infrastructures whose disruption, failure, or destruction would have a serious impact on public health, public and political affairs, the environment, security, and social or economic well-being." Criticality "refers to its relative importance in terms of consequences that a disruption, failure, or destruction would have on the population and its vital resources."[101] Similar to Australia, the national government takes a strong role handling much of the responsibility for

[97] Federal Ministry of the Interior, 4.

[98] Federal Ministry of the Interior, 4.

[99] Federal Ministry of the Interior, 7.

[100] Federal Ministry of the Interior, 7–8.

[101] Schweizerische Eidgenossenschaft, *The Federal Council's Basic Strategy for Critical Infrastructure Protection: Basis for the National Critical Infrastructure Protection Strategy* (Bern, Switzerland: Schweizerische Eidgenossenschaft, 2009), 4, https://www.babs.admin.ch/en/aufgabenbabs/ski/publikationen.html#ui-collapse-870.

identifying and prioritizing CI.[102] The cantons (federal states) and CIP operators (private and state) are mostly responsible for coordination and implementation of the CIP.[103]

Switzerland divides its CI into 10 sectors and 31 subsectors.[104] Switzerland considers all of the subsectors as critical, but each of the subsectors are rated as regular criticality, high criticality, or very high criticality.[105] The criticality rating is based on how interdependent other subsectors are on it, how it impacts the population, and how it affects the economy.[106]

f. *United Kingdom*

The United Kingdom's plan provides a key feature to determine the importance of CI in its Criticality Scale for National Infrastructure.[107] The United Kingdom's definition of infrastructure is similar to that of other countries. However, they differentiate between national infrastructure (NI) and critical national infrastructure (CNI). NI consists of "those facilities, systems, sites and networks necessary for the functioning of the country and the delivery of the essential services upon which daily life in the United Kingdom depends." CNI comprises "those infrastructure assets (physical or electronic) that are vital to the continued delivery and integrity of the essential services upon which the United Kingdom relies, the loss or compromise of which would lead to severe economic or social consequences or to loss of life."[108] The NI is categorized into 9 sectors (similar to other

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[102] Schweizerische Eidgenossenschaft, 5–7.

[103] Swiss Government. "Swiss Cantons (Federal States): Political Map and Statistics," All About Switzerland, accessed May 31, 2019, http://swiss-government-politics.all-about-switzerland.info/swiss-federal-states-cantons.html; Schweizerische Eidgenossenschaft, *The Federal Council's Basic Strategy for Critical Infrastructure Protection*, 5–7.

[104] Schweizerische Eidgenossenschaft, *The Federal Council's Basic Strategy for Critical Infrastructure Protection*, 5.

[105] Schweizerische Eidgenossenschaft, 8.

[106] Schweizerische Eidgenossenschaft, 8.

[107] Cabinet Office, *Strategic Framework and Policy Statement*, 25.

[108] Cabinet Office, 8.

countries) and further subdivided into 29 subsectors for clarification. The United Kingdom further distinguishes local critical infrastructure from national infrastructure.[109]

The United Kingdom has additional criteria to rate their critical infrastructure. Based on three “impact dimensions”: delivery of essential services, economic, and loss of life, the scale has six categories from CAT 0, which the loss of the infrastructure would have minor impact (on a national scale), to CAT 5, in which the loss of the infrastructure would catastrophically impact the United Kingdom. “These assets will be of unique national importance whose loss would have national long-term effects and may impact across a number of sectors. Relatively few are expected to meet the Cat 5 criteria.”[110] The interim categories contain relative thresholds for clarification of assignment of CI to the category (e.g. CAT 3 “could affect a large geographic region or many hundreds of thousands of people”).[111] The Criticality Scale is paired with an Assessment of Likelihood (a combination of vulnerability and threat) to form a grid to prioritize assets.[112]

The United Kingdom’s risk matrix priorities for planning are based on high risk (called “Likelihood”) and high criticality.[113] The “likelihood” is based on a combination of vulnerability and threat, but still is subjective and uses a scale from “low” to “high.”[114] The assessment, however, does provide a criticality rating scale for critical infrastructure from 0–5.[115] The system for categorizing criticality is still subjective with the range from minor national significance to “unique national importance” without any quantitative measurements.[116]

[109] Cabinet Office, 8.

[110] Cabinet Office, 25.

[111] Cabinet Office, 25.

[112] Cabinet Office, 20.

[113] Cabinet Office, 20.

[114] Cabinet Office, 20.

[115] Cabinet Office, 25.

[116] Cabinet Office, 25.

The descriptions in Chapter III.B.3. make it difficult to compare the similarities and differences of CI classification, definition, and rating impact criteria of the seven countries and the European Union. The following tables provide an overview of the key points regarding classification and rating of critical infrastructure. Table 1 provides the criteria for how each country and the European Union define what elements are considered CI. Table 2 lists the agencies within each country or the European Union that decide what is critical. Table 3 presents the number of CI sectors, the CIR levels, and the what is impacted should CI fail.

Table 1. Comparison of the Definition of Critical Infrastructure of the Seven Countries and the European Union

USA/ DHS	AUS	CAN	EU	GER	SUI	GBR
Assets and systems	Physical facilities, supply chains, informational technologies, communications networks	Processes, systems, facilities, technologies, networks, assets, services	Assets and systems	Organizational & physical structures & facilities	Infrastructure	Facilities, systems, sites, networks, services, and assets

Table 2. Comparison of who Determines what is Critical Infrastructure of the Seven Countries and the European Union

USA/ DHS	AUS	CAN	EU	GER	SUI	GBR
States and private	National government, States and territories	States, territories, and private	Member States	National government, private, & general public	National government, states, private	National government

Table 3. Comparison of the Number of CI Sectors, Levels of CIR, and Impacts of the Seven Countries and the European Union

	USA/ DHS	AUS	CAN	EU	GER	SUI	GBR
Sectors	16	10	10		9	31/10[117]	9
CIR		5 levels		2 levels		3 levels	6 levels
Security	X	X	X	X	X	X	
Economic	X	X	X	X	X	X	X
Public Health & Safety	X		X	X	X	X	X
Social/ Society		X		X	X	X	X
National Defense		X					
Government Functions			X				
Supply shortages					X		
Dramatic consequences					X		
Physical							
Environment						X	
Public Affairs						X	
Political Affairs						X	
Daily Life							X

[117] Switzerland has 31 subsectors divided among 10 sectors.

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IV. POTENTIAL SOLUTIONS FOR A HYBRID METHOD TO DETERMINE TOTAL CRITICALITY

In Chapter III, this thesis discussed rating systems used by governmental, academic, and CI agencies. Governmental systems rely on much subjectivity due to broad guidelines. The academic solutions require a level of mathematical understanding that exceeds the capabilities of most emergency managers and other persons responsible for CIP. Rating systems of CI agencies, such as utility companies, are simple and objective but focus on their particular CI without regard to the others. Furthermore, the systems have no uniformity or standard MOP.

This thesis took certain aspects of the above systems to synthesize a process to compare the criticality of different CI networks. This thesis then used that comparison to create a process to rate bridges or other structures that convey multiple CI networks.

A. USING INDIVIDUAL CI RATINGS TO DETERMINE AN OVERALL CRITICALITY

From examining the various methods used by academics, U.S. companies, and other countries to determine criticality of individual CIs, these rating systems can be used to synthesize an approach to rate the criticality of a node or link that transports multiple CI networks. One fundamental element in creating a method to rate criticality is to resolve the differences of the separate existing CI rating systems. Formulating a method to equate the different MOPs could also produce a method to rate criticalities. Once the above two steps are accomplished, an overall rating for the multi-network link can be established. While synthesizing a process to rate multiple CI networks links or nodes, two concepts must remain: 1) the process and formula must retain enough simplicity for the average emergency manager or other persons involved in CIP to use, 2) the simplicity of the process must retain objective accuracy.

1. Determining the Individual Critical Infrastructure Rating and Equating to the Others

Using the academic approaches described in Chapter III.B.1., the first step of my process is to break down the multi-network link into its individual CI networks and rate them individually.[118] The initial method for rating each network would be to utilize an MOP similar to what the CI agencies do to prioritize their links and nodes. The companies surveyed each used objective assessments: number of customers, flow rates, etc., to prioritize their lines. Although each had other factors that influenced their rating systems (electricity: CI tiers, telecommunications: number of customers for communication vs. transmission delay for data, etc.), a basic, quantifiable MOP could be determined.

The next step is to determine a method to equate the various MOPs for comparison purposes. By providing a common rating system, the CIs could be rated against each other and then combined to form an overall rating for the multi-network link (in this case, a bridge). The most straightforward technique is to use a simple rating system based upon dividing the MOP for the CI network link transported by the bridge by the maximum MOP for the CI network. For example, using traffic flow, bridge A handles 100,000 vehicles per day and bridge B handles 50,000 vehicles per day. If the maximum capacity for any link of the network is 100,000 vehicles per day, then bridge A has the maximum and would rate a 100 or 100%. Bridge B would then rate a 50, or 50%. For each of the CIs, the MOPs could be converted to a simple numerical figure and compared with other CIs.

The conversion would entail a simple equation

$$CIR_n = 100(MOP_n \div MOP_{max}),$$

where

MOP_{max} = the maximum measure of performance for the network,
MOP_n = the measure of performance for a particular link or node, and
CIR_n = the CI rating (percentage) for a particular link or node.

[118] Jenelius, Petersen, and Mattsson, “Importance and Exposure in Road Network Vulnerability Analysis,” 545–46; Nagurney and Qiang, “A Network Efficiency Measure with Application to Critical Infrastructure Networks,” 263, 265–69; Fang, Pedroni, and Zio, “Resilience-Based Component Importance Measures for Critical Infrastructure Network Systems,” 503.

2. Simplest Method for Determine the CIR of a Multi-Network Link or Node (such as a Bridge).

The next sequence in the process would be to combine the individual CI ratings to form an overall rating for the bridge (i.e., multi-network link). The easiest way to accomplish this is to merely add the ratings for the various CIs that the bridge conveys. The equation would be

$$CIR_t = \sum CIR_n,$$

where

CIR_t = the total criticality rating for the bridge.

To test this formula, this thesis created an imaginary city examining four CIs: transportation, electricity, water, and natural gas.

Figure 2 represents a simple network with four CIs represented: electricity (orange), water (blue), traffic (black), and natural gas (green). These CIs provide for the city (represented by the red circle). The CI must cross a river (represented by the light blue) to reach the city. Bridge A and Bridge B each convey a number of different kinds of CIs, and only those links going to the city via Bridge A or Bridge B are quantified. My model will be used to demonstrate the process for rating criticality of links that convey multiple CIs. For simplicity, only residential calculations will be used for the formulas without factoring in public, commercial, or industrial usage. A more detailed explanation of the individual CIs will be given in the calculations.

In this example, this thesis has already determined the rating for the four CIs based on serving the entire population of the city (100%). For example, bridge A conveys 40% of the traffic (CIR_v), 50% of the electricity (CIR_e), and 50% of the water (CIR_w) for a community. Bridge B conveys 60% of the traffic (CIR_v) and a pipeline (CIR_p) transporting 100% of the petroleum products (see Figure 2). Table 4 shows the comparison of the ratings for Bridge A and Bridge B using the percentages provided in the figure and the formula $CIR_t = \sum CIR_n$, yielding the following results.

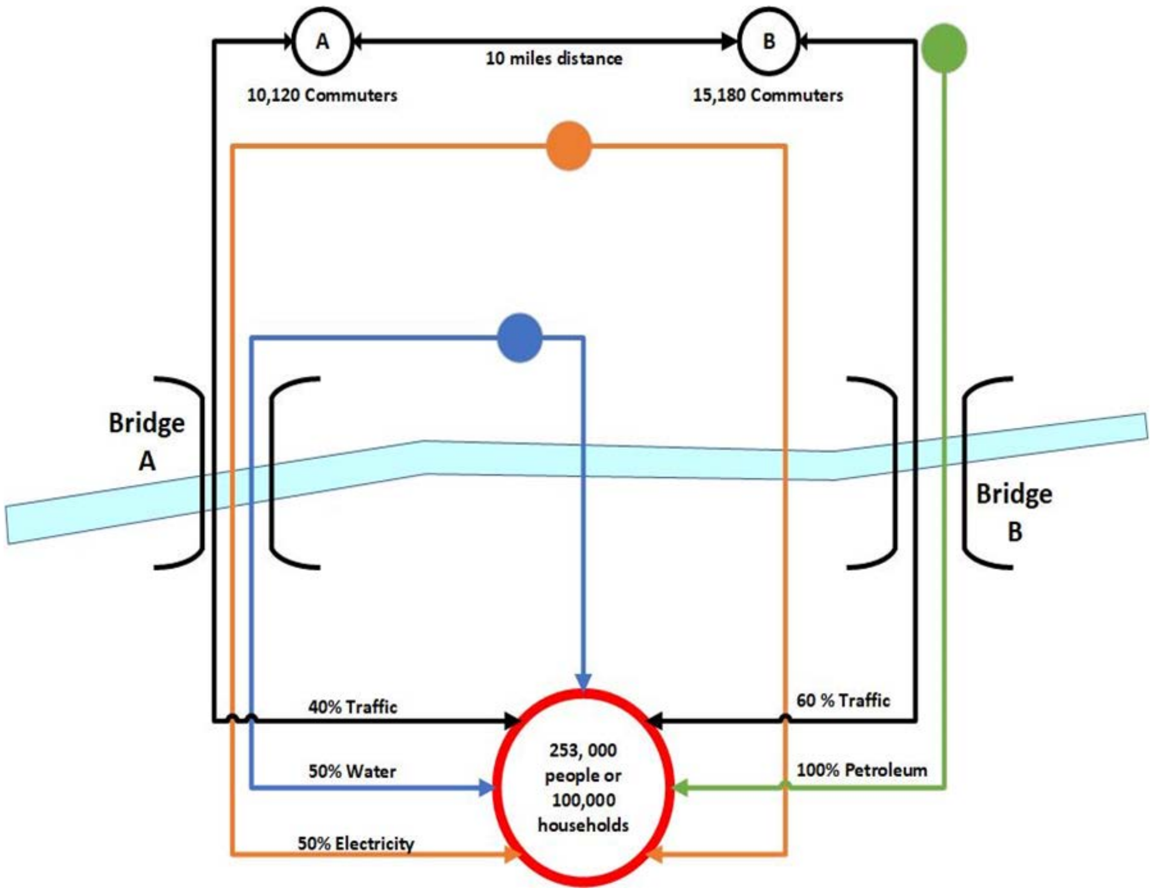

Figure 2. Hypothetical Representation of a CI Network Crossing Bridges

Table 4. CIR for Hypothetical Bridge A and Bridge B

	Bridge A	Bridge B
CIR_v	40	60
CIR_e	50	
CIR_w	50	
CIR_p		100
CIR_t	140	160

So, according to the simple calculations, despite Bridge A conveying more CI links, Bridge B has a higher criticality rating than Bridge A. In communities where the other electrical and water lines adequately supply the community or natural gas is more necessary, Bridge B would be more critical than Bridge A. It could be argued, however, that Bridge A is more important because its loss would result in a lack of electricity and water. Both of these critical resources may be more valuable to the community than the petroleum products, demonstrating that a robust measure of criticality is more complicated than this approach.

3. Establishing a Method to Provide a Higher Rating to more Critical CI

The deficiency in the simple summation of CI ratings is that every CI is considered equal in importance. Yet not all CIs should be weighted equally. As mentioned, other factors could necessitate weighing water or electricity higher than natural gas.

The academic solutions, discussed in Chapter III.B.1., factor in elements into their processes such as the cost of rerouting of traffic to determine the effect of the loss of each bridge.[119] If the unique CI conveyed by bridge A (electricity and water) is more vital than that carried by Bridge B (petroleum products), then the ratings should be weighted to reflect Bridge A's higher criticality. If the water and electricity networks have a redundancy factor (other transmission lines or redundancy built into the water network, for instance), then the loss from the destruction of Bridge A would be negligible. Adding factors into the calculations could adjust the criticality to give a higher rating to CIs that are more important.

The way to compensate for this rating deficiency is to add weight to each CIR so that CIs considered less critical would not receive the same consideration as CIs with higher criticality. The outcome for the adjustment is visually represented in the hypothetical graph Figure 3. The arrows on the x- and y-axes indicate higher values toward the right or upward. The exact values would be different depending on the rating system. CI that has a lesser impact on a community would be weighted with an overall less CIR. For example, CIR5 (green line) with a maximum value on the x-axis would still rate a lower overall CIR (impact; y-axis) than CIR1 (black line) that also has a maximum value on the x-axis.

[119] Jenelius, Petersen, and Mattsson, "Importance and Exposure in Road Network Vulnerability Analysis," 541–42.

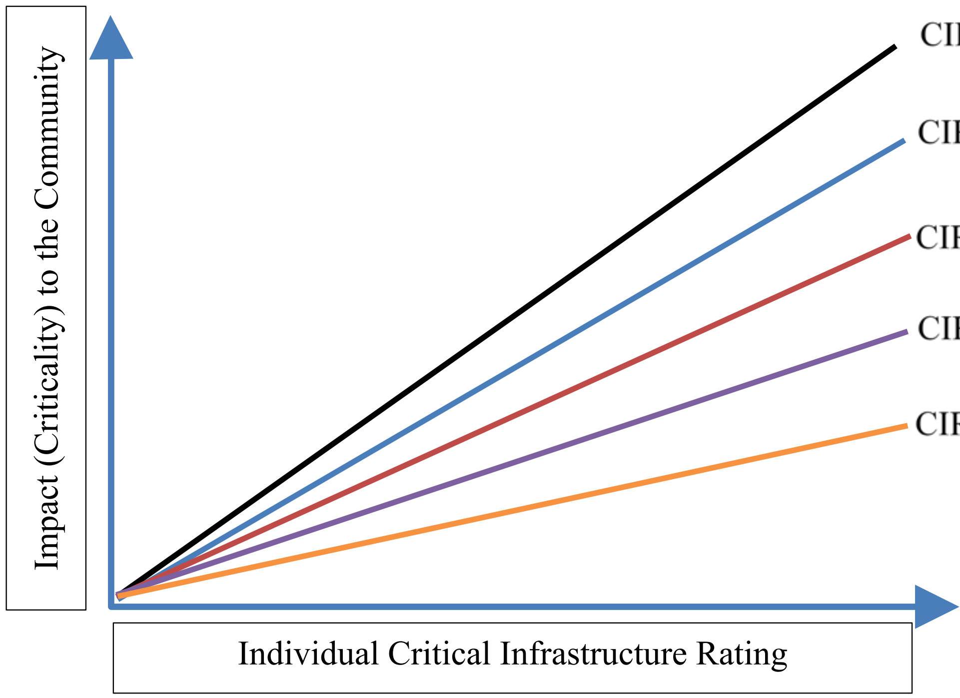

Figure 3. Graphic Representation of Graduated Critical Infrastructure Ratings

4. Using a Subjective Coefficient to Weigh the Calculations

A revised method to add weight to the CI ratings is to design a simple linear method, such as a multiplication factor. Adjusting the CIR with a multiplication factor satisfies two conditions: to ensure that CI with a lesser impact/criticality is not rated higher than a CI with a greater impact/criticality and retains the ease of use for the method. Such a gradient with an adjusted coefficient for the five CIs could be

$CIR_1 = MOP_1 \div MOP_{max}$,

$CIR_2 = 0.8(MOP_2 \div MOP_{max})$,

$CIR_3 = 0.6(MOP_3 \div MOP_{max})$,

$CIR_4 = 0.4(MOP_4 \div MOP_{max})$, and

$CIR_5 = 0.2(MOP_5 \div MOP_{max})$.

Although this presents a simple solution, CIR_5 will be less critical than CIR_1. CIR_5 could have a higher impact/criticality than CIR_1. If MOP_5 is 80% of its maximum MOP and MOP_1 is only 10% of its maximum MOP, then CIR_5 would have a higher rating than CIR_1 (CIR values of 16 and 10, respectively). Therefore, this weighting system could be effective. The deficiency lies in the subjectivity of determining which CI is the greatest and the least importance.

For example, I will, based upon experience, assign importance to the CI carried by a bridge as: electricity, water, telecommunications, vehicular traffic, and pipelines. I chose these 5 CIs to demonstrate the proposed method for CIR because their links are conveyed by bridges. The reasoning behind this ranking is that: without electricity, water pumps cannot deliver water, critical life support machines will not work, etc.; the average person can only live 3 days without water; communication is necessary to obtain outside assistance and coordinate response efforts; vehicular traffic can bring necessary resources including the products transported by pipelines.

The graduated scale would be

$CIR_e = MOP_e \div MOP_{emax}$,

$CIR_w = 0.8(MOP_w \div MOP_{wmax})$,

$CIR_c = 0.6(MOP_c \div MOP_{cmax})$,

$CIR_v = 0.4(MOP_v \div MOP_{vmax})$, and

$CIR_p = 0.2(MOP_p \div MOP_{pmax})$,

where

CIR_e = CI rating for electrical line,

MOP_e = the MOP for the specific electrical transmission line,

MOP_{emax} = the MOP for the largest transmission line in the network,

CIR_w = CI rating for the water line,

MOP_w = the MOP for the specific water pipe,

MOP_{wmax} = the MOP for the largest water pipe in the network,

CIR_c = CI rating for the telecommunications,

MOP_c = the MOP for the specific telecommunications line,

MOP_{cmax} = the maximum MOP for a telecommunications line in the network,

CIR_v = CI rating for the traffic flow over the bridge,

MOP_v = the MOP for the traffic over the bridge,

MOP_{vmax} = the MOP for the largest volume of traffic in the network,

CIR_p = CI rating for the pipeline,

MOP_p = the MOP for the specific pipeline, and

MOP_{pmax} = the MOP for the largest pipeline in the network.

Scaling the formulas with coefficients creates a graph Figure 4 that is very similar to Figure 3.

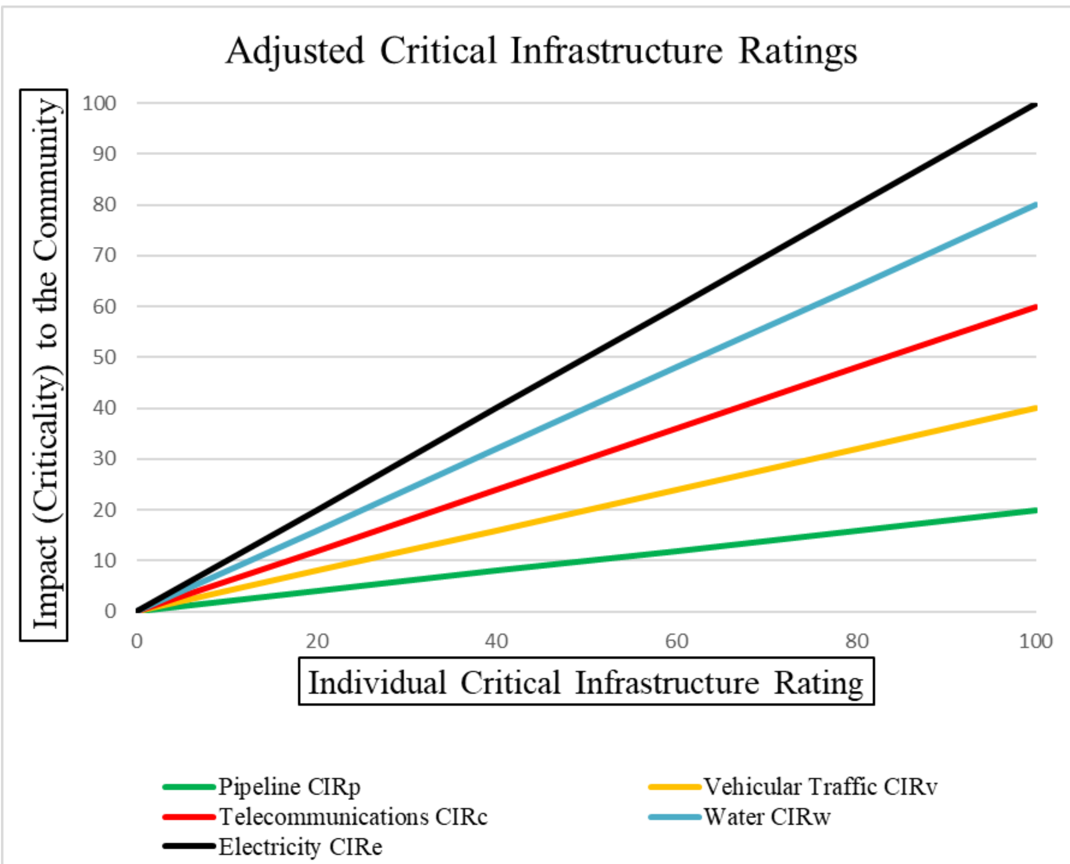

Figure 4. Adjusted Critical Infrastructure Ratings for the Bridge A/Bridge B Comparison Example

For our example of Bridge A and Bridge B, their CIR values would be adjusted as seen in Table 5.

Table 5. Adjusted CIR Comparison of Hypothetical Bridge A and Bridge B

	Bridge A	Bridge B
$(0.4)CIR_v$	16	24
$(1.0)CIR_e$	50	
$(0.8)CIR_w$	40	
$(0.2)CIR_p$		20
CIR_t	106	44

The adjusted formula greatly increases the CIR of Bridge A, demonstrating its importance. Again, this may not truly reflect the degree to which Bridge A may be more important than Bridge B, but the added scaling demonstrated a method to adjust the importance of different CIs.

However, this method, also, has shortcomings. Using subjective coefficients does not necessarily increase the accuracy of the criticality rating. Rather, it adds a major subjective element to the process, thus continuing the problem with current rating systems. Therefore, the coefficient may change depending on the biases of the user. The result is that ratings of similar bridges or other links that convey multiple CIs will vary from jurisdiction to jurisdiction or agency to agency. Agreement on a national standard may alleviate this issue, but such an agreement may prove difficult.

5. Using a Quantifiable Means Such as Revenue or Cost to Provide a Higher Rating to more Important CI

An additional mathematical formulation could achieve a more objective weighting. Cost to reroute or revenue lost per hour for the link's failure could adjust the criticality rating. Three of the academic papers reviewed in Chapter III.B.1. factor some monetary element into their formulas: the increased cost to reroute the system, the increased cost to use the system, the cost/benefit to repair the component, or the cost to the system from the failure of that component.[120] The formula for this could be

$$CIR_n = (CI_c \div CI_{ctot})(MOP_n \div MOP_{max}),$$

where

CI_c = the cost from the CI failing (either cost to repair/reroute or revenue lost to the network), and

CI_{ctot} = total cost of CI network (either cost to repair/reroute or revenue lost to the network).

Adding a monetary factor as a coefficient to the formula used above to calculate CIR is one method to modify the ratings. The first step is to establish the parameters for cost or loss of revenue. I chose the latter using national averages for the example city. For the population, I gave the city a population of 253,000 persons. At a national average of 2.53 persons per household, the number of households in the example city would be 100,000.[121] The revenue per day for each of the CIs in the example was calculated in the following manners.

Travel cost can provide a monetary coefficient to the equation. I used national averages and the government mileage reimbursement rate to calculate the daily travel cost spent. The average number of miles travelled per household per year commuting to and from work is 6,259 miles.[122] This annual trip averages 24.94 miles per day (using 251 workdays per year – 5-day work week minus holidays) per household. The government

[120] Jenelius, Petersen, and Mattsson, "Importance and Exposure in Road Network Vulnerability Analysis, 541–43; Nagurney and Qiang, "A Network Efficiency Measure with Application to Critical Infrastructure Networks," 10–11.

[121] Erin Duffin, "Average Size of Households in the U.S. 1960-2018," Statista, April 29, 2019, https://www.statista.com/statistics/183648/average-size-of-households-in-the-us/.

[122] J Wagner, "U.S. Average Annual Person Miles of Travel per Household 2017," Statista, September 3, 2019, https://www.statista.com/statistics/1003948/us-annual-person-miles-travel-per-household-by-type/.

mileage reimbursement rate for 2019 was $0.58/mile.[123] Multiplying this rate by the average number of miles per day yields $14.46 per day per household in travelling costs.

However, the formula calculated only the increase in cost for the traffic to reroute to the alternate bridge to reach the city. For this example, Figure 5 isolates the traffic portion of Figure 2 of hypothetical representation of a community. Here, the two black circles both represent suburbs with a certain population. Each commuter from those two suburbs will use the nearest bridge that is operational (denoted by A and B in Figure 2 and Figure 5). Therefore, the increase in cost to the commute would be the added distance that either commuters from A or B travel to reach the city. This example used a distance 10 miles. Therefore, the added cost per commuter is $0.58/mile x 10 miles, or $5.80. The calculations will assume that 25,300 people commute to the city every day (or a 10% increase in the city's population).

Therefore, using the values listed in Figure 5 and based on the number of commuters for my example, Bridge A would convey 10,120 commuters, and Bridge B would convey 15,180. The loss of revenue for Bridge A would be $5.80 times 10,120 commuters, or $58,696, and Bridge B would be $5.80 times 15,180 commuters, or $88,044.

[123] "IRS Issues Standard Mileage Rates for 2019," Internal Revenue Service, December 14, 2018, https://www.irs.gov/newsroom/irs-issues-standard-mileage-rates-for-2019.

Figure 5. Hypothetical CI Network with Traffic Isolated

This equation contains assumptions and shortcomings. The assumption is that both bridges can handle the extra traffic without a decrease in traffic flow rate. Decreases in traffic flow rate due to heavier traffic leads to increase in travel cost. Using only the government mileage reimbursement rate, the calculation does not consider the added cost due to the increase in time (and, thus, the longer fuel is being consumed). Calculating the increased cost of additional fuel consumption amplifies the complexity.

Electricity revenue can be calculated from the unit price times the amount consumed. The average usage for electricity is \$0.1327/kilowatt hour (KWH), with an average of 897 KWH/month per household.[124] Using 30 days as the standard for a month yields a usage rate 29.9 KWH/day per household. Multiplied by the cost per KWH, approximately \$3.97 is spent per day per household. For simplicity, only households'

[124] "Electricity Rates by State (October 2019)," ChooseEnergy, October 1, 2019, https://www.chooseenergy.com/electricity-rates-by-state/.

electricity usage is considered for this example. Businesses and commercial usage would increase the total revenue calculation, particularly when in operation.

Using this calculation in our network model for electricity (see Figure 6, which isolates the electrical network from Figure 2), the total revenue generated by electricity is $397,000. Half of the revenue lost from the destruction of Bridge A is $198,500. This calculation assumes, however, that 50% of the households exclusively receive their electricity from the line conveyed by the bridge. Any redundancy, such as the other link being able to absorb the increase in electrical usage, would nullify this factor by reducing the lost revenue to $0.

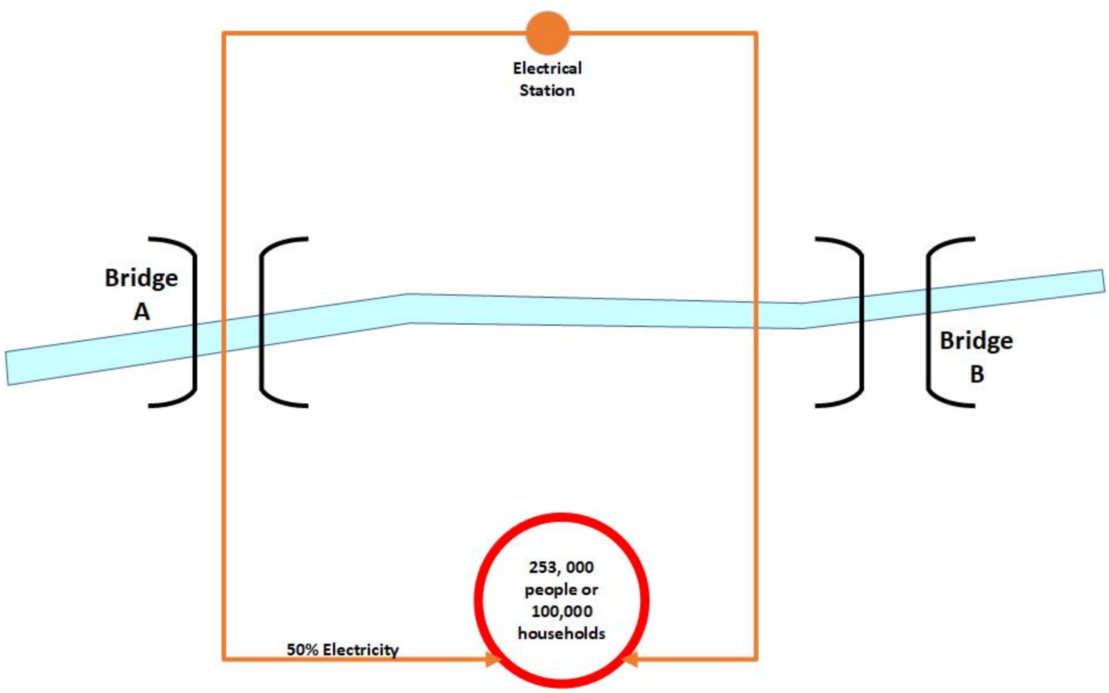

Figure 6. Hypothetical CI Network with Electricity Isolated

Calculating the revenue for water is much more straightforward. The average revenue generated for a family of 4 using 100 gallons/person per month is $70.39.[125] I

[125] T Wang, "Average Monthly Cost of Water United States 2018," Statista, August 9, 2019, https://www.statista.com/statistics/720418/average-monthly-cost-of-water-in-the-us/.

used this figure as the average person consumes 80–100 gallons of water per month.[126] Dividing the cost by 4 persons yields $17.60 per month per person. Again, using the 30-day month as the standard, the cost per day is $0.59/person per day. Only households are used in this example. Water consumption would be greater for certain businesses and industry.

For our water model, Figure 7, the amount of revenue generated by water would equal $0.59/person per day times 253,000, or $149,270. The loss of revenue from the destruction of Bridge A would then equal $74,635. As with the electricity example, this calculation assumes that half the households exclusively use the water line from Bridge A. Any redundancy would nullify this factor.

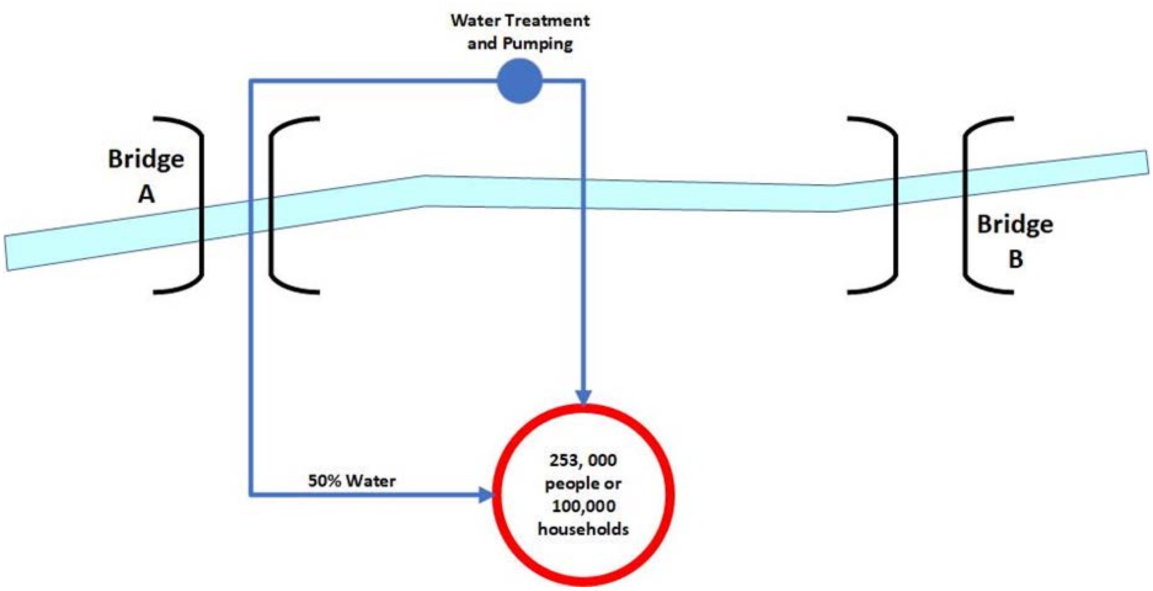

Figure 7. Hypothetical CI Network with Water Isolated

Calculating the revenue for natural gas requires more computation. Household usage of natural gas per year is 4.97 trillion cubic feet (cf) in the United States.[127] The

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[126] "Water Q&A: How Much Water Do I Use at Home Each Day?," USGS Science for a Changing World, accessed November 11, 2019, https://www.usgs.gov/special-topic/water-science-school/science/water-qa-how-much-water-do-i-use-home-each-day?qt-science_center_objects=0#qt-science_center_objects.

[127] "How Much Natural Gas Is Consumed in the United States? - FAQ," U.S. Energy Information Administration, June 23, 2019, https://www.eia.gov/tools/faqs/faq.php?id=50&t=8.

number of households in the United States is 127,590,000 equaling 38,952.9 cf used per household per year. The average price of natural gas in the U.S. is $17.89/1000 cf.[128] So, average use totals to $696.87 per year or $1.91 per day for natural gas.

As Bridge B conveys 100% of the natural gas for the community in the network, see Figure 8, the calculation would simply equal the revenue generated. The amount would equal $1.91 per household times 100,000 households, or $191,000 for Bridge B.

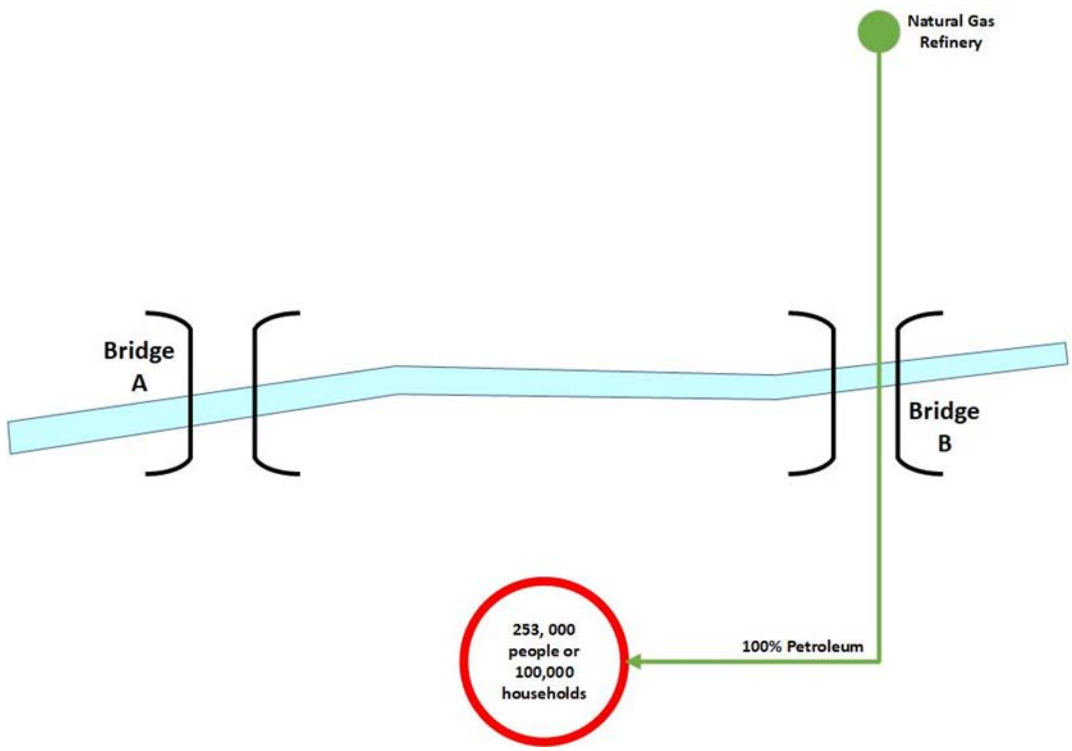

Figure 8. Hypothetical CI Network with Natural Gas Isolated

In looking at the monetary MOPs for the CIs, the calculation per person or household varies, hence the need to calculate both the population and the number of households. So, the daily rates for each of the CIs in the example are: travel cost increases to $5.80 per person; electricity's revenue (or loss) equals $3.97 per household, water's revenue (or loss) equals $0.59 per person, and natural gas's revenue (or loss) equals

[128] "U.S. Natural Gas Prices," U.S. Energy Information Administration, September 30, 2019, https://www.eia.gov/dnav/ng/ng_pri_sum_dcu_nus_m.htm.

$1.91 per household. The price indicates that travel is the most important with electricity, natural gas, and water, respectively, following.

The new CIR_t calculations for Bridge A and Bridge B would be

Bridge A $CIR_t = CIR_v + CIR_e + CIR_w$ = ($5.80/commuter x 10,120 commuters) + 0.5($3.97/household x 100K households) + 0.5($0.59/person x 253K people) = $331,831, and

Bridge B $CIR_t = CIR_v + CIR_p$ = ($5.80/commuter x 15,180 commuters) + ($1.91/household x 100K households) = $279,044.

Using this method, Bridge A now has a higher criticality than Bridge B. The monetary factor creates a broader range of CIR but prioritizes the most expensive CI. As the commuter distance becomes greater/cost increases and the other monetary values remain the same, eventually Bridge B will become more critical than Bridge A as its monetary value becomes greater (see Table 6). From an emergency management perspective, the focus of CI criticality is less monetary and more on reducing "the loss of life and property" (an entire phase of emergency management).[129] The complexity of determining the cost to the network of the loss of the component is demonstrated by the academic example presented in Chapter III.B.1.[130] This thesis aimed to avoid complex calculations by devising a system to rate criticality of multi-network links.

Table 6. Total Revenue Lost from the Loss of Bridge A and Bridge B

	CIR_t for Bridge A	CIR_t for Bridge B
10 Additional Miles to Travel	$331,831	$279,044
20 Additional Miles to Travel	$390,527	$367,088
30 Additional Miles to Travel	$449,271	$455,132

[129] "What Is Mitigation?," Federal Emergency Management Agency, September 19, 2018, https://www.fema.gov/what-mitigation.

[130] Jenelius, Petersen, and Mattsson, "Importance and Exposure in Road Network Vulnerability Analysis," 541–42.

6. Using a Coefficient with less Subjectivity to Weigh the Calculations

Arbitrarily granting importance to the various CIs creates a problem of subjectivity. Likewise, using monetary rating systems gives greater weight to the CIs that generate greater revenue/result in higher monetary loss if destroyed. The latter method may not truly represent which bridge is of greater criticality to the community. Either way, a bridge that conveys a few CIs with high MOP could be rated higher than another conveying many CIs with lower MOPs.

To reflect the potential increase in criticality of a bridge that conveys a greater number of CIs, a coefficient reflecting the importance of multiple links and nodes must be used. For this, I adjusted my method to use a factor that represents the bridges' number of CIs conveyed versus the maximum number of potential CIs. The factor could be represented by N-n, where N is the maximum number of CIs that could be conveyed (N) minus the number of CIs conveyed by the bridge (n). The new formula would be: $CIR_t = \sum CIR_n/(N-n)$. A bridge that carries the maximum number of CIs creates a mathematical problem as the divisor would now be 0. To easily overcome an undefined equation, the formula can adjust so that: $CIR_t = \sum CIR_n/(N-n+1)$.[131] Therefore, the divisor's lowest value would be 1. Applying these factors to our first example where Bridge A $CIR_t = 140$ and Bridge B $CIR_t = 160$. Bridge A carried three CIs; Bridge B carried two. So, Bridge A's divisor would be 3 and Bridge B's would be 4. These divisors would give Bridge A and Bridge B a CIR_t of 47 and 40, respectively. Bridge A is then rated narrowly more critical that Bridge B.

This adjustment could also be a monetary MOP as described in Chapter IV.A.5. In that example, Bridge A CIR_t = \$331,831 and Bridge B CIR_t = \$279,044. Applying the factor alters the CIRs in this manner: Bridge A CIR_t = \$110,610.33 and Bridge B CIR_t = \$69,761.

My method is not intended to be the final solution to the problem. Several deficiencies inherent in the system will be discussed in Chapter V.

[131] "Dividing by Zero," MathisFun, 2017, https://www.mathsisfun.com/numbers/dividing-by-zero.html.

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V. CONCLUSION AND RECOMMENDATIONS

The process outlined here represents a first step towards achieving a multi-sector criticality rating of a bridge. As presented, it contains shortcomings and insufficient precision for robust decision making because it does not investigate a broader set of co-located infrastructure network components. However, the approach presented does illustrate a process that would be repeatable and reproduce-able across jurisdictions and could be used as part of a generalized study. Further research and modelling will be needed to generate a standardized criticality rating that retains the simplicity demonstrated, here, yet yields a greater degree of precision using a defensible metric.

A. CONCLUSION

After exploring different methods, several points stand out as important to creating a method for rating the criticality of a structure with co-located infrastructure. One of the common rating metrics is financial impact, either as lost revenue or cost to repair the link or node of the network. The academic reports, as described in Chapter III.B.1., reviewed using cost as part of their rating systems. The utility companies often prioritize their lines and nodes by number of customers, which is directly related to generating revenue.

Another important aspect is the balance between accuracy and simplicity. As demonstrated in the academic papers reviewed in Chapter III.B.1., CIRs can be highly accurate. Those methods, however, require complex mathematical formulas to attain a high level of accuracy. However, examining the rating methods used by DHS and various countries in Chapter III.B.2. and Chapter III.B.3., methods that are too simplistic can be inaccurate because they rely too heavily on subjective measures. A method to rate CI must be usable by the average person and still be accurate.

I proposed a basic method that can be used by a person not skilled in higher mathematics to rate the criticality of a link or node that is important to multiple CI networks. The elemental nature of the system helps explain to officials why one bridge (or any multi-network link or node) is more critical than others. Also, although the example used to present the process used only two bridges, the process could be used to compare multiple bridges by rating the individual bridges.

The process presented here is intended to provide a foundation for creating a better system for rating multiple CIRs conveyed by a link or node, while retaining the principles of simplicity and accuracy. The system, however, has several shortcomings that must be addressed to create an improved rating system.

The first shortcoming is that the rating system needs a method to determine the base maximum MOP (MOP_{max}) values. The base MOP_{max} will vary depending on the scope of the agency applying the method. Municipalities, for instance, will have a smaller MOP_{max} than counties due to their smaller geographic region and population. For example, counties' MOPs would be smaller than states, which would be smaller than the MOP measured at a National level. To illustrate this concept, for a municipality with a population of 50,000, an MOP_{max}, based upon the number of impacted individuals, would have a value of 50,000. However, at a National level, MOP_{max} would be 328,231,241 (based on the U.S. Census).[132]

The second question to address involves weighted factors used to calculate an adjusted CIR. Initially, the proposal was to use a subjective coefficient based on perceived importance. In this thesis, from personal experience, I listed electricity as the most important CI, but this may not be universal for all jurisdictions. This thesis then used monetary factors to adjust the weight of the CIRs. Monetary factors, however, rank criticality based solely upon the potential lost revenue. To counter this, I used the number of CIs conveyed by a particular multi-sector link as an additional factor to the weight of the CIR.

The proposed method also avoids rail traffic, does not distinguish between commercial and private vehicular traffic, and combines communications and data transmission into one category, telecommunications, even though each is measured differently as described in Chapter III.B.2. Further exploration into these areas of CI may

[132] "Census Bureau Projects U.S. and World Populations on New Year's Day," U.S. Census Bureau, February 1, 2019, https://www.census.gov/newsroom/press-releases/2019/new-years-population.html.

rectify some of the problems in weighing the rating to reflect a more accurate rating of criticality.

Finally, the calculations avoided incorporating elements from the Financial Services Sector of DHS.[133] There are 142 bridges in the United States that generate toll fees.[134] These bridges, in addition of the potential to serve as a link for multiple CI networks, generate revenue for their agencies. The revenue could play a factor in the criticality of these bridges. Other financial aspects not incorporated into my proposed CIR method are cost to repair or replace the bridge, increased cost in rerouting traffic/other CI, and decrease in revenue not related to tolls. All of these factors must be incorporated into any new criticality rating system.

B. RECOMMENDATIONS

This thesis proposed a beginning to the process of creating a rating system for bridges, or other links and nodes, that convey resources from multiple CI networks. Further research and development are needed to refine the process in specific areas and, possibly, even expand to include additional crucial elements.

As the initial phase of the process depends upon rating the individual CIs, an MOP-based CIR standard should be applied for comparison. Calculating an MOP based rating entails establishing the MOP_{max} for any given CI. Further research should determine a common MOP_{max}, from which an MOP based rating system can be developed.

A comprehensive list of CIs conveyed by bridges should be incorporated into the calculations. The example included five common CIs carried by bridges for simplicity of demonstration and combined multiple CIs into one category. As mentioned,

[133] Department of Homeland Security, "Critical Infrastructure Sectors."

[134] Federal Highway Administration, *Toll Facilities in the United States: Bridges—Roads—Tunnels—Ferries* (Washington DC: Federal Highway Administration, 2018), http://www.fhwa.dot.gov/policyinformation/tollpage/.

telecommunications could be broken down into communications and data transmission, but the pipeline category could be divided into a rating for each product.[135]

The CIs then need to be ranked according to their importance to the jurisdiction. This thesis provided a ranking based on my experiences, but this ranking may not work for another city. Similar to determining the MOP, jurisdictions and agencies will reflect differences. Guidelines need to be developed to rank the importance of the CIs to produce an adjusted CIR.

After refining these steps, the basic formula presented in this thesis will become more accurate. Any enhancements, however, must maintain the overall simplicity of the approach presented in this thesis.

[135] "General Pipeline FAQs," Pipeline and Hazardous Materials Safety Administration, February 26, 2019, https://www.phmsa.dot.gov/faqs/general-pipeline-faqs.

APPENDIX. INTERVIEW RESULTS

I made over 120 attempts to contact various subject matter experts (via email and phone calls) for objective data on how they quantify the importance of their transmission lines (links). Below I have described the answers I received. They are divided into interviews and email responses with a brief description (years and area of expertise) and type of correspondence (phone, face-to-face, or email). Note that the questions asked in the interviews were intended to solicit objective factual data, not the opinions or preferences of the respondents.

A. INTERVIEWS

The interviews below only reflect the answers to the first question: What is your local procedure for quantifying the importance of your transmission lines or nodes (amount of product, number of customers served, other)? The answers to this question provided an adequate MOP for the purposes of my process.

1. Electricity—Retired Senior Enterprise Continuity Manager, 33 years with Kansas City Power and Light (KCPL) (retired 2016): 11 May 2019 (face-to-face interview)

<u>What is your local procedure for quantifying the importance of your transmission lines or nodes (amount of product, number of customers served, other)?</u>

Transmission lines are rated subjectively based on guidelines. The main line from the power generating station has the highest rating. Top rated lines are those lines designated as powering critical infrastructures: hospitals, first responders, water pumps, water treatment plants, etc. Second level lines are those designated as a "primary backbone" that are main feeder lines to distribution stations (which in turn feed customers). Third level lines are those that provide power to entire neighborhoods with the larger the population of the neighborhood designated with higher ratings. The lowest level are those lines that provide power to individuals.

Critical infrastructure for the top-rated lines are based the customers' or regulatory lists. The State of Kansas has generated a specific list of critical infrastructures; Missouri gives more leeway to the local jurisdictions. KCPL tends to follow the State of Kansas guidelines for Missouri customers.

2. Telecommunications—Field Technician, 23 years with Cox Communications, Inc.: 22 May 2019 (phone interview)

<u>What is your local procedure for quantifying the importance of your transmission lines or nodes (amount of product, number of customers served, other)?</u>

Transmission lines are categorized as main lines, nodes, and taps. Main lines feed nodes and taps; nodes contain ≤ 500 modems (for voice over internet protocol, or VOIP); and taps are lines direct to the customer. The main lines and taps are prioritized based on the number of customers served. Nodes are prioritized by the number of modems associated with the node.

3. Telecommunications—Fiber Manager, 14 years with the City of Kansas City, MO: 15 May 2019 (face-to-face interview)

<u>What is your local procedure for quantifying the importance of your transmission lines or nodes (amount of product, number of customers served, other)?</u>

Data transmission lines are rated on the lag time should the pathway need to be rerouted. In other words, if a particular line is down, how much extra time (in milliseconds) does the new pathway take to transmit the same amount of data.

4. Water—Emergency Management Program Director, 6 years with Metropolitan Water District of Southern California (MWDSC): 28 May 2019 (phone interview)

<u>What is your local procedure for quantifying the importance of your transmission lines or nodes (amount of product, number of customers served, other)?</u>

MWDSC measures the criticality of transmission lines (pipes) based on four factors. The first is how many acre feet of water that the line carries (an acre foot of water is 325,851 gallons).[136] The second criterion is the rate of flow in cubic feet per second.

[136] Boucher, “What Is an Acre-Foot of Water?.”

The third criterion is the sized of the pipe. The final criterion is the size of the "pressure zone." A pressure zone is defined as the area of the network that would be affected if the valve on the pipe were closed (i.e., how much of the rest of the system is needed to absorb the pressure). The number of customers served is taken into consideration with respect to the criteria.

B. EMAIL CORRESPONDENCE

1. Water—Process Management Coordinator, 7 years with WaterOne: 20 May 2019

What is your local procedure for quantifying the importance of your transmission lines or nodes (amount of product, number of customers served, other)?

Transmission lines are quantified by pipe size and capacity.

What is the cost to replace 1 unit (foot, yard, mile) of your transmission line?

Distribution mains average cost to replace is $140 per line foot. Transmission mains cost approximately $400 to $800 per line foot.

What does it cost to replace a node (whatever form that junction might take)?

The estimated cost to replace is $25,000 to $75,000 depending on the variation of 10 inches to 66 inches in diameter.

2. Highways—Area Engineer with Missouri Department of Transportation

What is your local procedure for quantifying the importance of your transmission lines or nodes (amount of product, number of customers served, other)?

Roads and bridges are classified into 3 categories: Interstate, Major, and Minor. We also rate their condition every year: Good, Fair, Poor.

What is the cost to replace 1 unit (foot, yard, mile) of your transmission line?

Typically, a pavement overlay costs $152,000 on Interstate, $132,000 on Major, and $38,000 for Minor. Costs are based on lane per mile. New pavement installation or replacement typically costs $1.4 million per lane per mile. Bridge replacement averages $248 per square foot.

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