Modeling the Resilience of Multimodal Rural Freight Corridors: An Integrated Area-based and Link-Based Framework

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Abstract

Resilience analysis for multimodal freight corridors involves assessing the ability of freight networks to sustain and robustly recover from major disruptions such as natural disasters, accidents, or system failures. Such resiliency analysis should consider factors such as the risk of different disruptions, infrastructure health and robustness, and the redundancy of different network components. The primary focus of the research presented in this thesis is the resiliency of rural multimodal freight corridors that serve local industries such as agriculture, livestock, manufacturing, and mining. The research was conducted through several major tasks: a comprehensive literature review to synthesize the results of previous research; review of data available in the federal, state, county, and city levels to identify and document the availability of data as well as to highlight gaps that exist in this data; and the development of an integrated area-based and link-based framework to model the resiliency of multimodal rural freight corridors.

Several disruptions are considered in this study including disruptions due to structural failure of one or more network element, disruptions due major crashes such as HAZMAT crashes on highway or railways, and disruptions due to natural hazards such as landslides, floods, and wildfires. While cyberattacks, such as ransomware attacks, can target ports and railway operations and cause considerable disruptions, they were not included in this research. Based on the review of data available for rural multimodal freight corridor analysis, several observations have been made:

- While structural health data for bridges and culverts on the state highways are available and can easily be accessed, such data are either not available or difficult to access for all structures on the local highway system and for structures on railway lines. This causes a significant gap in the data needed to assess the structural failure risk indicators for major elements of the rural multimodal freight corridors,
- Major crashes data on the highway system is available and accessible from different sources. However, crashes and incidents on private railway lines are not publicly available,
- Data for the risk indexes of different natural hazards is publicly available from federal sources at the county level. Few data are available in the more disaggregated route specific levels, and
- Data on past disruption incidents to document details of the disruption, the response plan, and the recovery plans are either not available or hard to access. This data is very valuable to document lessons learned from each disruption incident and to enhance coordination and communication among stakeholders to facilitate effective and prompt response and recovery efforts to future disruptions.

The integrated link-based and area-based framework introduced in this research can be used to estimate structural failure and HAZMAT/railway crash risk indexes for different links on the rural multimodal freight corridor networks. Additionally, at the link-based level, the redundancy and criticality index for each link can be estimated. Area-based natural hazards data can be used to estimate the natural hazards risk indexes that are associated with each link in the network. The outcome of this integrated framework can assist transportation agencies in the following tasks:

- Developing comprehensive risk management strategies that account for a wide range of potential disruptions and emergencies,
- Implementing the outcome of the criticality and redundancy indexes for different network links to create redundancy and alternative options for freight movement, and
- Establishing robust contingency plans and implementing data-driven decision-making processes to predict the likelihood of different disruptions and optimize response and recovery plans and operations.

Acknowledgments

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Dedication

I would like to deeply thank all my family and friends for their unlimited support in all stages I have been through while doing my thesis.

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Chapter 1: Introduction

1.1 Overview

Multimodal Freight corridors, that consist of interconnected network of roadways, railways, inland waterways, and ports, are critical elements of the supply chain that supports our nation's economy. The economic development and prosperity of rural areas depend on the multimodal rural freight network, as they heavily rely on agriculture, manufacturing, mining, and fishing. It is, thus, critical for the region's economic growth and global competitiveness that the rural multi-modal freight system is safe, efficient, and resilient. Such resiliency and robustness require the availability of reliable, real-time, accurate, and localized data. This data extends to the attributes and characteristics of various rural industry activities (land use, goods location, movement, and analysis), the conditions of different elements of the freight network, and the likelihood of man-made or natural events that disturb the system operations.

The research presented in this thesis aims to conduct a comprehensive review of previous research that addressed methodologies and approaches to model, assess, and improve the resiliency of the freight networks and synthesize the state-of-the-practice of transportation networks resiliency modeling at different levels. Furthermore, identify and document the data needed to model the resiliency of multimodal fright corridors as well as the availability and gaps that exist in this data. The research also aims to develop an integrated area-based and link-based framework to model the resiliency of multimodal rural freight corridors and conduct several case studies for different multimodal fright corridors in the state of Idaho to examine and implement the proposed integrated framework developed as part of this research. The results of this research can help transportation agencies define the vulnerabilities of different network elements and to promptly detect, respond to, accommodate, and recover from different disruptions to the fright corridor networks. The research outcome will also help agencies prioritize investment and resource allocation to maximize the resiliency of the multimodal rural freight network which will contribute to the overall objective of a resilient and robust supply chain for the state, the region, and the nation.

1.2 Background

The local and global trade depends mainly on Freight transportation corridors, which are considered the main arteries for supporting different agriculture and production activities as well as economic developments. A range of factors could affect the productivity and efficiency of freight corridors in rural areas. Those factors could be due to natural disasters (hurricanes, floods, landslides, earthquakes, pandemics, etc.) or they could be due to manmade events (structural failures, major crashes, cyberattacks, etc.). One of the most recent incidents is the disruption caused by Covid-19 pandemic, which affected urban and rural areas global transportation. The unfavorable effects of those recent incidents have shown the criticality of rural transportation networks and freight corridors and their significant role to the operation and mobility of rural communities. It is important to make rural freight corridors more resilient to overcome any future predictable or unpredictable events. Various state Departments of Transportations (DOTs) are focusing on a national transportation recovery plan to enhance the resiliency of freight corridors. The focus of these efforts is to enhance the resiliency and recovery of the multimodal freight corridors under various scenarios of disruptions (USDOT, 2009). Nowadays, resiliency is extremely considered a crucial element of the future for freight mobility, sustainability, and development.

A comprehensive review on the resiliency of transportation networks has been documented byMattson Göran, and Jenelius (2015). The resiliency of freight network has been defined as the “countermeasure of vulnerability”, which includes the capacity of the network to retrain its function and the system quickness to recover after a disruption. Major research has also been conducted on the resiliency of transportation networks (Caplice et al., 2008), (Goodchild et al., 2009), (Ortiz, , Ecola, and Willis, 2009), (Ta et a., 2009), (Cox et al., Rose 2011), (Adams et al., 2012), and (Faturechi, Reza, and Hooks, 2014 and 2015). In addition, resiliency could be defined by the four “Rs”, based on the Multidisciplinary Center for Earthquake Engineering Research (MCEER) and (Jansuwan et al., 2021).

- “Robustness (strength): the ability of the system to resist a given level of disruption without experiencing failure or loss of operation functionality.
- Redundancy: the availability of alternatives to satisfy operational requirements in case of disruptions that cause failures and loss of function.
- Resourcefulness: the ability to optimally utilize resources and implement effective and robust measures to offset the impacts of disruptions; and
- Rapidity: the ability to recover full system operations in a timely manner after disruption occurrence.

Although there is extensive research that has been carried out on freight network resiliency, only a few studies have established quantitative methods to assess the four “Rs” elements, mainly on how to assess the redundancy alternatives of transportation freight networks. Resiliency of transportation networks depends on numerous factors. Redundancy is one of those factors and is measured from the topology of the transportation network, (Comtois, Claude, and Slack, 2009). For example, the Alpha index could be used to measure the level of connectivity and redundancy of the networks. This index depends on the number of nodes and links in the network. An Alpha index value of one means a network with high redundancy and a value of zero means a high-risk network with no redundancy. Another method is to use a link criticality index that is based on the network equilibrium (Almotahari, Amirmasoud, and Yazici, 2019). Using the stochastic network equilibrium method is another way to assess redundancy (Jansuwan, Sarawut, and Chen, 2015).

Other studies have included quantitative methods for assessing network redundancy to improve resiliency (Godschalk, and David, 2003) and (Murray-Tuite and Pamela, 2006). Murray-Tuite, and Pamela M (2006) also defined redundancy as the level of functionally alike factors which could perform the same task, and therefore the network operations would not fail when one link fails. Additionally, this method depends on the concept of “alternative transport mode”, which protects the system from various disruptions. Goodchild et al. (2009) defined redundancy as one of the required properties of freight transportation resiliency. Redundancy has been defined as the availability and accessibility of several alternative options in the freight network. Jenelius and Erik (2010), on the other hand, proposed dual flow-based and impact-based indexes to measure the level of redundancy. The flow-based index considers the traffic flow level that is rerouted to the alternative links, while the impact-based index measures the increased delay that results from traffic rerouting. Finally, Ortiz, Ecola, and Willis (2009) proposed various alternatives to improve the resiliency of the freight corridors. In their research, they suggested routing freight to pre-identified ready-to-use alternative network segments and to robustly repair the infrastructure after any disruptions to add immediate load carrying capacity to the network.

1.3 Research Approach and Objectives

The research presented in this thesis was conducted through several major tasks. First, a comprehensive literature review was conducted to synthesize the results of previous research focusing on the resiliency of multimodal freight network under the effect of man-made and natural disasters. The state-of-the-practice review covers both quantitative and qualitative measurements that assess the efficiency and resiliency of the multimodal fright corridors that include interconnected network of local roads, highways, freeways, railways, inland waterways, and ports. The synthesis review also covers data elements for different resiliency indicators (vulnerabilities) that quantify redundancy and resiliency, post-disaster phases of resiliency, and the evaluation of the applicability of resiliency indexes of multi-hazard scenarios in rural multimodal freight corridors.

Second, a review of data available from various sources was conducted to develop a comprehensive view on data availability and gaps based on a detailed assessment of the current and future needs and challenges in freight network resiliency analysis. The available data was then used to develop an integrated framework to model and assess the resilience of multimodal fright corridors. The proposed framework uses both area based and link based measures to quantify and assess the vulnerabilities of different corridor elements. Graph-theory based indexes and network topology were used to measure the criticality of different network links. The proposed area-based and link-based framework presented in this thesis combines a grid approach that has been used in some studies to analyze vulnerability of transportation networks under. The proposed methodology involves covering the area under investigation with uniformly shaped and sized county-based grid cells with link-based network analyzed using graph-theory based measures. This combined approach covers both the extended areas that might be affected by natural or man-made disasters with the characteristics of different links of the network. The final task in this thesis work included case studies of several multimodal freight corridors in the state of Idaho using the area-based and link-based framework developed as part of this thesis.

The contributions of the work presented in this thesis are:

1. Develop a synthesis that documents the results of a comprehensive literature focusing on the resilience of multimodal freight corridors. The literature review explored various definitions of resiliency within multimodal freight corridors, examined the methodologies, measures and data used in the freight corridors resiliency analysis.
2. Review resiliency-related data currently available in the local, state, and federal levels and identify and document gaps in the data sets needed for multimodal freight corridor reliance assessment.
3. Develop an integrated area-based and link-based framework to assess the vulnerability of the multimodal freight corridors components to different disruptions. The proposed integrated framework allows transportation agencies to estimate risk indexes for different links of the freight corridors for different disruptions including structural failures, major highway and railway crashes, and natural hazards. The proposed framework allows agencies to develop

integrated and comprehensive risk management strategies for freight corridors that take into consideration all potential disruptions.

1.4 Thesis Outline

The work presented in this thesis is organized in six chapters. After the introduction, chapter 2 includes a synthesis of previous research. Chapter 3 presents a description of different freight corridors in Idaho. Chapter 4 includes the research methodology covering data available from various sources as well as the proposed model to analyze the resilience of multimodal freight corridors. Chater 5 presents the results of several case studies to verify the sue of the model. Finally, chapter 6 provides the research conclusions, recommendations, and suggestions for future research.

Chapter 2: Literature Review

2.1 Overview

This chapter is divided into four sections. The first section is the definitions of resilience that explain the different terms of resiliency for different fields. The second section introduces the resilience measurements as well as different methods to assess resilience. The third section explains how resilience performance is measured based on quantitative resiliency indexes. The fourth section represents the data needed to improve the resiliency for freight corridors.

2.2 Definitions of Resiliency

There are several definitions of resilience in freight transportation systems. Ta et al. (2010) presented four definitions of resilience in freight systems. The first definition is the capacity to meet the priorities and achieve goals for the system. The second definition implies the time capacity of the system facing infrastructure disturbance. Their third definition of resilience is the capacity of the network facing infrastructure disturbance. Furthermore, the capacity to reduce the consequences of disturbance occurred on the infrastructure. Moreover, the study discussed how to improve the resilience in freight systems by building new infrastructure or improving the existing one to manage the disturbance that might occur on the infrastructure. Also, they established six features of resilience for freight systems. The six features are redundancy, autonomous components, collaboration, efficiency, adaptability, and interdependence. The study proves that when resilience is performed well, the economy will get more benefits.

A previous study explained the concept of resilience in freight systems. Resilience is the ability of the system to cope with the disturbance occurred in the system. Furthermore, the resiliency is affected by the economic cost since the improvement of the resilience requires an investment from the government or private sector. Potter, Sorok, and Naim (2022) discussed how resilience operates. The study investigated the concept of resilience by measuring the time needed for the system to return to the original state. However, by the time any disturbance happens, that will decrease the lifetime of the infrastructure, so it needs to be improved or rebuilt to be able to handle the disturbance longer, to save cost. The decision to improve resilience should consider and observe the impact of the whole area, not only one sector, (Potter, Sorok, and Naim, 2022)

Resilience in general has two main key phrases. The first phrase is “absorb to change”, and the second phrase is “persisted”. Chen et al. (2017) explained that both phrases describe the main concept of resilience which is the capacity of the system to face and overcome the change occurring in the infrastructure. The terms used for resilience concept are recover, tolerance, return, restoration, and disturbance. Chen et al. (2017) represented how resilience and adaptability relationships. This relationship focuses on the economical aspect of resilience in the system. Also, resilience in transportation is divided into two sections. The first section is flexibility, which is the capacity to oversee the change or disturbance that happened in the system. The second section is the reliability that explains the probability of remaining the link between the nodes in the system, the travel time of reaching the destination, and the capability of the system to satisfy the demand. They considered all the definitions of resilience of their study, (Chen et al., 2017).

Zhou et al. (2019) defined resilience for different modes of transportation. There are two definitions for resilience in a freight system. The first definition is the ability of the system to absorb the consequence, reduce the impact of the disturbance, and maintain the mobility of the system. The second definition is the post-disaster expected to serve the demand that can be satisfied with specified recovery cost. Resilience is divided into two phases, the disturbance phase that includes Robustness, Redundancy, and the recovery phase that includes Resourcefulness, and Rapidity. Robustness is necessary to measure the ability of the system to deal with the induced damage. Zhou et al., (2019) measured resilience in different ways but they are all based on metric calculations. The resilience definition is generally about the recovery needed to deal with disturbance.

2.3 Resilience Measurements

For decades there have been a lot of attempts to reduce the infrastructure downtime which extend the age of the infrastructure and decrease the recovery cost. Cappaci, Biondini, and Frangopol (2022) studied the reliability of the infrastructure against the hazardous and disastrous events that might happen. They used what had happened in the past to avoid repeating the same mistakes that happened before. Resilience has been introduced by the author by a definition (The amount of distribution that can resist before any change might be happening in the system). Resilience is divided into four dimensions, technical, organizational, social, and economic. Seismic hazard has been focused on to extend the age of resilience. The methodology they used is to determine the resilience in the time between the occurrence and the horizon at the event, where the horizon time is constant. Bridge seismic hazard depends on the random value of the event with how much resistance the bridge can handle before it reaches the failure point. The way Cappaci, Biondini, and Frangopol (2022) handled the issue is to collect data about the traffic demand by origin and destination trips. The main idea of the article above is to improve the lifetime of the infrastructure in roadway networks and bridges by knowing how to improve resilience and how it affects society and the environment.

Weather conditions are a significant factor for any highway design since they provide hazard to motorists and pedestrians. The reason for the hazard is how weather affects resilience on highways. Weather affects a lot of aspects. However, the focus is on the road safety aspects. Fei and Zhang (2020) studied how spatial resilience influenced crashes on highways. The techniques that have been used for spatial resilience are K Nearest Neighborhood (KNN), distance to highways, and Kernal density. Highway resilience is related to the level of service which is determined based on travel time, capacity, and safety. The method they used for determining the spatial resilience is to through three data sets: geographical areas with difficult weather conditions, crash locations, and the highway networks. Determining the metric value for spatial resilience is necessary to decide whether the resilience of the highway weather conditions does really affect safety or not.

Railway infrastructure resilience is measured by identifying the natural hazard on the infrastructure. Fabella, Vigile, and Szymczak (2021) focused on the natural hazard in Germany. Germany has four natural hazards on the rail infrastructure: floods, tree falls, landslides, and fires. The data proves that natural hazard reduces the traffic demand. Floods have the highest percentage of all other hazards for reducing the demand by 19%. The reason for focusing on railway is because it has less network and operations than road network. The resilience definition in railway system is the capability to provide service. Two types of data have been used in the methodology: daily train traffic data, and event data for the four natural hazards. To collect the daily train traffic data there must be quality measures for the level of mobility service. Event data can be collected by using the accident database. Fabella, Vigile, and Szymczak (2021) involved different dimensions in the system, spatial distribution, and occurrence frequency to decide whether they affect resilience or not. Studying resilience for infrastructure is only the first step to define resilience for the entire system.

Poor resilience results from the higher impact of natural disasters on the infrastructure. Resilience dimensions have not been focused on much in most previous studies. The focus Nipa, Jahan, and Kermanshachi (2020) had was the resilience dimensions in transportations field. Performance along with resilience dimensions are going through four phases, performance before the disaster, disruptive phase, recover phase, and performance after disaster. There were eighteen dimensions identified in the study, and the aim is to develop a resilience model for transportation infrastructure. Different dimensions might have remarkable change due to different times of disaster events. The proposed framework was developed by understanding how different dimensions affect each other. They also found that one of the eighteen dimensions has a negative relationship while the others have a positive relationship with different resiliency measures. The model will help decision makers to prioritize the construction of infrastructure more.

Resilience is the performance of disturbance and quick recover time. Providing a new way to measure resilience is necessary to improve it. Transportation infrastructure has different components, railroad network, highway network, and airline network. The main problem of disaster events is that even if they happened in one node, they could have high economic and physical damage. Resilience in transportation infrastructure is the ability of the system to provide service. Structure modeling could optimize the resilience of transportation infrastructure by analyzing the resilience of different events. A conceptual framework is helping but there are some factors that need to be considered, network structure and power law distribution. Wang et al. (2020) focused on railway and air transportation to measure resilience of transportation infrastructure by network nodes, network links, weighted works, and undirected network. The new measure proves that it is more useful than the previous studies.

Previous studies provide different measurements to assess the resilience of transportation networks. However, a small portion of them can be used to measure the resilience in specific existing roadways. The main objective is to identify and establish new dimensions to measure the resilience of roadway for technical and organizational scopes. Previous studies have investigated the dimensions for measuring resilience. The results show that there are fourteen dimensions, and it has a negative correlation with pavement resilience. Nipa, Jahan, and Kermanshachi (2021) divided the study into four steps, reading only peered- research, database preparations, data collection, and analysis result. There are four main dimensions to measure resilience in all sectors. Also, another four additional important dimensions to measure resilience in transportation system are efficiency, diversity, strength, and mobility. However, the main objective is to measure the organizational aspect. The are fourteen dimensions listed in the study after collecting the data. The results explained how resilience affects the road users and the environment and how the resilience of roadways is weak, so these results might help to develop more strategies to improve the resilience in roadway infrastructure.

Having few dimensions of resilience makes it challenging to measure. This is a different level of complexity for any transportation project; thus, the aim of the study was to identify and find potential measures that can be used to assess resilience at a less complex level. A survey is conducted to understand what dimensions need to be considered. The survey focused on five sections including user demographic, project-based data, resilience definition, resilience measures, and best practices. Survey results are applied to statistical analysis to determine the probability and complexity of each dimension. Also, the results show the probability value for sixteen dimensions. However, an expert panel reported that they’re going to need 8 more dimensions because of the different circumstances. For example, the number of nodes in the intersections, so that project implementers should consider those different dimensions to avoid resilience failure in the project. Unfortunately, the researchers are focusing on resilience more than recovery. The author hopes that the study could be used to find more dimensions in different complexity levels, and to improve the resilience of transportation infrastructure.

There were lots of disaster events that occurred in transportation infrastructure and led to significant social, economic, and financial losses. Nipa, Jahan, and Kermanshachi (2023) previous studies mentioned how different dimensions that affect the measurements are rare, so the main goal is to provide more information about it, and to develop a model. Different definitions have been used to describe resilience, yet the common between them all is that time needed to recover for disruptive event. The study used the same survey that had been used to determine if the resilience is working as it should be or not. Using structural equation model was necessary to calculate the resilience and how several factors might affect it. The results help to develop a model that can be used to solve problems like delays.

Switching between different modes of transportation is a unique feature of multimodal freight transportation. Network robustness is necessary to be measured. Moreover, robustness is one of the four main dimensions needed to measure the resilience of transportation infrastructure. Robustness is about avoiding direct and indirect economic loss. Zhidong et al. (2021) study focused on freight transportation work in Netherlands. Robustness metric is the method used in the study to determine if the infrastructure failed or not. The metric is divided into two categories, topological, and traffic-based metric. It depends on the Origin-Destination connection between different modes. Also, it relies on two types of perturbation which are connectivity, and capacity of the mode. The results proved that improving the system will decrease the effect on the resilience and robustness of multimodal transportation freight system.

The measurement and maximization of resilience is challenging to do simultaneously, thus maximizing resilience is more important to put the limit when measuring the resilience. The main goal for the work conducted by Hooks et. al. (2012) was to assess and maximize the resilience for multimodal freight transportation networks. The problem was measured by knowing the maximum demand before the event, and the maximum demand after the recovery time. The destination will be known by origin and destination (O-D). After determining the resilience, the recovery cost will need to be calculated. The results haven’t given the optimal solution, which was meant to be, because the probability assumed to be equal for all scenarios. The study focused on recovery after disaster events that have limited time frame and budget to be done. It proves that recovery time is the only parameter that might improve resilience.

2.4 Resilience Indexes

Bakkensen et al. (2017) analyzed five prominent performances of resilience, and selected the indexes based on three criterions: 1) Based on the United States at the county level focused on the western side, 2) Resilience analysis for natural disasters, 3) The availability of public data on final index score. In addition, the study compared three resilience indexes. Baseline resilience index which calculates the final index score spread across five categories: social, economic, institutional, infrastructure, and community. Also, the metric score is on scale of 5, where 0 is least resilient while 5 is most resilient. The second index is community disaster resilience that uses comprehensive measures for community disaster based on four factors: social, economic, physical, and human. The score is based on the average score of each factor then combined to find the average score of all factors. Also, the score could be negative or positive. Least resilient is (-1.317) and the most resilient is (1.436). Resilience capacity is the third index compared with community disaster resilience and baseline resilience. The metric score spread across three categories: regional economic, sociodemographic, and community connectivity. In addition, the score range starts with negative score to positive score with -1.66 (least resilient) to 1.23 (most resilient). The study's authors found that resilience capacity index is the best of the three indexes.

Carvalhaes et al. (2021) explained the case of disaster resilience index by measuring numerical score of resilience performance to help decision makers to decide whether the resilience to the disaster is performing well or needs to be improved. The score is represented usually with negative value or zero to be the least resilient and where the score is positive, equals 1, or the highest score is the most resilient. To determine the score, the authors needed public data to use on their model to measure the metric score on disaster resilience index. However, the cost to improve the resilience is high which made the authors of the study decided to reduce the resilience of urban areas to improve the resilience in other locations with making sure the resilient disaster index is highest as possible to increase resilience and safety of the community. Also, the importance of data availability from the stakeholders to make sure that any research or project to improve the resilience is supported by the available data they can provide to the researcher or project organization.

The composite index is a mathematical measure used to summarize or review the characteristics of the system. Calculating resilience indexes is done by determining the quantitative and the qualitative aspects of the system. Mateos et al. (2021) focused on ports resilient index since there are a few projects to improve the resilience of ports infrastructure. The goal of the project was to provide resilience index of port to stakeholders to improve the resilience and the safety of infrastructure. Asking the stakeholders for the data is the core step to develop the resilience index for ports. The main factor to develop the resilience index is to determine the primary cause of the resilience disaster to occur on the system. The authors of the study concluded that there are five dimensions needed to be considered to develop resilience index for port infrastructure such as governance, society, infrastructure and facility, operational environment, and risk management. The authors also found that the tools were limited to develop a resilience index because of data availability from the stakeholders.

The Safety resilience index is one of the most important indexes that can be measured because it focuses on the safety of the community. Safety resilience index is full mathematical formulations that use binominal distribution to calculate the number of events because some events that could occur on the system are unknown and might be random which do not have any specific reason for the disaster to occur in the first place. Borja et. al, (2017) explained that the safety resilience index is following the same concept of disaster resilience index measurement, but the only difference is that safety resilience index uses the level of severity as the range of index score while disaster resilience index score depends on mathematical calculation considering different factors. Also, safety resilience index scores are determined by finding the probability of the event using binomial distribution. The authors of the study developed a safety resilience index after identifying all hazardous scenarios, and the cause-consequence of the scenario to determine the score as accurate as possible. The study represents different scores, yet the index needs to improve more to be primarily used to improve safety since some errors happened during application of this method to develop safety resilience index.

2.5 Data Used in Resiliency Analysis

Wiegmans et al. (2020) studied the impact of using large amounts of data and the analysis of data on international transport networks, especially on shipping in Europe. The characteristics of the large amount of data in database are: The identification of the geographic location (latitude, longitudinal), direction of wind, and weather conditions. The data used depends on the ship data origin and destination, ship name, type, company, and geodata. The data are managed mainly on origin and destination. The study focuses on the route choice for the ship trip which is most used. Moreover, the distance and the duration of the trip shows different results since when the distance is long, it doesn't mean the duration will be long too. Finally, the data collected by the trip voyage from Europe, but France data wasn’t containing lots of information needed to decide the impact of route choice. However, Netherlands has variety of data which help to understand the behavior of origin and destination for the trip.

A previous study focused on the data used to develop planning for freight corridor. The data used for planning was collected through Intelligent Transportation systems (ITS) devices located throughout the freight network that used Global Positing Systems (GPS) tracking devices to collect truck movements data. Srour, Jordan, and Newton (2006) found that the benchmark goals are truck traffic volume per day and the peak hour, mean travel time, selecting origin and destination travel time, and route. The GPS data was collected by installing GPS device on 52 trucks. Furthermore, the accuracy of the data was considered by comparing the travel time then determining the average of the travel time. The data was used to find the congested area to avoid the delay for the system which led to the use of different routes. The goal of the study was achieved by knowing the data need to be used to improve planning of freight transport and system. The methodology used to process the data is divided into two methods. The first method was the processing procedures by using GPS on trucks, and the geo-spatial data collected by ArcGIS software’s. After collecting the GPS data from the trucks, it was imported to ArcGIS to find the origin and destinations then link them together to find the route. The second method is analyzing the data by knowing the traffic volume and the speed of the trucks. The analysis was focused on monthly average speed and deviations, vehicle speed and volume travel and buffer time on GIS, Truck stop locations and rest durations. Liao and Fu (2009) ensured that the data analysis is accurate by using GIS and statistical model to determine the mean value of travel time and the vehicle traffic volume and speed. Finally, the analysis could help improve traffic and freight systems in transportation operations.

Air quality is a crucial factor to consider since the freight corridor relies on trucks and locomotives for its operations. The data was collected from private and public sectors that use the freight system. However, the private sector data collection is expensive compared to the public sector. Farzaneh et al. (2011) found that the public sector could provide the data set needs for Freight Analysis Framework (FAF). FAF collect their data using (O-D) focusing on the values and framework. The data collected was for both trucks and railways. Trucks’ freight activity depends on annual vehicle miles traveled (VMT), annual trucks and volume at ports. Railway freight activity depends only on (O-D). Moreover, some data is collected from GIS to get to know highways and railways movements. The data collected was enough to achieve the goal of the study to understand the impact of air quality on the freight system for both trucks and railways.

Chapter 3: Idaho Multimodal Freight Network

3.1 Overview

This chapter explains the three multimodal freight routes selected for this study. Each route has primary infrastructure, or intersections that need to be focused on since they might affect the resilience of the route. Of the three routes that have been selected for this study, two routes are highway-rail multimodal route and the third is water-rail multimodal route. Figure 3-1 and Figure 3-2 show the map of different freight corridors and modes in the state of Idaho, (Idaho Transportation Department, 2023A and Idaho Transportation Department, 2023B)

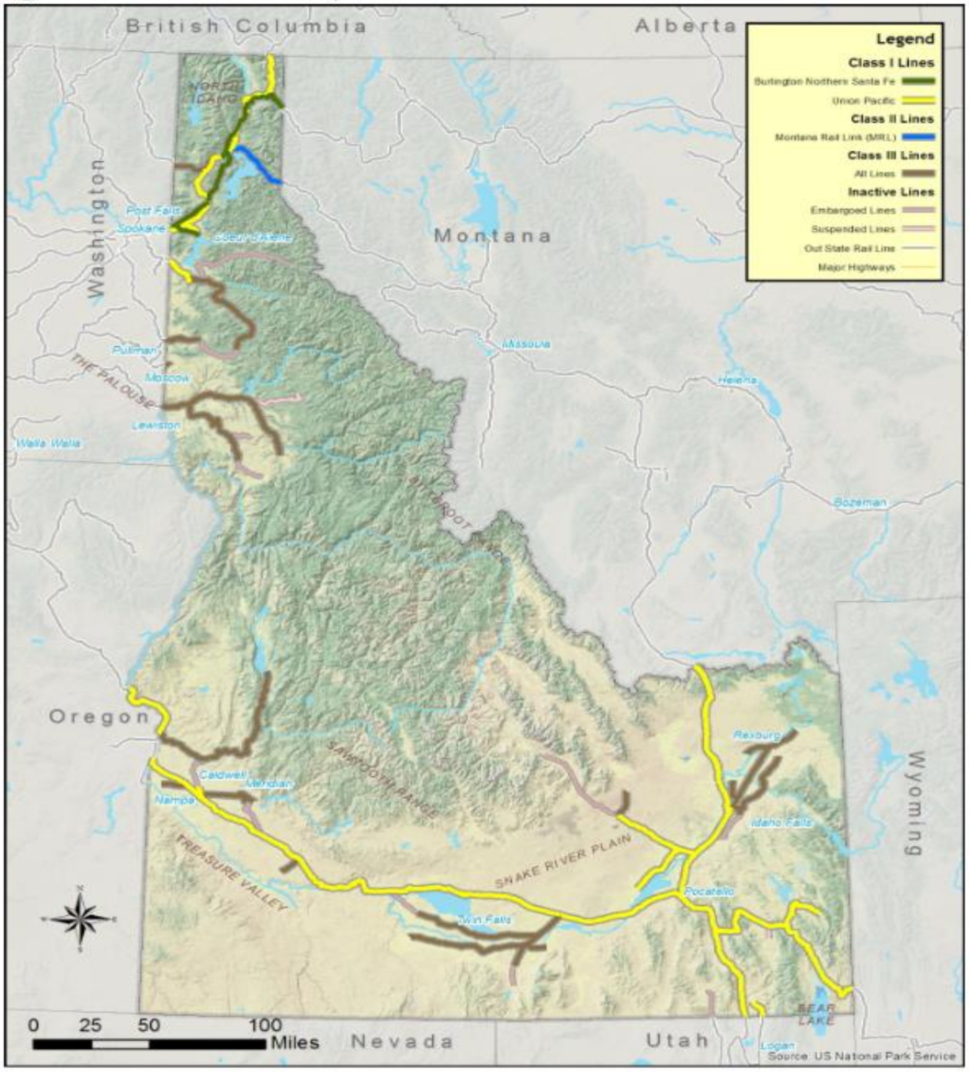

Figure 3-1: State of Idaho's Railway freight corridors (Idaho Transportation Department, 2023B)

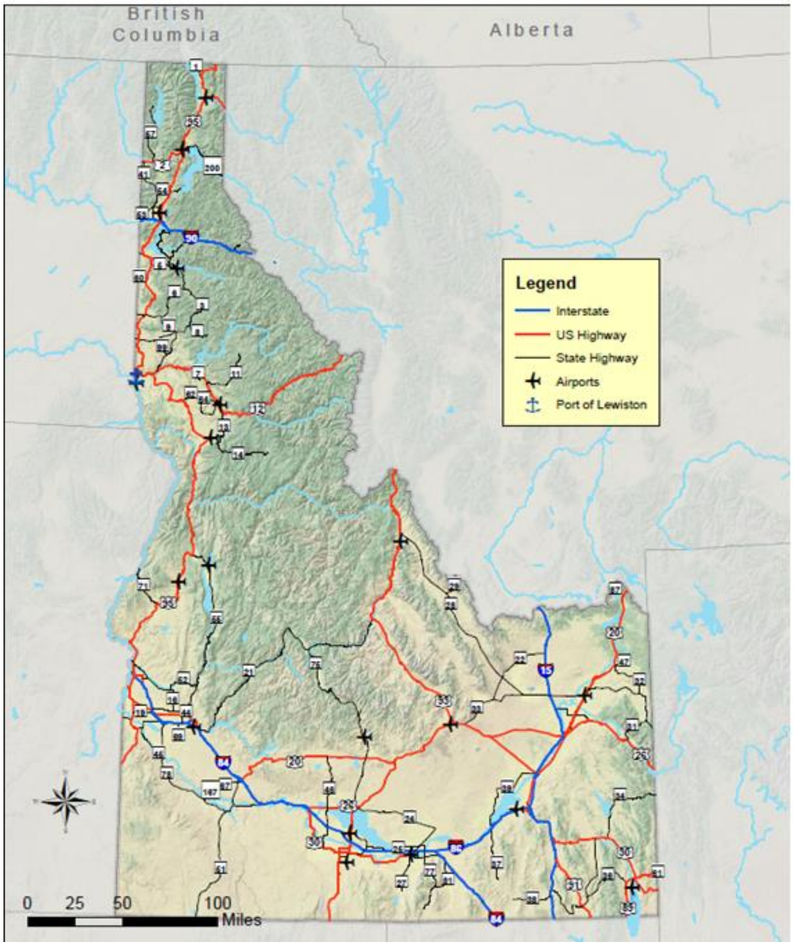

Figure 3-2: Highway, Air, and Waterway Freight Corridors (Idaho Transportation Department, 2023B)

3.2 Idaho Multimodal Freight Network – An Overview

Idaho multimodal freight network is important to delivering varying materials to different destinations. Multimodal freight delivers materials easily especially when goods, or materials are needed to be delivered to the most eastern, western, northern, and southern areas of the state. There are four modes that can be used in freight networks. The first network is through the highway where trucks are the primary mode of transportation used to deliver goods or materials on the highway. The second network is a railway network where heavy containers, transported from trucks, can be delivered through railway yards onto trains to transport the containers to their next destination. The third network is waterway (rivers, lakes, and canals), connected by ports, where vessels and container ships transport containers and other goods to their next destination. The fourth network is air where goods or materials are delivered by airplanes. Idaho multimodal freight route is mostly utilizing highways and railway. Water transportation is managed through the only port in the state of Idaho located in Lewiston and air transportation is used only for small packages. For instance, mining and agriculture industries, and for economic reasons, use railways as the primary freight mode to deliver their products to different destinations. Trucks can be used as part of the first or the last segment of the trip. In this study, the air mode of transportation will not be considered, our focus will be on highways, railways, and waterways multimodal corridors. Figure 3-3 shows the multimodal freight network and the intermodal facilities in Idaho state from Idaho transportation department. (Idaho Transportation Department, 2023B)

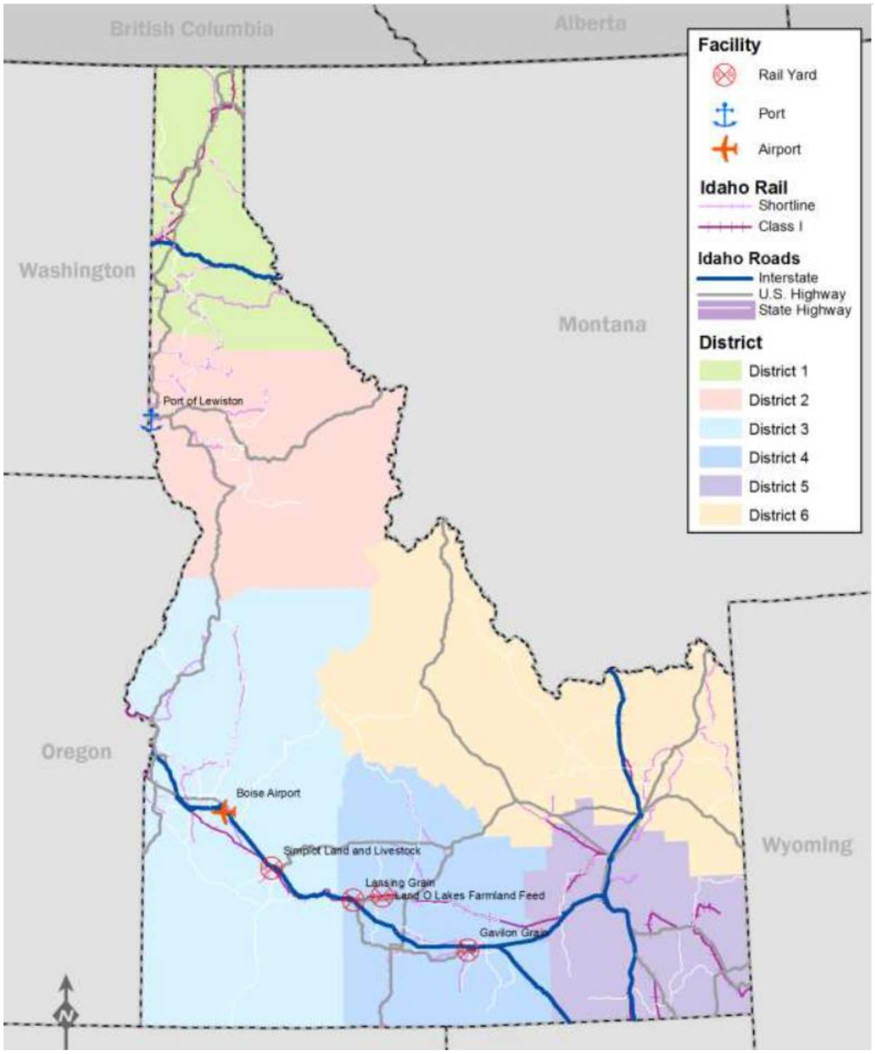

Figure 3-3: Idaho Multimodal Freight Facilities (Idaho Transportation Department, 2023B)

3.2.1 State of Idaho's Highway Network

The highway freight corridors consist of an interconnected network of freeways, U.S. highway routes, state highway routes, county roads, and local and city roads. The highway network is connected to the waterway network through a single point at the port of Lewiston. It is connected to the railway network through several multimodal highways/railways' interchange yards located at different locations in the state. The highway network consists of roadway segments and intersections. Most roadway segments have different structures such as bridges and culverts. The structural health of these structures is a key element to highway network operations. Any structural failure to one of the bridges or culverts could cause significant disruption to the network operations. The State implements strict truck weighing laws to prevent any structural damage to these structures. Another possible disruption to the highway network operations are major traffic crashes, especially for vehicles that carry hazard materials. Cleaning up such crashes could take several days and sometimes weeks, causing significant disruptions to the highway network operations. The availability of alternative roadway segments to carry the freight traffic from the ones that are not in service due to any disruption is a key element to the fright network resilience and recovery.

3.2.2 State of Idaho's Railway Network

Railways are the main freight mode to deliver heavy goods for agriculture, mining, and some manufacturing industries. In terms of cost, it is the most economic mode for transporting heavy goods. The intermodal operations between the highway network (trucks) and the railway network (trains) are managed in railway yards. The state of Idaho has four major intermodal highway/railway yards, mainly in the southern part of the state where there is a concentration of heavy-goods agriculture and mining industries. As can be seen in Figure 3-1, the state of Idaho's railway network consists of several class I lines (Union Pacific) in different parts of the state with a total length of 1,709.5 miles and one Class II line with a total length of 33.5 mile (Burlington Northern Sante Fe) in the northern part of the state with connections to the State of Montana to the east and the State of Washington to the west. There are several class III lines throughout the state to support different agriculture, manufacturing, and mining industries with a total length of 680.2 mile. (Idaho Transportation Department, 2023B)

3.2.3 State of Idaho's Waterway Network

Waterways are another economic mode to transport heavy goods from agriculture and mining industries. The waterway network consists of interconnecting water bodies such as rivers, lakes, canals, and – for international trade, oceans. Idaho has only one port in the city of Lewiston which is the gateway for all multi-state waterway freight transport. Several lakes and rivers in the state are also being used as connectors to the highway and railway networks.

3.3 Case Studies: Multimodal Freight Corridors in Idaho

For the research conducted in this study, and to assess the availability of data and the proposed analysis framework to conduct multimodal freight corridor resilience analysis, three case studies representing different industries and multimodal corridors were selected for the analysis. Details of these case studies are presented in the following sections.

3.3.1 The Gavilon Grain Multimodal Route

This freight corridor is a highway-railway multimodal freight route that supports the grain agriculture industry. The corridor starts at the Gavilon Grain company and ends at Union Pacific railroad station in Pocatello. Table 3-1 shows the details for different sections of the route. The details of the route are also presented in Figure 3-4. The total distance of the corridor is 189.5 miles (81.5 miles of highways and 108 miles railways). The corridor has several critical infrastructures on its links including the Idaho State route 27 bridges on the snake river, the railway bridge above US-93, and a bridge close to Old Town Bark Park in Pocatello just before the Union Pacific railway station.

Table 3-1: Gavilon Grainroute details.

Starting point	Ending point	Distance	Modal type
Gavilon Grian company	I-84	2.8 mi	Highway
I-84	I-46	52.1 mi	Highway
I-46	US-26	10.9 mi	Highway
US-26	Union Pacific railroad in Shoshone	15.7 mi	Highway
Union Pacific Railway Station in Shoshone	Union Pacific Railway Station - Pocatello	108 mi	Rail

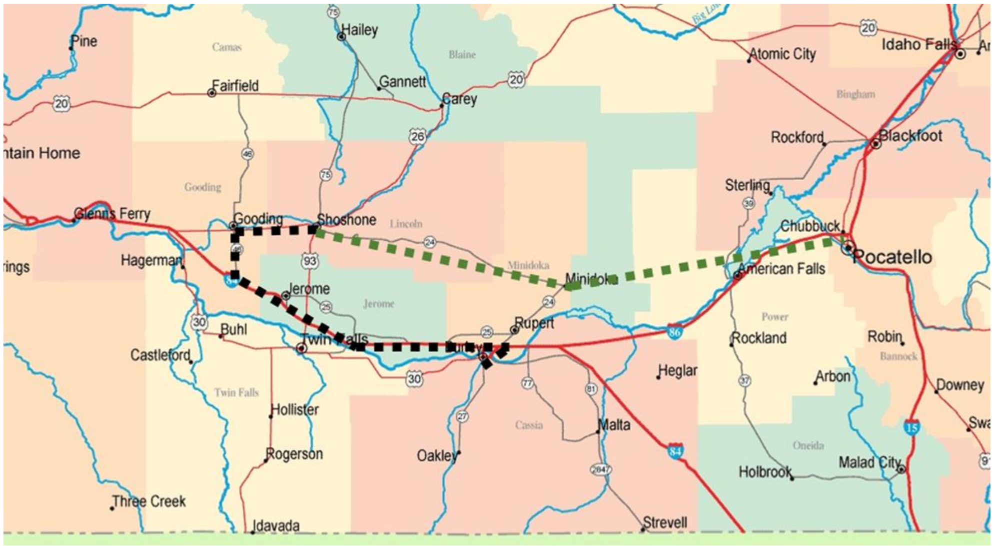

Figure 3-4: The Gavilon Grain Multimodal Corridor Routes

3.3.2 The Simplot land and livestock Multimodal Freight Route

This freight corridor is a highway-railway multimodal route. It starts at Simplot land and livestock center in Grand View and ends at Union Pacific railroad station in Shoshone. Table 3-2 lists the details of different segments of the corridor and Figure 3-5 shows the details of the corridor routes. The corridor total distance is 198.5 miles (63.5 miles of highways and 135.0 miles of railways). It has several critical infrastructure elements including the ID-45 bridge over the Snake River, the railroad bridge above ID-46, and the 6th Street bridge in Shoshone.

Table 3-2: Simplot land and livestock route details.

Starting point	Ending point	Distance	Modal type
ID-167	ID-78	4.3 mi	Highway
ID-78	ID-45	40.4 mi	Highway
ID-45	Union Pacific railroad in Nampa	18.8 mi	Highway
Union Pacific railroad in Nampa	Union Pacific railroad company in Shoshone	135 mi	Rail

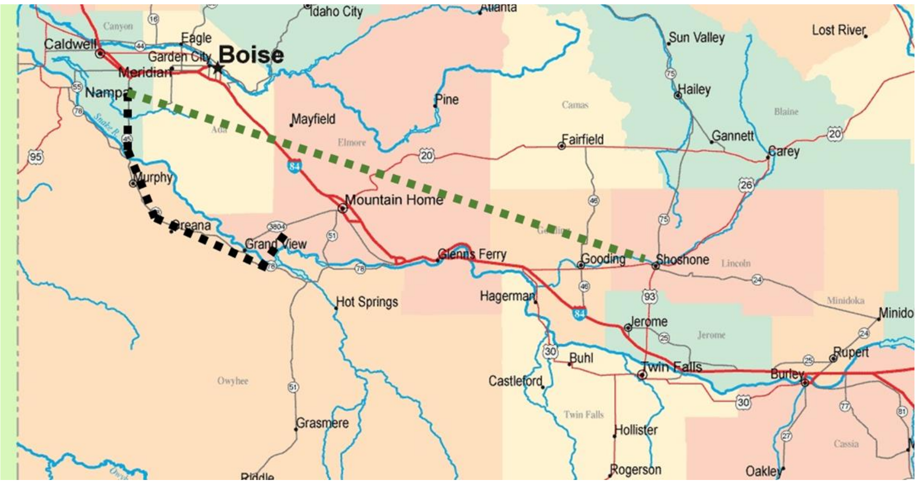

Figure 3-5: The Simplot Land and Livestock Multimodal Corridor Routes

3.3.3 The Kooskia-Port of Lewiston Railroad Corridor

This corridor is a waterway-railway multimodal route that starts at Kooskia and ends at the port in Lewiston. It carries agriculture products (grains, lumber, and livestock) from the North Central Idaho region to the port of Lewiston. This route consists primarily of 72 miles of the Bountiful Grain and Craig Mountain railway, a class III line. The route has several critical infrastructure elements including a railway bridge above the Clearwater River at Spalding, railway bridge above the Potlatch River, and a railway bridge above Clearwater River at Kamiah. The details of the route are shown in Figure 3-6.

Figure 3-6: The Kooskia-Port of Lewiston Railroad Corridor

3.4 Idaho’s Multimodal Freight Network

Figure 3-7 shows the state of Idaho’s multimodal freight network and facilities. It includes the major state highway links that carry most of the state’s freight traffic with their interconnecting nodes. It also shows the highway network intermodal connection nodes including both railway yards and the port of Lewiston. It should be noted that, in addition to the railway yards, several just-in-time delivery and mode exchange happen between truck freight and trains at different railway stations throughout the state. It should also be noted that several smaller waterway links such as lakes and rivers, are not included in this graph.

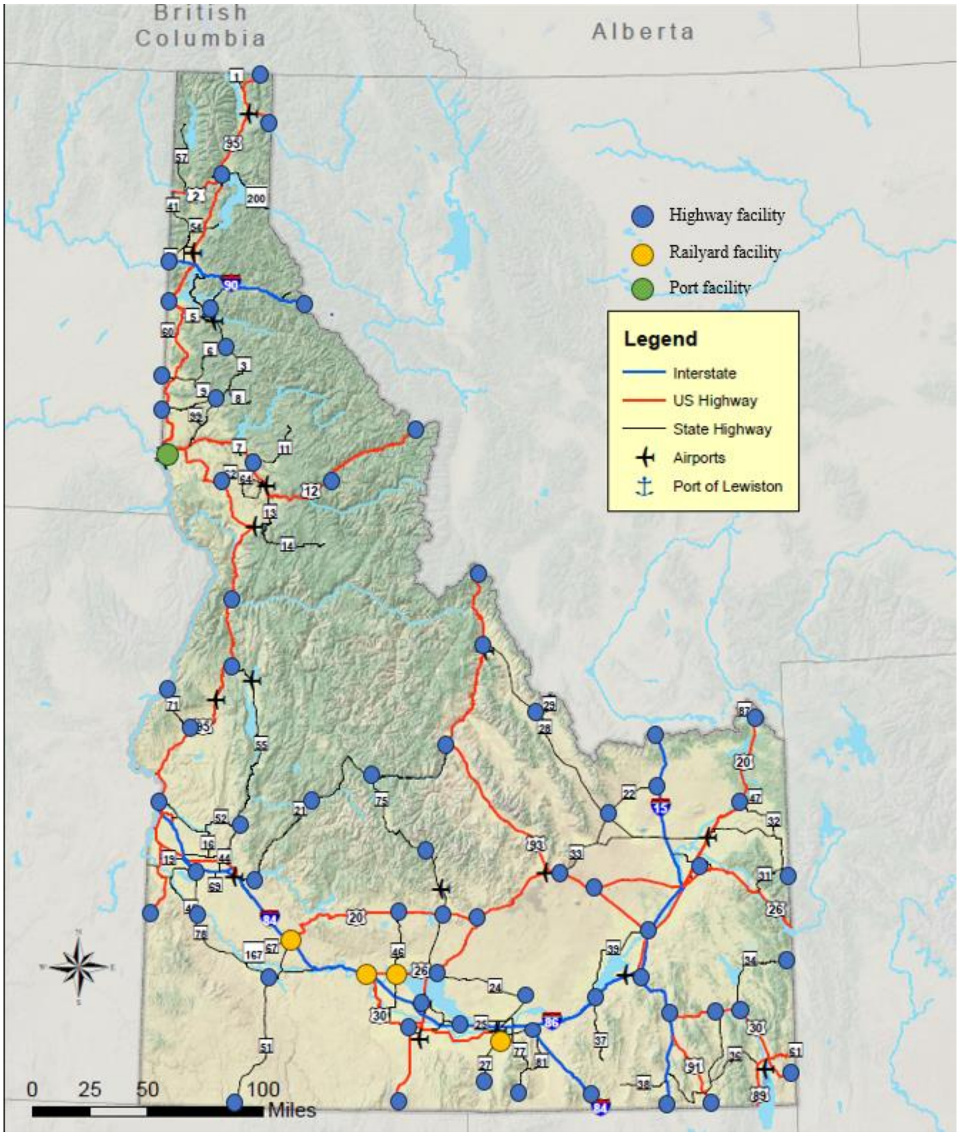

Figure 3-7: Idaho multimodal freight network.

Chapter 4: Study Methodology

4.1 Data Sources for Resilience Analysis

To assess the resilience of multimodal freight corridors, three data sources were used in this study. Each dataset represents a possible disruption to the network. The first dataset covers the structural health of different structural elements in the network, mainly bridges (both highway and railway bridges) and culverts. This structural health data comes from three different levels, the federal level (Federal Highway Administration (FHWA)), the state level (Idaho Transportation Department (ITD)), and the local level (Local Highway Technical Assistance Council (LHTAC)). The second data set is the historical crash data set for highways and railways focusing on crashes that involve trucks or trains that carry hazard materials. Such crashes can take an extended length of time to clean and could cause significant disruption to the freight network operations. Historical crash data are used to assess the probability of having such crashes on different parts of the multimodal network. The first two data sets are site specific and link specific. The third data set used in the analysis is the natural hazards risk index data. Unlike the first two data sets that are link specific, this data set is area specific at the county level. The following sections provide details about the three data sets used in the analysis.

4.2 Structural Health Monitoring Data

The resilience of the structures in any route or corridor is one of the most critical elements to maintain the operations. The structural health monitoring data available in different sources use structural load rating as the key indicator for the ability of the structure to carry and sustain the loads applied on it. The load rating data for different structures used in this study was provided primarily by ITD for structures located in the state highway system (Idaho Transportation Department, 2023C). Limited data were obtained from LHTAC for structures that are located in local roadway segments. The load rating data uses a score between 0 and 10. Higher scores indicate higher structure ability. Scores of 5 and less mean that the structure might be inadequate and needs to be further evaluated to avoid any structural failing that caused disruption to the network operations. An Example of the structural load rating data is shown in Table 4-1.

Table 4-1: An example of load rating data.

Segment mode and county			**Structures rating**			
			Bridge		**Culvert**	
Segment	Mode	County	Location	Load rating	Location	Load rating
1	Highway	Cassia	I-84/ Snake River, Overland BR	7	No culvert	N/A
2	Rail	Ada	Rail bridge at Indiana creek	No data found	No culvert	N/A

4.3 Historical Crash Data

Hazardous Materials (HAZMAT) and railway crashes can cause significant disruption to transportation networks. Cleaning after a HAZMAT crash is a complicated process that involves coordination among many agencies and could take days, weeks, and sometime months to offset the environmental hazard of the spilled HAZMAT. Similarly, railway crashes involve a significant structural investigation to ensure that the rails are structurally safe. This takes considerable time and might delay reopening the railway line. Historical crash data was used in this study to estimate the probability of such crashes happening on any roadway segment and use these probabilities to develop a major crash hazard index. The score is based on the number of crashes that occurred in the last 10 years at any segment. For this study, historical crash data was obtained from the ITD crash database and the FHWA Fatality Analysis Reporting System (FARS). (National Highway Traffic Safety Administration (NHTSA), 2023).

4.4 Natural Hazards Risk Assessment Data

Natural hazards are environmental factors that, if happened, can cause significant disruption to transportation network operations. The Federal Emergency Management Agency (FEMA) develops and maintains natural hazards risk indexes for different natural hazards scored by multiplying expected loss to community risk factor. This factor is estimated by dividing social vulnerability indicators by community resilience indicators. (Federal Emergency Management Agency (FEMA) National Risk Index for Natural Hazards, 2023). The FEMA risk index score is a five-level score ranging from “very low” to “very high”. It is an area-based index with the area unit being the county. The FEMA risk index covers a total of 18 natural hazards, however, indexes for five of these natural hazards (avalanche, coastal flooding, hurricane, tsunami, and volcanic activity) are not available for counties in Idaho. Figure 4-1 and Figure 4-2 show the FEMA natural hazards risk index for the U.S. and the risk index score range, respectively. The FEMA risk index parameters and how each factor of the risk index is calculated are listed in Table 4-2. An example of FEMA natural hazard data collected for one county in Idaho is shown in Table 4-3.

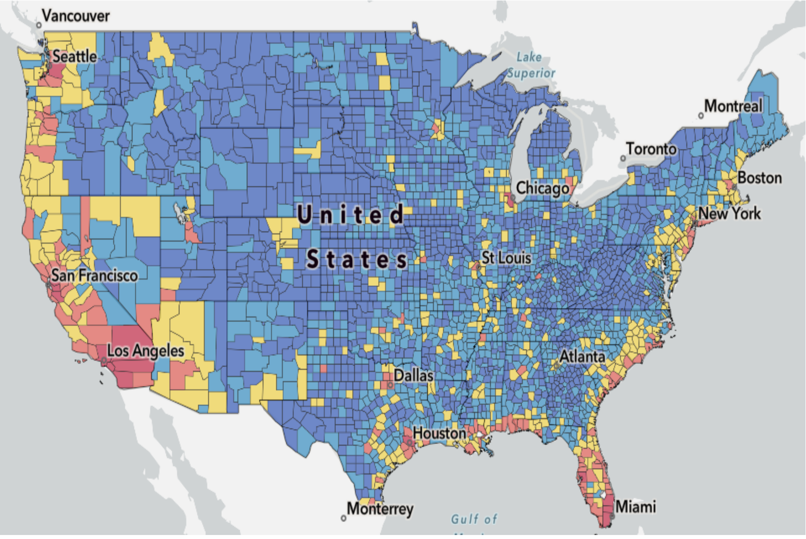

Figure 4-1: Natural Hazard Risk Index for Different Counties in the United State (FEMA, 2023)

National Risk Index
- 🟥 Very High
- 🟥 Relatively High
- 🟨 Relatively Moderate
- 🟦 Relatively Low
- 🟦 Very Low
- ⬜ No Rating
- ⬜ Not Applicable
- ⬛ Insufficient Data

Figure 4-2: FEMA Risk Index Score Range (FEMA, 2023)

Table 4-2: FEMA Risk Index Calculation ((FEMA, 2023)

Factor	Calculation	Description
Natural hazard risk index score	Expected annual loss × Social vulnerability / Community resilience	
Expected annual loss	Exposure value in Dollars × Annual frequency value or percent × Historical loss ratio	Historical loss ratio is the same as the levels used for score
Social vulnerability	Using the data table made by centers for disease control	The data table can be downloaded as an excel sheet
Community resilience	Calculated by using baseline resilience indicators developed by South Carolina hazard and vulnerability research institute	It's a census data, but there is no data download available

Table 4-3: An example of natural hazard data collected from FEMA.

County	#	Natural hazard	Risk index score	Expected annual event per year
Cassia	1	Cold Wave	Relatively high	0.3
	2	Drought	Relatively low	53.3
	3	Earthquake	Relatively low	0.1
	4	Hail	Very low	0.3
	5	Heat wave	Relatively low	0.3
	6	Ice storm	Very low	0.0
	7	Landslide	Relatively low	0.0
	8	Lightning	Relatively low	8.4
	9	Riverine flooding	Relatively low	0.8
	10	Strong wind	Relatively low	0.5
	11	Tornado	Very low	0.3
	12	Wildfire	Relatively moderate	1.2
	13	Winter weather	Relatively low	5.5

4.5 Integrated Multimodal Freight Corridor Resilience Analysis

In this study, an integrated framework was developed to model and assess the resilience of multimodal freight corridors. The proposed framework utilizes both link-based and area-based measures and indexes. The details of the proposed model are presented in Figure 4-3. The data sources for different indexes listed in the graph are coded in three colors: green for readily available and reliable data sources, yellow for data sources that are partially available, and red for data sources that are mostly not available.

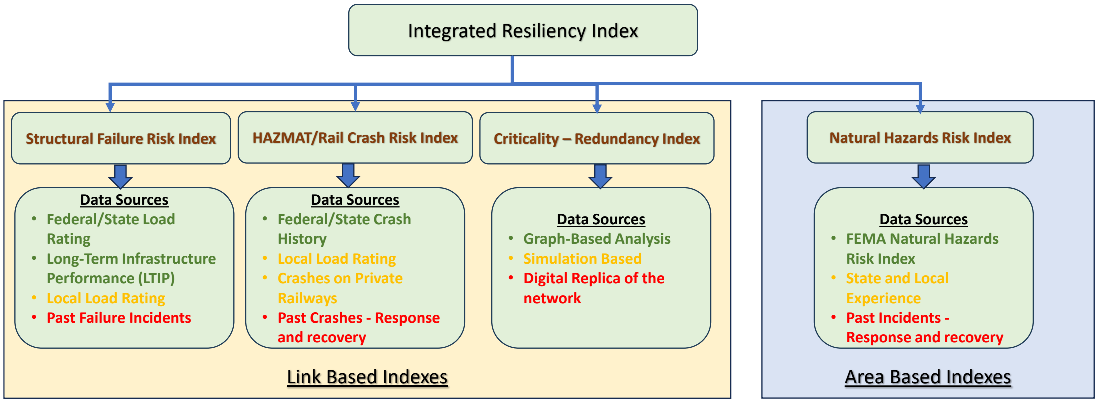

Figure 4-3 Integrated Framework for Multimodal Freight Corridors Resilience Analysis

4.6 Link-based Criticality- Redundancy Index – Graph-Based Analysis

The link-based graph analysis was used to assess the criticality and redundancy of different links on the network. The determination of connectivity index and redundancy indexes are based on graph topology and connectivity. The redundancy index is scored by analyzing the network graph and identifying if there is an alternative route that can carry the linked traffic in case the link had failure due to a disruption. If there is an alternative, the redundancy score is set to 1, and if not, it is set to 0. The connectivity index is determined based on graph theory analysis using different indexes that assess the graph connectivity. There are three different indexes that can be used: Iota index, Beta index, and Gamma index, their values depend on the number of network nodes (v) and links (e). (Abdel-Rahim, and Ismail, 2005)

1. Gamma Index: it is a graph index that measures the connectivity of the graph. It is defined as the relationship between the number of graph links and the number of possible nodes (Equation 1). The value of gamma is between 0 and 1.

$$\gamma = \frac{e}{3(v-2)} \qquad (1)$$

2. Beta Index: It a graph interconnectivity index that is estimated by dividing the number of links (e) by the number of nodes (v). Higher values of the Beta index suggest higher probability of alternative paths on the route.

$$\beta = \frac{e}{v} \qquad (2)$$

3. Iota Index: This graph index measures the ratio between the network length and its weighed nodes (vertices). It is determined by dividing the length of a graph (*L(G)*) by its vertices weight (*W(G)*). The weight of all nodes in the graph (*W(G)*) is estimated as the summation of each node's order (*o*) multiplied by 2 for all orders above 1. The order of the node (o) is the number of links that are connected to the node. The lower the value of the index the more efficient the network is from a connectivity point of view.

$$I = \frac{L(G)}{W(G)} \quad W(G) = 1, \forall\, o = 1 \quad W(G) = \sum_{e} 2 * o, \forall\, o > 1 \qquad (3)$$

The Iota Index is the equation used in this study to calculate the connectivity index for each link. This value is based on the percentage increase in the network Iota index after the removal of the link.

$$Connectivity\ Index\ for\ link\ i = \frac{I_{(n-i)} - I_{(n)}}{I_{(n)}} \qquad (4)$$

Where $I_{(n)}$ is the Iota index for the whole network graph and $I_{(n-i)}$ is the Iota index for the network graph after Link (*i*) is removed from the graph. The graph representations for the highway multimodal network and the railway network are presented in Figure 4-4 and Figure 4-5.

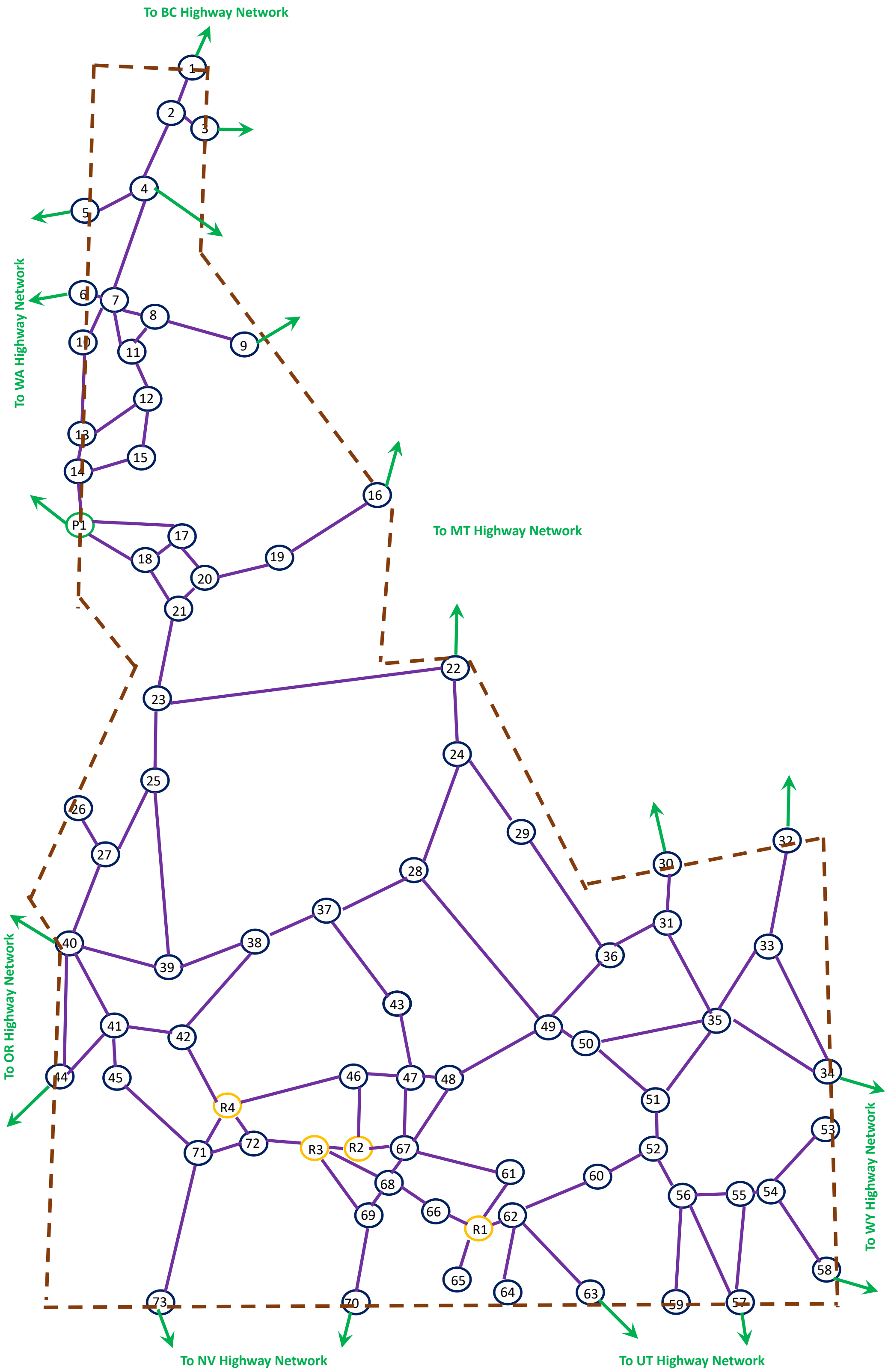

Figure 4-4 Idaho Freight Highway Multimodal Network – Graph Representation

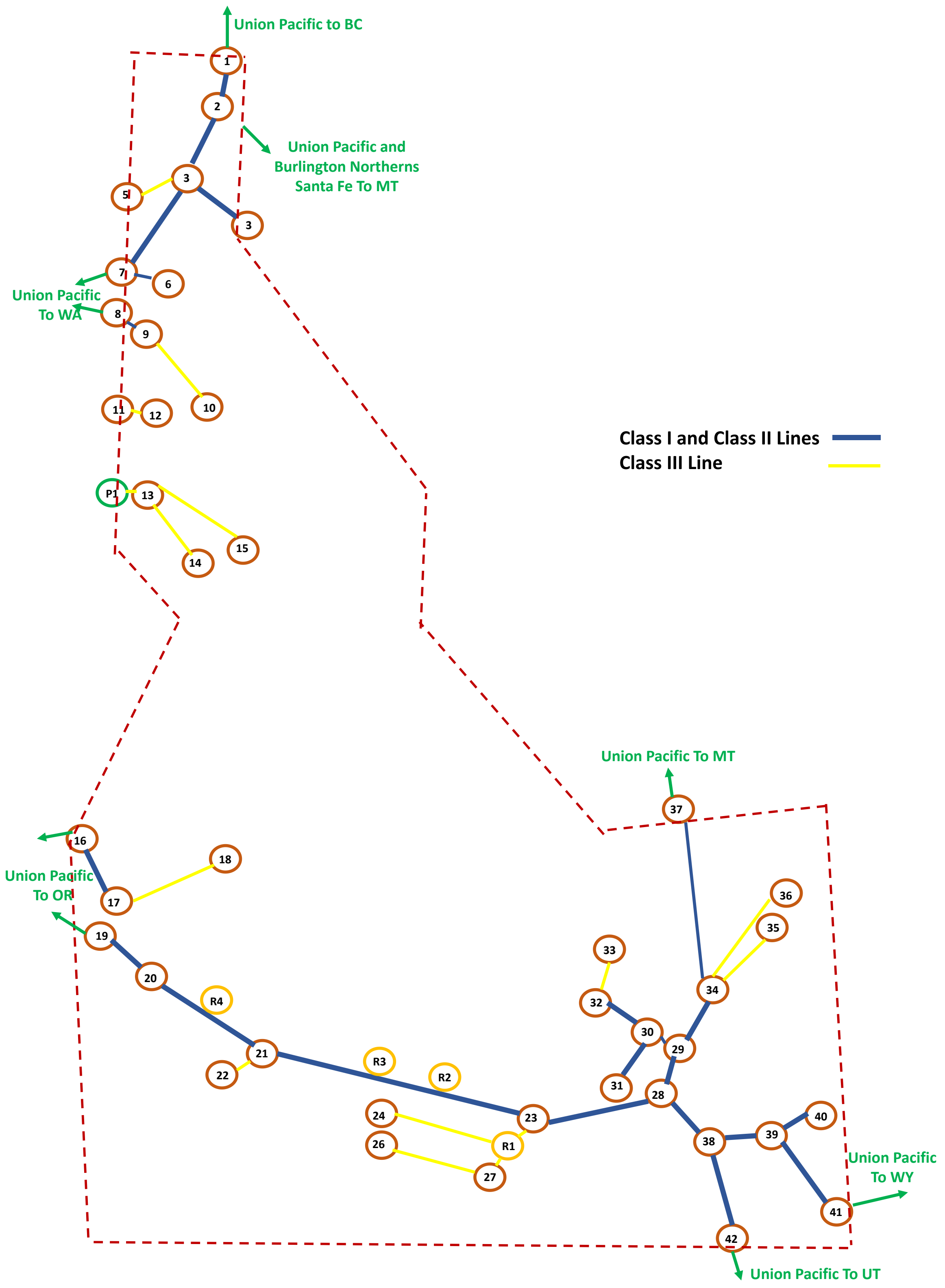

Figure 4-5 Idaho Freight Railway Multimodal Network – Graph Representation

Chapter 5: Data Analysis and Results

5.1 Data analysis

To demonstrate the applicability of the proposed integrated area-based and link-based framework to assess the resilience of multimodal freight corridors (presented in section 4.5), the framework was used to estimate the risk indexes for different disruptions for the three case studies included in this study. The results of these analyses are summarized and presented in the following sections.

5.1.1 The Gavilon Grain Multimodal Route

The Gavilon Grain multimodal route has 10 segments (5 highway segments and 5 railway segments) that go through 8 counties. Part of the highway segments of the route pass through 5 counties and the railway segments are in 5 counties (2 segments of the highways and 2 segments of the railways share the same two counties). The characteristics of different route segments are presented in Table 5-1. The link-based structural failure risk indexes, the HAZMAT and railway crashes risk indexes, and link criticality and redundancy indexes are presented in Table 5-2 and the area-based natural hazard risk index are presented in Table 5-3.

The results in the Tables provide system operators in different levels of the transportation sectors with the data needed to assess the risks to different components of the multimodal freight corridors. Some route segments with no redundant alternatives (for example 1, 4, 8 and 10) yet, have relatively moderate risk of natural hazards that can cause significant disruption to the corridor operations such as landslides, flash flooding and wildfires.) The results also highlight areas where additional data are critically needed to assess different risk factors for the corridors.

Table 5-1: The Gavilon Grain Multimodal Route Segments' Characteristics

Segment	Mode	Street/ Railroad	County	Structures	Distance
1	Highway	Gavilon grain to I-84	Cassia	1 bridge	1.4 mi
2	Highway	I-84	Minidoka	5 bridges /1 culvert	8.4 mi
3	Highway	I-84	Jerome	2 bridges	40.1 mi
4	Highway	I-84/I-46/US-26	Gooding	2 bridges/ 1 culvert	21.7 mi
5	Highway	US-26 to Union Pacific railroad in Shoshone	Lincoln	No structures	9.9 mi
6	Rail	Union Pacific line from Shoshone to Pocatello (1)	Lincoln	1 culvert	34.95 mi
7	Rail	Union Pacific line from Shoshone to Pocatello (2)	Minidoka	No structures	15.55 mi
8	Rail	Union Pacific line from Shoshone to Pocatello (3)	Blaine	No structures	15.6 mi
9	Rail	Union Pacific line from Shoshone to Pocatello (4)	Power	2 bridges /1 culvert	37.2 mi
10	Rail	Union Pacific line from Shoshone to Pocatello (5)	Bannock	2 bridges	4.7 mi

Table 5-2: The Gavilon Grain Multimodal Route Link-Based Risk Indexes

Segment	Mode	Structural Failure Risk Index[1]			Crash Risk Index[2]		Criticality Index[3]	Redundancy Index[4]
		# of structure	Data available	Average Index	HAZMAT	Railway		
1	Hwy	1	1/1	7	0		6.53	0
2	Hwy	6	3/6	6	2		6.53	0
3	Hwy	2	2/2	6.5	0		6.53	1
4	Hwy	3	2/3	6.5	1		6.53	0
5	Hwy	0	N/A	N/A	1		6.53	1
6	Rail	1	0/1	N/A		2	6.53	0
7	Rail	0	N/A	N/A		1	6.53	0
8	Rail	0	N/A	N/A		2	6.31	0
9	Rail	3	1/3	4		1	6.31	0
10	Rail	2	1/2	6		0	6.31	0

[1] based on load rating (1-10) higher numbers means more structural load carrying capacity
[2] based on actual number of crashes in the last 10 years
[3] based on graph-theory indexes (0 to 10) with higher value means higher network criticality
[4] based on network topography 0 = no redundant alternative and 1 = there is a redundant alternative

Table 5-3: The Gavilon Grain Multimodal Route Area-Based Natural Hazards Indexes

Seg	Mode	County	Natural Hazard Risk Index[1]												
			Cold wave	Drought	Earthquake	Hail	Heat wave	Ice storm	Landslide	Lightning	Riverine flooding	Strong wind	Tornado	Wildfire	Winter weather
1	Hwy	Cassia	**4**	**2**	**2**	**1**	**2**	**1**	**3**	**2**	**2**	**2**	**1**	**3**	**2**
2	Hwy	Minidoka	**4**	**2**	**2**	**1**	**2**	**1**	**2**	**2**	**1**	**2**	**1**	**1**	**3**
3	Hwy	Jerome	**4**	**2**	**1**	**1**	**2**	**2**	**2**	**1**	**1**	**1**	**1**	**2**	**3**
4	Hwy	Gooding	**4**	**2**	**1**	**1**	**2**	**2**	**3**	**1**	**1**	**1**	**1**	**3**	**2**
5	Hwy	Lincoln	**4**	**2**	**1**	**1**	**2**	**1**	**1**	**1**	**1**	**1**	**1**	**3**	**2**
6	Rail	Lincoln	**4**	**2**	**1**	**1**	**2**	**1**	**1**	**1**	**1**	**1**	**1**	**3**	**2**
7	Rail	Minidoka	**4**	**2**	**2**	**1**	**2**	**1**	**2**	**2**	**1**	**2**	**1**	**1**	**3**
8	Rail	Blaine	**4**	**1**	**2**	**1**	**1**	**1**	**3**	**2**	**3**	**1**	**1**	**3**	**4**
9	Rail	Power	**4**	**2**	**1**	**1**	**1**	**1**	**2**	**1**	**1**	**2**	**1**	**3**	**2**
10	Rail	Bannock	**4**	**1**	**2**	**2**		**1**	**2**	**2**	**3**	**2**	**1**	**3**	**3**

[1] (1=very low, 2=relatively low, 3=relatively moderate, 4=relatively high, and 5= very high).

5.1.2 The Simplot land and livestock Multimodal Freight Route

The Simplot land and livestock route has 8 segments in 5 counties. Table 5-4 lists the characteristics of the route segments. The link-based and areas-based risk indexes for the route segments are presented in Table 5-5 and Table 5-6, respectively. The results show high risk of wildfires for all segments in the corridor. They also show that landslides pose a very high risk for different critical segments in the corridor.

Table 5-4: The Simplot land and livestock Multimodal Freight Route Segment Characteristics

Segment	Mode	Street/ Railroad	County	Structures	Distance
1	Hwy	ID-167 to ID-78	Elmore	1 bridge	4.3 mi
2	Hwy	ID-78 to ID-45	Owyhee	1 culvert	40.4 mi
3	Hwy	I-45 to Union Pacific Line in Nampa	Canyon	1 rail bridge/ 1 bridge	18.8 mi
4	Rail	Union Pacific Line Nampa to Shoshone (1)	Canyon	3 bridges	4.5 mi
5	Rail	Union Pacific Line Nampa to Shoshone (2)	Ada	2 rail bridges	32 mi
6	Rail	Union Pacific Line Nampa to Shoshone (3)	Elmore	3 rail bridges/ 1 bridge	61.3 mi
7	Rail	Union Pacific Line Nampa to Shoshone (4)	Gooding	2 rail bridges	25.8 mi
8	Rail	Union Pacific Line Nampa to Shoshone (5)	Lincoln	No structure	11.4 mi

Table 5-5: The Simplot Land and Livestock Multimodal Route Link-Based Risk Indexes

Segment	Mode	Structural Failure Risk Index[1]			Crash Risk Index[2]		Criticality Index[3]	Redundancy Index[4]
		# of structure	Data available	Average Index	HAZMAT	Railway		
1	Hwy	1	1/1	6.0	1		7.94	1
2	Hwy	1	0/1	N/A	1		7.94	0
3	Hwy	2	1/2	6.0	2		7.63	1
4	Rail	3	3/3	7.3		0	7.63	0
5	Rail	2	0/2	N/A		1	7.94	0
6	Rail	4	2/4	6		0	7.94	0
7	Rail	2	0/2	N/A		2	7.35	0
8	Rail	0	N/A	N/A		2	7.35	0

Table 5-6: The Simplot Land and Livestock Multimodal Route Natural Hazards Risk Index

Seg	Mode	County	Natural Hazard Risk Index[1]												
			Cold wave	**Drought**	**Earthquake**	**Hail**	**Heat wave**	**Ice storm**	**Landslide**	**Lightning**	**Riverine flooding**	**Strong wind**	**Tornado**	**Wildfire**	**Winter weather**
1	Mode	County	**3**	**2**	**1**	**1**	**3**	**2**	**5**	**2**	**2**	**1**	**1**	**4**	**2**
2	Hwy	Elmore	**3**	**2**	**1**	**1**	**2**	**1**	**2**	**1**	**1**	**1**	**1**	**3**	**2**
3	Hwy	Owyhee	**3**	**2**	**2**	**2**	**4**	**3**	**2**	**4**	**2**	**2**	**1**	**3**	**4**
4	Hwy	Canyon	**3**	**2**	**2**	**2**	**4**	**3**	**2**	**4**	**2**	**2**	**1**	**3**	**4**
5	Rail	Canyon	**4**	**1**	**3**	**2**	**4**	**4**	**3**	**4**	**2**	**3**	**2**	**4**	**4**
6	Rail	Ada	**3**	**2**	**1**	**1**	**3**	**2**	**5**	**2**	**2**	**1**	**1**	**4**	**2**
7	Rail	Elmore	**4**	**2**	**1**	**1**	**2**	**2**	**2**	**1**	**1**	**1**	**1**	**3**	**2**
8	Rail	Gooding	**4**	**2**	**1**	**1**	**2**	**1**	**1**	**1**	**1**	**1**	**1**	**3**	**2**

[1] (1=very low, 2=relatively low, 3=relatively moderate, 4=relatively high, and 5= very high).

5.1.3 The Kooskia-Port of Lewiston Railroad Corridor

This corridor is a waterway-railway multimodal route that starts at Kooskia and ends at the port in Lewiston. The corridor has only railway segments to the port with no highway elements in the corridor. Table 5-7 lists the characteristics of the route segments. The link-based and areas-based risk indexes for the route segments are presented in Table 5-8 and Table 5-9, respectively. The results show that this corridor is at very high risk with three natural hazards that could cause significant disruption to the corridor operations, namely wildfires, landslides, and floods. The corridor experienced several accidents in the past 10 years, which is a relatively higher rate considering the limited operations on the railway line. Another important issue the results highlight is the need for up-to-date structural health data for different structures in the corridor.

Table 5-7: The Kooskia-Port of Lewiston Railroad Corridor Segments' Characteristics

Segment	Mode	Street/ Railroad	County	Structures	Distance
1	Rail	the Bountiful Grain and Craig Mountain railroad Line from Lewiston to Kooskia Lewiston (1)	Nez Perce	2 rail bridges/ 2 bridges	29.9 mi
2	Rail	the Bountiful Grain and Craig Mountain railroad Line from Lewiston to Kooskia Lewiston (2)	Lewis	2 rail bridges	33.5 mi
3	Rail	the Bountiful Grain and Craig Mountain railroad Line from Lewiston to Kooskia Lewiston (3)	Idaho	No structures	8.6 mi

Table 5-8: The Kooskia-Port of Lewiston Railroad Corridor Link-Based Risk Indexes

Segment	Mode	Structural Failure Risk Index[1]			Crash Risk Index[2]		Criticality Index[3]	Redundancy Index[4]
		# of structure	Data available	Average Index	HAZMAT	Railway		
1	Rail	4	2/4	6.0	🟩	1	🟩	0
2	Rail	2	0/2	N/A	🟩	2	🟩	0
3	Rail	0	N/A	N/A	🟩	0	🟩	0

Table 5-9 The Kooskia-Port of Lewiston Railroad Corridor Natural Hazards Risk Index

Seg	Mode	County	Natural Hazard Risk Index[1]												
			Cold wave	**Drought**	**Earthquake**	**Hail**	**Heat wave**	**Ice storm**	**Landslide**	**Lightning**	**Riverine flooding**	**Strong wind**	**Tornado**	**Wildfire**	**Winter weather**
1	Rail	Nez Perce	**1**	**1**	**1**	**1**	**3**	**1**	**3**	**1**	**1**	**1**	**1**	**3**	**2**
2	Rail	Lewis	**1**	**1**	**1**	**1**	**2**	**1**	**3**	**1**	**3**	**1**	**1**	**3**	**1**
3	Rail	Idaho	**1**	**1**	**1**	**1**	**2**	**1**	**5**	**1**	**3**	**1**	**1**	**4**	**2**

[1] (1=very low, 2=relatively low, 3=relatively moderate, 4=relatively high, and 5= very high).

Chapter 6: Conclusions

Freight corridors are essential and critical parts of the supply chain that supports local, regional, and national economy. Multimodal rural freight corridors consist of an interconnected network of local roads, freeways, railways, inland waterways, airports, and ports. Resilience analysis for multimodal freight corridors involves assessing the ability of freight networks to sustain and robustly recover from disruptions such as natural disasters, accidents, or system failures. Such resiliency analysis should consider factors such as the risk of different disruptions, infrastructure health and robustness, and the redundancy of different network components.

The primary focus of the research presented in this thesis is the resiliency of rural multimodal freight corridors that serve rural industries such as agriculture, livestock, manufacturing, and mining. The research was conducted through several major tasks. First, a comprehensive literature review was conducted to synthesize the results of previous research focusing on the resiliency of multimodal freight network under the effect of man-made and natural disasters. Second, the data available at levels was reviewed to identify and document the availability of data needed to model the resiliency of multimodal fright corridors as well as to highlight gaps that exist in this data. The third part of this research involved the development of an integrated area-based and link-based framework to model the resiliency of multimodal rural freight corridors and conducting resiliency analysis for several modal fright corridors case studies in the state of Idaho to test and implement the proposed integrated framework. The results of this research can help transportation agencies identify and quantify vulnerabilities and risks and develop strategies to enhance the overall resilience of freight corridors, ensuring the smooth and efficient flow of goods even in challenging circumstances. The research outcome also helps agencies prioritize investment and resource allocation to maximize the resiliency of the multimodal rural freight network which will contribute to the overall objective of a resilient and robust supply chain for the state, the region, and the nation.

The synthesis of previous research in freight multimodal residency covered several areas: definitions of resiliency, resilience assessment and measurements, resilience indexes, and data used in previous freight resilience research. The resiliency of freight network has been defined as the capacity of the network to retrain its function and robustly recover after a disruption. The freight network resilience is impacted by several network attributes: strength and robustness, redundancies availability, ability to identify problems, and the ability to effectively identify priorities and implement recovery plan in a timely manner. Although there is extensive research that has been carried out on freight network resiliency, only a few studies have established integrated and comprehensive quantitative methods to assess resiliency indicators. Redundancy and link criticality indexes are among those factors and are measured based on network topology and graph-theory based measures. These measures are used in the integrated framework proposed in this study.

Several disruptions were considered in this study including disruptions due to structural failure of one or more network elements, disruptions due major crashes such as HAZMAT crashes on highway or railways, and disruptions due to natural hazards such as landslides, floods, and wildfires. While cyberattacks, such as ransomware attacks, can target ports and railway operations and cause considerable disruptions, they were not included in this research for two reasons. First, they have little or no impact on the operations of the highway network, the backbone of the multimodal rural freight network. Second, they are mode specific rather than area or link specific which are the focus of this research. Based on this research review of data available for rural multimodal freight corridor analysis, the following observations can be made:

- While structural health data for bridges and culverts on the state highways are available and can easily be accessed, such data are either not available or difficult to access for all structures on the local highway system and for structures on railway lines. This causes a significant gap in the data needed to assess the structural failure risk indicators for major elements of the rural multimodal freight corridors,
- Crash data for major crashes on the highway system are available and accessible from different sources. However, crashes and incidents on private railway lines are not publicly available,
- Data for the risk indexes of different natural hazards is publicly available from federal sources at the county level. Few data are available in the more disaggregated route specific levels,
- Data on past disruption incidents to document details of the disruption, the response plan, and the recovery plans are either not available or hard to access. This data is very valuable to document lessons learned from each disruption incident and to enhance coordination and communication among stakeholders to facilitate effective and prompt response and recovery efforts to future disruptions,
- There is a need for implementing advanced data collection and monitoring technologies for real-time tracking for different resiliency-related data (traffic flow, structural health, natural weather indicators, etc.) to allow for real-time and adaptive risk management, and
- Real-time data could also be integrated into digital replica of the freight corridors (using macroscopic and/or mesoscopic simulation) to allow agencies establish and test robust

contingency plans and use digital replica simulations to test preparedness and response capabilities.

The integrated link-based and area-based framework introduced in this research can be used to estimate structural failure risk indexes and HAZMAT/railway crash risk indexes for different links on the rural multimodal freight corridor networks. Additionally, at the link-based level, the redundancy and criticality index for each lick can be estimated. Area-based natural hazards data can be used to estimate the natural hazards risks indexes that are associated with each link in the network. The outcome of this integrated framework can assist transportation agencies in the following tasks:

- Developing comprehensive risk management strategies that account for a wide range of potential disruptions and emergencies,
- Use outcome the criticality and redundancy indexes for different network links to create redundancy and alternative options for freight movement, and
- Establishing robust contingency plans and implementing data-driven decision-making processes to predict the likelihood of different disruptions and optimize response and recovery plans and operations.

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