Impact of Multimodal Freight Network on Private Sector Global Distribution

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16. Abstract
The objective of this research is to develop network models to quantify the impact of multimodal freight network components on private-sector operational efficiencies. For this purpose, during the first phase of this project, a mathematical programming formulation has been developed that considers the multimodal transportation network as a multi-layer, multi-commodity network in which decisions are made about flows (i.e., selection of transportation modes and routing for shipments in the network) that minimize total operational costs. The model also incorporates the capability of evaluating resilience metrics associated with topological characteristics of the multimodal freight transportation network such as network complexity, as well as service-related metrics like unmet demand. To implement and test the proposed formulation a test case scenario for the Pacific Northwest has been developed, however challenges with data acquisition have delayed the testing of the formulation and the development of insights that will inform the tasks defined for the second phase of this project. The second phase of this project will focus on the testing of the proposed model and the use of the insights from the analysis of the test case instance to inform the development of a mathematical model for the allocation of limited resources to improve the overall performance of the multimodal freight transportation network.

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Executive Summary

This project focuses on the effective modeling of multimodal freight transportation networks as a critical element for enhancing the efficiency and performance of distribution systems using this mode of transport for the dispatching of shipments from their points of origin to their destinations. One of the key challenges is analyzing how characteristics of the multimodal freight transportation network such as its network complexity, density and centrality impact the performance of operational activities like travel times, delays, and unmet demand in the distribution system. The aim is to provide a better understanding of the dependencies and interdependencies within the multimodal freight transportation system and the distribution systems.

Our main objective is to develop models to represent the interdependent multimodal freight transportation network to quantify the impact of the network components on private sector efficiencies, particularly in terms of operational costs. Additionally, we aim to implement the proposed optimization model using test data for the Pacific Northwest to identify key network components that influence performance metrics such as the total operational cost associated with the flows in the network.

To achieve this goal, we completed a literature review that includes recent contributions on multimodal freight transportation network modeling, multimodal freight transportation disruption modeling, and a summary about resilience concepts and metrics. From the literature review, there is evidence that multimodal transportation networks can effectively be modeled using network models and mathematical programming approaches. This report includes a summary of recent efforts in which mixed-integer programming formulations have been developed to support decision making in multimodal freight transportation networks. Other studies have focused on modeling disruptive scenarios and evaluating the resulting performance of the system. In this context, resilience metrics for both topological characteristics of the transportation networks and service level performance measures have been proposed and are summarized in the Literature Review section of this report.

To address the research objective of this project, we use a mathematical programming approach to model a multi-layer, multi-commodity network for multimodal freight transportation. The proposed formulation considers each mode of transportation as a layer in the multimodal network and establishes the interdependence between the different modes via potential transshipments at multimodal terminal nodes in the multi-layer network. The formulation determines the optimal dispatching of flows that minimizes operational (i.e., flow related) costs while satisfying a minimum desired percentage of demand in the system. At the same time, this formulation allows for the evaluation of resilience metrics for the multimodal freight transportation systems, such as the network complexity (i.e., the total number of network elements) and unmet demand (i.e., the percentage of demand that is not delivered across demand nodes in the network).

We have defined a test case for experimentation with the proposed model formulation of the interdependent multimodal freight transportation network. For the test case, we consider that the

Pacific Northwest includes the states of Washington, Oregon and Idaho. The size of the region and its geographic characteristics represent an appropriate scenario for the use of multimodal freight transportation as an alternative to shipments using a single transportation mode. The transportation modes that are included for the test case scenario include: road (trucking), rail, waterways, and air.

However, a significant challenge for the implementation of the proposed mathematical programming formulation is the availability of data. Facility location data is generally available from open sources, but proprietary data such as cost information for different transportation modes or shipment flow information is more difficult to collect. In this context, Robinsight's telematics data for road transportation can provide a good source of flow data for movements within the road transportation layer. Unfortunately, we experienced delays during this phase of the project in procuring the data that could be used to complete the implementation of the test case scenario for the Pacific Northwest and experiment with the proposed formulation. We will continue to address the unfinished research tasks of this phase of the project during the second year of this effort.

Still, although there is more work to be done to complete the tasks identified for the current phase of this project, we have also identified additional tasks that will be implemented during the second phase to quantify the impact of multimodal network components on the performance of distribution systems. The second phase of this project will focus on the development and testing of a mathematical model to evaluate the impact of potential investments in the multimodal network for improving the performance and resilience of distribution systems. As the efficiency of distribution systems depends on the inherent resilience and efficiency of the multimodal network, it is important to develop tools for supporting decision making when allocating limited resources for multimodal freight transportation network improvements that could be planned by service providers (e.g., carriers, terminal operators, etc.). At the end of this report, we summarize specific items that will be pursued during the second phase of the project to address this challenge.

Problem Description

The effective modeling of multimodal freight transportation facilities is critical for enhancing the efficiency and performance of distribution systems. A key challenge lies in understanding how network characteristics, such as centrality, density, and complexity, impact operational activities, including travel times, delays, and unmet demand. Additionally, the interdependencies between the transportation and distribution systems are not well understood, which creates difficulties in accurately predicting and optimizing network performance.

One of the main barriers to progress in this area is the absence of comprehensive data and the lack of advanced analysis methods to evaluate these relationships. Despite the availability of some data sources, such as Robinsight's telematics data and public-use carload waybill samples, there remains a significant gap in the ability to model and quantify the impact of multimodal network components on operational activities.

Thus, the objective of this research is to develop network models that quantify the impact of multimodal freight network components on private-sector operational efficiencies, particularly in terms of operational costs. By implementing a network model with available test data, the goal is to identify key network components that affect performance metrics like travel times, delays (due to congestion or queues), and operational costs. This will enable better decision-making and strategies to enhance the performance of distribution systems in multimodal transportation networks.

Literature Review

In today's world of growing global freight needs and intricate supply chains, it has become crucial to analyze and understand the interdependencies between various modes of transportation and their impact across supply chains. Specifically, we need to understand the impact of the structure of multimodal freight networks on private sector global distribution. This involves analyzing how network characteristics such as centrality, density, and complexity affect the performance of operational activities, including travel times, delays, and unmet demand. The main objective of this research project is to develop network models via mathematical programming to quantify the impact of multimodal network components on private sector efficiencies in terms of relevant metric such as operational costs. Additionally, there is a need to provide a better understanding of the interdependencies between multimodal freight transportation and distribution networks and to consider resilience metrics, which are key to addressing this issue.

This literature review includes recent contributions on multimodal freight transportation network modeling, multimodal freight transportation disruption modeling, and a summary about resilience concepts and metrics in this context.

Multimodal Freight Transportation Network Modeling

Multimodal transportation network modeling has garnered significant attention in recent years due to the growing need to optimize complex transportation systems that allow for transshipments across multiple transportation modes such as road, rail, air, sea, waterways, and others (e.g., pipelines). Multimodal freight transportation integrates various transportation modes into a cohesive framework to enhance the efficiency, reliability, and sustainability of freight movement. Several studies have focused on modeling these networks to improve performance metrics such as travel times, operational costs, and service reliability. We summarize some of these contributions below and highlight the methodologies used for this purpose.

Recently, Nayak et al. (2024) investigated the improvement of tactical and operational planning decision making in multimodal freight transportation networks by developing a model for a Multi-Echelon Multimodal Transportation (MMT) network. Their approach integrated shallow-draft inland waterways (IWT) with roadways and railways by developing a Mixed-Integer Non-Linear Programming (MINLP) model. Their modeling considered financial incentives, vehicle types, barge capacities, and maintenance logistics for shallow-draft waterways. They concluded that incorporating IWT into a multimodal network with roads and railways led to significant cost savings and societal benefits, such as reduced congestion and environmental impact.

In another study, Li et al. (2023) designed a multimodal hub-and-spoke transportation network for emergency relief during the COVID-19 pandemic. They also proposed a Mixed-Integer Nonlinear Programming (MINLP) model to optimize transportation efficiency and cost-effectiveness in the delivery of emergency relief to zones affected by the pandemic from surrounding areas. This model included multiple types of emergency relief commodities and various transportation modes which are crucial for timely and efficient disaster response.

Another recent example in this area is presented by Yin et al. (2023) who optimized a multimodal freight transportation network for regional hub seaports in China, enhancing transportation efficiency between seaports and inland cities. They used a gravity model to assess city correlations and an entropy weight TOPSIS model to select transshipment cities. The goal of their approach was to minimize total transportation costs under space-time constraints. Their test case demonstrated that the model is able to select a subset of cities as freight consolidation centers, with several other cities designated as transshipment nodes, fostering regional integration and efficiency.

Multimodal Freight Transportation Disruption Modeling

In transportation planning, it is crucial to consider the interdependencies between the road network and multimodal terminals for the efficient delivery of goods. In this regard, Zukhruf et al. (2022) investigated the restoration of multimodal transportation networks disrupted by catastrophic disasters such as an earthquake and tsunami for the delivery of relief goods. They developed an optimization model that integrates decisions about road restoration activities considering the interdependencies between the road network and multimodal terminals using a dynamic programming approach. They also developed a greedy heuristic to improve the computational efficiency and stability of the solution. From their experimentation, they demonstrated that their model's optimal solution significantly reduced unsatisfied demand for relief goods.

Azucena et al. (2021) studied the impact of extreme natural events on the U.S. inland waterways and their effect on the interconnected multimodal transportation system. Their main goal was to develop a predictive model and a simulation tool to evaluate and manage the disruptions caused by such events and scenarios. Their simulation tool allows for quick evaluation of the performance of Interdependent Critical Infrastructures (ICIs) under extreme natural event scenarios where it also assists in decision-making by providing a flexible means to simulate operations and understand interdependencies within the multimodal transportation network.

In another study, He et al. (2021) addressed the challenge of evaluating the robustness of multimodal freight transportation networks by developing a better understanding of how the interconnection and interdependency of transportation network nodes (e.g., junctions, terminals, and crossings) and links (pathways) affect the overall robustness of the network, especially when faced with disruptions. They utilized a multi-layer network model where nodes represent junctions, terminal and crossings, while links represent pathways, to capture the features of interconnection and interdependency among different transport modes (e.g., inland waterway, road, and railway). They also evaluated robustness based on the increase in total travel time caused by disruptions at different elements in the network. Their analysis found that the criticality of nodes follows a power-law distribution, indicating a scale-free property for the networks. This implies that the network is relatively robust against random single disruptions. Also, the most critical nodes can be identified by their topological properties, which helps in prioritizing maintenance efforts. For the disruptions, a single interdependent node (e.g., bridge, tunnel, railway crossing) affects multiple modalities, highlighting the importance of these nodes in maintaining network robustness. Thus, their assessment shows that certain nodes have a higher impact on the total travel time when disrupted, which can guide maintenance scheduling and priority setting. All in all, their network shows robustness against random single disruptions due to its scale-free nature, however, identifying and protecting critical nodes is essential to maintain this robustness.

Transportation Resilience Concepts and Metrics

As for transportation system resilience concepts and measures, Hosseini et al. (2016) completed an extensive literature review of definitions and measures of system resilience emphasizing some qualitative and quantitative approaches to provide a better understanding of the system resiliency concept. They define *resilience* as the inherent ability to keep or recover the steady state of a system. Resilience is also defined as the capability to predict risk, restrict adverse consequences, and return rapidly through survival, adaptability, and growth in the face of turbulent changes. From the economic perspective, it could be explained as the inherent ability and adaptive response that enables firms and regions to avoid maximum potential losses. However, from the engineering perspective, it could be defined as the intrinsic ability of a system to adjust its functionality in the presence of a disturbance and unpredicted changes. They also introduced a couple of general measures for resiliency by comparing the performance of the system before and after a disruption without concentrating on system-specific characteristics and some other deterministic approaches. They evaluated *robustness,* that is the strength of a system or its ability to prevent damage propagation through the system in the presence of a disruptive event. And, they also included *rapidity,* that is the speed or rate at which a system could return to its original state or at least to an acceptable level of functionality after the occurrence of a disruption.

Misra & Padgett (2022) were more concerned about quantifying resiliency of rail-truck intermodal freight transportation networks when subjected to regional disruptions, such as natural hazards using some key metrics such as network functionality to measure the ability of highway and railway networks, along with intermodal terminals, to perform their intended functions post-disruption. Another metric presented is network throughput to quantify the volume of freight the network can handle during the recovery period followed by restoration assessment procedures to model the recovery process, estimating how functionality is restored over time based on the severity of damage and the effectiveness of response efforts. Lastly, their findings suggest that enhancing the resilience of intermodal terminals and ensuring robust connections between highway and railway networks can significantly improve overall network resilience.

More recently, Trucco & Petrenj (2023) introduced some key metrics to measure resilience of a system including robustness which in this case is defined as the ability of a system to withstand disruptions without significant performance degradation. Metrics include the percentage of operational capacity retained after a disruption and the maximum load a system can handle before failing. Redundancy considers the presence of backup components or pathways that can take over in case of failure and it can be measured by the number of alternative routes in transportation networks. Another measure presented in this paper is resourcefulness, which is defined as the ability of a system to mobilize resources quickly in response to disruption and can be assessed by the time taken to allocate resources, the efficiency of resource distribution, and the flexibility in resource usage. Another two key metrics were found to be crucial in their study including rapidity which is the speed at which a system can recover from a disruption including the recovery time to full operational capacity, the rate of system performance improvement post-disruption, the duration of service outages, and lastly, adaptability which is the ability of a system to adapt to changing conditions and learn from past disruptions and can be measured by the frequency of system upgrades, the implementation of lessons learned from previous disruptions, and the adaptability of infrastructure to new threats.

Finally, to emphasize the importance of flexibility in enhancing system resiliency, Garrido et al. (2023) determined that the implementation of alternative transportation modes can significantly reduce transportation costs which is a key insight to enhance resiliency across systems highlighting the cost-effectiveness of multimodal transportation systems.

Approach

The specific tasks that were identified to address the stated research problem of this project are described in the subsections below.

Task 1. Perform a literature review of multimodal transportation network modeling

First, a review of the existing literature on multimodal transportation network modeling and the interdependencies between multimodal transportation networks and distribution networks will be completed. The review will focus on efforts that incorporate several network elements of multimodal transportation systems and analyze how network characteristics (e.g., centrality, density, complexity, etc.) impact the performance of operational activities (e.g., travel times, delays, unmet demand, etc.) of distribution systems. It will be important to understand how dependencies and interdependencies between the transportation and the distribution system have been modeled and what challenges need to be addressed to improve on the existing models. For completeness, the review will include journal papers, conference papers and project reports.

In addition, the literature review will also cover potential data sources for multimodal freight transportation flow information. Sources such as the Freight Analysis Framework (FAF), EROAD/Robinsight freight telematics data for trucking, and public use carload waybill sample data for rail will be explored that could be used to inform the development of a network flow model of multimodal transportation and to generate test cases for the validation and testing of the developed model.

Task 2. Develop network model for multimodal transportation

The research team will develop a network flow model of a multimodal freight transportation system that incorporates network components (e.g., facilities, multimodal terminals, roads, rail segments, etc.), their placement, and their relationships. This task will include the modeling of dependencies and interdependencies between the multimodal freight transportation network and distribution networks. Existing mixed integer liner programming formulations for multimodal transportation network design can be extended to incorporate the relationships with distribution systems and evaluate relevant metrics associated with system performance such as total travel times, expected cost, expected unmet demand, and others. The modeling will incorporate the ability to evaluate uncertain scenarios due to demand and supply variability and potential disruptions in the multimodal transportation network.

Task 3. Implement and test network model for multimodal transportation

The network model developed in Task 2 will be implemented and tested as part of Task 3. The model will be validated and tested using a test case focused on the Pacific Northwest to identify network components that affect distribution system performance metrics such as travel times, delays, unmet demand, and operational cost. The research team will perform additional numerical experiments for different scenarios to complete a thorough sensitivity analysis of the developed model and obtain relevant insights about the impact of the multimodal freight transportation network on the performance of distribution systems in the region.

Task 4. Explore valid approaches for deriving shipper behavior

Shipper behavior is an important element that contributes to the final selection of routes and modes of transportation depending on relevant criteria. The research team will explore valid approaches to elicit shipper behavior for incorporation in the network flow model as a subsequent task in the next phase of this project. It is envisioned that the next phase of this research will focus on the development of optimization models that can support decision making as investments are made to improve the performance of the interdependent multimodal transportation and distribution systems.

Task 5. Summarize research findings and develop final deliverables

The research findings from the prior tasks will be thoroughly documented in a final report that will include a description of the methodologies used, the findings from the testing and experimentation with the network model, and the implications for decision makers. As part of the final documentation, the research team will summarize the research paths forward for the subsequent phase of this project and which external funds would be pursued to extend the research.

In addition to the final report, and to disseminate the research findings, a journal paper will be drafted and submitted for review, and one or more conference presentations will be pursued in venues like the Annual Conference of the Institute of Industrial and Systems Engineers (IISE) or the Annual Meeting of the Institute for Operations Research and Management Sciences (INFORMS). Both conferences have tracks (Logistics and Supply Chain (LSC) and Transportation Science and Logistics (TSL), respectively) that are focused on transportation modeling and planning that would be appropriate for sharing the research findings with other academics and practitioners.

Methodology

As described in the literature review, multimodal freight transportation networks have been modeled using mathematical programming and network flow models. For this study, the functional relationships between components of interdependent multimodal freight transportation networks are modeled using a network-based approach where nodes correspond to the physical facilities with supply, demand, and transshipment roles. The network elements of each transportation mode network are included in a single layer of a multi-layer network that allows for transshipment between the different transportation modes through links that connect multimodal facilities (e.g., terminals, ports, etc.). The movement of commodities across network nodes occurs through directed links within each sub-network.

The interdependency between transportation modes is defined as a bidirectional relationship between two modes in which the state of the network elements of each transportation mode affects the state of the other. The network perspective is often utilized to present the relationships between components of the networks. In this way, the nodes may function as generation (supply), consumption (demand), or relay (transshipment) points with the links representing the relationships between them. For example, interdependent links represent the transshipment of a commodity from the road network to the rail network or vice versa.

Network Modeling for Multimodal Freight Transportation

Interdependent multimodal transportation networks can be generalized as single unimodal transportation networks that are coupled together. Due to the different roles (e.g., supply, transshipment, and demand) that nodes perform in a single transportation mode network, the functional relationships within each transportation mode network are still analogous to those observed in any logistic networks with supply and demand links. Several graph algorithms have been extensively studied in the analysis of logistics or transportation networks. In general, well-established graph models have been used to describe the random, small-world, and scale-free networks that are representative of real-world infrastructures, e.g., transportation. These network models allow graphs to be generated with controlled topologies and characterized through graph metrics such as average degree distribution, average clustering coefficient, and average path length and other network metrics.

On the other hand, service-based performance assessment requires analysis of network flow in directed graphs since undirected graphs cannot capture the interdependencies between the different networks. Our approach implements a mathematical programming approach to model interdependent freight transportation networks in a multi-layer network in which network flow across different node types is possible within each individual mode network and across transportation modes at transshipment nodes. The proposed formulation supports making decisions about flows to minimize the total cost of transportation across the multimodal freight transportation network while satisfying a minimum required percentage of the demand (i.e., minimizing unmet demand). In addition, the mathematical programming formulation can be adapted to also evaluate topological resilience metrics such as network complexity.

Mathematical Programming Formulation

This section presents a mathematical programming formulation for the interdependent multimodal freight transportation network when it is modeled as a multi-layer network of individual transportation modes that are connected at transshipment terminals. This formulation is an adaptation of the model from Tiong & Vergara (2023) for resilient interdependent critical infrastructures. Table 1 shows the notation for sets and parameters used for the model. The notation for decision variables is shown in Table 2. The decision variables are associated with the use of network elements, the allocation of flows in the interdependent multimodal freight transportation network, the unused supply, and the unmet demand.

Table 1: Sets and parameters for the mathematical model of interdependent multimodal transportation networks.

Sets	
K	Set of interdependent freight transportation networks k
R	Set of commodities r in interdependent freight transportation networks
R^k	Set of commodities r in freight transportation network $k \in K,\ R^k \subseteq R$
$\bar{R}^k$	Set of commodities r not originating from freight transportation network $k \in K,\ \bar{R}^k \subseteq R^k$
N^k	Set of nodes i in freight transportation network $k \in K$
N_s^{rk}	Set of supply nodes for commodity $r \in R^k$ in network $k \in K,\ N_s^{rk} \subseteq N^k$
N_t^{rk}	Set of demand nodes for commodity $r \in R^k$ in network $k \in K,\ N_t^{rk} \subseteq N^k$
N_o^{rk}	Set of transshipment nodes for commodity $r \in R^k$ in network $k \in K,\ N_o^{rk} \subseteq N^k$
A^k	Set of links (i,j) between nodes $i,j \in N^k : i \neq j$ in network $k \in K$
A^{kl}	Set of interdependent links (i,j) between nodes $i \in N^k$ in network $k \in K$ and $j \in N^l$ in network $l \in K :\ l \neq k$
Parameters	
c_{ij}^{rk}	Unit cost of flow on link $(i,j) \in A^k$ for commodity $r \in R^k$ in network $k \in K$
c_{ij}^{rkl}	Unit cost of flow on interdependent link $(i,j) \in A^{kl}$ for commodity $r \in R^k$ in networks $k \in K$ and $l \in K : l \neq k$
s_i^{rk}	Supply at node $i \in N^k$ of commodity $r \in R^k$ for network $k \in K$
d_i^{rk}	Demand at node $i \in N^k$ of commodity $r \in R^k$ for network $k \in K$
α^r	Minimum percentage of total demand for commodity $r \in R$ to be satisfied
β_i^{rk}	Minimum percentage of demand for commodity $r \in R^k$ to be satisfied at demand node $i \in N_t^{rk}$ in network $k \in K$
γ_i^{rk}	Minimum percentage of demand for commodity $r \in \bar{R}^k$ to be satisfied at demand node $i \in N_t^{rk}$ in network $k \in K$
q_{ij}^{rk}	Flow capacity for link $(i,j) \in A^k$ for commodity $r \in R^k$ in network $k \in K$
q_{ij}^{rkl}	Flow capacity for interdependent link $(i,j) \in A^{kl}$ for commodity $r \in R^k$ in network $k \in K$ and $l \in K : l \neq k$

Table 2: Decision variables for the mathematical model of interdependent multimodal transportation networks.

Decision Variables	
$\mathbf{y}_i^k$	1 if node $i \in N^k$ in network $k \in K$ is used and 0 otherwise
$\mathbf{z}_{ij}^k$	1 if link $(i,j) \in A^k$ in network $k \in K$ is used and 0 otherwise
$\mathbf{z}_{ij}^{kl}$	1 if interdependent link $(i,j) \in A^{kl}$ in networks $k \in K$ and $l \in K : l \neq k$ is used and 0 otherwise
$\mathbf{x}_{ij}^{rk}$	Flow on link $(i,j) \in A^k$ of commodity $r \in R^k$ in network $k \in K$
$\mathbf{x}_{ij}^{rkl}$	Flow on interdependent link $(i,j) \in A^{kl}$ of commodity $r \in R^k$ in networks $k \in K$ and $l \in K : l \neq k$
$\mathbf{u}_i^{rk}$	Unused supply at node $i \in N_s^k$ for commodity $r \in R^k$ in network $k \in K$
$\mathbf{v}_i^{rk}$	Unmet demand at node $i \in N_t^k$ for commodity $r \in R^k$ in network $k \in K$

Objective Function

The proposed model minimizes the total cost of flows in the interdependent multimodal freight transportation network. In the objective function shown in (1), the flow costs are determined according to the decision variables denoting the quantity of flow traversing links in the interdependent multimodal freight transportation network.

$$\underset{\mathbf{x}}{\text{Min}}\ \mathbf{Z}_1 = \sum_{k \in K} \sum_{r \in R^k} \left(\sum_{(i,j) \in A^k} c_{ij}^{rk} \mathbf{x}_{ij}^{rk} + \sum_{l \in K : l \neq k} \sum_{(i,j) \in A^{kl}} c_{ij}^{rkl} \mathbf{x}_{ij}^{rkl} \right) \tag{1}$$

Constraints

The constraints enforce network connectivity and flow balance requirements as well as demand satisfaction requirements.

$$\mathbf{z}_{ij}^k \leq \mathbf{y}_i^k \quad \forall (i,j) \in A^k,\ k \in K \tag{2}$$

$$\mathbf{z}_{ij}^{kl} \leq \mathbf{y}_i^k \quad \forall (i,j) \in A^{kl},\ k \in K,\ l \in K : l \neq k \tag{3}$$

$$\sum_{(i,j) \in A^k} \mathbf{x}_{ij}^{rk} + \sum_{l \in K : l \neq k} \sum_{(i,j) \in A^{kl}} \mathbf{x}_{ij}^{rkl} - \sum_{(j,i) \in A^k} \mathbf{x}_{ji}^{rk} - \sum_{l \in K : l \neq k} \sum_{(j,i) \in A^{kl}} \mathbf{x}_{ji}^{rkl}$$
$$= \begin{cases} s_i^{rk} - \mathbf{u}_i^{rk} & \forall i \in N_s^{rk},\ r \in R^k,\ k \in K \\ 0 & \forall i \in N_o^{rk},\ r \in R^k,\ k \in K \\ -d_i^{rk} + \mathbf{v}_i^{rk} & \forall i \in N_t^{rk},\ r \in R^k,\ k \in K \end{cases} \tag{4}$$

$$\mathbf{x}_{ij}^{rk} \leq q_{ij}^{rk} \mathbf{z}_{ij}^k \quad \forall (i,j) \in A^k,\ r \in R^k,\ k \in K \tag{5}$$

$$\mathbf{x}_{ij}^{rkl} \leq q_{ij}^{rkl} \mathbf{z}_{ij}^{kl} \quad \forall (i,j) \in A^{kl},\ r \in R^k,\ k \in K,\ l \in K : l \neq k \tag{6}$$

$$\sum_{k \in K} \sum_{i \in N_t^{rk}} \mathbf{v}_i^{rk} \leq (1 - \alpha^r) \sum_{k \in K} \sum_{i \in N_t^{rk}} d_i^{rk} \quad \forall r \in R \tag{7}$$

$$\mathbf{v}_i^{rk} \leq d_i^{rk} \left(1 - \mathbf{y}_i^k\right) + \left(1 - \beta_i^{rk}\right) d_i^{rk} \mathbf{y}_i^k \quad \forall i \in N_t^{rk},\ r \in R^k \setminus \bar{R}^k,\ k \in K \tag{8}$$

$$\mathbf{v}_i^{rk} \leq d_i^{rk} \left(1 - \mathbf{y}_i^k\right) + \left(1 - \gamma_i^{rk}\right) d_i^{rk} \mathbf{y}_i^k \quad \forall i \in N_t^{rk},\ r \in \bar{R}^k,\ k \in K \tag{9}$$

$$\mathbf{y}_i^k \in \{0,1\} \quad \forall i \in N^k,\ k \in K \tag{10}$$

$$\mathbf{z}_{ij}^k \in \{0,1\} \quad \forall (i,j) \in A^k,\ k \in K \tag{11}$$

$$\mathbf{z}_{ij}^{kl} \in \{0,1\} \quad \forall (i,j) \in A^{kl},\ k \in K,\ l \in K : l \neq k \tag{12}$$

$$\mathbf{x}_{ij}^{rk} \geq 0 \quad \forall (i,j) \in A^k,\ r \in R^k,\ k \in K \tag{13}$$

$$\mathbf{x}_{ij}^{rkl} \geq 0 \quad \forall (i,j) \in A^k,\ r \in R^k,\ k \in K,\ l \in K : l \neq k \tag{14}$$

$$\mathbf{u}_i^{rk} \geq 0 \quad \forall i \in N_s^{rk},\ r \in R^k,\ k \in K \tag{15}$$

$$\mathbf{v}_i^{rk} \geq 0 \quad \forall i \in N_t^{rk},\ r \in R^k,\ k \in K \tag{16}$$

Constraints (2) and (3) are switching constraints relating the status of links to that of the origin nodes (i.e., a link can only be used if the nodes at each end of the link are being used). Constraints (4) are the node flow balance constraints for the supply, transshipment, and demand nodes. Constraints (5) and (6) enforce the maximum capacity of the existing links within each individual mode network and those connecting the multiple modes across layers, respectively. Constraints (7) define a specific percentage of the total demand for commodity *r* that must be met. The relationship between the unmet demand and the status of demand nodes is established in (8) and (9) which enforce the minimum demand of commodity that must be met at the demand node to remain functional. Specifically, constraints (9) represent the physical interdependency between networks since the supply nodes of one network act as demand nodes for the commodity originating in the other network. Finally, constraints (10) to (16) are the variable type constraints.

Resilience Metrics Evaluation

Similar to the resilience score from Tiong & Vergara (2023) for interdependent critical infrastructure networks, network performance for the multimodal freight transportation network can be evaluated using both topology-based and service-based network performance metrics. The topology-based metric is the network complexity while the service-based metric is the unmet demand.

Network Complexity:

Based on previous studies of topology-based metrics in the supply chain and transport networks, the *network complexity* is selected as a metric of resilience. The network complexity metric consists of the node and link complexities which represent the total number of nodes and links in the networks, respectively. The network complexity always increases as the network adds more elements (e.g., nodes and links). A network that is complex is more vulnerable to high-impact failures while a network with low network complexity is less vulnerable to high-impact disruptions.

For the network complexity metric (Z_2), all existing elements of the interdependent multimodal freight transportation network are considered in equation (17).

$$\mathbf{Z}_2 = \left(\sum_{k \in K} \left(\sum_{i \in N^k} \mathbf{y}_i^k + \left(\sum_{(i,j) \in A^k} \mathbf{z}_{ij}^k + \sum_{l \in K : l \neq k} \sum_{(i,j) \in A^{kl}} \mathbf{z}_{ij}^{kl} \right) \right) \right) \tag{17}$$

Unmet Demand:

At the same time, for the service-based resilience metric, we use the unmet demand which is the difference between the anticipated and the satisfied demands of commodities at the demand nodes in the network. The unmet demand is the complement to the service level which measures the percentage of satisfied demands. In this context, a network with low unmet demand is preferred and denotes higher resiliency of the multimodal freight transportation network.

The total unmet demand metric (Z_3) is the sum of unmet demand from all nodes that are in the network as shown in equation (18).

$$\mathbf{Z}_3 = \sum_{k \in K} \sum_{r \in R^k} \sum_{i \in N_t^k} \mathbf{v}_i^{rk} \tag{18}$$

The resilience metrics can be evaluated for any solution by including equations (17) and (18) in the mixed integer programming (MIP) mathematical model presented below:

$$\text{Minimize } \mathbf{Z}_1 \ (1)$$
$$\text{Subject to : } (2) - (18)$$

Solution Method

The mathematical model for the interdependent multimodal freight transportation network can be solved using commercial optimization software. The optimization software executes state-of-the-art solution algorithms for different types of mathematical programming formulations including MIPs such as the model presented above. The mathematical programming model is implemented in Python and a model file is created for an instance of the problem that is then passed to the solver to find solutions. Once a solution is obtained by the solver, it can be saved for analysis.

Test Case Development and Implementation

In this project, we implement the mathematical model for the interdependent multimodal freight transportation network using the Pacific Northwest as a test case scenario. We consider that the Pacific Northwest includes the states of Washington, Oregon and Idaho. The size of the region and its geographic characteristics represent an appropriate scenario for the use of multimodal freight transportation as an alternative to shipments using a single transportation mode.

The transportation modes that are included for the test case scenario include: road (trucking), rail, waterways, and air. Facility location data for the different modes of transportation was collected from different public sources. A description of the sources used for obtaining facility location data is presented in the Findings section of this report.

In addition to the facility location data, link distance information was obtained for the road network layer by using the shortest path algorithm. Link distance information for other modes of transportation can also be obtained assuming great circle distances.

Besides facility location data and link information for the different modes of transportation, additional parameters that need to be available for the implementation of the proposed mathematical programming formulation are the per unit per distance unit cost flow information as well as supply and demand data for shipments in the region.

Incorporating Shipper Behavior for Route Choice Modeling

The proposed formulation assumes that flows will be determined based on the objective of minimizing total costs in the network subject to restrictions on the capacity of links in the network. This assumption is valid when a central decision maker has control over the selection of routes and modes of transportation for all shipments in the interdependent multimodal freight transportation network and a system optimum is specified as the goal for traffic assignment.

An alternative representation of the selection of modes and routes for the dispatching of loads can be achieved by incorporating shipper behavior in our modeling to capture the decentralized nature of decision making in this context. According to the literature review, there are alternatives that can be explored for this purpose. He et al. (2021) lists user equilibrium where decision maker behavior is captured by the Nash equilibrium of an underlying non-cooperative game as an approach for traffic assignment. A potential direction for the second phase of this project could be a reformulation of the proposed mathematical programming formulation to incorporate a bi-level optimization approach where shippers and carriers are making decisions with different objectives.

Findings

Data documentation

The analysis of multimodal freight transportation networks in the Pacific Northwest is supported by various data sources, including open-source multimodal transportation facilities data from the Washington State Department of Transportation (WSDOT) and the Bureau Transportation Statistics (BTS) websites ((*Airports in the United States of America - Humanitarian Data Exchange*, n.d.; *Freight Analysis Framework (FAF5) Network Nodes | Geospatial at the Bureau of Transportation Statistics*, n.d.; *Transportation System Plan TSP Freight Facilities | ArcGIS Hub*, n.d.; *WSDOT - Freight Data Freight Intermodal Facilities | Washington State Geospatial Open Data Portal*, n.d.)).

To visualize the key components of the transportation infrastructure in this region, the following figures provide a detailed overview. Figure 1 shows facility data for rail, Figure 2 illustrates truck intermodal facilities, Figure 3 presents port intermodal facilities, and Figure 4 shows the air cargo facilities in the Pacific Northwest.

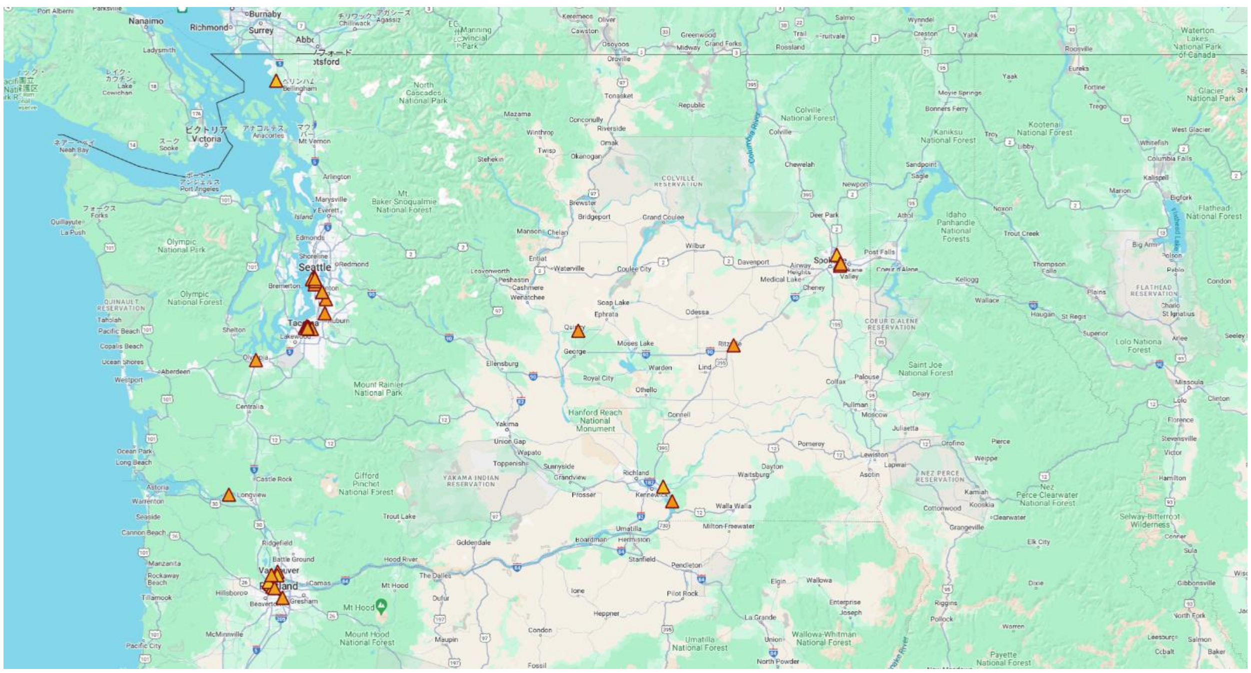

Figure 1: Rail Intermodal Facilities in the Pacific Northwest – This figure shows the locations of rail intermodal facilities, which are crucial for understanding rail network connectivity and operations.

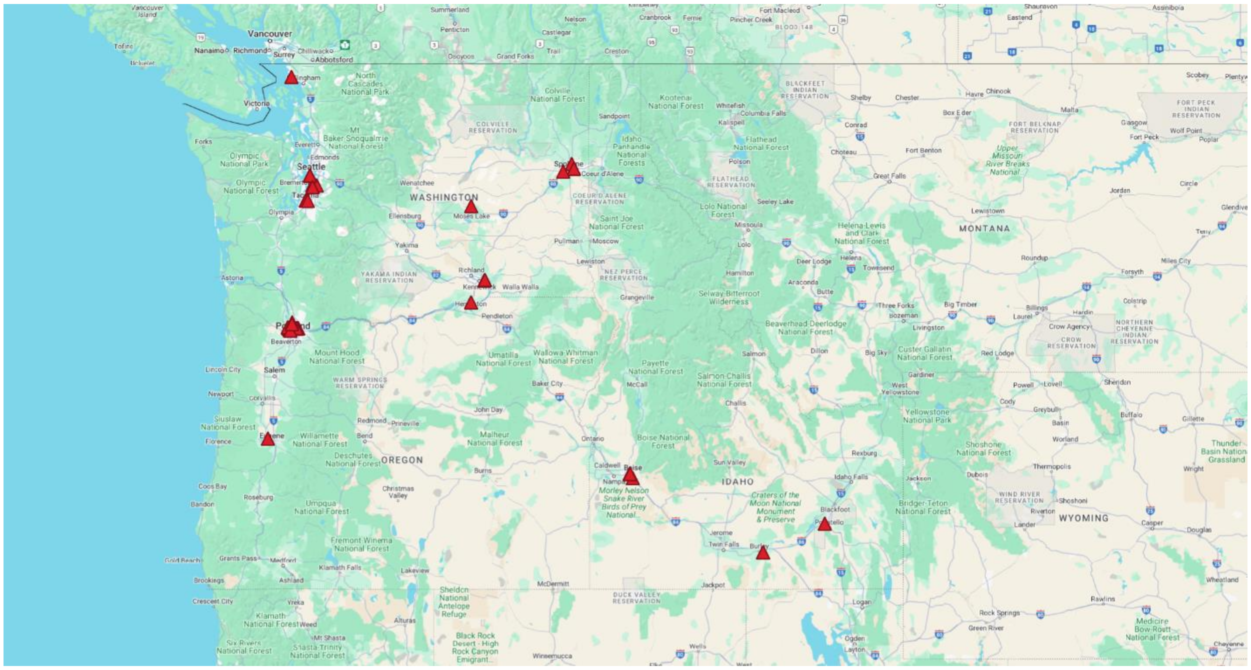

Figure 2: Truck Intermodal Facilities in the Pacific Northwest – This illustration highlights the truck intermodal facilities, which play a significant role in freight movement and distribution.

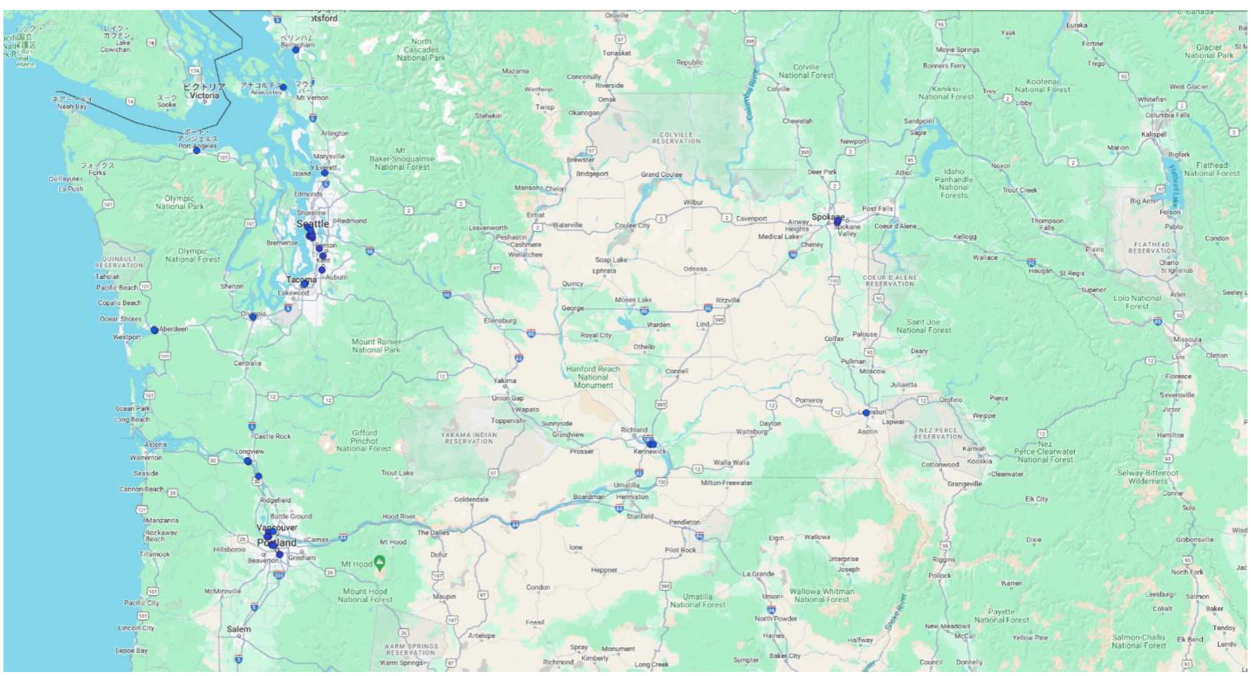

Figure 3: Port Intermodal Facilities in the Pacific Northwest – This figure maps out the port facilities, essential for maritime freight and its integration with other transportation modes.

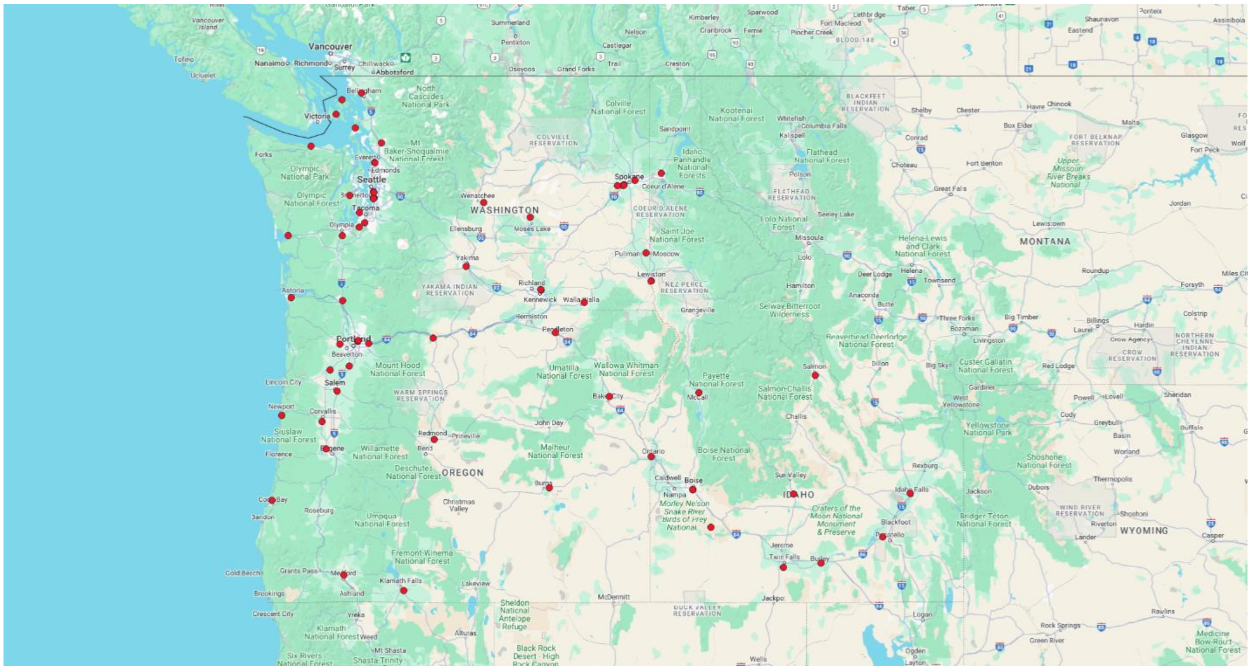

Figure 4: Airport Cargo Intermodal Facilities in the Pacific Northwest – This visualization shows large and medium airport cargo facilities.

We also obtained information for other facilities that are relevant to the operation of the multimodal network such as the location of rest areas for truck drivers (Figure 5) and the location of border crossings for international flows between the U.S. and Canada (Figure 6).

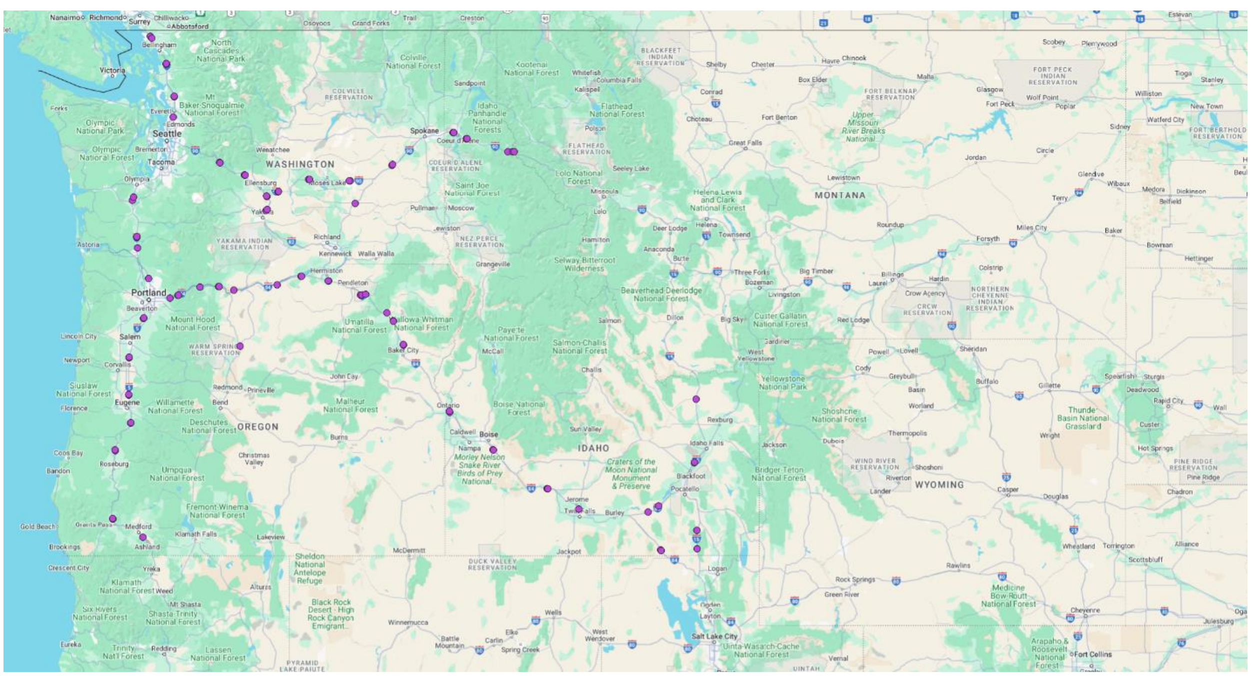

Figure 5: Rest Areas in the Pacific Northwest – This figure depicts rest areas, which are important for long-distance truck drivers and their impact on travel times and logistics.

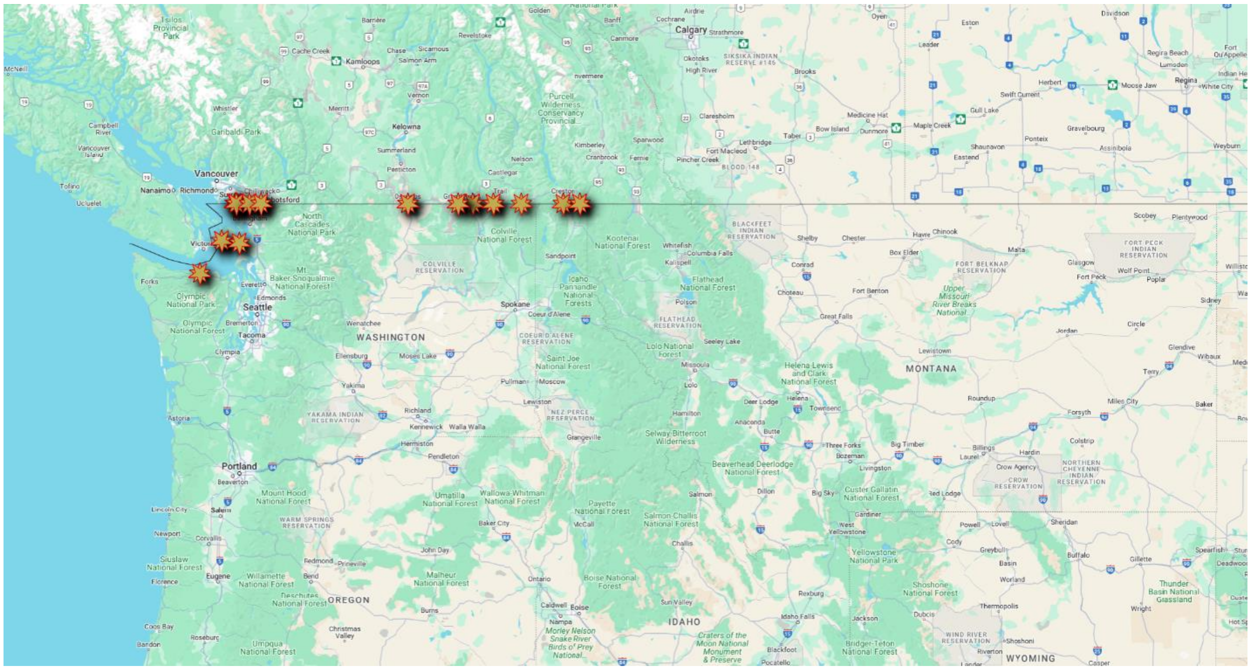

Figure 6: Border Crossings in the Pacific Northwest – This figure illustrates border crossing points, which are critical for international freight and trade flows.

Table 3 shows the number of nodes (node complexity) for the different transportation modes for freight transportation in the Pacific Northwest.

Table 3: Number of nodes (node complexity) for freight transportation modes in the Pacific Northwest.

	Number of nodes
Rail	37
Truck	61
Ports	37
Airports	2*

* Only large airports that handle cargo are included.

In addition to the multimodal facility data, the links or connections for individual transport modes were obtained by applying the shortest path algorithm for pairs of origin-destination nodes in the network. A distance matrix was constructed for each of the individual transportation modes.

Freight flow data for road transportation is collected from Robinsight telematics data. However, a delay in the availability of the data has resulted in a delay in the testing of the mathematical programming formulation for the Pacific Northwest test case instance.

Technical Transfer and Commercialization

Presentations & Publications

A brief presentation about this research project was presented during the FERSC Annual Research & Engagement Conference at Texas A&M University in April 2024. An abstract will be submitted to the Logistics and Supply Chain (LSC) Track of the 2025 Institute of Industrial and Systems Engineering (IISE) Annual Conference to be held in Atlanta, GA between May 31 and June 2, 2025. A journal paper will be completed and submitted for publication in a relevant journal in the field after the tasks of this phase of the project are completed.

Community Engagement

No community engagement efforts have been completed at this time.

Other relevant efforts

The available data collected for this project is available to other researchers and practitioners via Zenodo. We will update the repository as the tasks for this phase of the project are completed.

In support of FERSC workforce development goals, a graduate student has been part of the research team performing tasks related to the objectives of the project such as the literature review and data collection. More opportunities to engage graduate and undergraduate students in tasks related to the project will be available during the second year of the project.

Conclusions

A few conclusions can be made from the outcomes of the project tasks that have been completed by this point.

From the literature review, there is evidence that multimodal transportation networks can effectively be modeled using network models and mathematical programming approaches. Several studies that are summarized in this report provide examples of the development and implementation of mixed-integer programming formulations to support decision making with respect to multimodal transportation networks. This is the approach that has been used in this project to model a multi-layer, multi-commodity network for different modes of transportation. We adapted a formulation previously used for expansion of interdependent critical infrastructures for the case under study in this project. The formulation considers each mode of transportation as a layer and establishes the interdependency between the different modes via the possible transshipments at multimodal terminal nodes in the multi-layer network. This type of formulation allows for the evaluation of metrics for the performance of the multimodal transportation systems, such as operational costs and resilience metrics like network complexity and unmet demand.

However, a significant challenge for the implementation of the proposed mathematical programming formulation is the availability of data. Facility location data is generally available from open sources, but proprietary data such as cost information for different transportation modes or shipment flow information is more difficult to collect. In this context, telematics data for road transportation can provide a good source of flow data for movements within the road transportation layer. Unfortunately, we experienced delays during this phase of the project in procuring the data that could be used to complete the implementation of the test case scenario for the Pacific Northwest and experiment with the proposed formulation. We will continue to address the unfinished research tasks of this phase of the project during the second year of the effort.

Recommendations

Although there is more work to be done to complete the tasks of the current phase of this project, we can identify additional tasks that will be implemented during the second phase to quantify the impact of multimodal network components on the performance of distribution systems. Phase 2 will focus on the development and testing of a mathematical model to evaluate the impact of potential investments in the multimodal network for improving the performance and resilience of distribution systems. As the efficiency of distribution systems depends on the inherent resilience and efficiency of the multimodal network, it is important to develop tools for supporting decision making when allocating limited resources for multimodal freight transportation network improvements planned by service providers (e.g., carriers, terminal operators, etc.).

The following research objectives have been identified for Phase 2 of this project:

- Develop an approach to assess what network components in a multimodal transportation network are critical to the performance of distribution systems under different conditions.
- Apply the developed approach to the test case for the Pacific Northwest to demonstrate its validity and assess its performance.
- Derive insights from the solutions to the test case for the Pacific Northwest that could be generalizable to other regions and scales.

We anticipate the following impacts and applications from the outcomes of this research:

- Better understanding of the relationship between multimodal transportation network design and performance of private distribution systems.
- A framework for evaluation of critical multimodal network components that impact performance of distribution systems in scenarios with and without disruptions. This framework could be applied by multimodal service providers or state DOTs to evaluate potential improvements to the multimodal transportation infrastructure.

To achieve the research objectives stated above, the following five research tasks are anticipated in Phase 2:

Task 1. Develop a mathematical model to improve performance of multimodal transportation and distribution system: Formulate an extension of the network model developed in Phase 1 representing the interdependent multimodal transportation and distribution network of the Pacific Northwest. The extended model will use performance metrics identified in Phase 1 such as total cost and unmet demand to evaluate potential investment opportunities to improve or expand network components (e.g., facilities, multimodal terminals, roads, rail segments, etc.). The resource allocation problem will be modeled using a mixed integer programming approach. This approach allows us to define alternatives as binary decision variables and evaluate which ones improve the performance of the interdependent multimodal transportation and distribution network the most under specific constraints such as budget limitations and other operational rules.

Task 2. Implementation of the mathematical model with test data: The model will be implemented in Python for solution using optimization software. Test instances will be developed with data from sources identified in Phase 1 such as the Freight Analysis Framework (FAF), Washington State Department of Transportation, and EROAD freight telematics data for trucking. The test instances will represent the interdependent multimodal transportation and distribution network of the Pacific Northwest including facilities and operations in Oregon, Washington, and Idaho.

Task 3. Simulation of disruption scenarios: We will develop simulated scenarios of potential disruptions to network components to evaluate their impact on the performance of the interdependent multimodal network and distribution system. A static Monte Carlo simulation approach will be used to generate disruption scenarios by probabilistically determining if a network component is affected by a full or partial disruption (i.e., capacity is reduced 100% or less than 100%). Scenarios with single and multiple disruptions will be generated for testing.

Task 4. Computational testing of simulated network disruption scenarios: The mathematical model developed in Task 1 and implemented in Task 2 will be applied to the instances with the simulated disruption scenarios from Task 3. We will develop insights from the computational testing of the generated instances about the performance of the interdependent multimodal network and distribution systems.

Task 5. Summary of research outcomes: A final report will be prepared that includes a summary of the research tasks completed for this project. A journal paper will also be drafted from the report and submitted for publication. Code and test data will also be made available in an online repository.

Appendix

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