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Modeling Multimodal Freight Transportation Network Performance under Disruptions

Jing Dong, Ph.D.
Transportation Engineer
Center for Transportation Research and Education
Iowa State University

Micah Makaiwi
Graduate Research Assistant

Navid Shafieirad, M.S.
Graduate Research Assistant

Yundi Huang, M.S.
Assistant Engineer
The Fifth Survey and Design Institute

Iowa State University

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MATC

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Jing Dong, PhD
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Micah Makaiwi
Graduate Research Assistant
Department of Civil, Construction, and Environmental Engineering
Iowa State University

Navid Shafieirad, MS
Graduate Research Assistant
Department of Civil, Construction, and Environmental Engineering
Iowa State University

Yundi Huang, MS
Assistant Engineer
The Fifth Survey and Design Institute (Group) CO., LTD of CRCC
Beijing, China

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16. Abstract

To facilitate a region's freight transportation systems planning and operations and minimize the risk associated with increasing multimodal freight movements, this study presents a modeling framework for evaluating and optimizing freight flows on a multimodal transportation network under disruption. Unexpected events such as earthquakes, floods, and other manmade or natural disasters would cause significant economic losses. When parts of the transportation network are closed or operated at a reduced capacity, the delay of commodity movements would further increase such losses. Shifting to an alternative route or mode might help to mitigate the negative impacts. In this study, a multimodal freight transportation network was developed to simulate commodity movements, evaluate the impacts of disruptions, and develop effective emergency operation plans. A fluid-based dynamic queuing approximation was used to estimate the delays at classification yards and locks caused by disruption. Using the Federal Highway Administration's (FHWA) Freight Analysis Framework version 3 (FAF3) database, a case study was constructed to model the transportation of cereal grains from Iowa to other states. Three hypothetical disruption scenarios were tested: a reduced service level at locks along the Mississippi River, a bridge outage on I-80 at the Missouri River, and severe weather in central Iowa closing the Union Pacific tracks in the area. The impacts of these disruptions were quantified and analyzed using the presented freight network model.

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EXECUTIVE SUMMARY

Unexpected events such as earthquakes, floods, and other manmade or natural disasters would cause significant economic losses. When parts of the transportation network are closed or operated at a reduced capacity, the delay of commodity movements would further increase such losses. Shifting to an alternative route or mode might help to mitigate the negative impacts. In this research, to address the need for a quick and relatively accurate performance assessment of the degraded network, the freight transportation system was modeled as a dynamic queuing network. Each terminal was viewed as a queuing server (or system) to approximate the delays at classification yards, ports, locks, or intermodal terminals. To demonstrate the operational effectiveness of the proposed modeling approach, a case study focusing on freight flow in Iowa was conducted. The network performances across multiple modes, under normal and disrupted conditions, were analyzed using geographic information system (GIS) software. A risk area and what-if scenarios were generated to assess the vulnerability and resiliency of the study area. Different emergency response and recovery plans were compared in terms of delays, economic impacts, and recovery time by using the proposed dynamic network model and stationary model for the different scenarios. The results indicate that, altthough an incident affects only a small area, the impact on the freight flows throughout the entire region is considerable.

CHAPTER 1. INTRODUCTION

Traditional supply chain design and management aim at achieving cost effectiveness, operational efficiency, and high service quality under normal conditions. To this end, a variety of strategies have been proposed and adopted, such as lean manufacturing, outsourcing, off-shoring, factory specialization, and warehousing and distribution centralization. However, this trend of supply chain management makes the supply chain more complex and vulnerable to uncertainty or risk due to artificial or natural disasters, volatile demand, abrupt technology changes, or other factors (Simchi-Levi 2009). Unexpected events such as earthquakes, floods, and terrorist attacks may damages roads, railways, and waterways and lead to significant economic losses (Kim et al. 2002). This research builds a data-driven freight transportation network model that incorporates an intermodal network and the assignment of commodity flows on each route. In the event of disasters, part of the network will be closed or operated at a reduced capacity. By simulating commodity movements on the disrupted freight transportation network, the network model enables the estimation of freight transportation network performance under disruptions and the evaluation of emergency response and recovery plans in the immediate aftermath.

1.1 Background

Natural and manmade disasters can significantly impact freight transportation. For instance, the 2010 volcanic eruptions in Iceland caused a huge disruption to air travel across western and northern Europe, resulting in substantial delays to the transport of high-tech products and high-value flowers (Dong and Lu 2011). Hurricanes Katrina and Rita in 2005, to take another example, caused a significant impact on the transportation network in the United States. Disruption of the CSX railroad in New Orleans immediately affected a huge portion of the U.S rail network (Grenzebck and Lukmann 2008). Since 1990, Iowa has experienced 37 presidentially declared disasters (Iowa Homeland Security 2014). Iowa's lead hazards include severe weather (e.g., flooding, tornadoes and high winds, ice storms, and blizzards) and hazardous materials spills (at fixed facilities and during transportation). For example, in July 2010 the rising of the Mississippi River in Davenport put the area's rail operation at risk, and rail traffic was diverted away from the Quad Cities. Later, the Missouri River flooding in July 2011caused severe damage to Interstate 29 and Interstate 680 north of Council Bluffs (Iowa DOT 2010).

As an important agricultural state, Iowa produces about 7% of the nation's food supply. According to the Federal Highway Administration's (FHWA) Freight Analysis Framework version 3 (FAF3) database, Iowa exported a total of 107,352 kilotons of goods to other states and countries through rail, roads, and waterways in 2007. Shipments typically experience a considerable amount of delay at terminals, such as locks, classification yards, and border crossings, because of the required processing times and associated waiting times in queues. In particular, in the United States more than 70% of the total delay in the railway system occurs inside classification yards. The Bureau of Transportation Statistics (BTS) reported that, in 2009, the time waiting at terminals accounted for 64% of the total time of inland commercial traffic. In the event of natural or artificial disasters, part of the freight transportation network (or a certain mode) might be impacted, which would lead to reduced terminal service rates and/or link capacities. As a result, longer delays are expected during such major disruptions. Moreover, the terminal delays change with time of day, reflecting the time dependence of shipment flows. Thus, it is essential for a multimodal freight transportation network model to explicitly capture the time varying, non-stationary delays at terminals.

1.2 Project Objective

This research project is aimed at developing a modeling framework for evaluating and optimizing freight flows on a multimodal transportation network under disruption. A multimodal freight transportation network, including road, rails and inland waterways, was developed to simulate commodity movements, evaluate the impacts of disruptions, and develop effective emergency operation plans. Data were collected from various sources, including FAF3, railroad performance measures, and the U.S. Army Corps of Engineers Lock Queue Report (USACE). A fluid-based dynamic queueing approximation was used to perform a quick and relatively accurate estimation of the delays at classification yards, ports, locks, or intermodal terminals caused by disruptions in the network. By simulating commodity movements on the disrupted freight transportation network, the proposed network model enables (1) estimation of freight transportation network performance under disruptions; (2) evaluation of emergency response and recovery plans in the immediate aftermath; (3) information provision regarding alternative shipping routes and modes for shippers, receivers, and carriers; and (4) vulnerability and resiliency analysis of the freight transportation network, identification of the vulnerable links, and development of proactive strategies.

1.3 Report Organization

This remainder of the report is organized as follows. Chapter 2 provides a literature review on freight transportation modeling. In this chapter, previous work on freight network modeling is divided into two categories: freight network modeling under normal conditions and under disruption. Furthermore, the cost of shifting the shipment to another mode is reviewed. Chapter 3 provides a summary of freight movement in the United States and commodity flow in Iowa based on FAF3. Chapter 4 describes the stationary and fluid-based approximation model. The queueing process at terminals and the corresponding delay are discussed in this chapter. Chapter 5 describes the case study of this report and the disruption scenarios. This chapter explains how the data were collected for this research and describes the disruption scenarios in Iowa. The impacts of disruption are shown in this chapter for three different scenarios, and the results are discussed.

CHAPTER 2. LITERATURE REVIEW

2.1 Freight Network Modeling

In recent years, freight modeling has been developing quickly in different directions all over the world (Tavasszy 2006). Many models have been developed to address different areas of freight modeling, including freight-economy linkages, logistic behavior, and freight networks. In this study, we mainly focus on freight movements on a multimodal network under disruption, as well as on the economic impact of capacity loss on freight transport.

2.1.1 Freight Modeling under Normal Conditions

Movement of freight is considered to be one the most challenging issues for the transportation system. The main reason identified for this is lack of available data and analysis tools. However, many studies have addressed these issues in the past few decades. For instance, Crainic et al. (1984) and Guelat et al. (1990) proposed a multimodal multiproduct network freight assignment model for strategic planning, implemented in a strategic transportation analysis tool called STAN that solves a system-optimal assignment problem with the objective of minimizing the total delay at arcs and node transfers. In Crainic et al.'s model, the operation inside a classification yard is modeled as a (stationary) M/M/1 queue, and the average delay through the yard is estimated by a delay function that relates product types and traffic flows. Mahmassani et al. (2007, 2008) developed a dynamic freight network simulation assignment platform for the analysis of multiproduct intermodal freight transportation systems. The platform consists of three main components: a multimodal freight network simulation component, a multimodal freight assignment component, and a multiple product intermodal shortest path procedure. The freight network simulation component incorporates a queuing model to evaluate the transfer delay experienced by shipments at intermodal transfer terminals, classification yards, and ports.

2.1.2 Freight Modeling under Disruptions

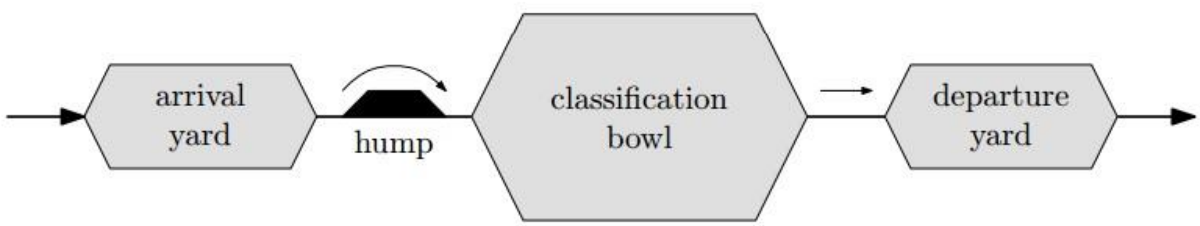
Witnessing the adverse impact of abrupt interruptions on the transportation network and their impact on the supply chain, an increasing number of studies have been devoted to addressing disruptions and to improving the supply chain's robustness and resilience (Christopher and Lee 2004, Ponomarov and Holcomb 2009, Trkman and McCormack 2009). Various strategies and methods have thus been presented in the literature, such as agile distribution (Collin and Lorenzin 2006), quick responsiveness (Klibi et al. 2010), flexibility or redundancy (Naim et al. 2006, Yu et al. 2011), collaboration (Anane et al. 2008), operational integration, and supply chain re-engineering. Among these methods, agile distribution and quick responsiveness have drawn increasing attention. For example, Christopher (2004) suggested that agility is the key component for surviving in a changing environment, especially by the creation of responsive supply chains. Successful agile distribution and/or quick responsiveness rely on rapidly estimating the impacts of abrupt disasters and developing emergency response plans that can be implemented in the immediate aftermath. To this end, various operations research techniques have been adopted to develop emergency response plans, and these techniques typically call for a freight transportation network model that is able to explicitly represent the reductions of terminal service rates and link capacities, reflecting various degrees of disaster damage.

2.2 Terminal Delays

Unlike urban road traffic, due to the required processing times and associated waiting times in queues, shipments typically experience a considerable amount of delay at locks, classification yards, and border crossings. In the event of natural or artificial disasters, part of the freight transportation network (or a certain mode) might be impacted, resulting in longer delays for the shipments. In this study, we considered each freight terminal, such as rail yards and locks, as a server and calculated the delay at locks based on an M/M/1 queue system.

2.2.1 Freight Movement at Rail Yards

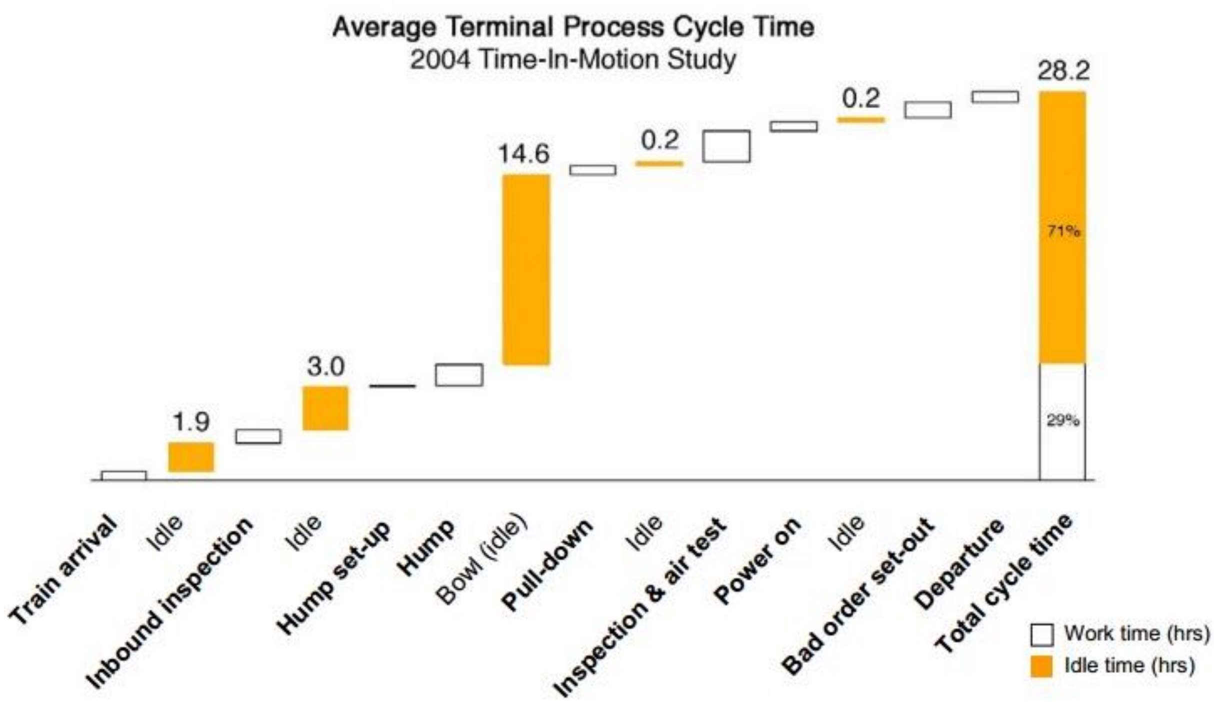
Freight railroad terminals receive inbound trains, classify or regroup railcars, and build outbound trains (Lin and Cheng 2011). Rail terminals fall into two categories: (1) hump yards, which use gravity to sort railcars, and (2) flat switching yards which rely on locomotives for movement. Generally, hump yards are more efficient than flat switching yards (Lin and Cheng 2011). A hump yard typically contains a receiving (arrival) yard, a classification yard (also known as bowl), and a departure yard. Figure 1 shows a typical hump yard.



Bohlin et al. 2011

Figure 1. Hump yard

The classification process at yards is complex and usually results in a significant amount of delay for outbound trains (Bohlin et al. 2011). In fact, a majority of total travel time is spent in yards. As shown in Figure 2, cars were idled over 71% of the average dwell time in the yard (Drinberger and Barkan 2006).



Bohlin et al. 2011

Figure 2. Average terminal process cycle time (2004 time-in-motion study)

Considering the notable amount of delay trains experience in classification yards, any disruption can significantly affect operational procedure.

2.2.2 Freight Movement at Locks

Inland waterway transportation is quite important in the U.S. and other regions, especially for heavy or bulky commodities, because it is inexpensive, energy efficient, and safe (Dai and Schonfeld 1998). During normal conditions, barges do no need to wait for lockage. However, due to high traffic volumes or severe weather, congestion at locks is inevitable and can significantly extend the waiting time for barges. Table 1 displays the summary statistics of six different locks for the period of 2000 through 2010.

Table 1. Summary statistics of waiting times

Lock	Zero Wait Time (%)	Average Wait Time (minutes)	Standard Deviation (minutes)	Maximum Wait Time (minutes)
Ohio Emsworth	61	63	237	4,761
Ohio Markland	52	83	228	3,307
Ohio Lock 52	70	190	582	10,462
Mississippi Lock 20	25	120	228	14,490
Mississippi Lock 25	22	160	351	14,368
Illinois LaGrange	44	155	366	11,033

Source: America's Locks & Dam: "A ticking time bomb for agriculture?" Texas Transportation Institute

In this report, we monitored the movement of barges for one month through the Mississippi River for locks 9 to 19 in order to obtain the delay and travel time. All the data were collected from the U.S. Army Corps of Engineers lock performance monitoring system report website.

2.3 Freight Demand Elasticity

2.3.1 Cost Function

A variety of sources have tried to estimate the cost of shipping goods and services over a variety of modes. A simplistic method for determining link cost was determined by Ham et al. (2005) using data for nine states, including Iowa (2005). The authors used Evans' algorithm and the convex combination method to determine that the total cost is a sum of intermediate demand and final demand in all subregions. Jourquin and Beuthe (1996) used European origin-destination (O-D) matrices from the Eurostat O-D data set to determine that the total cost is a function of loading and unloading costs, possible transshipping costs, and the costs of moving goods over the route links. Lingaitienė (2008) derived three cost equations for each individual mode (rail, road, and water). Three main components were identified: technological costs (fuel costs, maintenance, road taxes, driver wages, and cargo forwarding expenses), time of transportation (in € per hour), and insurance expenses. However, these equations cannot be used directly for the Iowa case study; the data is based on European freight, which has a different cost structure than American freight. Additionally, inland river transportation, a major component of freight in Iowa, was not accounted for.

2.3.2 Elasticities of Freight Demand

Beuthe et al. (2001) examined modal cross-elasticity in Europe. Different elasticities were calculated for each of the three modes broken up by the following: total cost versus travel cost, metric tons versus tons-km, short versus long distances, and per commodity as defined by the European NST-R goods classification standard. Table 2 shows the cross elasticities in metric tons for all commodities shipped when the total cost is decreased by 5%.

Table 2. Summary statistics of waiting times

	Long-Distance			Short-Distance		
	Road	**Rail**	**Water**	**Road**	**Rail**	**Water**
Road	-0.63	0.14	0.09	-0.58	0.08	0.04
Rail	2.13	-1.54	0.97	2.26	-2.06	2.73
Water	1.03	0.32	-1.34	5.47	0.58	-2.62

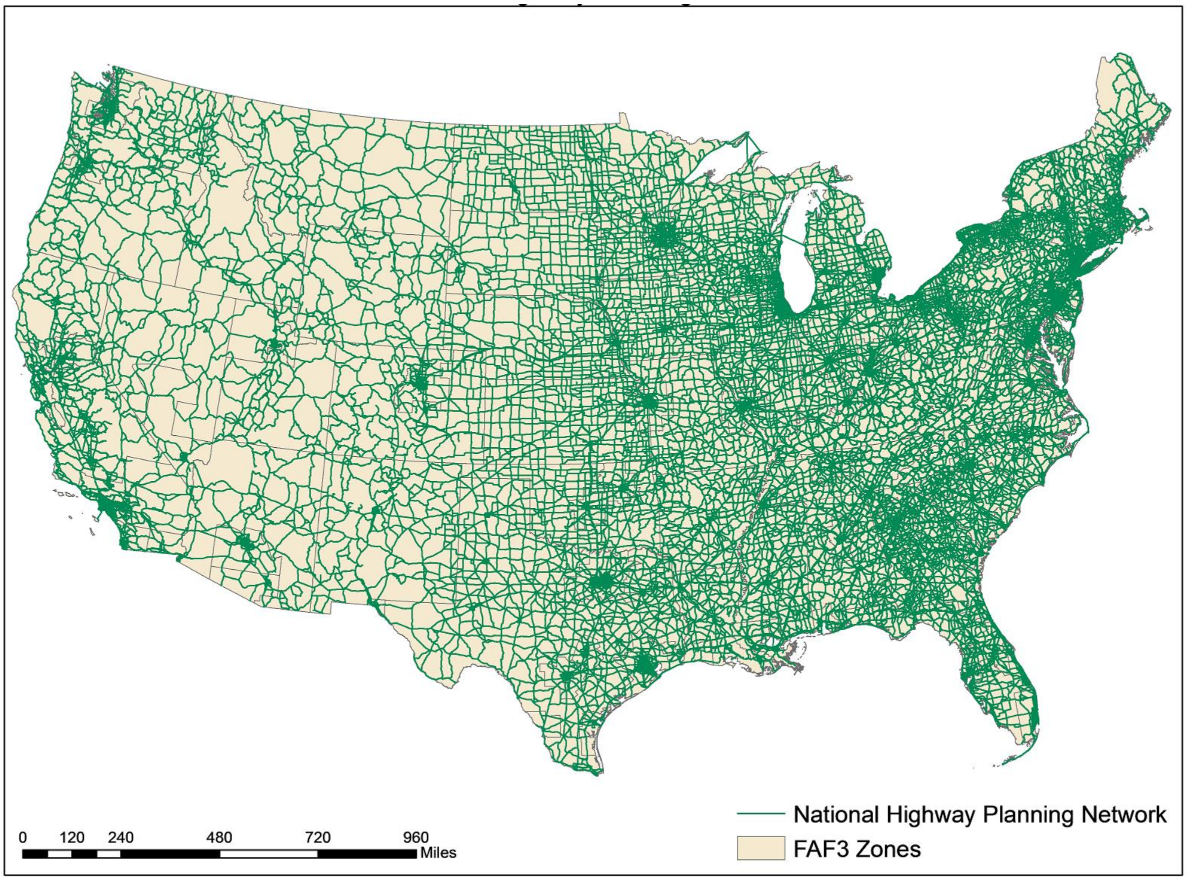
Source: Beuthe et al. 2001, p. 261

The elasticities for other cases were similar. However, these values cannot be used directly in the Iowa case study. Elasticities are only valid when they are used for prices similar to the original ones. Elasticities can only be assumed to be constant near the point from which they are estimated and vary non-linearly as price changes become more extreme.

CHAPTER 3. DATA DESCRIPTION

3.1 Multimodal Freight Distribution Network

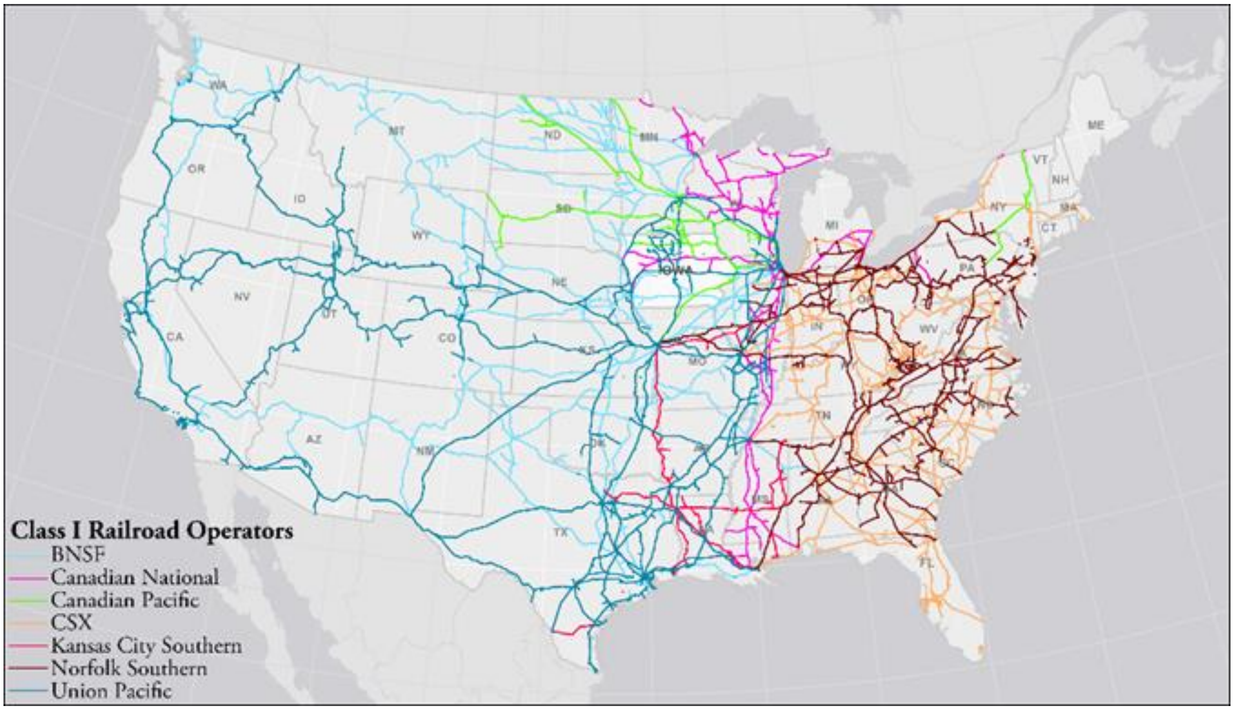
The multimodal freight transportation network was built based on the geo-located files from North American Transportation Atlas Data (NATAD), published by the Bureau of Transportation Statistics. The network includes highways, railways, waterways, classification yards, containerized intermodal terminals, and ports. The network for each mode is shown in Figures 3 through 5. Highways provide a major network throughout the states, and the highway network is denser on the eastern side of the U.S. (see Figure 3).



FAF3 FHWA

Figure 3. National highway planning network

The freight rail network in the U.S. is divided by the Mississippi River. As shown in Figure 4, CSX, and Norfolk Southern dominate the railroad operations to the east, while operations to the west, are mainly dominated by Union Pacific and BNSF (Grenzebck and Lukmann 2008).



National Geospatial Data Asset rail network

Figure 4. Class I railroad carrier track in the U.S.

The waterways are mainly used along the Mississippi River (BTS 2011) (see Figure 5).

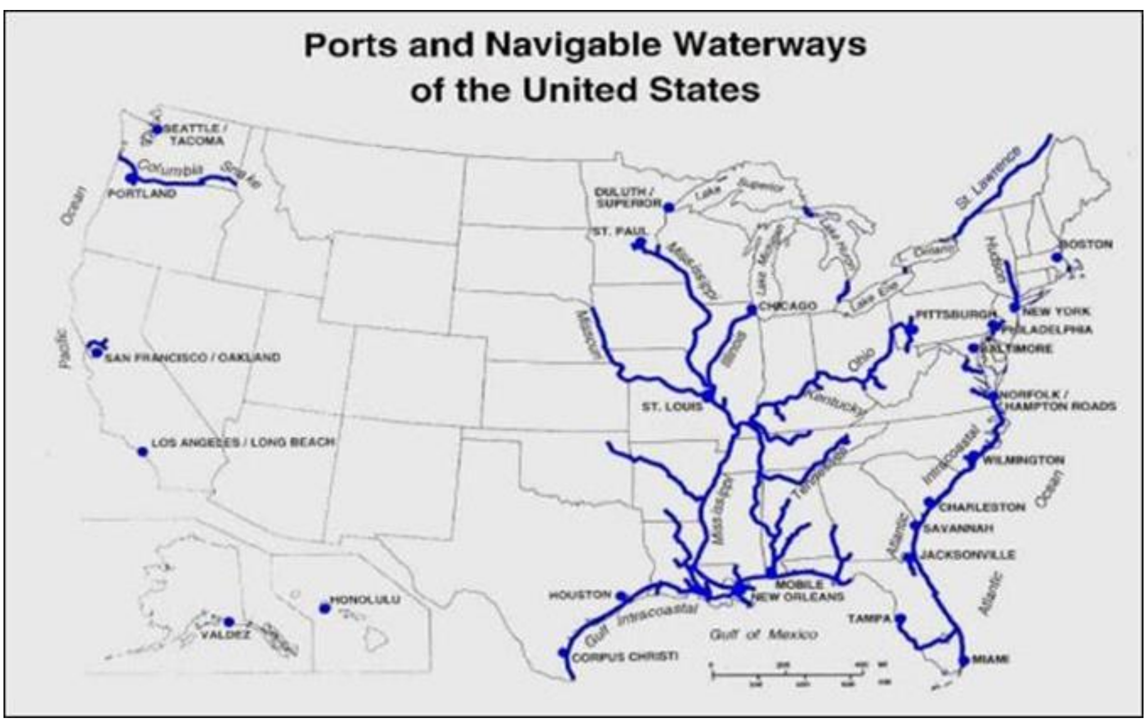


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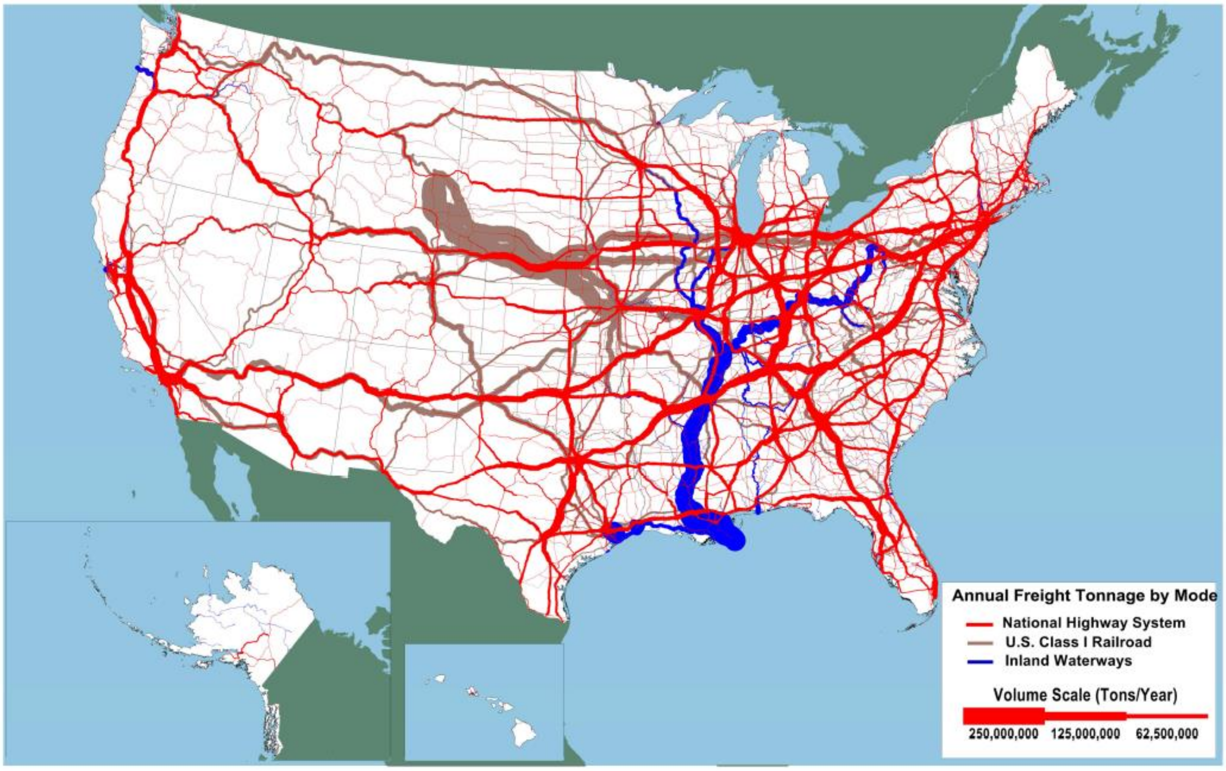
Figure 5. National ports and navigable waterways

The Mississippi River is one of the world's major river systems in size, habitat diversity, and biological productivity (Crainic et al. 2004). The Mississippi is the second largest river in the U.S. (USGS 2014), flowing 2,340 miles from Lake Itasca in north central Minnesota to the Gulf of Mexico.

3.2 Commodity Flow

FAF3, an FHWA funded and managed data and analysis program, provides estimates of the total volumes of freight moved between individual states, major metropolitan areas, sub-state regions, and major international gateways. The FAF3 freight flows matrix is made up of 131 origins, 131 destinations, 43 commodity classes, and 8 modal categories for 2 metrics—annual tons and annual dollar values—for calendar year 2007. A set of U.S. highway network link- and route-based truck flow assignments were developed using the FAF3 freight flows matrix. Freight flows throughout the network were estimated based on the U.S. Commodity Flow Survey (CFS) and FAF3.

The network for 2007 commodity movement is shown in Figure 6. As the figure shows, highways constitute a major network throughout the U.S., and the network is denser in the eastern U.S. Railways are mostly used in the midwest region of the U.S. and in 2007 carried dense tonnages in Nebraska and South Dakota. The waterways are mainly used along the Mississippi River and its tributaries.



Highways: U.S. DOT, FHWA, FAF version 3.4, 2012. Rail: Based on Surface Transportation Board, Annual Carload Waybill Sample, and rail freight flow assignments done by Oak Ridge National Laboratory. Inland Waterways: U.S. Army Corps of Engineers (USACE), Annual Vessel Operating Activity and Lock Performance Monitoring System data, as processed for USACE by the Tennessee Valley Authority; and USACE Institute for Water Resources, Waterborne Foreign Trade Data, Water flow assignments done by Oak Ridge National Laboratory.

Figure 6. Tonnage on highways, railroads, and inland waterways in 2007

3.3 Travel Time Cost and Estimation

The travel times by different modes were estimated differently using various data sources. For trucks, FAF3 provides average speed (in mph) for 2007 and 2040 peak hours as well as the delay for 2007 and 2040 (in hours). These data can be used to calculate peak hour travel time (and variables denoted with an * are taken directly from the FAF3 dataset), as follows:

$$TravelTime_{2007} = {length^*}_{2007} \big/ {speed^*}_{2007}$$
$$TravelTime_{2040} = {length^*}_{2040} \big/ {speed^*}_{2040} \quad \textbf{(1)}$$

The free-flow travel time is calculated as the total (congested) travel time minus the delay:

$$TravelTime_{Free-Flow} = TravelTime_{2007} - {Delay^*}_{2007} \quad \textbf{(2)}$$

For rail, an overland speed of 24.0 mph was used. This value was derived from the self-reported speed of the rail carriers. Terminal delay data was gathered from the railroad performance measures website (www.railroadpm.org). The average speed for the second quarter of 2013 was used.

In addition, according to FAF3 data, 6,940 kilotons of goods ship annually from Iowa to their domestic and international destinations via the Mississippi River. Eleven of the 26 locks on the Mississippi River are located across the east side of Iowa. The U.S. Army Corps of Engineers publishes online data for each vessel on the Mississippi River. All the required data, such as service time, arrival rate, and total travel time, were derived and calculated based on one month of observations of locks 9 to 19 on this river.

The cost data used in this study are derived from Ballou (1998). A flat rate was assumed for each mode. Because the main goal was to get approximate comparisons of costs between modes, these numbers will suffice for the purposes of the case study.

Table 3. Costs associated with each mode (per ton-mile)

Mode	**Water**	**Rail**	**Road**
Cost (1995 USD)	1¢	3¢	25¢
Cost (2014 USD)	1.6¢	5.0¢	$3.88

CHAPTER 4. METHODOLOGY

This section presents the network modeling approach for the performance evaluation of freight transportation systems under disruption. The multimodal freight transportation network is conceptualized as a non-stationary queuing network. Shipment flows are propagated in the network following their assigned paths. An analytical, point-wise, fluid-based approximation is used to estimate delays attributable to the queuing process at terminals.

4.1 Assumptions and Problem Statements

This study considers a freight transportation network, where G = (N, A) and N is the set of nodes (locks and terminals) and A is the set of links connecting the nodes in N. The entire period of planning interest is discretized into small time intervals. The time-dependent multiproduct shipment O-D demand data are loaded to the network, and the shipments follow assigned intermodal paths to travel through the network. The disruptions in the freight transportation network are presented by removing the impacted links and nodes and shifting the shipments to different routes and modes. In general, shipments experience a significant amount of delay at terminals, such as ports, classification yards, and locks, because of the required processing time (also known as service time) and the amount of time spent in queue. In this research, service time is assumed to be fixed and is based on actual monitored data.

The multimodal freight transportation system is modeled as a non-stationary queuing network, as shown in Figure 7, where a set of nodes representing classification yards, ports, and intermodal terminals are considered to be the queuing servers connected by a set of links representing highways, railways, and waterways.. When the transportation network is under disruption, a dynamic queuing network approach was adopted to realistically estimate time varying, non-stationary queuing delays at terminals.

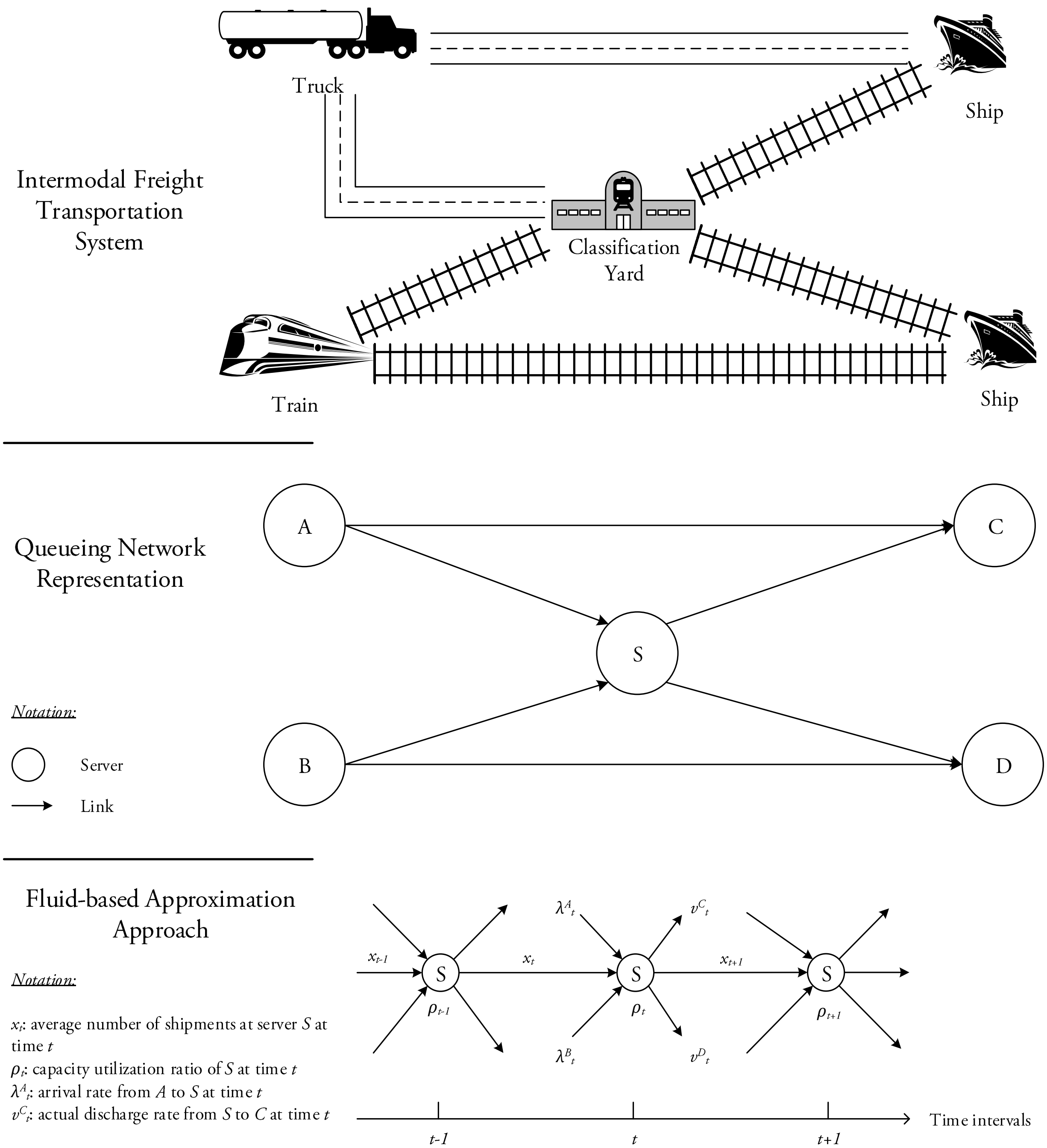


Figure 7. Dynamic queuing model for a multimodal freight transportation network

4.2 Queuing Process at Terminals

One critical issue in evaluating the impact of disruption on the performance of the freight transportation system is to quantify the (average) delays at the terminals, namely the time spent at the servers in the queuing network. The arrivals of shipments at a single-server terminal are assumed to follow a Poisson process with the rates $\lambda(t), t=0,1,\ldots,T$, and the service time is exponentially distributed with the rate *s*. Using Kendall's notation (Tijms 2003), this queuing system is described by M(*t*)/M/1.

4.2.1 Steady-State Queuing Theory

Ignoring the non-stationarity, the queuing system can be viewed as a conventional M/M/1 queue, with the following arrival rate:

$$\bar{\lambda} = \frac{1}{T}\int_0^T \lambda(t)dt \tag{3}$$

$$\bar{x} = \frac{\bar{\rho}}{1-\bar{\rho}} \tag{4}$$

However, the steady-state assumption does not hold for the problem of interest, and thus the conventional relationship between stationary average queue length and the server utilization ratio cannot be directly applied. In fact, the non-stationary arrivals tend to increase the expected delays compared to a stationary arrival process of the same average rate. Based on empirical results, Green et al. (1991) showed that a stationary model can underestimate delays significantly, even when the arrival rate is only modestly non-stationary.

4.2.2 Fluid-Based Approximation

This study adopts the analytical fluid-based approximation method, which is a branch of point-wise fluid-based approximation for queuing systems with Poisson arrival processes, to model dynamic (non-stationary) freight queuing processes at terminals. In addition to its computational efficiency, this fluid-based approximation scheme can effectively represent the queue buildup and dissipation processes over time.

In the fluid-based approximation approach, the state transition between any two consecutive time intervals, *t* and *t*+1, needs to maintain fluid balance, i.e., the change in the number of shipments at terminal *n* over time equals the number of arrivals minus the number of departures, as follows:

$$x_n(t+1) = x_n(t) + \lambda_n(t) - v_n(t), \forall n, t \tag{5}$$

where,

- $x_n(t)$ = the number of shipments at terminal *n* in time *t*,
- $\lambda_n(t)$ = the number of arrival shipments at terminal *n* in time *t*, and
- $v_n(t)$ = the number of departure shipments at terminal *n* in time *t*.

The exit flow, $v_n(t)$, is determined by the product of the maximum service rate, $s_n(t)$, and the capacity utilization ratio, $\rho_n(t)$, at terminal *n* in time *t*, as follows:

$$v_n(t) - s_n(t) \times \rho_n(t) = 0, \forall n, t \tag{6}$$

where,

- $s_n(t)$ = maximum service rate at terminal *n* in time *t*, and
- $\rho_n(t)$ = the capacity utilization ratio at terminal *n* in time *t*.

For an M/M/1 system, the capacity utilization ratio at terminal *n* in time *t* is estimated based on the following equation:

$$\rho_n(t) = \frac{x_n(t)}{x_n(t)+1}, \forall n, t \tag{7}$$

4.3 Flow Propagation in the Queuing Network

By loading the shipments on the predetermined paths, the arrivals at each terminal (server) can be obtained and can thus provide a basis for a performance evaluation of the freight network. This section describes the processes of shipment flows propagating along links and merging and splitting at terminals.

In a steady state, the departure process of an M/M/1 queue with arrival rate λ is a Poisson process of the same rate (Burke 1956). For non-stationary queuing systems, Foley (1982) showed that the departure process from an Mt/Gt/∞ queue was a Poisson process, possibly non-stationary. The Mt/Gt/∞ queue is an infinite-server queue with a stationary or non-stationary Poisson arrival process and a general service time distribution. Although this property does not hold for finite queuing systems, the departure process of a non-stationary finite-server queue can be assumed approximately as a non-stationary Poisson process (Tipper, 1990).

4.3.1 Flow Propagation along a Link

Figure 8 illustrates flow propagation along a link, i.e., the discharge flow from node *m* travels on link *m* → *n* and arrives at node *n* at a later time.

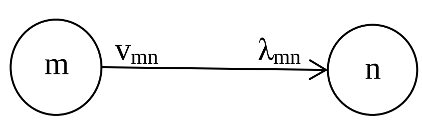


Figure 8. Flow propagation along a link

Recall that link travel times are assumed to be known and fixed in this study. Because the departure of shipments from node *m* is assumed to follow approximately a Poisson process, the arrival process at node *n* is also a Poisson process. The arrival rate at node *n* equals the discharge rate from node *m* by a time shift $c_{mn}(t)$, which is the link travel time in time *t*, as follows:

$$\lambda_{mn}(t) = v_{mn}(t - c_{mn}(t)), \forall n, t \quad \textbf{(8)}$$

4.3.2 Merge of Multiple Incoming Flows

In the cases when multiple incoming links are incident to one terminal, the arriving flow at terminal *n* is a combination of shipments from all the incoming links.

In Figure 9, the circles and triangles represent the arrival of shipments from links *m* → *n* and *m* → *n*, respectively, both of which follow a Poisson process.

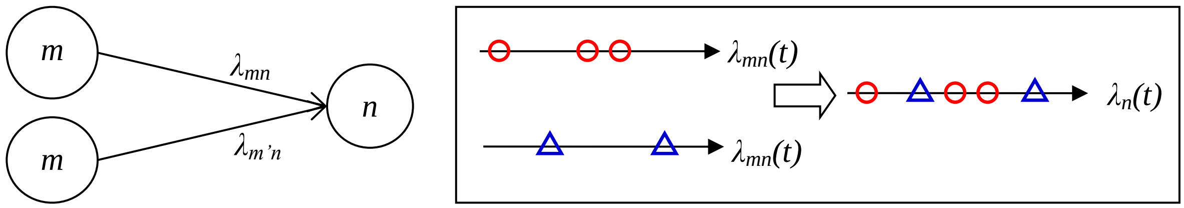


Figure 9. Merge of arrival flows

Because merging multiple independent Poisson processes creates a Poisson process, the arrival flow at the terminal *n* follows a Poisson process with a rate equal to the summation of arrival flows from all incoming links, as follows:

$$\lambda_n(t) = \sum_{m \in I(n)} \lambda_{mn}(t), \forall m, n, t \quad \textbf{(9)}$$

4.3.3 Split of Multiple Departure Flows

If multiple links are incident from one terminal, the discharge flow from the terminal is split into multiple flows, each of which is assigned to an outgoing link with a certain probability. For example, in Figure 10 two Poisson departure processes are generated.

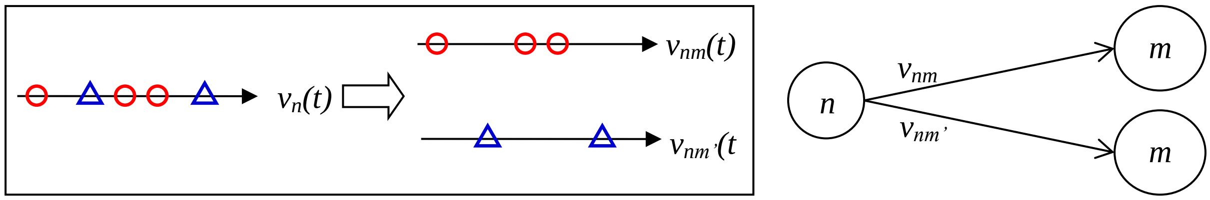


Figure 10. Split of departure flows

The splitting probabilities (or proportions) are determined by the numbers of shipments assigned to the different paths, and the sum of the proportions is 1, as follows:

$$v_{nm}(t) = p_m \cdot v_n(t), \forall m \in E(n) \text{ and } \sum_{m \in E(n)} p_m = 1 \tag{10}$$

4.4 Route Creation

The line segments from FAF3 and the railway and commercially navigable waterway datasets were used to create the shipping routes using ArcGIS. In particular, segments of road and railway in the FAF3 transportation network feature classes were manually selected and combined into a single continuous route. This route was then converted into a linear referencing system (LRS). This allowed referencing of the original segments to the LRS to calculate attributes such as the percentage of a highway route that is on freeways and how much of a railroad line is double-tracked.

For most O-D pairs, one or two truck and rail routes were created. The truck routes correspond to plausible routes, preferring Interstates and U.S. highways. For rail, as much of the route as possible is on track owned by the railroads, with track that the railroads has rights to being secondary. If water is available, up to two water routes to the destination are generated.

In addition, certain routes do not start at the Iowa centroid. For instance, most road traffic heading to the northeast destination passes through Chicago. Therefore the routes headed there start at Chicago. This also occurs in situations where multiple railroads must be used due to the regional nature of Class I carriers. During post-processing, different permutations are combined to get the final routes.

After creation of the routes, the individual line segments from the original data were referenced to the LRS. In addition, information such as railway terminals (from the Railroad Performance Measures website) and locks (from the U.S. Army Corps of Engineers lock performance monitoring system,)were referenced to the routes as well. From those data, the following variables were derived for each mode:

- *Length*: Average length to destination in miles
- *Time*: Average free-flow travel time to destination in hours

- *Delay*: For roads, the total peak-hour congestion delay along entire route; for rail and water, the total lock and terminal delay
- *Speed*: The average overland speed to the destination, not including terminal delay or congestion in miles per hour

These variables were averaged per destination, weighting the quickest/shortest route per destination with four times the weight of other routes. This produced one row per destination. These aggregate variables listed above were combined with the following variables, which are unique to each destination:

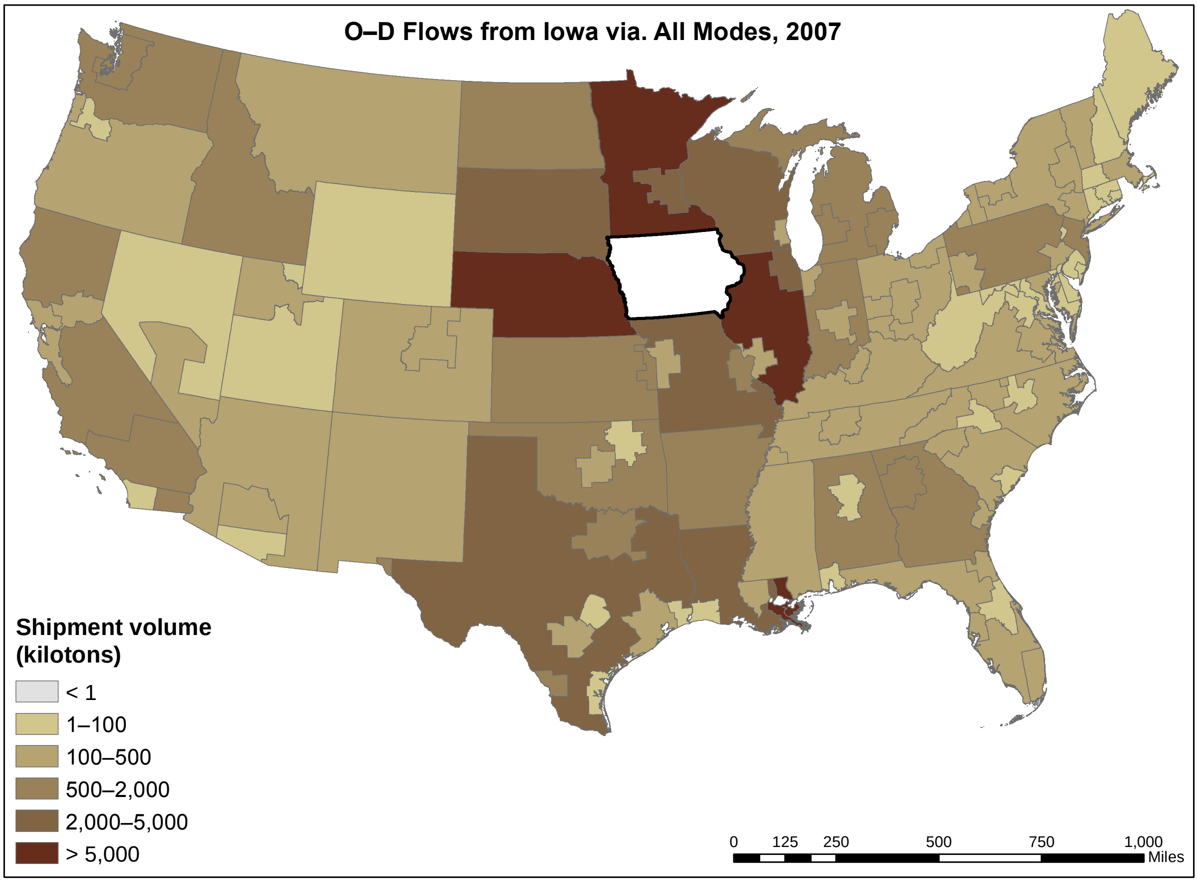
- *Water available*: An indicator variable; 1 if water is available to the destination; 0 otherwise
- *Tonnage*: The total tonnage per mode that is shipped from Iowa to the destination (million gross ton-miles)
- *Percent mode share*: The percent of total tonnage per mode; the response variable

CHAPTER 5. CASE STUDY

The freight network in Iowa is important for carrying various commodities, especially agricultural products. The demand for goods has been growing over the past 50 years, so that a cost-effective network involving highways, railways, waterways, multimodal routes, and other modes is essential. GIS was applied to develop O-D maps and a commodity flow assignment network. The functions provided in GIS such as selection and join tables were used to extract the state of Iowa from national maps. Simulation of the commodity flow was conducted based on the O-D maps and the proposed reasonable rail network. The travel time to each destination was estimated from the travel distance and constant average speed, using the data provided by each private carrier. In addition, the generalized total travel cost and direct and cross-elasticity were adopted from past studies. Both the unit cost and the elasticity were averaged and weighted to appropriately match the situation in the U.S. The equations for the generalized total cost for each mode were also modified to fit the freight transportation data in the U.S.

5.1 Freight Transportation in Iowa

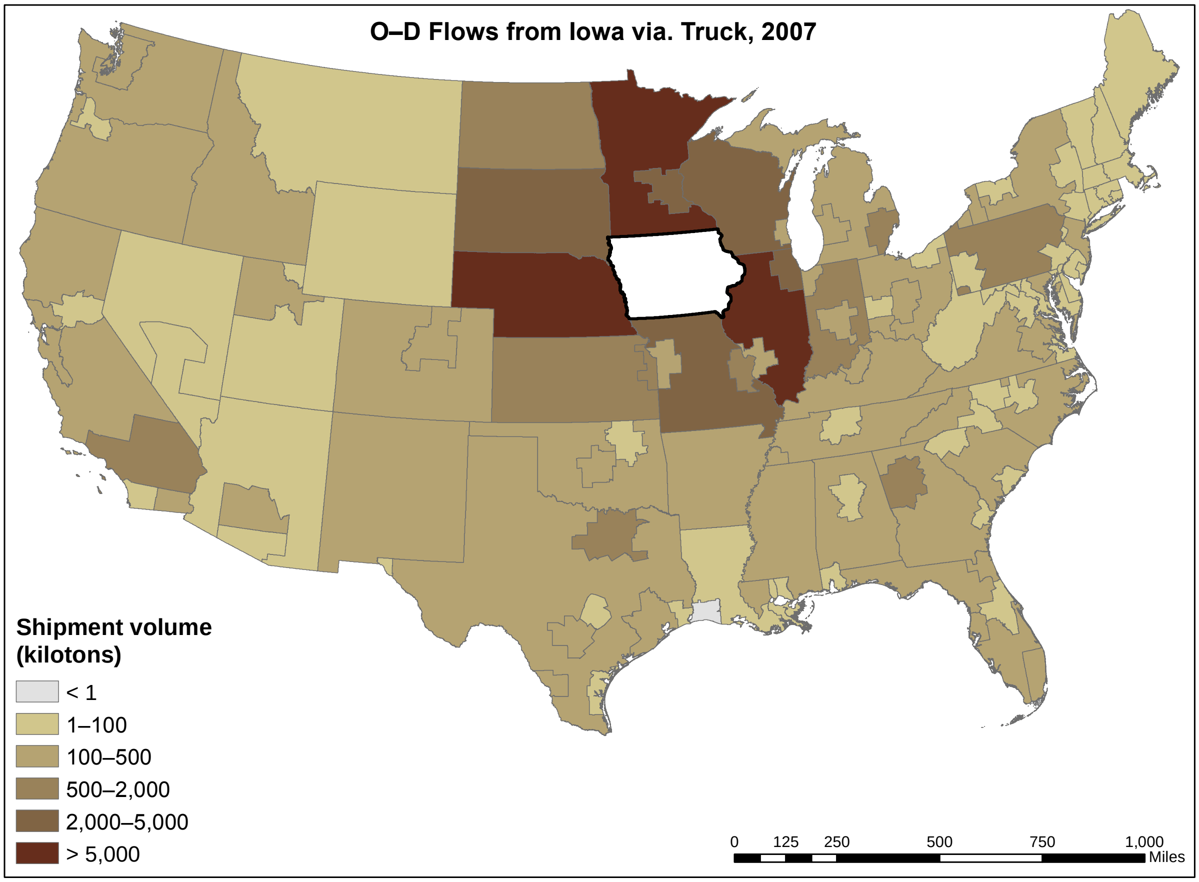
Among the commodity flow, around 88% of all commodities were carried by trucks, about 7% were carried by rail, and 3% were carried by multiple modes, as in the case of mail. Airways and other modes carried some precision instruments but rarely carried any agricultural products. Iowa as an origin exported various commodities, including cereal grains, gravels, animal feed, and other commodities, to the major destinations of Illinois, Minnesota, and Nebraska. The quantities of various commodities exported from Iowa in 2007 by all modes are shown in Figure 11.



FAF3 FHWA

Figure 11. Quantity of commodities exported from Iowa by all modes in 2007

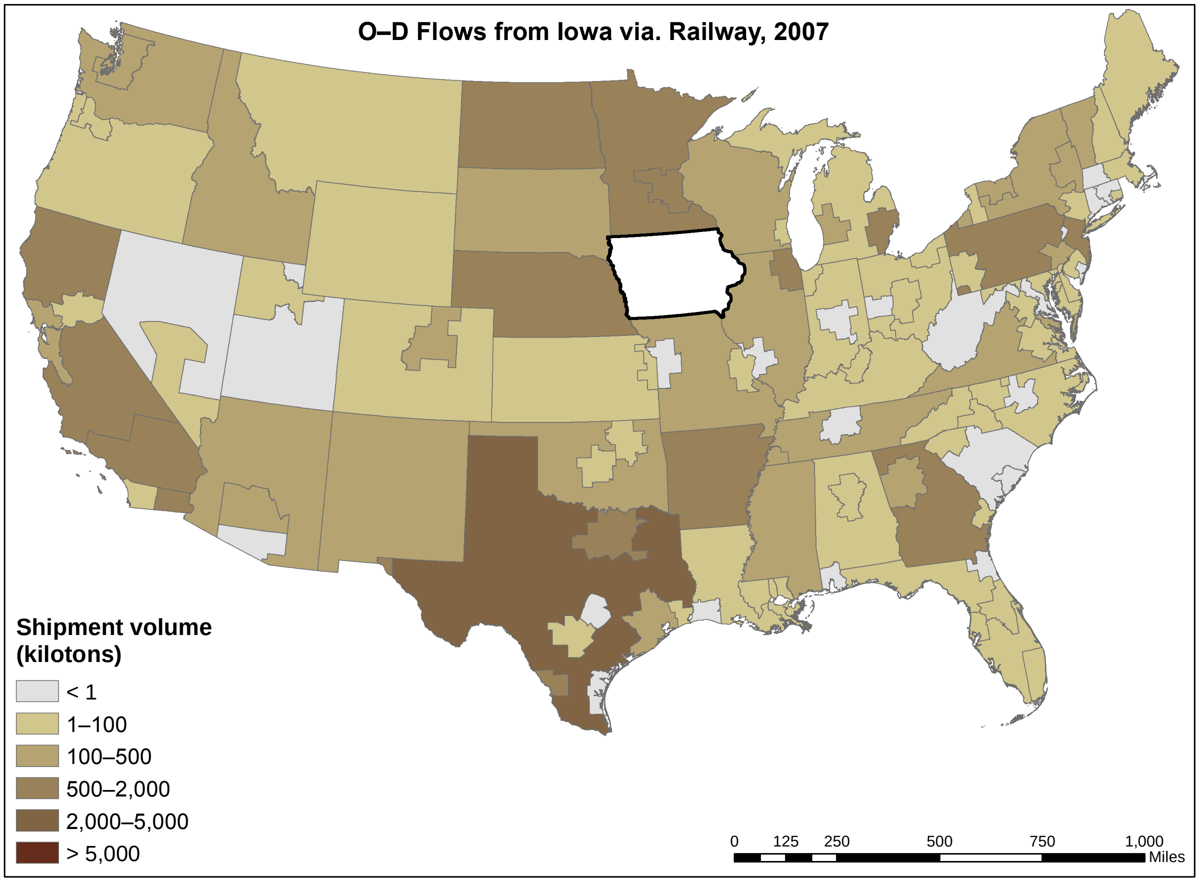
Specifically, trucks carried the majority of commodities, such as building stones, coal, crude petroleum, live animals, logs, and tobacco, to the nearest states (Illinois, Minnesota, and Nebraska). The quantities of various commodities exported from Iowa in 2007 by truck are shown in Figure 12.



FAF3 FHWA

Figure 12. Quantity of commodities exported from Iowa by truck in 2007

Rail tended to carry most of the alcoholic beverages for longer trips to Arkansas, California, Georgia, New York, and Texas. The quantities of various commodities exported from Iowa in 2007 by rail are shown in Figure 13.



FAF3 FHWA

Figure 13. Quantity of commodities exported from Iowa by rail in 2007

Waterways were used to transport commodities from Iowa to Alabama, Illinois, and New Orleans, Louisiana, along the Mississippi River, carrying mainly agricultural products such as cereal grains. The quantities of various commodities exported from Iowa in 2007 by water are shown in Figure 14.

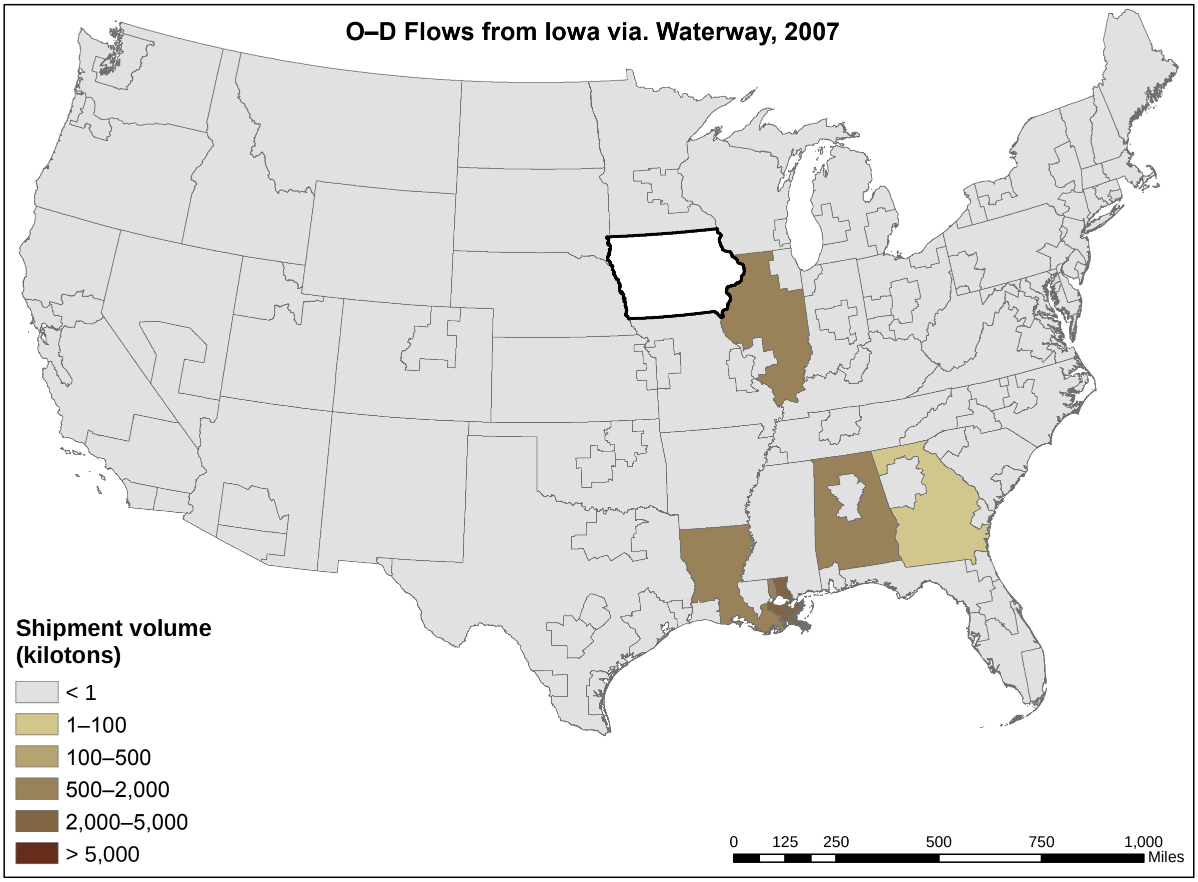


Figure 14. Quantity of commodities exported from Iowa by water in 2007

For the case study, a single commodity was chosen to simplify the model. After examining the FAF3 dataset, cereal grains was chosen because there is a significant volume of cereal grains shipped on all three modes examined in the analysis: rail, road, and water. After cereal grains was chosen, ArcGIS was used to visualize the overall volume of shipments to a specific region by ton-miles. Some regions had very small overall volumes. The FAF3 dataset has a single region for each state, except for large metropolitan areas, which are separated into their own regions. A metropolitan area spanning multiple states is split into different regions at state lines. To reduce the number of zones, similar regions were aggregated. Low-volume destinations were grouped with higher volume ones so the volumes of goods were comparable between regions. Also, metropolitan areas that span multiple state boundaries were kept together. Figure 15 details which routes were grouped together and the 2007 mode share according to FAF3.

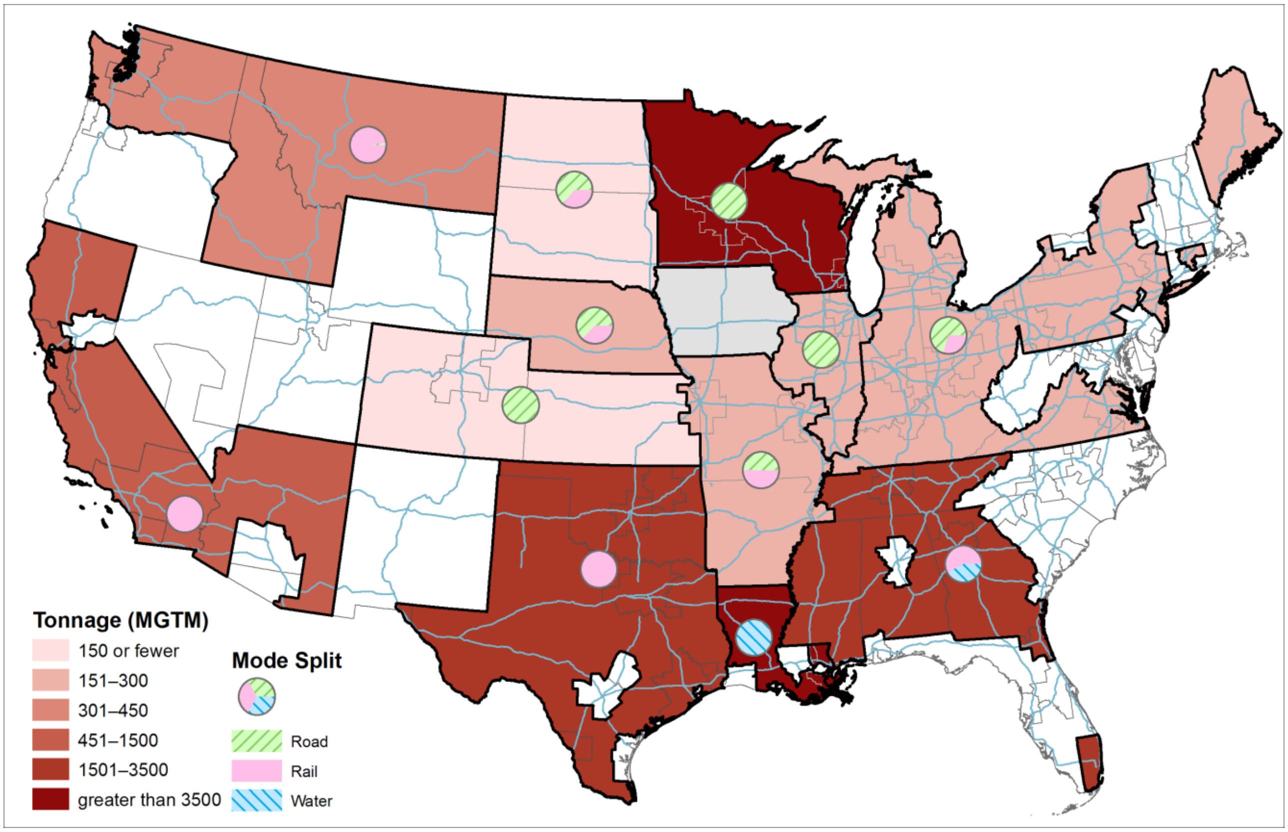


Figure 15. Overview of aggregated destinations and modal shipment volumes of cereal grains

As stated, for each destination a variety of routes was created between the centroids of the destinations. The centroids of the destinations were weighted based on the tonnage shipped to each zone and manually moved to be near Interstates and railways. On some occasions, Chicago (rail and road) and St. Louis (inland waterway) were used as hubs. For instance, all road or rail routes to the northeastern U.S. zone (centroid near Cleveland) pass through Chicago. Therefore, all road and rail routes to this zone are a combination of a rail or road route to Chicago and then a road or rail route to Cleveland. Figure 16 shows two examples of routings between destinations.

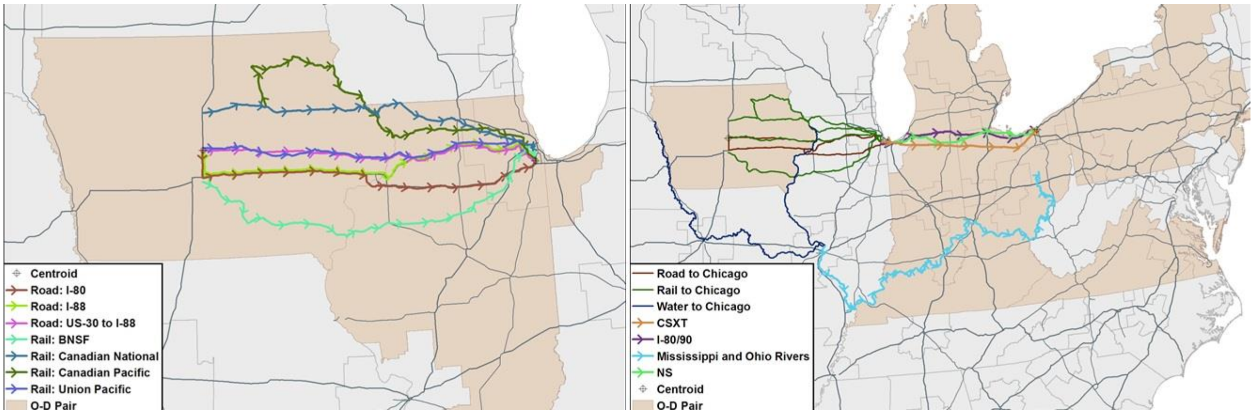


Figure 16. Examples of network routes, with routes to the Illinois region (left) and routes to the northeast region (right)

5.2 Commodity Flow

Three disruptions were modeled in the case study. Each disruption affected a different mode more than others.

5.2.1 Mississippi River Lock Delays

It is not unprecedented for extreme drought or extreme flooding to cause lock closures along the Mississippi River. The top left map in Figure 17 shows this disruption scenario. In this case, a few alternatives exist for shipping:

- Delay shipment until the disruption ends
- Divert traffic to truck
- Divert traffic to rail
- Divert traffic to the Missouri River
- Use road or rail to enter the Mississippi River from farther south

Diverting is not always an option. Shipping by truck is usually an option, but it costs much more than any other of the modes under consideration. Rail is not accessible to all shippers in Iowa due to the regional nature of the rail lines. The Missouri River is not a good option for shipments originating from the east side of the state because it requires rerouting barges from the Mississippi River (to a smaller channel that cannot handle as large of vessels as the Mississippi River).

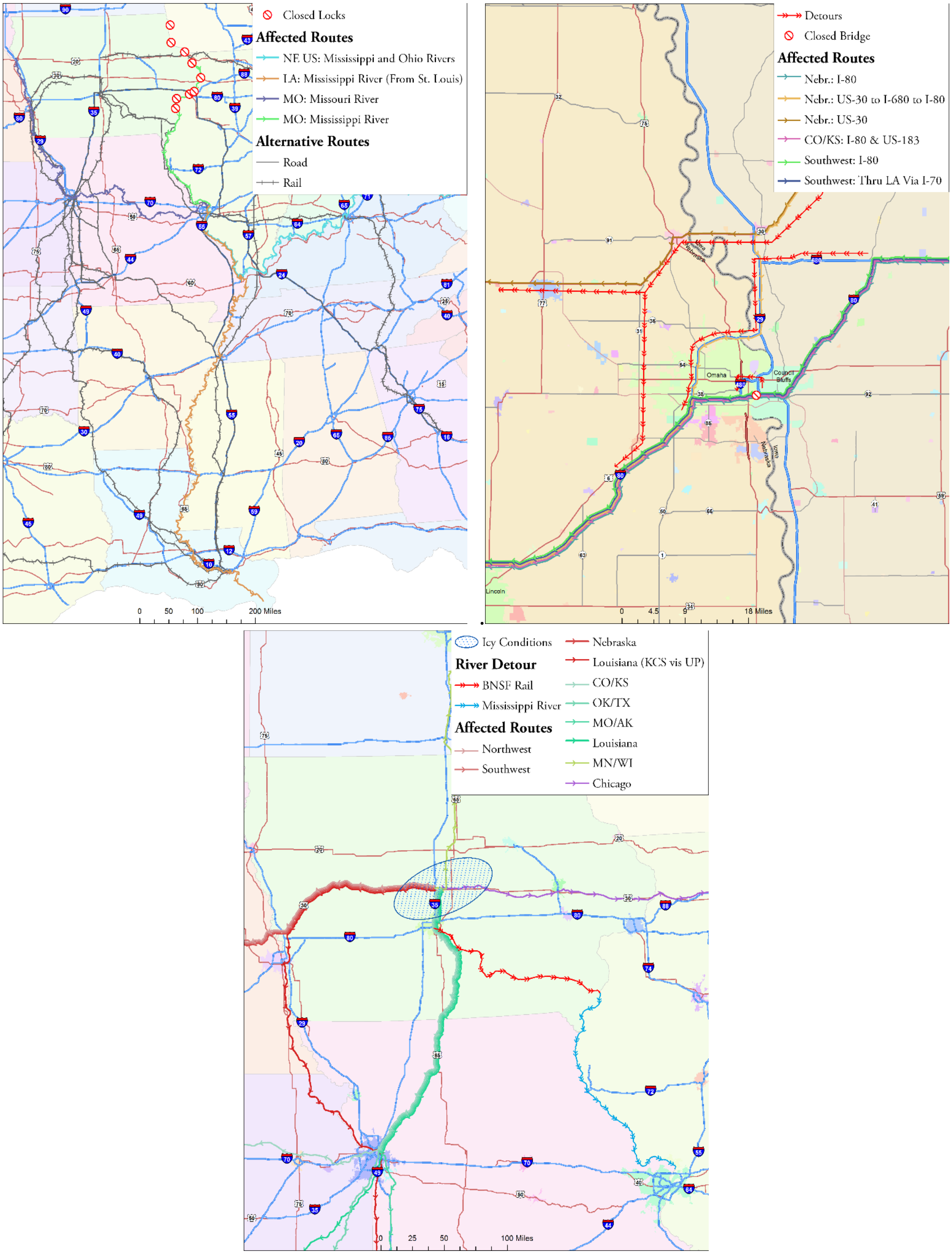


Figure 17. Mississippi River lock closure disruption (upper left), I-80 bridge closure disruption (upper right), and central Iowa rail closure disruption (bottom)

5.2.2 I-80 Bridge Closure

The I-80 bridge over the Missouri River between Omaha, Nebraska, and Council Bluffs, Iowa, is a critical part of the I-80 corridor. Construction on the bridge or closure due to flooding or other severe weather events would cause major disruptions to transportation in the area. The upper right map in Figure 17 details this disruption. Compared to other modes, roadways are able to accommodate diversion easily to another route. However, there are capacity constraints throughout the Omaha–Council Bluffs metropolitan area. These constraints will cause significant delay during peak-hour periods. The diverting routes include the following:

- I-480 with eight lanes
- I-680 with four lanes
- US 30 with two lanes

5.2.3 Central Iowa Rail Closure

Two major Union Pacific railway lines cross just outside of Ames, Iowa. Rail travel is particularly susceptible to disruption from winter storms. In the event of a winter storm, Union Pacific might have to close its railroads. A number of alternatives exist (detailed in the map at the bottom of Figure 17), including the following:

- Divert to another railroad
- Divert to road
- Divert to water
- Delay shipment

Similar to the first disruption scenario, diverting to other modes is not always possible. Other rail carriers and waterways may be located too far away, and trucking may be too costly.

5.3 Terminal Queuing Model

The performance of the freight transportation network is evaluated using the proposed dynamic queuing network model.

5.3.1 Delay at Locks

Travel time was calculated based on the observation of arrival and departure times of vessels at each lock for a one-month period. The system performance is determined by the operations of the servers (11 locks). The operation of each server (i.e., lock) is modeled as an M(t)/M/1 queuing system. The arrival rate for the base scenario (i.e., normal operations) is assumed to be fixed. For the two proposed scenarios, the arrival rate is assumed to follow a non-homogeneous Poisson process. In other words, the arrival rate changes over time. The service rate is assumed to be constant for the entire study and is calculated based on U.S. Army Corps of Engineers data.

To demonstrate the effect of non-stationary arrivals on the system performance, both steady-state and dynamic queuing models are applied to calculate the average number of shipments at Locks. As shown in Figure 18, two different arrival patterns were assumed for disruption scenarios.

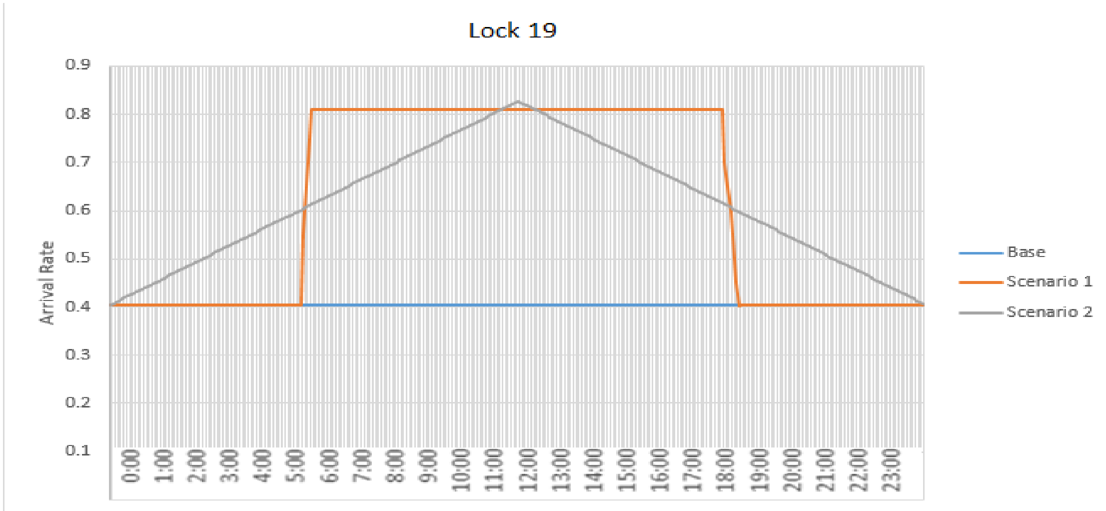


Figure 18. Arrival rate at Lock 19 for three different scenarios

In the first scenario, we assumed that the arrival rate doubles from 6 a.m. to 6 p.m. For the second response scenario, the arrival rate gradually increases to double and then decreases to the normal condition. The total arrivals in these two scenarios are equal. The difference is in the arrival rate during the time horizon. The average number of shipments (see Figure 19) and the average delay (see Figure 20) were calculated for each 5 minute interval for a 24 hour planning horizon.

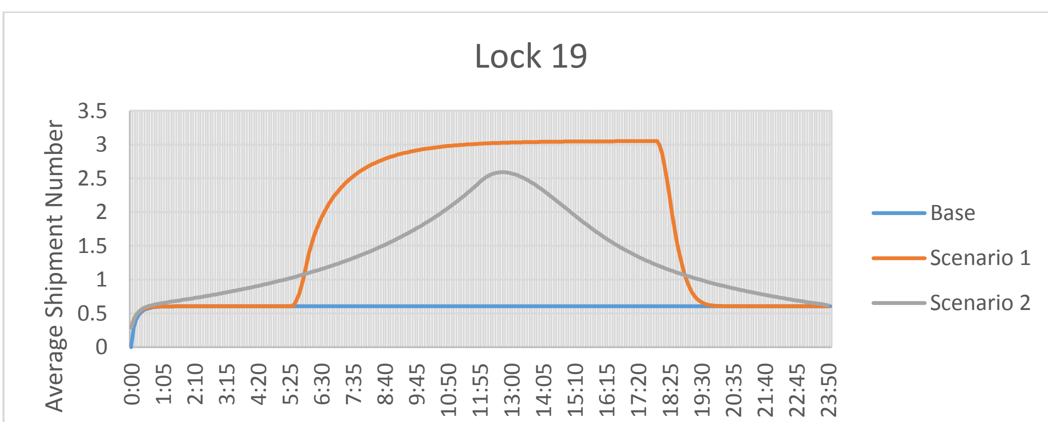


Figure 19. Average number of shipments at Lock 19 for three different scenarios

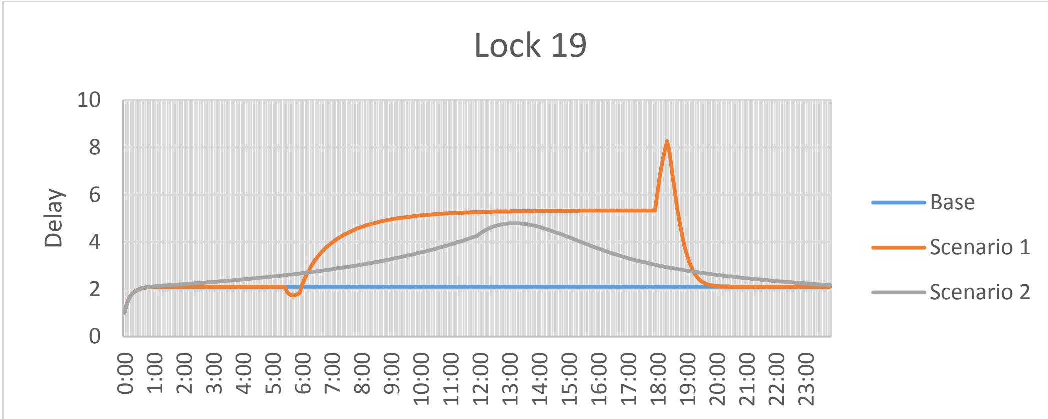


Figure 20. Average delay at Lock 19 for three different scenarios

Tables 4 through 6 show the effect of disruption on the total travel time of vessels under the disruption scenarios compared to the real-world locks' operation.

Table 4. Performance of Locks 15 through 19 under normal conditions

Lock	Arrival time at lock	Delay time at lock	Lock's average service time	Average travel time to next lock	Total time
Lock 15	12:00 p.m.	1:22	0:52	6:18	8:32
Lock 16	8:32 p.m.	1:00	0:37	2:25	4:12
Lock 17	12:44 p.m.	1:19	0:57	5:53	8:09
Lock 18	8:30 a.m.	1:19	0:47	7:26	9:32
Lock 19	6:23 p.m.	2:06	1:19	–	3:25
Release time from lock 19	9:50 p.m. the next day		**Total travel time**		33:50

Table 5. Performance of Locks 15 through 19 under Scenario 1

Lock	Arrival time at lock	Delay time at lock	Lock's average service time	Average travel time to next lock	Total time
Lock 15	12:00 p.m.	2:11	0:52	6:18	9:21
Lock 16	9:21 p.m.	1:52	0:37	2:25	5:04
Lock 17	2:25 a.m.	1:30	0:57	5:53	8:20
Lock 18	10:45 a.m.	2:00	0:47	7:26	10:13
Lock 19	8:58 p.m.	6:00	1:19	–	7:19
Release time from lock 19	4:17 a.m.		**Total travel time**		40:17

Table 6. Performance of Locks 15 through 19 under Scenario 2

Lock	Arrival time at lock	Delay time at lock	Lock's average service time	Average travel time to next lock	Total time
Lock 15	12:00 p.m.	1:42	0:52	6:18	8:52
Lock 16	8:52 p.m.	1:25	0:37	2:35	4:37
Lock 17	1:29 a.m.	1:15	0:57	5:53	8:05
Lock 18	9:34 a.m.	1:34	0:47	7:26	9:47
Lock 19	7:21 p.m.	4:00	1:19	-	5:19
Release time from lock 19		12:40 a.m.	**Total travel time**		35:40

A case was simulated in which a vessel arrives at 12 p.m. at Lock 15, waits in the queue, and is released after being served. Service time is considered fixed, and delay is calculated using the dynamic queue model. After being served, the vessel starts to travel to the next lock. The average travel time is added to the total delay for each server. As shown in Tables 4 through 6, increasing the arrival rate in Scenario 1 (see Figure 18) resulted in a significant delay, and the peak delay occurred around 30 minutes after a 12 hour increasing arrival rate. On the other hand, gradually increasing the arrival rate resulted in a bell-shaped graph, and the maximum delay occurred 50 minutes after the time that the arrival rate became two times greater than in the base scenario.

5.3.2 Delay at Rail Yards

Similarly, the delay at rail yards during a disruption can estimated using the dynamic queuing model. Under normal operations, we assume that the total time spent at the yard is 24 hours, according to the rail performance measures website (http://www.railroadpm.org). Lin and Cheng (2011) noted that the majority of time that rail cars spent in terminals (up to 77% of total dwell time) is idle time waiting for the next step in the process. In this study, we assumed 13 hours of idle time, 56% of dwell time, for each train.

5.4. Results

This section presents the estimated changes that could be expected for different detours and mode switches for the three disruptions in the case study. All times given are in hours. The cost changes are in U.S. dollars per ton of cargo.

5.4.1 Mississippi River Lock Delays

In this disruption, mode share logistic regression was used to calculate the share of road vs. rail for the Louisiana/New Orleans destination because, prior to the disruption, all traffic to this destination was over water. The logistic model predicts a share of 4.8% over road and 95.2% over rail when water is not available. This lines up well with nearby destinations, which use rail exclusively and do not use roads (Texas/Arkansas and the southeast U.S.; see Figure 15).

Table 7 contains the different cost and time differences for the options previously identified. The increases and decreases are compared to the normal operation conditions.

Table 7. Estimated change to shipment time and cost for Mississippi River disruption

	Option	Time change	Cost change
Louisiana	**Delay shipment**	Length of disruption	Minimal
	Divert to road	Decrease 90%	Increase 1,100%–1, 200%
	Divert to rail	Decrease 50%–80%	Increase 57%–100%
	Divert to Missouri River	Increase 23%	Increase 24%
	Rail to St. Louis	Decrease 60%	Increase 25%
Southeast U.S.	**Delay shipment**	Length of disruption	Minimal
	Divert to road	Decrease 90%	Increase 1,200%–1,400%
	Divert to rail	Decrease 50%-70%	Increase 45%–110%
	Divert to Missouri River	Increase 21%	Increase 22%
	Rail to St. Louis	Decrease 58%	Increase 23%

Overall, the routes affected by this disruption have longer distances. This makes completing the entire trip via road or rail more expensive. Therefore, it is usually more cost-effective to either divert to the Missouri River or use another mode to reach a terminal farther south. However, many shippers do not have many alternative options due to location and other factors. For these shippers, the cheapest option in terms of cost and time may be to wait until the end of the disruption, especially if the duration is known beforehand.

5.4.2 I-80 Bridge Closure

This disruption affects roadways, so very little traffic will divert to other modes because the change in time for the disruption is much less than the change in time to switch modes. Figures 21 through 23 and Tables 8 through 10 contain the differences in travel time for the three identified travel times when compared to the detour from the start of each corresponding detour to the end for free-flow, 2007 peak-hour, and 2040 peak-hour scenarios. Note that traffic throughout the Omaha–Council Bluffs metropolitan area is currently very congested; during the disruption, travel times are likely to be closer to 2040 peak for the detours due to the increased volume on these already congested highways.

I-480

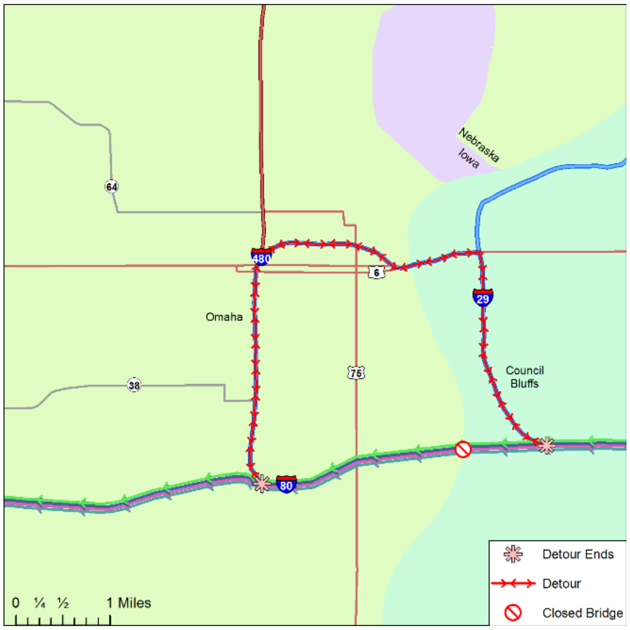


Figure 21. I-480 detour detail

Table 8. I-480 detour results

Travel Time	Normal Route	Detour
Free-flow	0:03	0:08
2007 Peak	0:55	2:30
2040 Peak	8:32	12:39
Total length	3.33 miles	4.75 miles

I-680

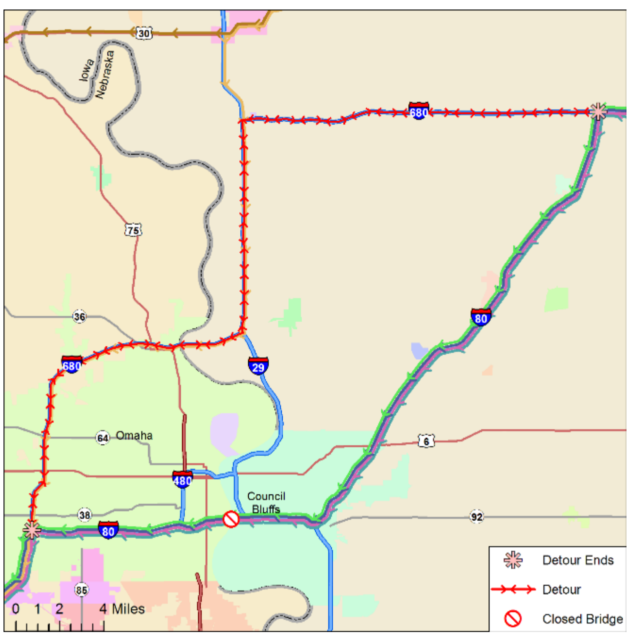


Figure 22. I-680 detour detail

Table 9. I-680 detour results

Travel Time	Normal Route	Detour
Free-flow	0:35	0:38
2007 Peak	7:19	2:21
2040 Peak	10:52	10:43
Total length	37.13 miles	42.49 miles

US 30

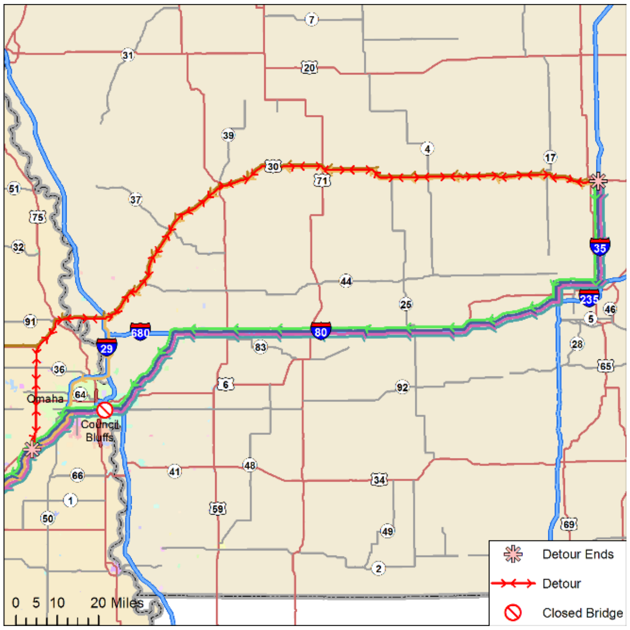


Figure 23. US 30 detour detail

Table 10. US 30 detour results

Travel Time	Normal Route	Detour
Free-flow	2:45	3:30
2007 Peak	11:57	3:37
2040 Peak	19:15	3:58
Total length	184.58 miles	173.77 miles

5.4.3 Central Iowa Rail Closure

Table 11 contains the expected changes for the identified options for this disruption. The table is split per destination and mitigation option. The cost and time changes are arrived at by comparing to base conditions. The option that makes the most sense from a numerical standpoint for many destinations is to divert to another rail carrier. The change in cost and time for this option will be marginal. However, another rail carrier is not always an option due to accessibility issues. Delaying shipment for a short-term disruption (less than a week) would result in a time increase less than that of using a waterway. However, the longer the disruption, the more attractive a waterway is as a mode. Even just shipping to St. Louis to offload onto other Union Pacific tracks has a relatively low cost and moderate delay.

Table 11. Approximate change to shipment time and cost for central Iowa rail closure

Destination	Option	Time change	Cost change
All	Delay shipment	Length of disruption	Minimal
Northwest U.S.	Divert to other rail operator*	Increase 16%	Decrease 1%
	Divert to road	Decrease 65%–75%	Increase 500%–650%
Southwest U.S.	Divert to other rail operator	Increase 28%	Increase 22%
	Divert to road	Decrease 65%	Increase 700%–775%
Colorado & Kansas	Divert to road	Decrease 45%–90%	Increase 650%
Texas & Oklahoma	Divert to other rail operator	Increase 30%	Increase 18%
	Divert to road	Decrease 75%	Increase 750%
Nebraska	Divert to other rail operator	Increase 30%	Decrease 10%
	Divert to road	Decrease 85%–90%	Increase 725%–800%
Minnesota & Wisconsin	Divert to other rail operator	Increase 128%	Increase 17%
	Divert to road	Decrease 67%	Increase 650%
Missouri & Arkansas	Divert to other rail operator	Decrease 12%–50%	Increase -5%–20% Decrease 20%
	Divert to road	Decrease 45%–90%	Increase 615%–715%
Louisiana	Divert to other rail operator	Increase 12% Decrease 50%	Increase 0%–23%
	Divert to road	Decrease 85%	Increase 600%
	Divert to waterway	Increase 83%–125%	Decrease 50%–60%
Illinois	Divert to other rail operator	Increase 5%–20%	± 5%–10%
	Divert to road	Decrease 85–90%	Increase 731%–800%

* Only takes into account the differences in cost for shipments starting with a new carrier. Does not take into account the cost of switching shipments from one carrier to another.

CHAPTER 6. CONCLUSIONS

Modeling the freight transportation network under disruption is one of the most challenging issues for the transportation system. Lack of available data, insufficient time for decision making, and limited tools make addressing this challenge difficult. However, with an emphasis on effectively and efficiently estimating time varying, non-stationary terminal delays in the freight transportation network under abrupt disruption due to artificial or natural disasters, this study adapts an analytical, point-wise, fluid-based approximation method to develop an intermodal freight network model. This network model is a dynamic queuing network, where terminals and locks are considered to be the Mt/M/1 queuing servers connected by highway, railway, and waterway links. Given the time-dependent O-D demands of shipments and their paths through the network, the proposed network model, consisting of fluid balance, exit flow, and capacity utilization ratio equations, aims to estimate the queuing delay of shipments at the servers. The results show that, for the same amount of arrivals, gradually increasing the flow would be expected to generate less delay at terminals than if the flow were suddenly increased.

Nonetheless, considering the cost of shifting the shipments to other modes, as well as the amount of time that it takes for loading/unloading the shipments to the new mode, waiting until the end of the disruption is another possible option for short-term disruptions.

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