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Identifying the shortest log trucking routes and optimizing those constrained by low-weight bridges in Mississippi

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Timber haulage in Mississippi incurs the greatest portion of logging expenses because of a myriad of closed and posted (restricted) bridges. This study utilized Dijkstra's algorithm method in ArcGIS Pro to derive 129 feasible shortest optimal trucking routes between 46 harvest sites and 32 softwood sawmills in Mississippi. Among these routes, 30 of them had restricted bridges along the way; however, only 13 viable alternative routes were identified due to distance and weight restrictions. The additional trucking distance for alternative routes ranged between 1.5 to 12.9 miles, whose effect on transportation cost was determined using a Mixed Integer Linear Programming optimization model incorporating weight limits of the restricted bridges. Restricted bridges along optimal routes resulted in an additional transportation cost of $4.09 million, representing a 4.07% increase in total transportation cost or 0.34 per ton of softwood sawlogs transported. All these cost increases were exclusive to softwood sawlogs.

Keywords: Network Analysis, Logging Operations, Optimization, Transportation

DEDICATION

To my family for their endless love, support, and inspiration throughout my life and academic journey.

To my advisors for sharing their expertise and knowledge and pushing me to grow both intellectually and personally.

To my friends for their constant love and support throughout this journey.

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CHAPTER I

INTRODUCTION

1.1 ECONOMIC IMPORTANCE OF THE FORESTRY SECTOR

Many countries rely on the forest sector at the national, regional, and local economic levels (Rönnqvist 2003). These industries produce thousands of products ranging from paper to furniture and generate significant economic benefits from forest product trade (Rönnqvist 2003; Sun and Zhang 2018). Between 1996 – 2016, the United States exported forest products worth an average of $31.5 billion annually (Sun and Zhang 2018). During the same period, the country imported forest products worth an average of $67.5 billion per year. More recently, in 2019 and 2020, the United States exported forest products amounting to $36.8 and $33.5 billion, while importing $44.4 and $44.6 billion respectively. (USITC 2021).

The forestry sector contributes more than $200 billion annually in the United States (Oswalt 2021). The Southern and Pacific Northwestern regions of the United States are major timber producers and harvesters, economically benefitting the stakeholders involved in the timber supply chain (Oswalt et al. 2019; Jessup et al. 2022). Forestry in the US South employs over a million people and accounts for around 2% of the gross regional product (Brandeis and Hodges 2015). Mississippi relies on the forestry sector for its economic growth, development, and sustainability (Brandeis and Hodges 2015; Pelkki and Sherman 2020). In 2018, forest-based industry in Mississippi generated more than $13.12 billion, approximately 5% of the state’s GDP for that year (Tanger and Measells 2020). In the same year, this sector provided 69,600 jobs that generated more than $2.96 billion as income.

1.2 TRANSPORTATION COST PROBLEM IN THE FORESTRY SECTOR

In the southern US, more than 200 million tons of softwood and hardwood timber are harvested annually (Oswalt et al. 2019), which is hauled to processing mills by log trucks. Mississippi alone harvested over 15 million tons of pine sawtimber in 2020 and 2021 (Auel 2021; Measells and Auel 2022). Like any other industry, this sector faces challenges that include efficient resource allocation, vehicle routing/scheduling, and escalating transportation costs (Audy et al. 2011). Particularly, efficient transportation of raw materials from harvest areas to processors and associated high transportation costs are serious worldwide issues (Palmgren et al. 2003; Mokhirev et al. 2019).

Raw material transportation occupies the largest portion of the overall operational cost in the forest industry worldwide (D’amours et al. 2008; Audy et al. 2022). This cost represents about 36% of the total operational cost in Canada (Michaelsen, 2012 as cited in Audy et. al., 2012), 25-35% in the southern US (Greene, 2012 as cited in Audy et. al., 2012), and 40-60% in Mississippi (Grebner et al. 2005). From 2018 – 2021, transportation costs in Mississippi’s forestry sector constituted about 46 – 52% of total expenses (Auel 2019, 2020, 2021; Measells and Auel 2022). Mississippi’s timber gate value was $1.15 billion, which includes $504.5 million for raw materials acquisition and $644 million to harvest and transport it to the processors in 2018 (Auel 2020). It was $1.12 billion – $ 537 million for the purchase of raw materials and $590 million to transport them in 2021 (Measells and Auel 2022). This implies that minimizing transportation costs is one way to help logging operators accrue huge savings (Palmgren et al. 2003). Moreover, due to its high proportion of the total cost, transportation costs might soon be a constraint in the forestry sector (Reddish et al. 2011; Conrad 2018). Thus, it is imperative to reduce this cost to increase profitability and ensure the sustainability of this critical link in the timber supply chain (Rönnqvist 2003).

1.3 FORESTRY TRANSPORTATION COST MINIMIZATION APPROACH

The application of optimal routing and optimization techniques, either individually or in combination with one another, help in minimizing forestry transportation costs (D'amours et al. 2008; Keramati et al. 2018; Simões et al. 2022). Most forestry transportation studies place emphasis on developing transportation cost minimization models (Malladi and Sowlati 2017). These models facilitate optimal resource allocation and ideal route selection among the available options for the efficient and cost-effective delivery of raw materials (Lotfalian et al. 2022). As a result, their application is increasing in the forestry sector to solve transportation routing problems (Carlsson and Rönnqvist 2005). However, gaps still exist in forestry transportation studies. For instance, the presence of numerous closed and weight-restricted, or "posted," bridges in Mississippi lead to higher transportation costs. According to 2022 National Bridge Inventory (NBI) data from the Federal Highway Administration (FHWA), 6.5% of bridges in Mississippi (1,097 out of 16,782) are structurally deficient. Another 2,685 bridges are posted to lower weight limits (ARTBA 2023). Similarly, the Mississippi Department of Transportation (MDOT) reported that out of 5,825 state-maintained bridges, 159 are in poor condition, and 311 are either closed or posted (MDOT 2023). Ganucheau (2018) stated that around 200 bridges in Mississippi were posted in 2018, which increased transportation costs because hauling trucks had to take longer alternative routes from their source to reach their destination. This is a pressing challenge for the logging sector and requires immediate attention. While numerous transportation cost minimization models aim to reduce forestry transportation costs, failing to incorporate bridge weight limits represents an identified gap. Considering the large number of structurally deficient bridges in Mississippi, it is critical, yet pragmatic, to include a bridge weight limit-related variable in transportation cost optimization models to determine their impacts on achieving or failing to achieve minimum transportation cost. Therefore, this research aimed to investigate the trade-offs associated with bridge weight limits within the context of minimizing transportation costs in Mississippi's forestry sector. An optimization model that considers bridge weight limits was developed to achieve this goal.

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CHAPTER II

IDENTIFYING THE SHORTEST LOG TRUCKING ROUTES BETWEEN HARVEST SITES AND SOFTWOOD SAWMILLS OF MISSISSIPPI

2.1 INTRODUCTION

Optimal routing is a spatial-level, decision-making process that determines the most cost-effective route between two locations (Rönnqvist 2003). It is more complex than shortest route identification as important variables like road types and conditions, traffic conditions, weight limits, etc., must also be considered (Shahrier and Hasnat 2021). Optimal routing can be conducted by performing "Network Analysis" in a Geographic Information System (GIS) system (Akay et al. 2006; Harouff et al. 2008). This chapter discusses the application of GIS to determine the optimal trucking route between harvest sites and softwood sawmills (hereafter referred to as sawmills or mills interchangeably) and the implications of bridge conditions on route optimization. Here, the optimal routes are the derived shortest route between individual harvest sites and sawmill pairs (hereafter referred to as pairs), while adhering to road types, conditions, and weight limits on both roads and bridges.

GIS-based technology is widely applicable in forest operations, management, and logistics due to its effectiveness in mapping, processing, and analyzing spatial data (Gumusay and Sahin 2009; Wing et al. 2010). Additionally, advancements in GIS technology have enabled their applicability to solve complex analyses, including spatial problems related to transportation (Sakar 2010). Environmental Systems Research Institute, Inc (ESRI)'s ArcGIS product –

ArcGIS Desktop (and has now migrated to ArcGIS Pro) has a built-in powerful extension, “Network Analyst,” that can perform a wide range of network-based spatial analyses, like optimal routing, for solving transportation and routing problems (ESRI n.d. -a, n.d. -b, n.d. -c).

The “Network Analysis” extension in ArcGIS includes various tools such as “Closest Facility”, “Location-Allocation”, and “Origin-Destination (OD) Cost Matrix” to perform analyses associated with routing, travel directions, closest facility, and service area analysis (ESRI n.d -c. n.d -d.; Rodrigue et al. 2020). The “Closest Facility” tool calculates the desired number of closest facilities to a given incident based on travel time or distance and determines the best routes between them (ESRI n.d. -c. n.d. -d). Similarly, the "Location-Allocation” tool identifies the best locations for facilities to serve a set of demand locations. Likewise, the OD cost matrix tool determines the least-costly paths along the network from multiple origins to multiple destinations. Furthermore, these tools allow users to simulate realistic network conditions by allowing users to incorporate attributes like speed and weight limits, travel directions, etc. (ESRI n.d. -c) and therefore is beneficial for the fields reliant on logistics services. This extension with regards to the forest sector helps optimize the flow of harvested timber between the harvest location and the processing plants through optimal routing (ESRI n.d. -d; Akay et al. 2012) and reducing transportation costs (Akay et al. 2012).

Akay et al. (2012) used the “Closest Facility” tool to determine the optimal route for minimizing the transportation cost between harvest sites and forest depots in Turkey. This chapter employed Akay’s methodology to determine the optimal routes between 46 harvest sites and 32 active sawmills in Mississippi. The focus was to investigate the practical application of the “Closest Facility” tool in solving real-world forestry transportation problems and to provide a comprehensive explanation regarding the effective utilization of this tool. Although the shortest path is usually the ideal path for transportation, various factors like weight and speed restrictions, road classification, county-specific regulations, traffic congestion, and other related issues may render it unfeasible (Akay et al. 2012; Neumann 2014). Available timber resources within an economically feasible transportation range of processing facilities can be assessed by mapping these two points in GIS and analyzing the transportation network between them (Harouff et al. 2008). The “Network Analysis” extension can help determine the shortest path between the harvest areas and sawmills while complying with the legal weight restrictions to minimize transportation costs.

Due to the comprehensive road infrastructure in the United States, trucking is the predominant mode of timber transportation (Conrad IV 2018). Loggers in the Appalachian region perceive trucking as a limiting factor in forest operations, particularly for small-scale producers and landowners (Luppold et al. 1998). Escalating fuel costs and longer hauling distances demand better planning of transportation networks that connect forests to processors (Mendell et al. 2006). Trucking distance impacts transportation costs and efficiency; longer trucking distance results in higher variable costs (associated with labor, fuel, and maintenance) and lower transportation efficiency (Harouff et al. 2008). Similarly, weight restriction policies imposed by federal, state, and local governments on roads and bridges greatly impact transportation costs. Grebner et al. (2005) found that reducing Mississippi’s legal truck gross vehicle weight (GVW) limits by 6.4 tons increased hauling costs for new trucks, ranging from $2.38 to $7.68 per ton in 2005 ($3.73 to $12.05 in constant 2023 USD). For used trucks, it increased hauling costs ranging from $1.46 to $4.93 per ton in 2005 ($2.29 to $7.73 in constant 2023 USD). The constant USD was calculated by adjusting for inflation using Consumer Price Index (CPI) (U.S. Bureau of Labor Statistics 2023). The observed cost increment can be attributed to factors that include an increase in the number of truckloads needed for transporting raw materials or longer haulage distances and durations due to weight restrictions compliance.

2.2 OBJECTIVE

The general objective was to estimate the additional distance hauling trucks are required to traverse from the harvest location to sawmills because of the impediments (closed and posted bridges) along the shortest optimal trucking route.

The specific objectives are to:

- Identify the shortest optimal trucking route between the harvest areas and sawmills.
- Detect the impediments along those routes and determine the alternative routes that bypass these impediments.

2.3 MATERIALS AND METHODS

2.3.1 STUDY AREA

The study area established was the geographical area encompassing a 50-mile radius surrounding 32 active sawmills located in Mississippi based on information from the Mississippi Forestry Commission (MFC) *(https://www.mfc.ms.gov/)* and the Resource Information Systems Inc. (RISI) mill asset database *(https://www.lib.ncsu.edu/databases/risi-mill-asset-database)*. Data on harvest sites and bridges within this defined radius were gathered for analysis. The study area comprised a major portion of Mississippi, along with some parts of Alabama, Louisiana, Tennessee, and Arkansas. The rationale for choosing this specific area was their proximity within the harvesting distance of the selected sawmills. Its total size was 40.4 million acres (calculated using ArcGIS Pro). The study area is shown in Figure 2.1.

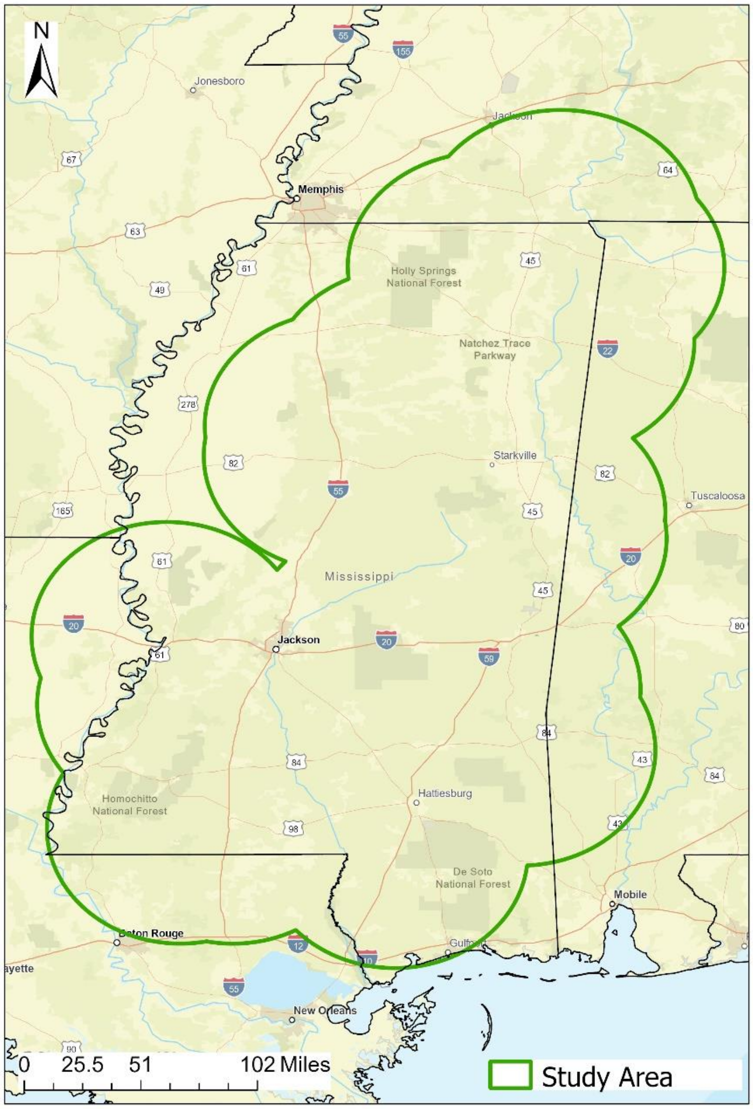

Figure 2.1 The study area used to determine the land base for haul distance to mills. The area represents buffered distances of 50 miles around each of the 32 active sawmills in Mississippi.

2.3.2 DATA

2.3.2.1 RESOURCE BASE DATASET

The resource data were downloaded from the USDA Forest Service FIA database *(https://apps.fs.usda.gov/fia/datamart/datamart.html)* for the years 2010 – 2020, which stores information in various tables like plot, tree, condition table, etc. The database does not provide immediate access to resource base data, and processing is required to obtain the relevant information. Therefore, the data were processed in "RStudio" using various functions under the "rFIA" package (Stanke and Finley 2021). Initially, the data were imported using the "readFIA" function. Next, the data were clipped to the extent of the study area using the "clipFIA" function (Stanke and Finley 2021). Then, plot-level information on trees Per Acre (TPA), Basal Area Per Acre (BAA), and volume per acre for the Southern Yellow Pines (*Pinus taeda* L., *Pinus echinata* Mill., *Pinus palustris* Mill.*, and Pinus elliottii* Engelm.) were extracted. The function, "tpa" was used to estimate the TPA and BAA, and the "volume" function was applied to calculate the merchantable tree volume. Among the multiple land types, "timber" was filtered to get information about the forestland with high site potential (producing at least 20 cubic feet per acre per year) and non-reserve status. Similarly, "gs" (growing stock) was selected under the treetype field as it contains information about the live stems with DBH greater than 5 inches from which at least one 8 ft merchantable log can be harvested. The volume type category "net volume" was filtered to acquire the tree's net volume, exclusive of rot and form cull. Additionally, "BOLE_CF_ACRE" was selected to get the estimate of mean merchantable bole volume per acre (Stanke and Finley 2021). Afterward, the output was filtered according to the "Operability" field in the condition table to determine the plots currently accessible for harvesting. In the final step, the output was again filtered according to the harvest type (HARVEST_TYPE1_SRS) in the condition table, from where clearcut or partially harvested areas were selected. This step provided a list of 208 plots, whose GPS locations were extracted using the "returnspatial" function. Figure 2.2 shows the location of all 208 plots within the study area, where the black border is the boundary, and the red squares represent the spatial location of all 208 FIA plots where the partial or clearcut had been conducted. The harvestable volume of the plots was provided in cubic feet per acre, which was converted into tons per acre using the USDA Forest Service conversion factor for standing pine timber as below:

$$Harvestable\ volume\ (tons\ per\ acre) = cubic\ feet\ per\ acre * \left(\frac{69\,\frac{lb}{ft^3}}{2000\ lb}\right) \tag{2.1}$$

Then, the plots with a minimum harvestable pine sawtimber volume of 26.8 tons per acre were selected as the harvest sites for further analysis, as the payload capacity of each truck was assumed to be 26.8 tons. Out of the *n* = 208 plots, only *n* = 46 plots met the above criteria and were identified as the "harvest area". Figure 2.3 shows the location of the FIA plots selected as the "harvest area." In the figure, green circles are the spatial location of the selected harvest sites. However, it should be pointed out that the publicly provided GPS coordinates for the FIA plots are not the plots' actual locations. They are fuzzed for privacy protection. The "fuzzing" of the plots' true positions is limited to one square mile (Stanke and Finley 2021).

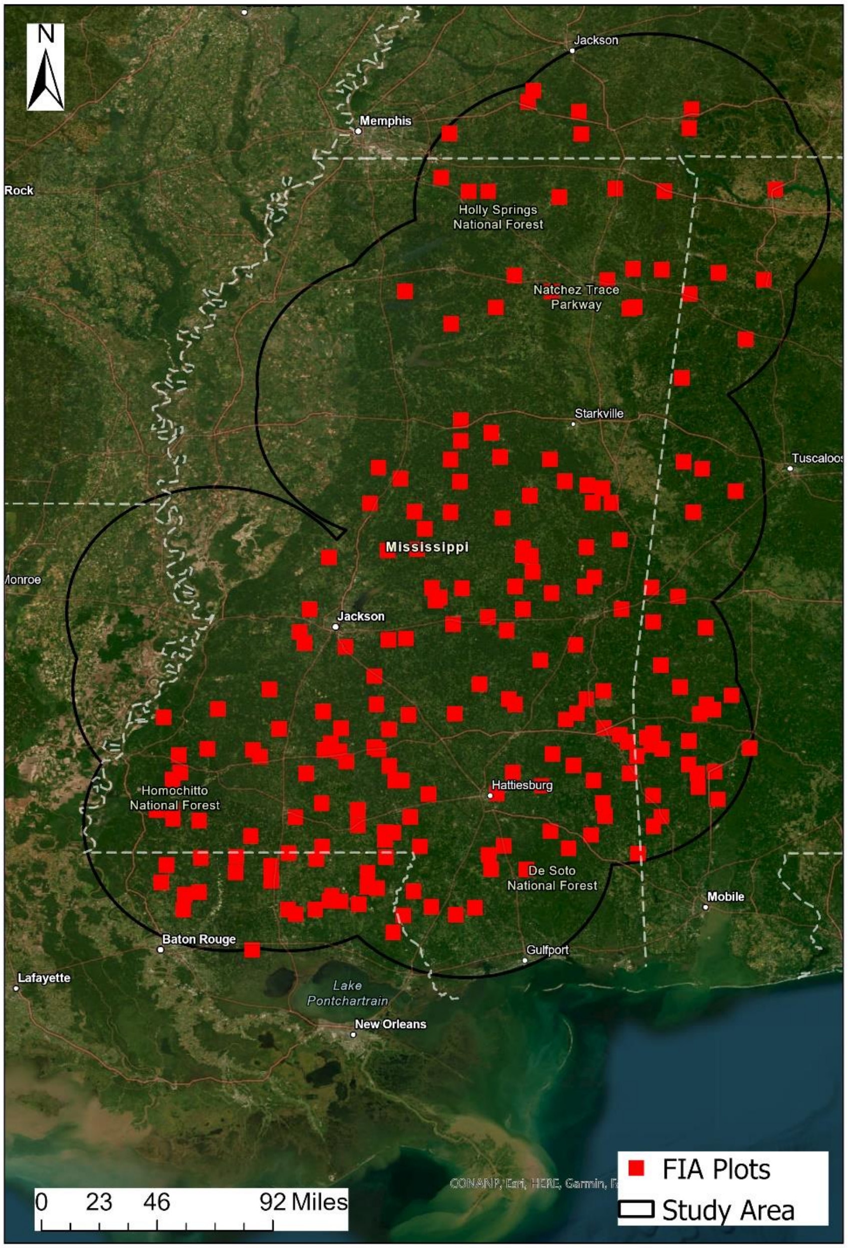

Figure 2.2 The spatial location of 208 FIA plots within the study area for the years 2010 to 2020, where clearcut or partial harvest has been carried out.

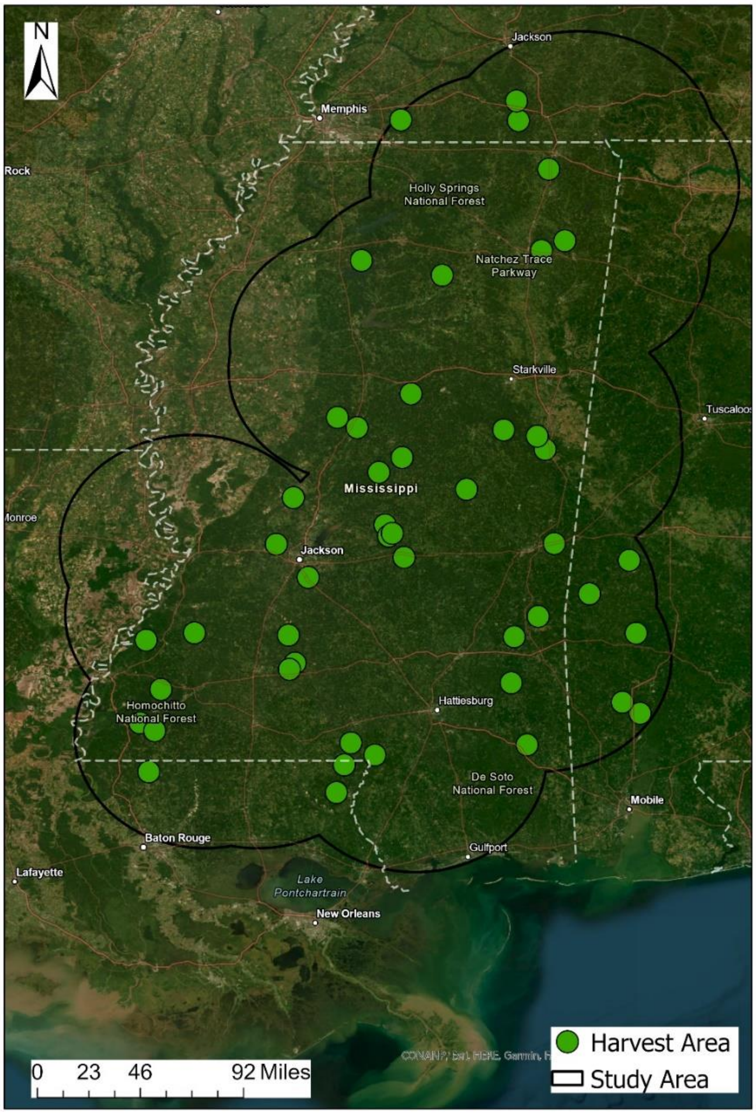

Figure 2.3 Location of all 46 FIA plots selected as harvest sites for the research.

2.3.2.1 SAWMILL INFORMATION

Along with the harvest site location, the sawmill location and the road network are pivotal to determining the optimal routes between those pairs. Sawmill information (including X and Y coordinates for each sawmill) was obtained from the Mississippi Forestry Commission (MFC) and the RISI mill asset database, and their locations were displayed in ArcGIS Pro.

Figure 2.4 shows the spatial location of the sawmills within Mississippi. The green area in the figure is the study area, and the symbol resembling industry is the location of the sawmills in Mississippi. The closest facility tool requires only sawmill and harvest site location. Sawmill demand information was also collected to facilitate further analysis aimed at identifying the optimal routes for each harvest site to sawmill pairs, to minimize total transportation cost. The dataset had sawmill demand, expressed as million board feet (MMBF) of lumber output and bone-dry metric tonnes per year (BDMT/Y). The BDMT/Y were converted into standard short tons as below:

$$Demand\ in\ Tons = MMBF * \left(\frac{1{,}000{,}000}{7.5}\right) * \left(\frac{63}{2000}\right) \tag{2.2}$$

where 7.5 was the assumed lumber recovery factor (board feet of lumber output per cubic foot of log input) and 63 was the pine scaling factor (pounds of wood plus bark divided by the volume of wood excluding the bark). The scaling factor was derived using loblolly pine's specific gravity of 0.47 (Forest Products Laboratory 2010), an assumed dry-basis moisture content of 100% (50% wet-basis), plus 10% for the bark's weight.

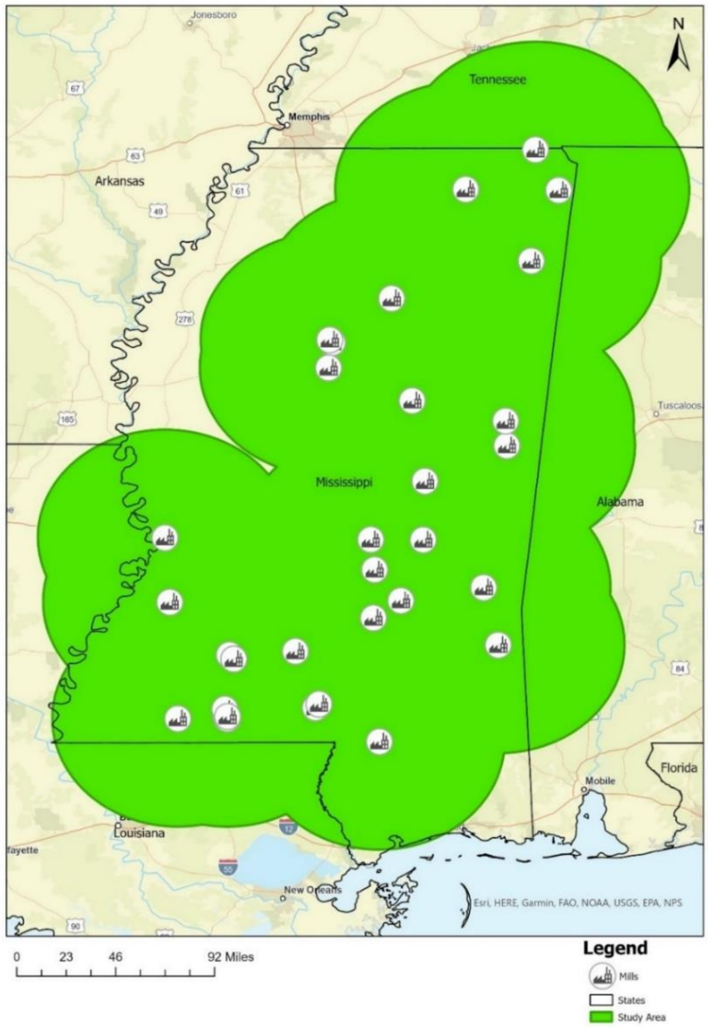

Figure 2.4 Study area map showing the spatial location of 32 active softwood sawmills in Mississippi.

Table 2.1 presents the list of sawmill names, accompanied by their respective latitude and longitude coordinates, and mill IDs utilized in the study.

Table 2.1 Name and XY-Coordinates of the selected sawmills along with the Mill ID used in the research as a unique identifier for each of the sawmills.

SN	Mill ID	Mill Name	Address	longitude	latitude
1	M0	Weyerhaeuser	Bruce	-89.346	33.986
2	M1	Weyerhaeuser	Mangolia	-90.460	31.171
3	M2	Weyerhaeuser	Philadelphia	-89.122	32.757
4	M3	Littrell Lumber	Luka	-88.223	34.713
5	M4	Bazor Lumber	Quitman	-88.727	32.044
6	M5	Interfor Corporation	Bay Springs	-89.284	31.956
7	M6	Hankins Inc	Ripley	-88.848	34.719
8	M7	Hankins Lumber	Elliott	-89.746	33.689
9	M8	Greentree Lumber Company	Liberty	-90.785	31.162
10	M9	Southeastern Timber Products LLC	Ackerman	-89.208	33.298
11	M10	Shuqualak Lumber Company	Shuqualak	-88.571	32.997
12	M11	Canfor Corp – Hermanville Plant	Hermanville	-90.840	31.946
13	M12	Rex Lumber	Brookhaven	-90.438	31.590
14	M13	Seago Lumber	McComb	-90.468	31.225
15	M14	Magnolia Lumber Co Inc.	Fernwood	-90.452	31.162
16	M15	W L Byrd Lumber	Fernwood	-90.450	31.176
17	M16	Lincoln Lumber Co.	Brookhaven	-90.409	31.562
18	M17	Foxworth & Thompson Lumber Co.	Foxworth	-89.860	31.236
19	M18	Rogers Lumber Corporation	Columbia	-89.835	31.260
20	M19	King Lumber Company	Forest	-89.488	32.365
21	M20	Georgia-Pacific Company	Taylorsville	-89.469	31.839
22	M21	Jack Batte & Sons Inc.	Forest	-89.461	32.162
23	M22	Barge Forest Products Co.	Macon	-88.580	33.162
24	M23	Tri-State Lumber Co.	Fulton	-88.408	34.238
25	M24	Biewer Lumber	Newton	-89.133	32.363
26	M25	Hood Industries Inc.	Waynesboro	-88.629	31.656
27	M26	Hood Industries Inc.	Silver Creek	-89.994	31.613
28	M27	Vicksburg Forest Products LLC	Vicksburg	-90.871	32.378
29	M28	Mission Forest Products	Corinth	-88.379	34.985
30	M29	Hankins Lumber	Grenada	-89.763	33.708
31	M30	Biewer Lumber	Winona	-89.726	33.525
32	M31	Idaho Forest Group	Lumberton	-89.430	31.007

2.3.2.2 ROAD DATASETS

The road dataset for the entire US was downloaded from the United States Census Bureau *(https://www.census.gov/geographies/mapping-files/time-series/geo/tiger-line-file.html)* and loaded into ArcGIS Pro as a road layer. The layer was then clipped to the extent of our study area using the "clip" function to reduce the dataset's size. The road layer contained information about all roads and streets, so it was necessary to identify the relevant road types for the project. The relevant road types, like "US highways", "state highways", "county roads", and "local roads" suitable for trucking were extracted using the "query" function. Figure 2.5 shows interstate, US, and state highways in the study area; blue, red, and gray lines denote the interstate, US, and state routes respectively.

Mississippi's highway system comprises two different routes based on maximum allowable Gross Vehicle Weight (GVW), specifically low and high-weight highways with a weight limit of 57,650 and 80,000 pounds, respectively (Mississippi Department of Transportation Office of Enforcement n.d.). Hauling trucks are prohibited from using the low-weight limit route as a shortcut between the two high-weight limit routes. However, they are allowed to weigh the maximum allowable GVW on the low-weight limit route if the product to be hauled originates on the low-weight limit route until they merge into the first high-weight highway across the travel direction. Similarly, a maximum load can be hauled on low-weight limit routes if the hauling truck is traveling via high-weight-limit routes, but the destination is located on the low-weight-limit road. On the other hand, trucks are allowed to weigh only 57,650 pounds if they must travel entirely on a low weight-limit route (Mississippi Department of Transportation Office of Enforcement n.d.). Mississippi highways with low and high weight limits were identified to determine whether any harvest sites and sawmills are located on the low-weight roads. For this purpose, a map containing the Mississippi highway system with maximum allowable GVW was downloaded from MDOT *(https://mdot.ms.gov/documents/Planning/Maps/Truck%20Weights/Legal%20Truck%20Weight%20Map.pdf)* and loaded as an image into ArcGIS Pro for georeferencing and digitizing. Forty-five control points (landmarks of various cities and highways) were added to the image with the "Spline transformation" method used to ensure alignment between the spatial and referenced data. The spline transformation is a rubber sheeting technique based on a piecewise polynomial that maintains continuity and smoothness between adjacent polynomials. It transforms the source control points accurately to target control points and has a high level of local accuracy. This transformation requires a minimum of 10 control points, and the addition of additional control points increases the accuracy of this transformation (ESRI n.d. -e). After georeferencing and spline transformation, the low-weight limit routes were selected on the collected road layer using the "select" feature. These layers were extracted as a separate shape file as low-weight limit routes for further analysis. Figure 2.6 shows the low-weight limit routes throughout Mississippi. The blue line denotes the national and state-designated low-weight limit routes, the red line indicates the state-maintained low-weight limit routes and the black line illustrates locally maintained low-weight limit routes.

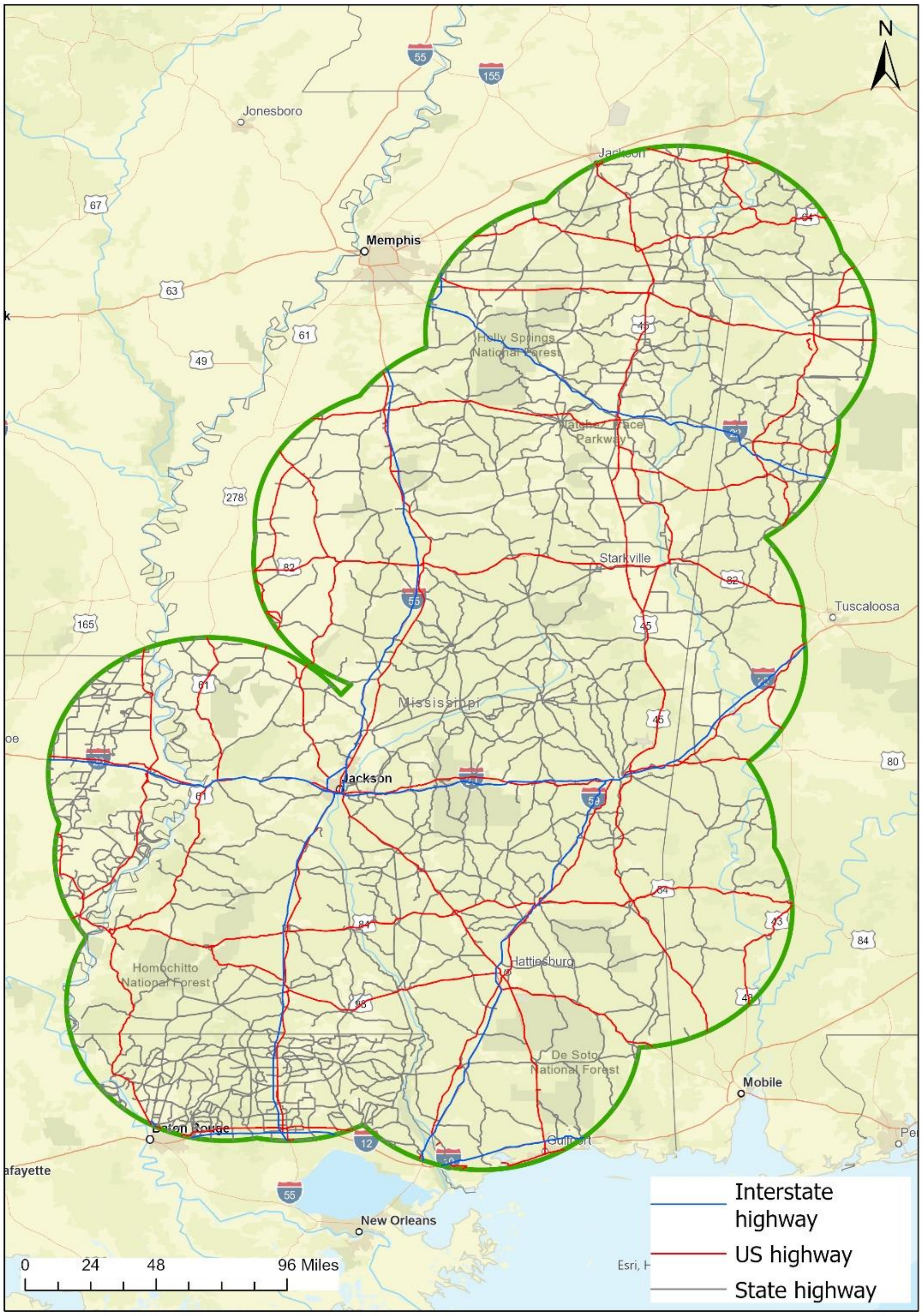

Figure 2.5 Interstate, US, and state highways along the study area.

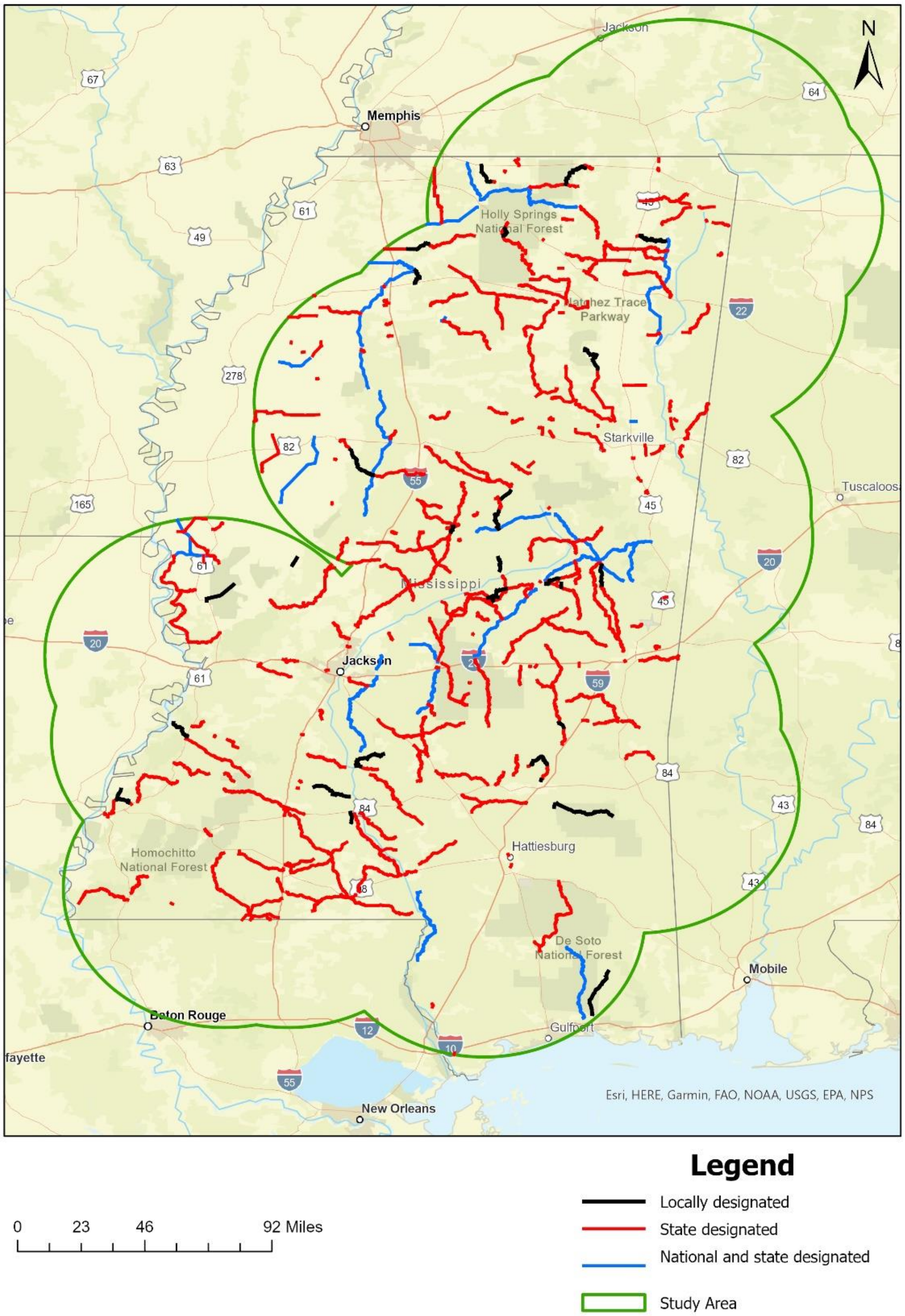

Figure 2.6 Mississippi's national, state, and locally maintained low-weight limit trucking routes within the greater study area.

2.3.2.3 BRIDGE DATASETS

Required bridge information for the federal, state, and county bridges within the study area was collected from MDOT *(https://path.mdot.ms.gov/bridges)*, Mississippi Office of State Aid Road Construction (MOSARC) *(https://www.osarc.ms.gov/Docs/idx/idx-x.html?https://www.osarc.ms.gov/Docs/data/Br-x.htm)*, and the Homeland Infrastructure Foundation-Level Data (HIFLD) website *(https://hifld-geoplatform.opendata.arcgis.com/datasets/a9b05a595ff94f3fa3888d1240545740_0/about)*. The MDOT and MOSARC datasets were used for Mississippi, while the National Bridge Inventory (NBI) data downloaded from the HIFLD was used for other states. The inclusion of multiple datasets was necessary because although the NBI data had information about the closed and posted bridges, it did not provide precise information on posted weight limits for the bridges posted to lower limits, which was available in the MDOT and MOSARC data. The decision to use two data sources for Mississippi was based on MDOT's coverage of bridges on interstates, US routes, and state highways, while MOSARC provided information on county and local bridges.

The "query" function in ArcGIS was used to separate between the "open", "posted", and "closed" bridges. Posted and closed bridges were further separated into interstate highway bridges, US highway bridges, State highway bridges, County Road bridges, and other bridges. This was because the interstate highway bridges have the maximum allowable GVW of only 80,000 pounds while all the other bridges have maximum allowable GVW limits of 84,000 pounds. For this purpose, the "Select Layer by Location" tool was used. The input feature for selection was the bridge layer and the selecting feature was the 10-meter buffer polygon of interstate highway, US highway, state highway, and county roads. The bridges that did not fall into any of the above-mentioned roads were kept but designated other bridges. It was found the total number of posted and closed bridges within the study area was 2,752 and 269, respectively. Although the bridges were categorized as posted bridges, only 693 of them had posted weight limits. Therefore, those 693 posted bridges with weight limits less than 84,000 lbs and all 269 closed bridges were considered as restricted bridges to determine the alternative routes of the affected optimal routes. Table 2.2 summarizes the total number of closed and posted bridges according to their types.

Table 2.2 Summary of the closed and posted bridges within the study area.

Number of bridges	**Interstate highway**	**US highway**	**State highway**	**County bridges**	**Other bridges**	**Total**
Closed	0	2	11	33	223	269
Posted	4	48	315	553	1,832	2,752
Posted with weight limits	1	19	121	113	439	693
Final restricted bridges	1	21	132	146	662	962

Figure 2.7 shows the total number of closed bridges within the study area according to the route types associated with them. The blue, red, brown, and green dots in the figure represent the state highway, US highway, county road, and other closed bridges, respectively. There were not any closed bridges along the interstate highways. Figure 2.8 displays the total number of posted bridges within the study area according to the route types. In this figure, black, blue, red, brown, and green dots denote the interstate highway, state highway, US highway, county road,

and other posted bridges respectively. Likewise, Figure 2.9 illustrates the posted bridges within the study area with weight limits on them. The symbols in this figure are identical to the symbols in Figure 2.8, and they denote the same bridge types. Finally, Figure 2.10 exhibits the total restricted bridges for hauling trucks within the study area. The restricted bridges are composed of all the closed bridges (red dots) and all the posted bridges with posted weight limits on them (blue dots).

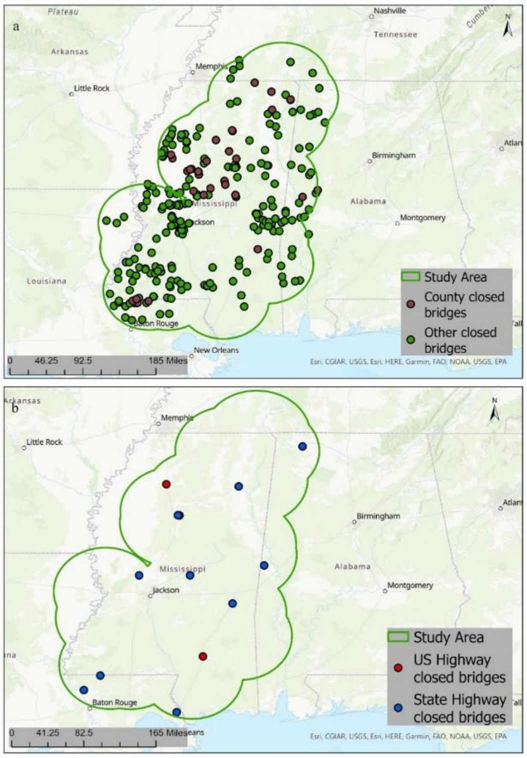

Figure 2.7 Total closed bridges within the study area according to the route type. County and other bridges are represented by brown and green dots (a), while US and State Highway bridges are denoted by red and blue dots (b).

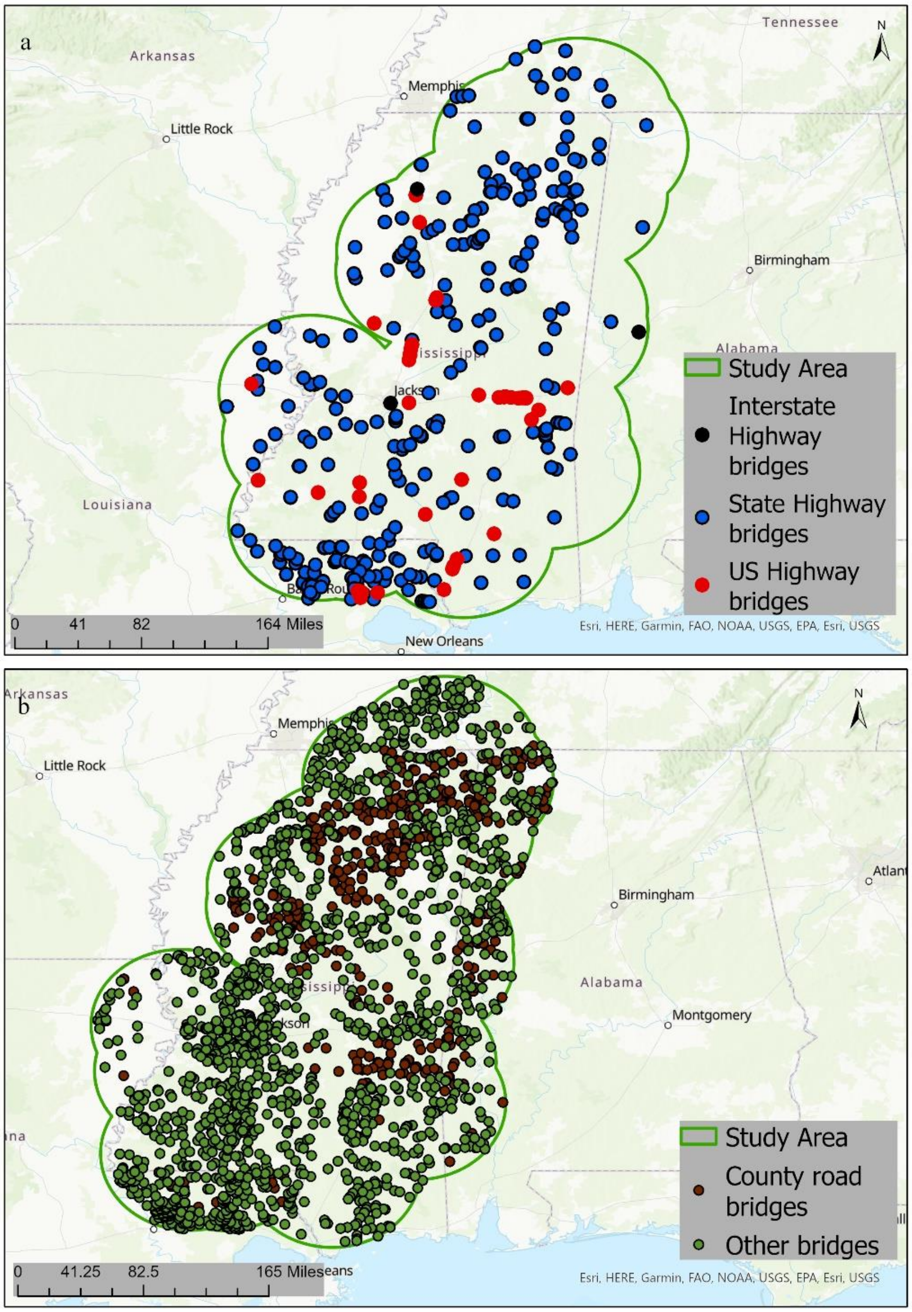

Figure 2.8 Total posted bridges within the study area according to route type. Interstate, State, and US Highway bridges are illustrated as black, blue, and red dots (a), whereas county roads and other bridges are portrayed as brown and green dots (b).

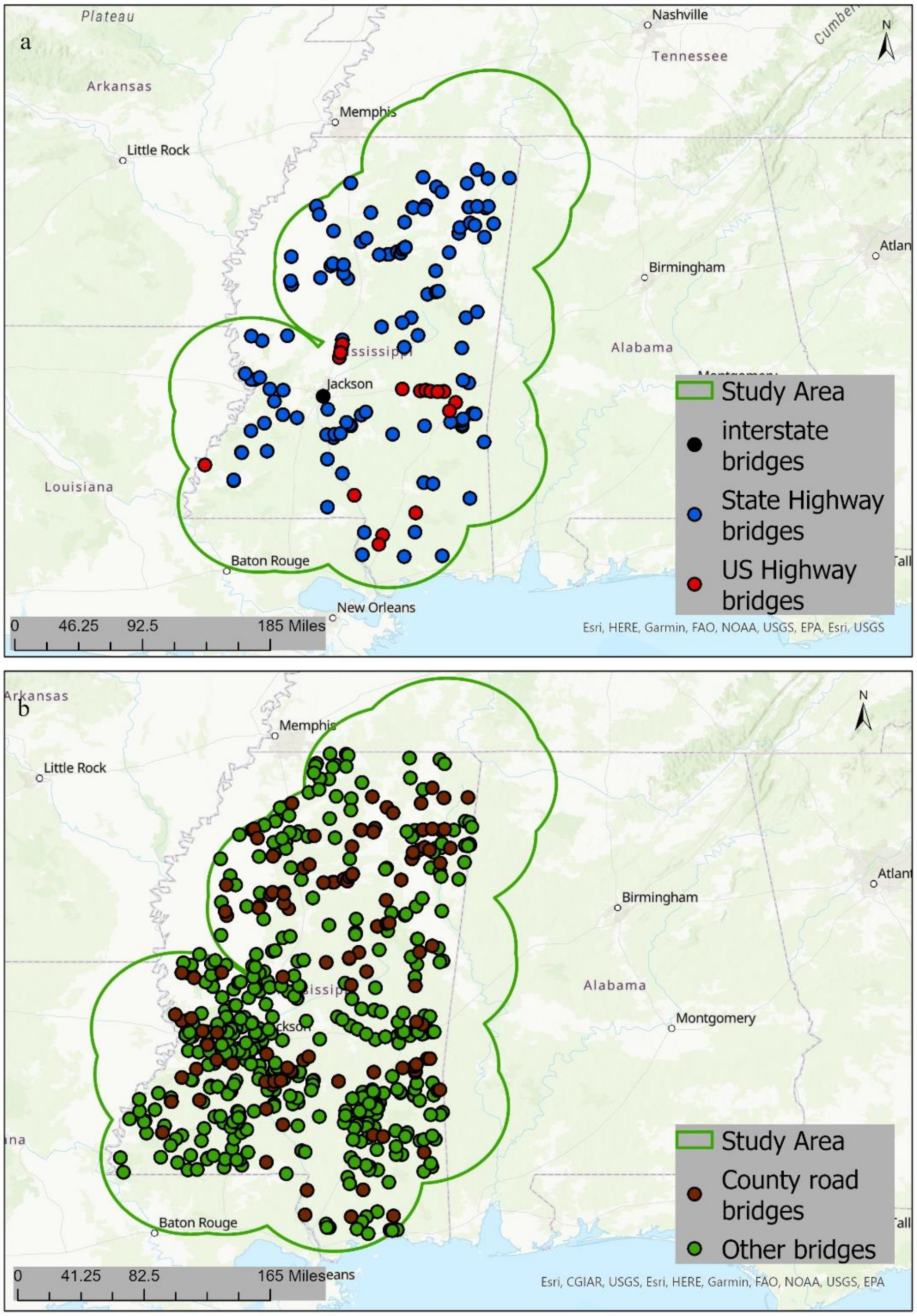

Figure 2.9 Posted bridges with posted weight limits within the study area according to the route type. Interstate, State, and US Highway bridges are shown by black, blue, and red dots respectively (a), whilst county roads and other bridges are represented by brown and green dots (b).

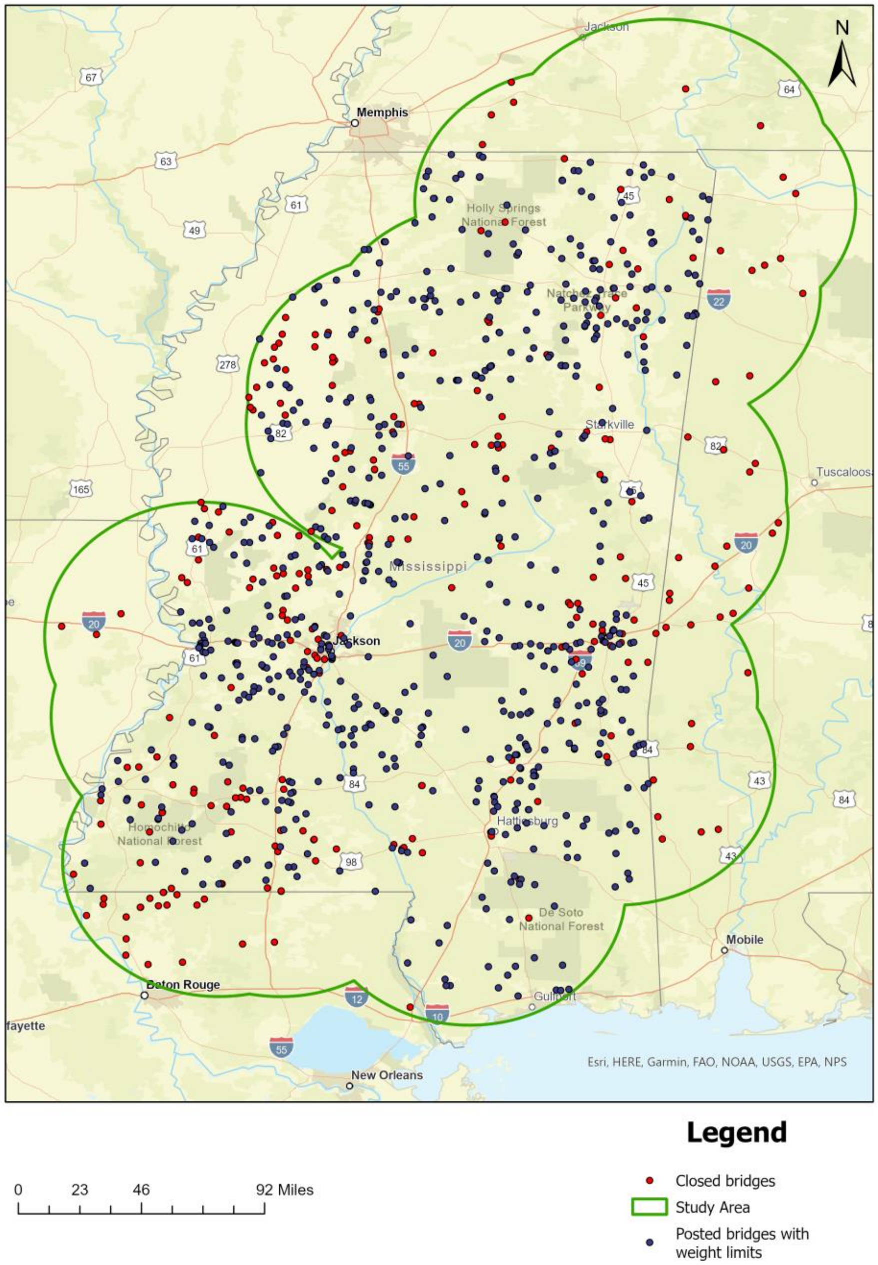

Figure 2.10 The spatial locations of the closed and posted bridges selected as the restriction within the study area. Red and blue dots symbolize the closed and posted bridges respectively. These bridges will be referred to as restrictions or impediments from now on.

2.3.3 DATA ANALYSIS

The "Closest Facility" tool under the "Network Analysis Extension" in ArcGIS Pro was used. This tool utilizes a multiple-origin and multiple-destination algorithm that is based on Dijkstra's shortest path algorithm (ESRI n.d. -d; Kai et al. 2014). Dijkstra's shortest path algorithm can only solve single-source, shortest-path problems to calculate the shortest path from a source to destination nodes in a network (Cormen et al. 2001; Kai et al. 2014).

Figure 2.11 illustrates the working mechanism of Dijkstra's shortest path algorithm, that operates on directed and weighted graphs denoted as $G = (V, E)$. Here, V represents the vertices or nodes (s, t, x, z, and y in Figure 2.11), and E represents the directed edges or arcs connecting the vertices. Each edge has a non-negative value or edge weight, indicating the distance required to traverse that edge. This algorithm progressively builds a set of vertices S with finalized shortest-path weights from the starting or source vertex s. The algorithm determines the shortest path from a source vertex to a destination vertex by iteratively selecting the vertex with a minimum shortest-path estimate and updating the shortest-path estimates for its neighboring vertices (Cormen 2001). In each iteration, the algorithm identifies the vertex with the minimum shortest-path estimate, adds it to the set S, and updates the shortest-path estimates of its unvisited neighboring vertices. This process continues until the destination vertex is included in S, resulting in the shortest path from the source to the destination.

In our case (Figure 2.11), the source vertex s represents the sawmill location from where the shortest distance to the available harvest sites is to be determined. The vertices t, x, y, and z indicate the available harvest sites from the sawmill s. The edges represent the routes between these locations and each edge carries a value which is distance between the linked vertices.

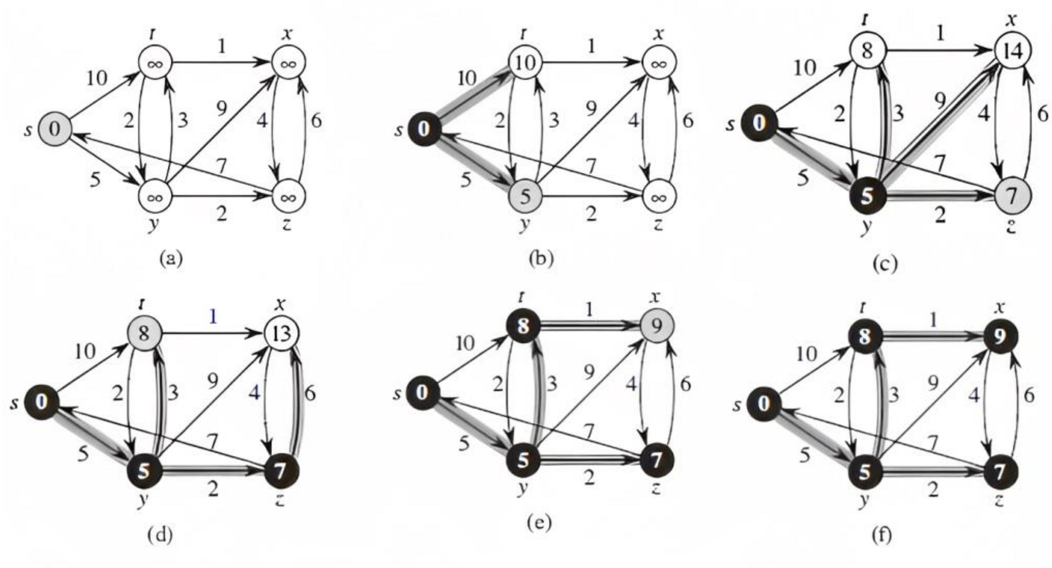

Figure 2.11 Dijkstra's Shortest path algorithm's working mechanism (Cormen et al. 2009). Vertex *s* is the source vertex and ∞ represents the initial distance of unvisited nodes from the vertex *s*. The estimated shortest path value replaces ∞ in the vertices. Shaded vertices are the selected vertices between the available neighboring vertices, black vertices are those whose values have been updated in set *S* after being selected and the white vertices are the vertices in queue. The shaded edges are the predecessor values.

The algorithm initiates by selecting the shortest edge that connects the starting vertex to its neighboring vertex, exemplified by the edge connecting vertex *y* and *s* with a weight of 5 in Figure 2.11. The second step is to update the distance of the neighboring vertex that is connected to the source vertex by the shortest edge. This process involves checking if the distance of a vertex *s* plus the weight of the edge connecting *s* and *y* is less than the current distance of vertex *y*. If so, the distance of *y* is updated accordingly. In Figure 2.11 (b), the distance of vertex *s* is 0, and the weight of the edge connecting the selected vertex *y* to the source vertex *s* is 5. Initially, the distance of vertex *y* in Figure 2.11 (a) is set as infinity, indicating that it has not been visited yet. However, after considering the sum of the distance of vertex *s* and the weight of the edge connecting *y* and *s*, which is 5 (less than infinity), the distance of *y* is updated to 5 in Figure 2.11 (b). The same process is applied to update the distance of vertex *t* in Figure 2.11 (b). In Figure 2.11 (c), the distance of vertex *y* is 5, and the weight of the edge connecting vertex *y* to vertex *t* is 3. The sum of these values results in 8, which is less than the previous distance of *t* (10 in Figure 2.11(b)). Hence, the distance of *t* is updated to 8. This process is repeated to calculate the distances of vertices *z* and *x* as 7 and 14, respectively. The process continues until the distance from the source vertex *s* to the destination vertex *x* is determined, which is calculated in Figure 2.11 (f).

Network Analysis layer available in ArcGIS online was used to run the "Closest Facility" tool for data analysis. On the network analysis layer, required roads can be prioritized based on the hierarchy of routes depending on the user's requirement. Furthermore, some restrictions like "nonoperating bridges" can be added later as "point barriers," as well as "restricted roads" can also be added as "line barriers" as per the requirements while running the analysis. This can be done from the "Route" tab on the "Network Analysis" ribbon. Under the "Route" tab, there is a "travel settings" button, which further opens into "travel mode". The travel mode" expands into "costs", "restrictions", "U-turn", and "Advanced". The desirable conditions and criteria for optimal routing can be set under the "Restrictions" tab depending on the requirement. After setting up all the restrictions, "Closest Facility tool" is ready to determine the shortest path between the incidents and the facility.

To determine the shortest route between harvest sites and sawmills, a series of steps were followed. Initially, the transportation mode was set as trucking, and certain roads, such as carpool lanes, express lanes, and truck-prohibited roads were prohibited. Roads under construction, truck-restricted roads, and unpaved roads were avoided, except when necessary.

Preferred truck routes were prioritized in the routing process. The hierarchy of roads was not considered in the analysis, as it was observed that the GIS model tended to favor interstate roads over US, State, and county roads. While road hierarchy benefits cars to travel through timesaving, it was not utilized in this case due to the lower GVW limit on interstate routes compared to US, State, and county roads. The closest facility tool was then used to determine the shortest path between the harvest sites and the sawmills while adhering to the defined conditions. Generated routes provided the shortest optimal trucking routes between the harvest sites and sawmills. These routes were not simply the shortest distance between these pairs of locations, as they were influenced by the aforesaid preferred and restricted conditions that needed to be considered for haulage.

Sawmill-wise analysis was then conducted whereby only one sawmill's location was added as a facility and all the harvest sites within the 50-mile radius were loaded as incidents. The data were analyzed in two different scenarios. The first scenario assumed no bridge restriction along the routes. The shortest optimal trucking routes were determined for transporting timber products from the respective harvest sites to the sawmills, keeping a cutoff distance of 57 miles. This constraint was imposed due to the additional cost implications associated with long-haul premiums. It was recently learned Mississippi log trucking companies operate at an average haul distance of 57 miles with the data right skewed when company size was considered. There were fewer larger companies, but they hauled more wood from longer distances on average (James Shannon, Costs and Challenges of the Mississippi Log Trucking Industry, unpublished data). Instead of avoiding low-weight limit roads from the beginning, the shortest optimal trucking routes without accounting for restrictions were derived. A subsequent examination was conducted to determine if these routes utilized low-weight limit roads as shortcuts between two high-weight limit roads. This approach allowed including harvest sites or sawmills that might be located on low-weight limit roads. If it was discovered the shortest route used low-weight limit roads as shortcuts between high-weight limit roads, that specific road segment was added as a line barrier to generate new routes that would avoid these shortcuts. The same procedure was applied to prevent the utilization of interstate highways due to inconsistency in the maximum allowable GVW between interstate and other highways (US, State, and locally maintained) (Conrad IV 2020, 2021). Interstate highways allow for GVW up to 80,000 lbs., while other high-weight limit roads permit up to 84,000 lbs (Branning and Sparks 2022). In the second scenario, a bridge restriction was assumed along the shortest optimal routes derived in the first scenario. After deriving the shortest optimal routes that did not travel via low-weight limit roads and interstate highways, the routes that traveled along the restrictions were identified by loading the spatial location of these restricted bridges and using the “Select Layer by Location” feature in ArcGIS Pro. Restricted bridges were loaded as the point barrier and the alternative routes were derived for the shortest optimal routes that traveled along impediments. Table 2.3 summarizes the two scenarios analyzed in this chapter.

Table 2.3 Summary of the two different scenarios analyzed in the study.

Scenarios	**Description**
Scenario I (also referred to as first scenario interchangeably hereafter)	• Did not account for bridge restrictions along the shortest optimal trucking routes between the harvest sites and the sawmills. • Only the shortest optimal trucking routes are derived between the harvest areas and the sawmills because of the assumption of no closed and posted bridges between these two points.
Scenario II (also referred to as second scenario interchangeably hereafter)	• Considers and identifies the bridge restrictions along the shortest optimal trucking routes between the harvest sites and sawmills. • Alternative routes were derived for those shortest optimal trucking routes that had closed or posted bridges along them.

After deriving the shortest optimal and alternative trucking routes, the additional distance that hauling trucks need to traverse due to the bridge restrictions along the shortest optimal routes and the percentage increase in trucking distance for alternative routes caused by these restrictions were calculated using formulas:

$$Additional\ distance = (alternative - optimal) \tag{2.3}$$

$$Percentage\ change = \frac{additional\ distance}{Optimal} \times 100\% \tag{2.4}$$

where optimal was the trucking distance (in miles) for the shortest optimal trucking route between the harvest site and sawmill pairs and alternative was the trucking distance for the alternative route for the same pairs.

2.4 RESULTS

One hundred and twenty-nine routes were initially obtained for the first scenario, of which 23% (30 routes) had restrictions along them. These routes will be alternatively referred to as the "affected routes" from here onwards. Out of the 30 affected routes, an alternative solution was derived for only 13 of them (approx. 43% of the affected routes). The remaining 17 routes (57%) did not have viable alternatives due to weight and distance restrictions. In some instances, no feasible alternative was available other than via the interstate highway (HA4 – M24) or low-weight limit roads (HA18 – M7). As a result, those routes were excluded from the analysis.

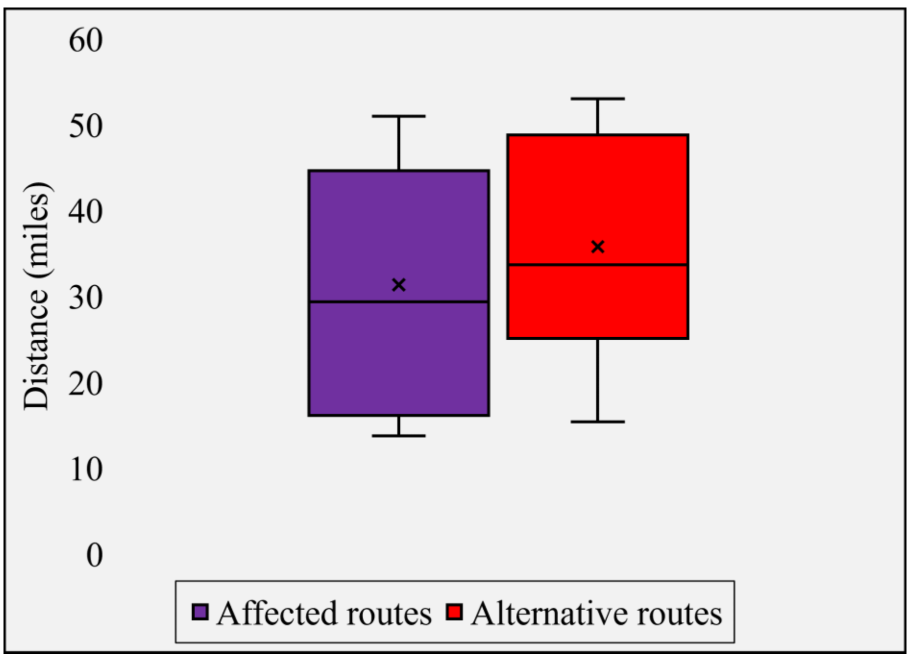

Figure 2.12 Box and whisker plot comparing 13 alternative routes to their corresponding affected routes.

Figure 2.12 is a Box and Whisker (B&W) plot comparing the trucking distance of 13 alternative routes, connecting the harvest sites and sawmills, to their corresponding affected routes (shortest optimal routes encountering bridge restrictions along them). The plot provides an overview of the impact of bridge restrictions on the shortest optimal routes and how they affect the overall trucking distance. The trucking distance of selected affected routes ranged from 13.70 to 50.95 miles. In contrast, the range of trucking distance of alternative routes due to bridge restrictions increased to 15.35 to 52.96 miles. The selected affected routes had an average distance of 31.30 miles, which increased to 35.74 miles in the case of alternative routes. The median distance for selected affected routes was 29.33 miles, indicating that half of these routes were longer than this distance, and the remaining half were shorter. Similarly, the median distance for alternative routes was 33.63 miles.

Figure 2.13 compares the trucking distance in miles between the harvest sites and sawmills for the 13 shortest optimal routes along with their alternative routes resulting from the presence of restrictions along the shortest optimal routes. The figure also displays the additional distance in miles required for the trucks to reach the same harvest site – sawmill pairs due to the presence of restrictions along the shortest optimal route. This additional distance was obtained by subtracting the distance of the shortest optimal routes from the distance of the additional routes. The figure also presents the calculated percentage increase in the distances of additional routes for the affected pairs as compared to the original shortest optimal routes. This helps to illustrate the severity of the impact of these restricted bridges on affected routes in relative terms of the additional trucking distance. The figure showed that the trucking distances of alternative routes were longer than their shortest optimal counterparts. The additional trucking distance of the alternative routes ranged from 1.53 miles (HA32 – M18) to 12.93 miles (HA13 – M11). These additional distances corresponded to a 3.47% to 74.89% increase in trucking distance due to the bridge restrictions.

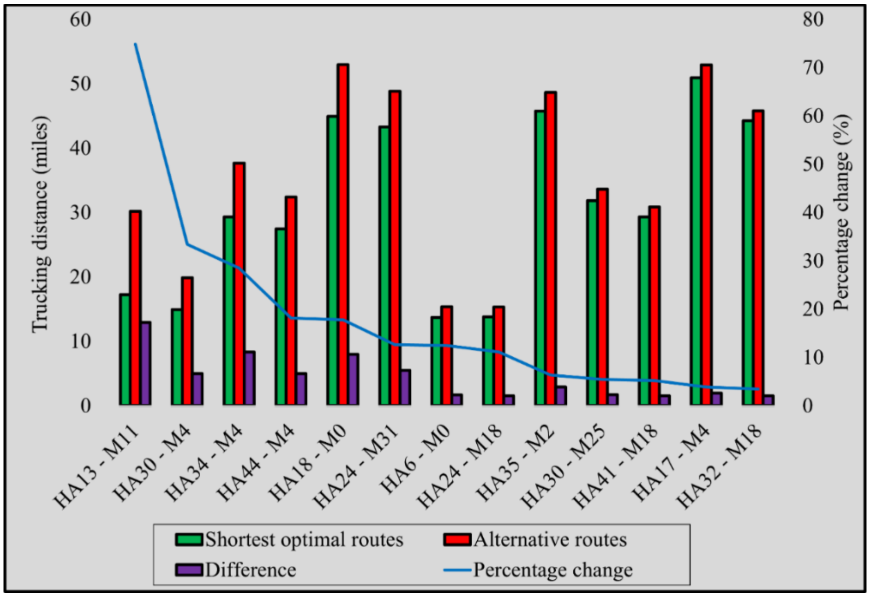

Figure 2.13 Shortest optimal, alternative, and additional trucking distance and percentage change of additional trucking distance for the affected pairs due to the presence of restricted bridges along the shortest optimal trucking routes.

The shortest optimal and alternative routes between the harvest site and sawmill pairs affected by the restricted bridges are shown in Figures 2.14 through 2.17. Also displayed are the spatial locations of the harvest sites (green dots) and the sawmills (blue industry-like image). Red dots are the spatial location of the restricted bridges. Similarly, blue lines represent the shortest optimal route between each sawmill–harvest pair, and the red line displays the alternative routes for these pairs.

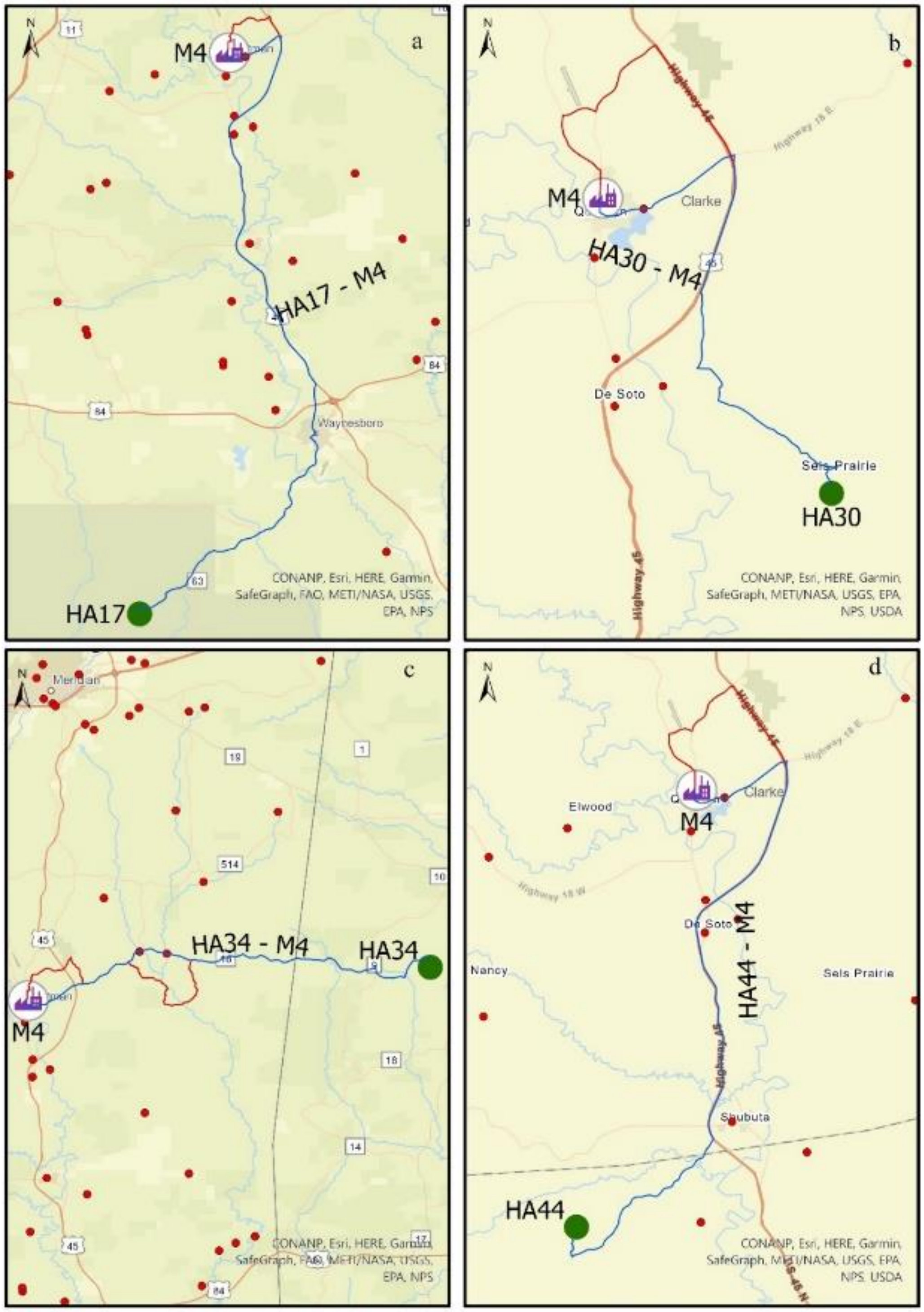

Figure 2.14 The shortest optimal and alternative trucking routes between the harvest sites and sawmill pairs of HA17 – M4; (a), HA30 – M4; (b), HA34 – M4; (c), and HA44 – M4; (d).

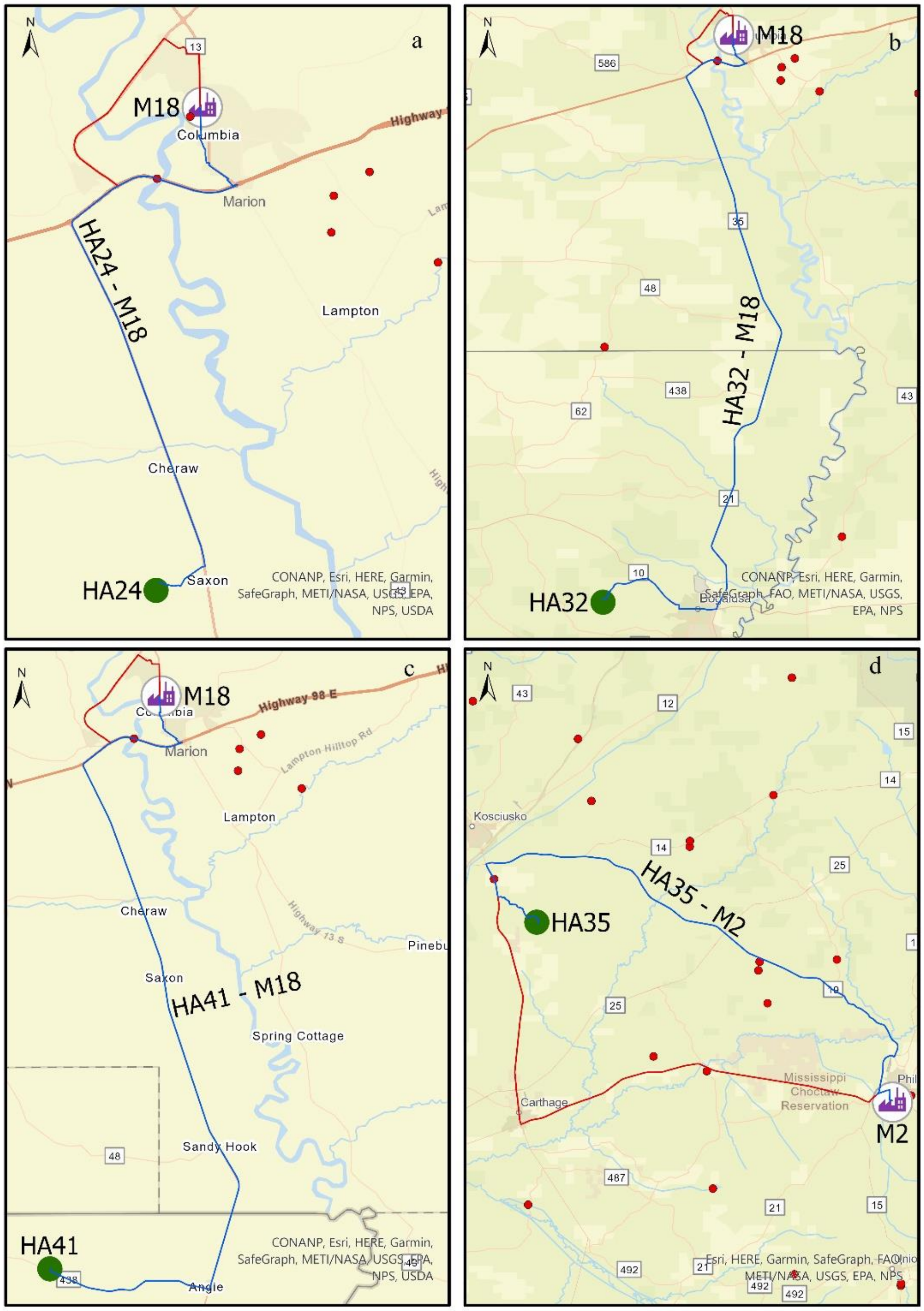

Figure 2.15 Shortest optimal and alternative trucking routes between pairs HA24 – M18; (a), HA32 – M18; (b), HA41 – M18; (c), and HA35 – M2; (d).

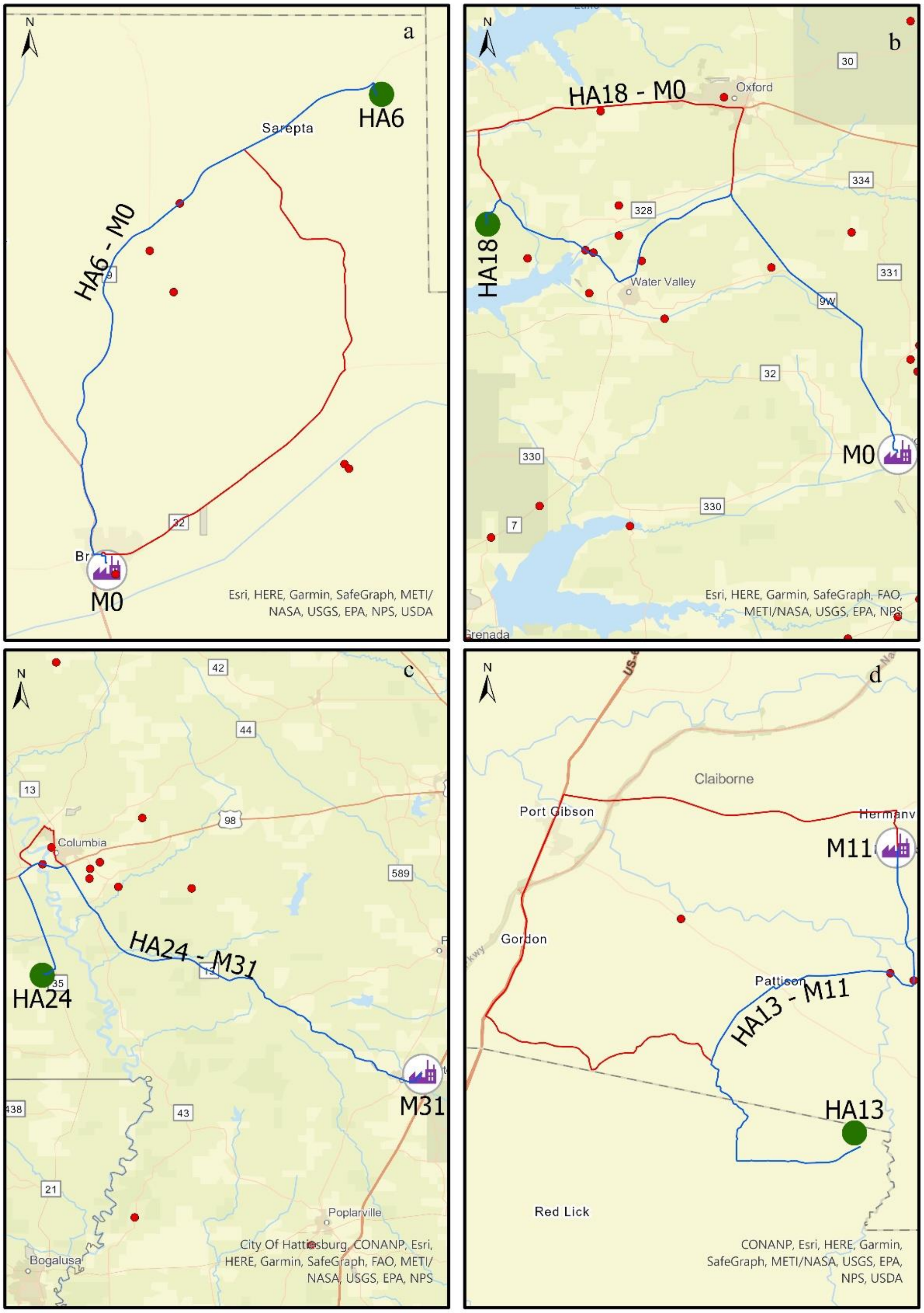

Figure 2.16 The shortest optimal and alternative trucking routes between pairs HA6 – M0; (a), HA18 – M0; (b), HA24 – M31; (c), and HA13 – M11; (d).

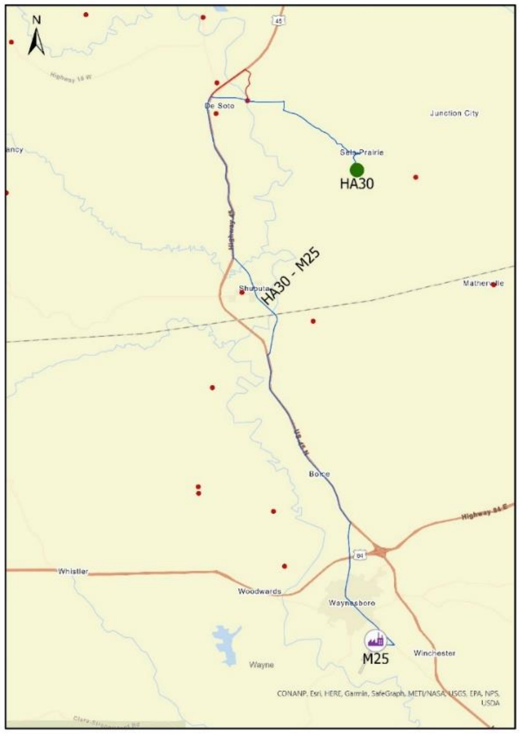

Figure 2.17 The shortest optimal and alternative trucking routes between pair HA30 – M25.

The average increase in optimal trucking distance (one-way transport of loaded trucks) for specific sawmills caused by the presence of restricted bridges was determined through a subsequent analysis at the sawmill level. It was calculated by dividing the total additional distance caused by restricted bridges for a given sawmill by the total number of shortest optimal routes that were originally derived. For instance, sawmill 11 had two shortest optimal routes connecting it to two different harvest locations. However, only one of these routes encountered restricted bridges, which required taking an alternative route that was 12.93 miles longer than the shortest optimal route. Therefore, the additional 12.93 miles was divided by 2 to determine the average additional distance of 6.46 miles for sawmill 11 (refer to Table 2.1 for the name and location). The average increase in optimal trucking distance for the impacted sawmills ranged from 0.25 (sawmill 24 i.e., Tri-State Lumber Co., Fulton) to 6.46 (sawmill 11 i.e., Canfor Corp, Hermanville) miles, as illustrated in Figure 2.18. This means logging operators would need to travel an additional 0.25 to 6.46 miles on average to transport timber to those sawmills due to the presence of restricted bridges along the shortest optimal routes. Additionally, a weighted average of all the affected pairs were calculated for accurate estimation of the additional distance logging companies are required to haul, on average, for all the affected sawmills due to the presence of restricted bridges along the route. This was found to be 1.78 miles.

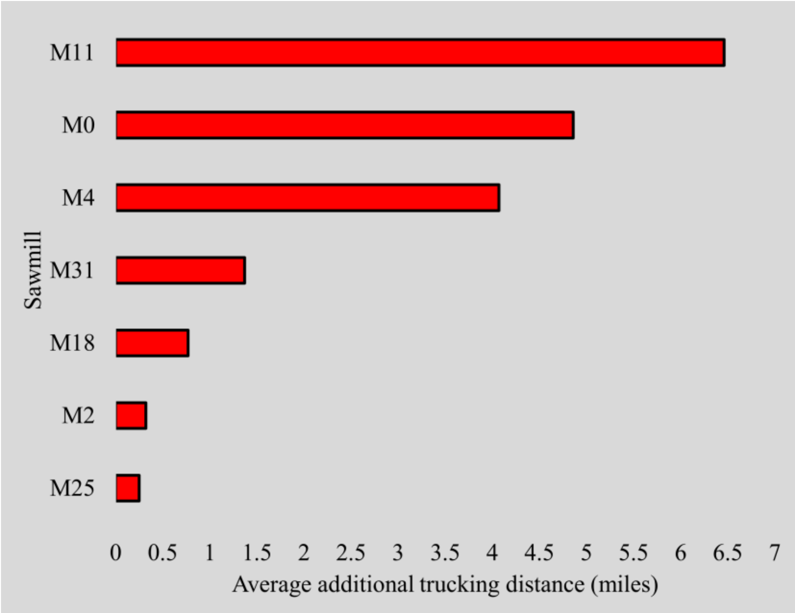

Figure 2.18 Sawmill-wise average increment in trucking distance due to the presence of restricted bridges in the shortest optimal routes.

Finally, an analysis was conducted to determine the total increment for trucking distance for the affected sawmills along with the percentage change in additional distance (Figure 2.19). This analysis was essential in understanding the impact of restricted bridges on the trucking distance for different sawmills. The green and red bars represent the aggregated sum of all derived shortest optimal and alternative routes, respectively, for a particular sawmill. The purple bar represents the total additional distance associated with that specific sawmill. These are denoted in the graph as without restriction, with restriction, and difference, respectively. The blue line represents the percentage increase in trucking distance caused by restricted bridges along alternative routes relative to the original shortest optimal routes. It is denoted as a percentage (%) change in the graph. Sawmill 0 (Weyerhaeuser in Bruce) experienced the highest percentage increment of 16.57%, followed by Sawmill 11 (Hermanville's Canfor Corp) (13%), and Sawmill 4 (Bazor Lumber, Quitman) (12.55%).

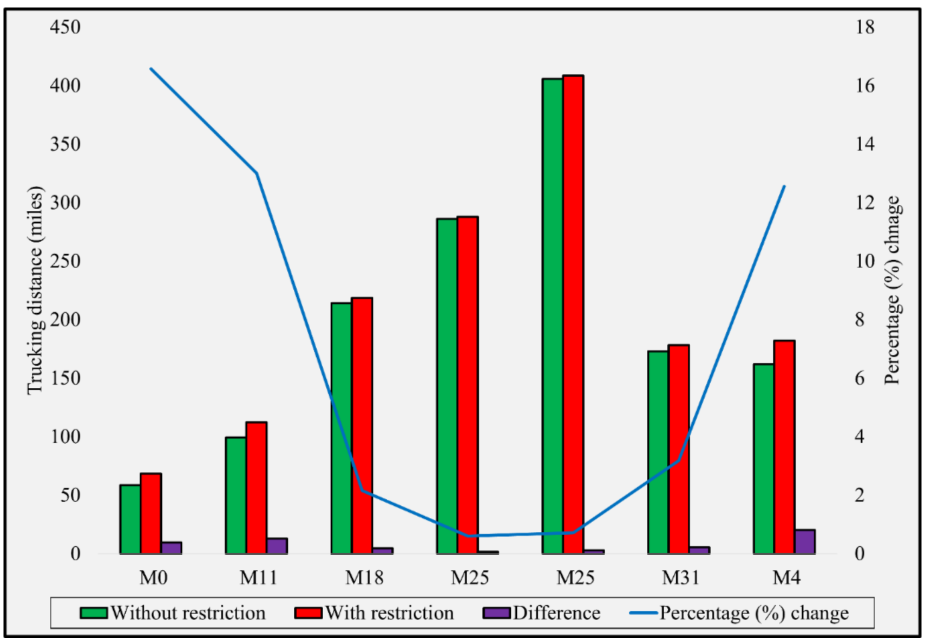

Figure 2.19 Shortest optimal, alternative, and additional trucking distance, and percentage change of additional trucking distance for the affected sawmills due to restricted bridges along the shortest optimal trucking routes.

2.5 CONCLUSION, IMPLICATIONS, AND LIMITATIONS

The objective was to identify the shortest optimal routes between each harvest site and sawmill pair, locate restricted bridges along these routes, and derive alternative routes for the affected shortest optimal route. One hundred and twenty-nine shortest optimal routes were derived between the harvest sites and the sawmills, among which around 23% had restricted bridges along them. However, alternative routes were only found for 43% of the affected routes, while the remaining 57% of the affected routes were not further investigated because of weight and distance restrictions. Pairs HA13 - M11, HA34 – M4, and HA18 – M0 were the most impacted routes, requiring an additional trucking distance of 12.93, 8.37, and 8.01 miles, respectively. Similarly, in terms of percentage increment in the additional distance, HA13 – M11, HA30 – M4, and HA34 – M4 were the top three most affected pairs due to restricted bridges with the respective percentage change of 74.89, 33.40, and 28.54%. These restrictions increased the trucking distance for specific sawmills, with an average additional distance ranging from 0.25 to 6.46 miles depending on the sawmill. The overall average additional distance for all affected sawmills was found to be 1.78 miles. Sawmill 0 (Weyerhaeuser – Bruce plant) experienced the highest percentage increment of 16.57% when comparing its additional distance to the shortest optimal distances.

The findings provide valuable insights into transportation planning and logistics for the forest industry in Mississippi and can aid decision-makers in reducing transportation costs by identifying efficient and cost-effective trucking routes. The findings suggest it is essential to consider weight restrictions on road and bridge infrastructure when dealing with transportation cost minimization problems to accurately estimate a minimum cost solution. The results can be utilized for not only calculating transportation costs between harvest sites and sawmills. They can also be used to assess the economic impact of restricted bridges on the forest industry in Mississippi by analyzing the jobs and income effects of these restrictions on local economies and stakeholders. This can be coupled with other economic analyses to create a priority ranking for maintaining and upgrading these bridges.

This study had a few limitations. Not having posted weight limits on all posted bridges was one, as only a few data sources had such information. All the closed bridges and only the posted bridges with posted weight limits could be used for further analysis. Obtaining road data with maximum allowable GVW was challenging but was overcome by georeferencing and digitizing the map of the Mississippi highway system with the maximum allowable GVW available from MDOT. Additionally, the sample of harvest areas selected represented only a small subset of the total harvest areas within the 50-mile radius of the sawmills. Future research could address this limitation by expanding the sample of harvest areas and incorporating additional data sources to identify the resource base.

The impact of these restricted bridges on harvest scheduling and mill receipts should be considered for future research. The harvest schedule is impacted by changes to the road and bridge infrastructure because they specify which stands must be harvested in what quantities using which routes during a particular time (Clark et al. 2000). Timber demand and supply, the proximity of processing mills to forest stands, and the accessibility of road and bridge infrastructure around the forest stand all affect the harvest schedule. Thus, the presence of restricted bridges along the optimal path might require adjustments to the harvesting plan by harvesting from alternative stands. The increased distance required to travel via an alternate route because of restricted bridges may also cause additional turnaround time from stands to processors and back, which reduces firm output and adds cost. In conclusion, this study highlighted the importance of considering the constraints and limitations imposed on roads and bridges while designing optimal trucking routes in the forest industry.

2.6 REFERENCES

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CHAPTER III

OPTIMIZING SHORTEST LOG TRUCKING ROUTES CONSTRAINED BY LOW-WEIGHT BRIDGES IN MISSISSIPPI

3.1 INTRODUCTION

Optimization techniques solve complex problems through improved decision-making processes across a given scenario (Matoušek and Gärtner 2007). These techniques help in the wise utilization of available resources (Prifti et al. 2020). Operational-level transportation optimization involves decisions about product movement, storage, pre-processing, and vehicle routing/scheduling (Malladi and Sowlati 2017). Methods like network analysis, linear programming (LP), dynamic programming, and heuristic techniques can be utilized to minimize transportation costs while considering real-world travel restrictions and constraints among multiple available routes (Akay et al. 2006). These optimization models consider different combinations of sources, destinations, and paths for determining and distributing the optimal quantity of goods between these points to minimize transportation costs (Prifti et al. 2020). Furthermore, these models can incorporate various variables and constraints based on the specific requirements and objectives to assist decision-makers in selecting the best options from the available choices to achieve the model's objective. Most forestry transportation optimization models account for backhauling (Abasian et al. 2017) and log-truck scheduling problems (LTSP) (Monti et al. 2020) for minimizing transportation costs. Backhauling is an efficient practice that involves utilizing trucks to transport a load from the destination during their return journey back to the source where initial loading took place (Palander et al. 2004). The hauling practice where trucks travel loaded from source to destination but return empty after unloading has an efficiency rate of only 50% (Rönnqvist 2003). Backhauling enhances transportation efficiency and minimizes costs by utilizing the return trip to carry additional loads.

Weintraub et al. (1996) developed an operative and computerized system for Chilean forest industries, named Assign Truck (ASICAM) to solve daily truck scheduling problems using a simple heuristic algorithm. El Hachemi et al. (2011 and 2013) proposed a two-step hybrid solution procedure that involved mixed integer linear programming (MILP) and a heuristic approach to minimize transportation costs by solving LTSP using truck scheduling. Their approach minimized the cost associated with non-productive activities like truck waiting time and empty return routes after the trucks are unloaded. Their model also optimized the designated load between the mills and the harvest area. Gronalt and Hirsch (2007) applied Tabu Search heuristics for solving LTSP by prioritizing the destination of each load. Similarly, Carlsson & Rönnqvist (2007) developed a transportation cost minimization model that accounted for the backhauling. Abasian et al. (2017) developed a profit maximization optimization model that also considered backhauling in forestry. Monti et al. (2020) developed a MILP model to minimize the transportation costs for forestry logistic problems.

Linear programming (LP) is used to address problems with linear system models and objective functions (Prifti et al. 2020). In LP, linear constraints are the inequalities or equalities that bound the feasible solutions, and the linear function of the considered quantities evaluates the solution's effectiveness (Matoušek and Gärtner 2007). Sectors focusing on logistics problems widely employ LP to optimize the transportation of required goods between source and destination, while adhering to the provided constraints (Matoušek and Gärtner 2007; Prifti et al. 2020). In forestry, LP optimizes resource allotment between harvest sites and processing mills to minimize transportation costs. This approach utilizes supply availability, demand capacity, and distribution locations to derive optimal solutions (Prifti et al. 2020).

Integer programming (IP) is an approach for solving optimization problems involving integer (or discrete) and binary (0/1) variables. Discrete variables denote indivisible values, while binary variables represent binary decisions that represent the decision maker's choices. In IP, all variables must be integers (Wolse 1998). On the contrary, the variables in MILP can be both continuous and integer variables, unlike a pure integer program with no continuous variables (Wolse 1998; Rodriguez 2019). Therefore, it is employed to minimize transportation costs as the transportation problem contains integer, binary and continuous variables. Selecting specific source/destination pairs for resource allocation, determining transport paths between them, and identifying the required number of truckloads for transporting allocated resources require the use of either binary or integer variables. However, the quantity to be transported and the unsatisfied demand requires the use of a continuous variable, which are divisible quantities. Therefore, a MILP model was developed in this chapter to minimize the transportation cost between harvest areas and sawmills. Some optimization models are developed based on the shortest path approach (El Hachemi et al. 2011), while others are based on the shortest time approach (Keramati et al. 2018). The model developed here is based on the shortest path approach and utilizes the shortest optimal and alternative routes derived in Chapter II.

3.2 OBJECTIVE

The overall goal was to investigate the trade-offs associated with bridge weight limits within the context of minimizing transportation costs in Mississippi's forestry sector by developing an optimization model that considers bridge weight limits.

The specific objectives were to:

- Calculate the minimum transportation cost for moving softwood sawlogs from harvest sites to softwood sawmills (hereafter referred to as sawmills or mills interchangeably) without bridge restrictions along the shortest optimal routes.
- Calculate the minimum transportation cost for moving softwood sawlogs from harvest sites to sawmills with bridge restrictions along the shortest optimal routes.
- Calculate the difference in minimum transportation cost between the scenarios of the presence or absence of bridge restrictions along the shortest optimal routes.

3.3 MATERIALS AND METHODS

3.3.1 DATA

The essential data required for developing a MILP transportation model included the origin (or source) and destination locations, distance matrix (See section 3.3.1.2 for definition), supply availability at the source, demand capacity at the destination, and the transporting vehicle's capacity. Additional information on the presence or absence of closed and posted bridges along the available paths and the fraction of weight reduction on the bridges was required for this model. The analysis involved two separate scenarios, as explained in Section 2.3.3. The additional factor considered in these scenarios for the analysis is summarized in Table 3.1.

Table 3.1 An additional variable considered in the analysis between two different scenarios.

Scenarios	Description
Scenario I	• Reduction in the bridge weight limits was not considered.
Scenario II	• Reduction in the bridge weight limits was calculated for the closed and posted bridges.

3.3.1.1 SOURCE AND DESTINATION LOCATION, AND DISTANCE MATRIX

The source and destination here refer to the harvest sites and the softwood sawmills, respectively. Their location was determined in Chapter II, using the methodology outlined in the same chapter. Two separate distance matrixes were used in the model, one for each of the two scenarios given in Table 3.1.

The model requires 1,472 routes (46*32*1) between the harvest sites and the sawmills for scenario I. In this case, "46" and "32" are the number of harvest sites and sawmills, and "1" represented the shortest optimal trucking route (by distance), considering that there were no restricted bridges along the shortest optimal routes in this scenario. The model required 2,944 routes (46*32*2) between the harvest areas and sawmills in scenario II. Here, "2" represented the shortest optimal and alternative routes with restricted bridges being considered. However, only 129 shortest optimal routes were obtained between the harvest sites and sawmills due to the weight and distance restrictions, as explained in Chapter II. Among the 129 derived shortest optimal routes, 30 were affected by the closed and posted bridges; 13 of those had alternative routes deemed eligible for further study. The alternative routes for the remaining 17 affected routes could not be derived because they were either longer than 57 miles or traveled through the interstate highways. To summarize, the distance matrix had 129 routes for the first scenario and

142 routes for the second scenario, but the model required 1,472 and 2,944 routes. Thus, to ensure the distance matrix's completeness (which is pivotal for running the model), the undetermined routes were assigned a large distance of 20,000 miles. This prevented these routes from being mistakenly considered optimal solutions in the minimization problem, as their high values rendered them infeasible for minimizing cost. This distance matrix was one of the model's parameters and was represented as d_{ijp} in the model. The distance matrix is a matrix containing the distances between the set of harvest sites to the set of sawmills.

3.3.1.2 DEMAND AND SUPPLY DATA

The data section of Chapter II explains the procedures involved in determining both the supply availability in harvest areas and the demand for sawmills. These are also the model's parameters represented as S_i and d_j, respectively (See section 3.3.2.2. for definition). These parameters were kept constant for both scenarios.

3.3.1.3 GROSS VEHICULAR WEIGHT LIMIT AND NET PAYLOAD CAPACITY

The maximum GVW was assumed to be 84,000 lbs, which was the legal weight limit with the purchase of a harvest permit at the study's initiation. The vehicle tare weight was 30,243 lbs (Reddish et al. 2011). Subtracting the tare weight from the GVW gave a net payload of 53,757 lbs (26.8 tons), which was considered as truck capacity in the model. This was also a constant parameter for both scenarios.

3.3.1.4 BRIDGE WEIGHT CAPACITY AND FRACTION OF WEIGHT REDUCTION

The bridge capacity information was assessed from the data collected through various sources detailed in Chapter II. Additionally, the fraction of weight reduction on these bridges was calculated using the formula:

$$Fraction\ of\ weight\ reduction = 1 - \frac{W_1}{W_2} \tag{3.1}$$

where W_1 represents the bridge's posted weight limit, and W_2 denotes the maximum allowable GVW. If no values regarding the bridge weight were specified, a default maximum allowable weight of 84,000 lbs was assumed.

The fraction of the weight reduction parameter varied according to the scenario to be analyzed. In scenario I, this parameter was kept as 0 for all the routes as no bridge was assumed to be a limiting factor in that case. In the second scenario, this parameter was changed to the respective fraction of weight reduction for all the shortest optimal routes affected by restricted bridges. In the case of the shortest optimal routes unaffected by restricted bridges, this parameter was kept to its default value of 0.

3.3.2 DATA ANALYSIS

The MILP model was developed in Python (PyCharm) using Gurobi Optimization's solver for minimizing transportation costs between harvest areas and sawmills. The model chose optimal combinations of harvest areas and sawmills for allocating softwood sawlogs between them, selecting the best path among available options between these points. In addition, the model optimized the number of truckloads and the amount of softwood sawlogs transported between these two points, considering parameters including fixed and variable costs, route distance, hauling premiums, supply availability, demand capacity, truck capacity, and bridge weight reduction. These parameters and the model's output were then incorporated into mathematical formulas to calculate the overall total transportation cost, as well as individual transportation costs for each sawmill, and each harvest area – sawmill pair.

The formulas used for calculating the transportation costs were:

$$TC = \sum TFC + \sum TVC + \sum THP \tag{3.2}$$

Equation (3.2) represents the total transportation cost (TC), which is calculated by summing the total fixed cost (TFC), the total variable cost (TVC), and the total hauling premiums (THP). The sigma symbol (∑) denotes the summation of individual costs. This equation provides a concise illustration of how the total transportation cost is determined by incorporating different cost components. These components can be further broken down into

$$TFC = FC * Amount\ transported \tag{3.3}$$

Fixed Cost (FC) are the costs that remain constant regardless of the level of production. In this case, fixed costs are the expenses that are unaffected by the distance traveled including equipment purchasing/renting, insurance, and overhead costs. This cost was expressed as dollars per ton of softwood sawlogs transported. The amount transported is the total amount of softwood sawlogs transported between the pairs of harvest sites and sawmills and was measured in tons. In the above equation, FC was a fixed quantity, whereas the amount transported was a variable quantity.

$$TVC = VC * Distance * Payload\ capacity * Number\ of\ truckloads \tag{3.4}$$

Variable Cost (VC) are the costs that change proportionally with the level of production. In Equation 3.4, VC is the variable cost of transporting softwood sawlogs from harvest areas to sawmills, expressed as dollars per ton per transported mile. In this analysis, VC were the costs that depend on the distance traveled like fuel, maintenance costs, labor, minor repairs, regular maintenance (filters, oil, lube, etc.), and wear and tear (tires, brakes, etc.). Payload capacity is the maximum amount of weight that a vehicle can carry safely in addition to its empty weight. The number of truckloads refers to the number of truckloads required for transporting softwood sawlogs from the harvest sites to sawmills. In the above equation, VC and Payload capacity were fixed quantities whereas the distance and the number of truckloads were variable quantities.

$$THP = HP * Amount\ transported \tag{3.5}$$

$$HP = VC + 50\% * VC * (Distance - 50) \tag{3.6}$$

Equation (3.5) calculates the total hauling premium, which is an additional charge to the transportation cost, applied for the hauling distances longer than the minimum hauling distance. The minimum hauling distance is the threshold distance under which a minimum haul rate or fixed variable cost base rate is applied, regardless of the distance traveled (Norris Foundation 2022). This total hauling premium is obtained by multiplying the hauling premium rate by the amount of softwood sawlogs transported. The hauling premium (HP) is calculated from the variable cost (VC) and the route distance (Equation 3.6). The hauling premium is not applied for routes below 50 miles and is charged incrementally for routes longer than 50 miles, as indicated by (Distance - 50), where distance is the hauling distance.

3.3.2.1 SETS

The sets used in the model were ***I, J,*** and ***P*** which represented the sets of all possible harvest areas, sawmills, and the path between these two points.

3.3.2.2 PARAMETERS

The parameters used in the model were:

S_i : Supply availability (in tons) at harvesting site $i \in \boldsymbol{I}$

d_j: Demand (in tons) at mill $j \in \boldsymbol{J}$

d_{ijp}: Distance between harvesting site $i \in \boldsymbol{I}$ to mill $j \in \boldsymbol{J}$ using path $p \in \boldsymbol{P}$

ξ_{ijp} : Fixed cost ($/ton) of using a truck between harvesting site $i \in \boldsymbol{I}$ to mill $j \in \boldsymbol{J}$ using path $p \in \boldsymbol{P}$

c_{ijp}: Unit variable cost ($/ton/mile) of transporting softwood sawlogs between harvesting site $i \in \boldsymbol{I}$ to mill $j \in \boldsymbol{J}$ using path $p \in \boldsymbol{P}$

β_{ijp}: Fraction of weight reduction due to the presence of a bridge in path $p \in \boldsymbol{P}$ between harvesting site $i \in \boldsymbol{I}$ and mill $j \in \boldsymbol{J}$

π_j : Unit penalty cost ($/ton) associated with unsatisfied demand at mill $j \in \boldsymbol{J}$

v^{cap}: Truck capacity (in tons)

Here Si was the amount of softwood sawlogs available at a specific harvest site, i among the set of harvest sites $\boldsymbol{I}$. Variable dj represented the amount of softwood sawlogs demanded by a particular sawmill j in the set of sawmills $\boldsymbol{J}$. Likewise, d_{ijp} represented the distance of the available paths between the harvesting sites and sawmills. The fixed cost incurred when transporting softwood sawlogs from *i* to *j* using a specific path *p* from the set of all possible paths ***P*** was denoted by ξijp. Furthermore, c_{ijp} indicated the variable cost of transporting softwood sawlogs between *i* and *j*. The fraction of weight reduction for loaded trucks due to the presence of closed and posted bridges along path *p* was β_{ijp}. The cost per ton of unsatisfied demand π_j was the penalty cost associated with the unfulfillment of demand at sawmill *j*. Finally, v^{cap} represents the truck capacity or the maximum amount of softwood sawlogs that a truck can transport at once.

TimberMart-South reported an average variable cost of forestry transportation across the US South as $0.18/ton/loaded mile (Norris Foundation 2022). However, information regarding fixed costs was not provided. Therefore, fixed and variable costs both were calculated using the Mississippi State University Forest and Wildlife Research Center's Route Chaser program (Stuart and Grace n.d.). The fixed cost using Route Chaser was determined to be $2.39 per ton. The variable cost was calculated as $0.17/ton/mile, aligning with the value provided by TimberMart-South (Norris Foundation 2022). The calculated costs are provided in Table 3.4. The inputs used in the Route Chaser program to arrive at the calculated value are provided in Tables 3.2 and 3.3

Table 3.2 Various inputs and their values used in the Route Chaser program to calculate the fixed and variable costs.

Inputs		References
Equipment Purchase Price		
Truck tractor	$135,000	forestrytrader.com
Trailer	$24,500	pitts.com
Add-ons (taxes, equipment)	$7,975	5% add-on of truck-trailer sum (assumed)
Total Cost	$167,475	
Financing		
Amount	$167,475	
APR	0.0549	Kansas City federal reserve 2022 year-to-date average
Years	5	
Labor		
Base wage/Hour	$22.64	US Department of Labor Occupational Employment Statistics 2021
Fringe Benefits + Worker's Compensation (Percent)	30	Assumed
Repair and Maintenance per mile (Limited Access Highway as Base)		
Brakes	$0.24	
Tires	$0.18	
Normal maintenance (Filters, lube, oil)	$0.05	
Minor Repair	$0.03	
Insurance (per year)		
Liability	$7,500	(Conrad IV 2017)
Collision/FTV	0	
Overheads (per year)		
License – Apportioned tags	$1,358.25	https://www.fhwa.dot.gov/ohim/hwytaxes/2001/pt11b.htm
Ad Valorem taxes	$0 (for Mississippi)	
Heavy Use Tax	$25 (harvest permit)	

In addition to these inputs, Route Chaser required fuel cost information for calculating the fixed and variable costs. The value used was $3.05 per gallon, obtained as a 10-year real 2022 average (2012 – 2022) from the data of Gasoline and Diesel Fuel Update - U.S. Energy Information Administration (U.S. Energy Information Administration 2022)

Table 3.3 Routes inputs used for calculating the fixed and variable costs in the Route Chaser program.

Road type	**Distance (miles)**	**Speed (MPH)**	**Fuel use (MPG)**
Forest Road	1	8	2.4
Graveled County Road	1	25	3.7
Paved County Road	2	35	4.6
State or Federal 2-Lane Highway	38.87	55	5.3
Limited Access Highway	1	60	5.3
Urban Streets	1	25	2.5

The distance of the state or federal two-lane highway (Table 3.3) was calculated by averaging the derived routes. The distance of all other road types was assumed.

Table 3.4 The value of the fixed and variable costs derived from the Route Chaser program.

	Annual	**Per day**	**Per ton**	**Per ton-mile**
		Fixed Costs		
Equipment	$39,207.94	$156.83	$1.94	$0.05
Insurance	$7,500	$30	$0.37	$0.01
Overheads	$1,383.25	$5.53	$0.07	$0
Total	$48,091.19	$192.36	$2.39	$0.06
		Variable Costs		
Labor	$68,061.50	$272.25	$3.38	$0.08
Fuel	$41,260.93	$165.04	$2.05	$0.05
Brakes	$19,471.50	$77.89	$0.97	$0.02
Tires	$11,979.90	$47.92	$0.59	$0.01
Normal Maintenance - Filters, lube, oil -	$2,092.81	$8.37	$0.10	$0
Minor Repair	$1,974.15	$7.90	$0.10	$0
Total	**$144,840.79**	**$579.36**	**$7.18**	**$0.17**

Table 3.4 shows fixed and variable costs amounted to $2.39 per ton and $0.17 per ton mile, respectively. No information was obtainable regarding a penalty cost associated with unsatisfied demand at sawmills. This cost represents the additional cost incurred with the inability to meet the demand of certain mills. Incorporating this cost in transportation cost minimization problems ensures that the solution along with minimizing transportation costs also accounts for the financial consequences of unmet demand. When this component is overlooked

in the objective function, the model might only focus on minimizing transportation costs without trying to meet the mill's demand. In other words, the model may choose to transport the softwood sawlogs only to the nearby mills. Disregarding slightly further mills makes the solution practically unsuitable, although mathematically accurate. However, including this component in the objective function allowed the model to consider both transportation and the unmet demand costs to balance cost minimization and demand requirements. The solution could then be regarded as both practical and useful for applied questions. Rix et al. (2014) assigned a penalty cost of \$60/m^3 (\$73.10/ton) for the Canadian forest industries through consultation with industry decision-makers. This value, when adjusted for inflation to 2022 dollars, was \$91.32/ton. Kong et al. (2012) also stated penalty costs should be large enough to ensure mill demands were satisfied. So, the value of \$100/ton was maintained for this model considering those two studies.

3.3.2.3 DECISION VARIABLES

The decision variables used in the model were:

Z_{ijp} : Number of truckloads transported between harvesting site $i \in \boldsymbol{I}$ to mill $j \in \boldsymbol{J}$ using a path $p \in \boldsymbol{P}$

X_{ijp} : Amount of softwood sawlogs (in tons) transported between harvesting harvesting site $i \in \boldsymbol{I}$ to mill $j \in \boldsymbol{J}$ using path $p \in \boldsymbol{P}$

U_j : Amount of unsatisfied demand (in tons) at mill $j \in \boldsymbol{J}$

Here, Z_{ijp} and X_{ijp} represented the number of truckloads and amount of softwood sawlogs transported between i and j, respectively. Meanwhile, U_j represented the unsatisfied demand at a particular mill j. Among the decision variables, Z_{ijp} was an integer variable indicating the discrete number of truckloads used for transportation, while X_{ijp} and U_j were continuous variables (real numbers) representing the continuous quantity of softwood sawlogs transported and unsatisfied demand, respectively.

3.3.2.4 OBJECTIVE FUNCTION AND CONSTRAINTS

In this section, we assume mills are the cost minimizers as represented by the model's objective function (Equation 3.7). This function comprised fixed costs, variable costs, and penalty costs. The function was subject to several constraints – supply availability restrictions, truck capacity limitations, demand satisfaction restrictions, and non-negativity restrictions. The model's objective function and constraints are explained in detail below:

Objective function:

$$Minimize\colon \sum_{i\in I}\sum_{j\in J}\sum_{p\in P}(\xi_{ijp}Z_{ijp} + c_{ijp}d_{ijp}X_{ijp}) + \sum_{j\in J}\pi_j U_j \tag{3.7}$$

Subject to:

Supply availability restrictions:

$$\sum_{j\in J}\sum_{p\in P}X_{ijp} \leq s_i;\ \forall i \in I \tag{3.8}$$

The supply availability restriction equation (Equation 3.8) ensured the quantity of softwood sawlogs transported from a given harvesting site to any mill traveled via any path cannot exceed the amount of softwood sawlogs available at that site.

Capacity restrictions:

$$X_{ijp} \leq v^{cap}(1-\beta_{ijp})Z_{ijp};\ \forall i \in \boldsymbol{I},\ j \in \boldsymbol{J},\ p \in \boldsymbol{P} \tag{3.9}$$

$$Z_{ijp} \leq \left\lceil \frac{d_j}{max\,\{1, v^{cap}(1-\beta_{ijp})\}} \right\rceil;\ \forall i \in \boldsymbol{I},\ j \in \boldsymbol{J},\ p \in \boldsymbol{P} \tag{3.10}$$

The truck capacity restriction (Equation 3.9) computed the quantity of softwood sawlogs to be transported from a specific harvesting site to a designated sawmill while considering the truck's capacity (v^{cap}), fraction of bridge weight reduction (β_{ijp}), and the number of truckloads required to transport the computed amount of softwood sawlogs (Z_{ijp}). This equation ensured that the amount of softwood sawlogs transported between the harvest sites and mills did not exceed the truck's capacity. It considered the weight reduction in bridges and the number of truckloads available for transportation. Here, $(1-\beta_{ijp})$ was the portion of softwood sawlog's weight retained after accounting for the bridge-weight-related reductions.

The number of truckloads restriction (Equation 3.10) calculated the number of truckloads required to transport softwood sawlogs from a specific harvesting site to a particular mill, considering the truck capacity and the fraction of weight reduction due to bridges. This equation ensured that the optimal number of truckloads were utilized to transport the required amount of softwood sawlogs to the specified mills, considering both truck capacity and bridge-related weight reductions. This equation sets an upper bound limit on the number of truckloads required to prevent an infinite number of truckloads as solution. Here, $v^{cap}(1-\beta_{ijp})$ was the effective capacity of a truck after accounting for the weight reduction due to bridges.

Demand satisfaction restrictions:

$$\sum_{i \in \boldsymbol{I}} \sum_{p \in \boldsymbol{P}} X_{ijp} + U_j = d_j;\ \forall j \in \boldsymbol{J} \tag{3.11}$$

The demand satisfaction restriction (Equation 3.11) ensured the sum of the softwood sawlogs transported from any harvesting site to a particular mill, and the amount of unsatisfied demand at that mill (left-hand side), was equal to that mill's demand (right-hand side). In this equation, U_j is a slack variable that simulates the demand from other sources not present in the data collected.

Non-negativity restrictions:

$$X_{ijp} \in \mathbb{R}^+;\ \forall i \in \boldsymbol{I}, j \in \boldsymbol{J}, p \in \boldsymbol{P} \tag{3.12}$$

$$Z_{ijp} \in \mathbb{Z}^+;\ \forall i \in \boldsymbol{I}, j \in \boldsymbol{J}, p \in \boldsymbol{P} \tag{3.13}$$

$$U_j \in \mathbb{R}^+;\ \forall j \in \boldsymbol{J} \tag{3.14}$$

Equations 3.12 and 3.14 state that the amount of softwood sawlogs transported, and the unsatisfied demand must each be a positive real number, either discrete or continuous. On the other hand, Equation 3.13 states the number of truckloads transported must be a positive integer or a whole number. For example, assume 2,853.2 tons of softwood sawlogs are available at a specific harvest site, and the intended sawmill requires a total of 3,500 tons. This would result in an unsatisfied demand of 646.8 tons, which is a decimal. However, considering a payload of 26.8 tons per truck, it is not feasible to transport the softwood sawlogs using a fractional number of truckloads. Consequently, we would need to utilize 106 truckloads (a whole number or an integer) instead of 106.46 (2,853.2/26.8) to transport the materials efficiently.

3.4 RESULTS

3.4.1 ORIGINAL MODEL'S COMPUTATIONAL EFFICIENCY AND ACCURACY

The model achieved an optimality gap of 0.0003% and a running time of 0.001 seconds in both scenarios. The running time shows the computational efficiency of the model and determines in how many seconds the model can solve the given problem. The optimality gap of 0.0003% of the model indicated a highly accurate solution, and the running time of 0.001 seconds shows that the model is highly efficient and solved the given problem in 0.001 seconds.

3.4.2 ORIGINAL MODEL IMPACT ON TRANSPORTATION COST AND COMPONENTS

Table 3.5 (original optimization model's result) provides a general overview of the impact of the restricted bridges on transportation costs. The total cost of transporting softwood sawlogs from the harvest sites to the mills was $98.85 million in scenario I which increased to $102. 91 million in scenario II. This was an increase of about 4.06 million USD, equivalent to a 4.11% rise from the original value. Both scenarios transported 12.06 million tons of softwood sawlogs. Per-ton transportation cost was $8.20 for scenario I and $8.54 for scenario II, an additional cost of 34 cents per ton. Similarly, scenario II required 12.41 thousand more truckloads due to restricted bridge weight capacity than scenario I, representing a 2.77% increase in the number of truckloads.

To determine the component of the total transportation most affected by the restricted bridges, the total transportation cost was further analyzed and broken down into fixed cost, variable cost, and hauling premium cost (Table 3.6).

Table 3.5 Comparison of the amount of softwood sawlogs transported, total transportation cost (USD), transportation cost per ton of softwood sawlogs transported (USD/ton), and the number of truckloads utilized between two analyzed scenarios.

Scenarios	**Amount transported (million tons)**	**Total TC (million USD)**	**TC per ton (USD/ton)**	**Number of truckloads required (in thousand)**
Scenario I	12.06	98.85	8.20	448.70
Scenario II	12.06	102.91	8.54	461.11
Difference in scenarios I and II	0	4.06	0.34	12.41
Percentage (%) change between scenarios I and II	0	4.11	4.11	2.77

Table 3.6 Breakdown of total transportation cost into its components and comparing them between the two analyzed scenarios.

Scenarios	**Total TC (million USD)**	**Total FC (million USD)**	**Total VC (million USD)**	**Total hauling premiums (million USD)**
Scenario I	98.85	28.82	69.47	0.56
Scenario II	102.91	28.82	73.44	0.64
Difference in scenarios I and II	4.06	0	3.97	0.083
Percentage (%) change between scenarios I and II	4.11	0	5.73	0.015

Variable costs occupied the greatest proportion of the transportation cost followed by the fixed cost and hauling premiums (Table 3.6). In Scenario I, the fixed, variable, and hauling premiums accounted for 29.16%, 70.27%, and 0.57% of the total cost, respectively. Scenario II's increased trucking distance and decreased allowable weight limits changed these proportions to 28.01%, 71.36%, and 0.63%. The presence of restricted bridges along the shortest optimal path did not affect the fixed cost, but they did influence the variable cost and hauling premiums. When the bridges along the shortest optimal path were either closed or posted to lower weight limits, the variable cost and hauling premiums increased by 5.73% and 14.73% (Table 3.6).

3.4.3 ORIGINAL MODEL'S IMPACT ON TRANSPORTATION COST FOR SAWMILLWISE LEVEL

Figure 3.1 presents the restricted bridge's effect on individual sawmills. The green and red bars represent scenarios I and II, and the purple bar indicates the difference between these scenarios. The blue line represents the percentage increase in these scenarios. Figure 3.1 (a) illustrates that out of 32 mills, trucking to 11 of them (34.37%) experienced increased transportation costs due to restricted bridges. Sawmills 2 (Weyerhaeuser, Philadelphia), 11 (Canfor Corp, Hermanville), and 24 (Tri-State Lumber Co., Fulton) were most affected by additional transportation costs that amounted to $1.08 million, $800 thousand, and $762 thousand respectively. These three sawmills were classified as additional transportation costs exceeding $500,000. Sawmills 31 (Idaho Forest Group, Lumberton), 25 (Hood Industries Inc., Waynesboro), and 18 (Rogers Lumber Corporation, Columbia) had additional transportation costs below $100,000. Sawmill 18 had the lowest additional cost, with an additional cost of $5,747. Sawmills 19 (King Lumber Company, Forest), 11 (Canfor Corp, Hermanville), and 2

(Weyerhaeuser, Philadelphia) had the greatest percentage increase in transportation costs between the two scenarios, with increments of 59.96%, 41.27%, and 11.88% respectively.

Figure 3.1(b) displays the total transportation cost in USD per ton of softwood sawlogs transported for the affected sawmills in both scenarios and compares them. Sawmills 19, 11, and 2 were the top three affected mills in terms of additional transportation costs per ton, with additional costs of $3.56, $2.20, and $1.08 per ton. The transportation cost per ton of softwood sawlogs transported to individual sawmills was then broken down into fixed, variable, and haulage premium costs per ton to determine the changes in these costs for both scenarios. As the total fixed cost remained unchanged, the focus was on comparing the variable and haulage premium costs for Scenario I and II. Sawmills 19, 11, and 2 had the highest increment in variable cost per ton of softwood sawlogs transported, with an additional cost of $3.55, $2.19, and $0.99 for scenario II per ton of softwood sawlogs transported (Figure 3.1(c)). Sawmills 19, 11, and 4 (Bazor Lumber, Quitman) had the greatest percentage increment in variable cost per ton transported with corresponding increases of 100.37%, 74.89%, and 16.66%. Sawmills 2 (Weyerhaeuser, Philadelphia), 5 (Interfor Corporation, Bay Springs), 12 (Rex Lumber, Brookhaven), 13 (Seago Lumber, McComb), 15 (W L Byrd Lumber, Fernwood), 16 (Lincoln Lumber Co., Brookhaven), and 20 (Georgia-Pacific Company, Taylorsville) incurred hauling premium costs as shown in Figure 3.1(d)). Only Sawmill 2 hauling premium increased even further among them. This amounted to $0.08 per ton transported or a 44.41% increase in the hauling premium due to restricted bridges. Sawmill 15 had the highest per-ton haulage premium of $0.80/ton, followed by Seago Sawmill 13 ($0.40/ton) and Sawmill 20 ($0.30/ton).

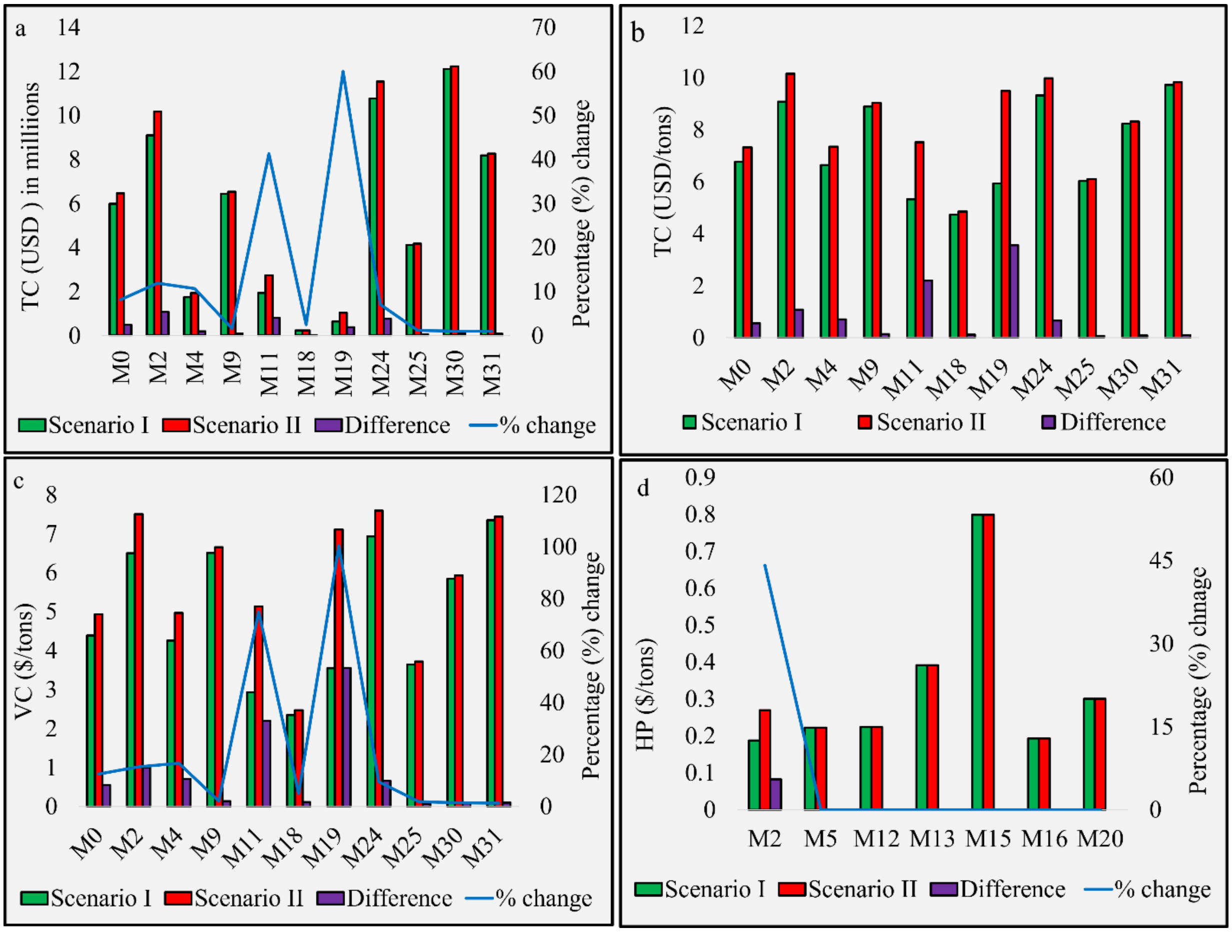

Figure 3.1 Comparison of total transportation cost (TC) (a), TC per ton of softwood sawlogs transported (b), variable cost (VC) per ton of softwood sawlogs transported (c), and total hauling premiums (HP) per ton of softwood sawlogs transported (d) for sawmills affected by restricted bridges in both scenarios.

Figure 3.2(a) shows the amount of softwood sawlogs transported for each sawmill, while Figure 3.2(b) depicted the number of truckloads required for transporting the allotted softwood sawlogs in both scenarios. The quantity of softwood sawlogs transported remained constant for each sawmill in both scenarios, however, the required number of truckloads varied. This difference was a result of the model's approach to minimizing transportation costs by selecting between using additional trips to haul with reduced weight loads on posted bridges or opting for longer hauls with the maximum allowable GVW. The model determined that in certain situations, it was more cost-effective to transport the materials with reduced weight on the trucks, leading to the increased number of truckloads for scenario II.

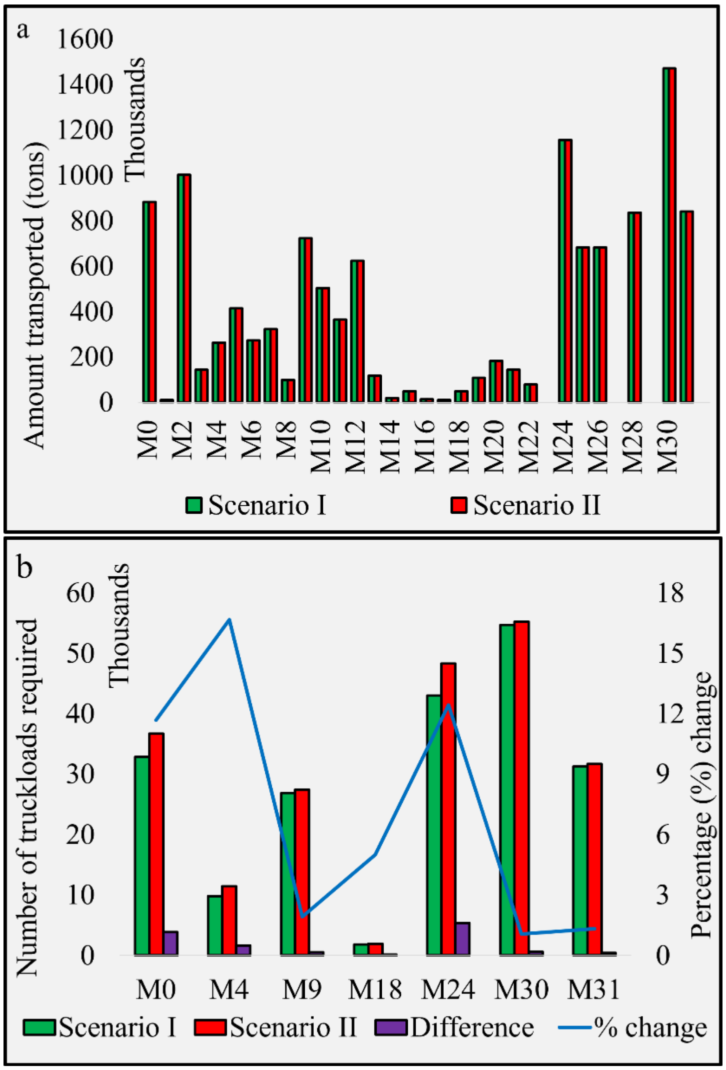

Figure 3.2 Comparison of the amount of softwood sawlogs transported for each sawmill (a) and the number of truckloads required to transport those softwood sawlogs to the respective mills (b) in scenario I and II.

Out of the 11 affected Sawmills, 4 maintained the same number of truckloads in both scenarios, while the remaining 7 increased the number of truckloads delivered due to weight restrictions on bridges. This indicated that for 36% of the Sawmills, it was more cost-efficient for log truckers to travel additional distances fully loaded at the maximum GVW from the paired harvest sites and sawmills. Conversely, for the remaining 64% of the affected sawmills, it was more cost-effective for log truckers to carry partial loads at posted weights and travel over compromised bridges for some pairs of harvest areas and the sawmills. The top three increases in the number of truckloads required were for Sawmills 24 (Biewer Lumber, Newton), 0 (Weyerhaeuser, Bruce), and 4 (Bazor Lumber, Quitman), with 5347, 3836, and 1631 additional loads. Those three were also the top three in terms of percentage increase in the order – Sawmill 4 (16.67%), Sawmill 24 (12.44%), and Sawmill 0 (11.68%).

Figure 3.2 (a) states that Sawmills 23 (Tri-State Lumber Co., Fulton), 27 (Vicksburg Forest Products LLC, Vicksburg), and 29 (Hankins Lumber, Grenada) did not receive any softwood sawlogs from collected harvest data although there was surplus of softwood sawlogs in the harvest sites. Instead, the slack variable imitated the demand from the other sources or shadow harvest sites, which exist mathematically, but were not present in the actual data collected. This represents the sampling problem in FIA data collected. Excluding low-weight limit roads and interstate highways from the derived routes left no feasible routes from harvest sites to Sawmills 23 and 27, resulting in these mills receiving no softwood sawlogs from the actual data collected. Sawmill 29, despite having available routes, did not receive any softwood. To gain further insight regarding the allocation of the softwood, an additional analysis was conducted to determine the percentage of demand fulfilled for each sawmill (Figure 3.3).

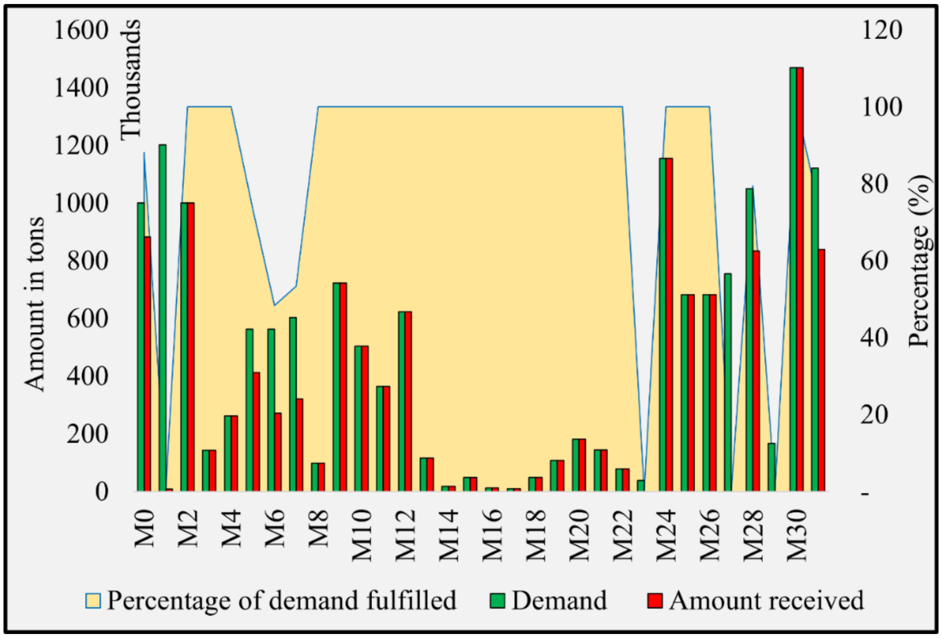

Figure 3.3 Sawmill demand, amount of softwood sawlogs received by them, and percentage of their demand fulfilled.

Figure 3.3 illustrates that Sawmills 23, 27, and 29 had 0 percent of their demand fulfilled from the collected data. Sawmill 1 (Weyerhaeuser, Mangolia) had only 0.81% of its demand fulfilled, while Sawmill 6 (Hankins Inc, Ripley) managed to fulfill 48.43% of its demand. The other remaining sawmills had at least 50% of their demand fulfilled. Twenty-two of those fully satisfied their demand.

3.4.4 ORIGINAL MODEL'S IMPACT ON TRANSPORTATION COST FOR INDIVIDUAL HARVEST SITE – SAWMILL PAIR

A pair-level analysis was conducted to examine the impact of restricted bridges on individual pairs of harvest sites and sawmills. From here onwards, pairs represent harvest sites – sawmill pairs. While all mills received the same amount of softwood sawlogs in both scenarios, some pairs had variations in softwood sawlog's distribution, leading to changes in the amount to be transported for those specific pairs. The limited availability of timber at the harvest sites and constant demand from the sawmills in both scenarios necessitated a balanced distribution approach. Timber was allotted considering factors like availability and transportation cost, to minimize transportation costs while meeting the mill's demand. Therefore, specific allocation decisions varied between scenarios to optimize timber utilization, resulting in variations in the quantity of softwood sawlogs transported as illustrated in Figure 3.4.

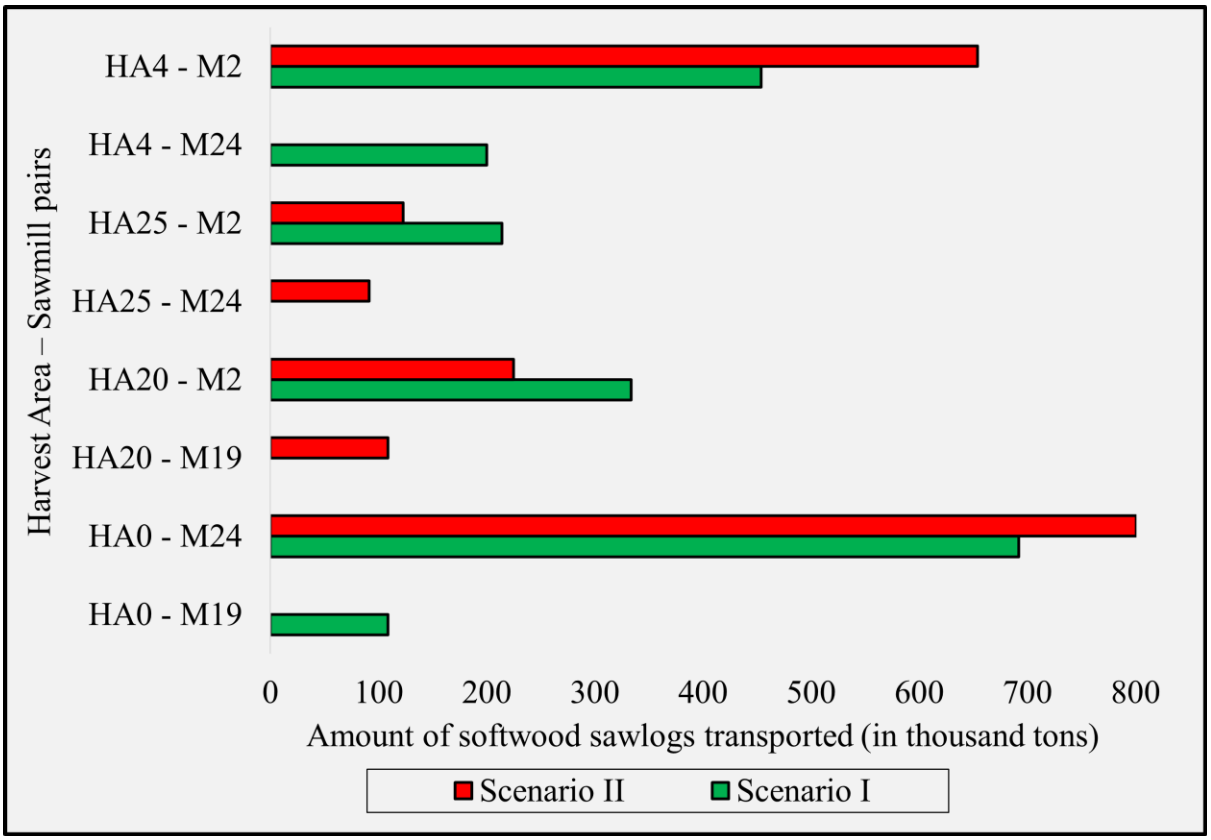

Figure 3.4 Comparison of the amount of softwood sawlogs transported among pairs exhibiting varying allocations between the two scenarios.

The amount of softwood sawlogs transported decreased in scenario II for the pairs HA25 – M2 and HA20 – M2. The quantity of softwood sawlogs transported increased in scenario II for the pairs – HA4 – M2 and HA0 – M2. Pairs HA4 -M24 and HA0 – M19 were those between which softwood sawlogs were transported in scenario I but not in scenario II, whereas HA25 – M24 and HA20 – M19 were the pairs where the transportation occurred only in scenario II.

Figure 3.5 (a) compared the total transportation cost per ton of softwood sawlogs transported for affected pairs between the two scenarios. This approach was more accurate and meaningful than comparing the total cost alone, because it accounted for the weight transported. It also provided a clearer comparison as the total amount transported for the individual pairs changed for a few pairs. Thirteen pairs had additional transportation costs per ton transported, among which pairs HA13 – M11, HA18 – M0, and HA0 – M24 had the most additional cost per ton in Scenario II as compared to Scenario I, with corresponding values of \$2.19/ton, \$1.03/ton, and \$0.95/ton respectively. In terms of percentage change, HA13 – M11, HA34 – M4, and HA18 – M0 were most affected by experiencing increases of 41.27%, 11.26%, and 10.29%. Four pairs had total percentage increases of over 10%. The transportation cost per ton from the site to the mill(s) was broken down into fixed, variable, and hauling premiums to understand what component was most affected by the restricted bridges. Fixed costs were the same for all the pairs.

Figure 3.5 (b) calculated the variable cost per ton of softwood sawlogs transported for the affected pairs in both scenarios. Pair HA13 – M11 had the highest additional variable cost of \$2.19 (74.89% increase), followed by HA18 – M0 at \$1.03. Seven out of 15 affected pairs had variable costs increased by more than 10% due to restrictions.

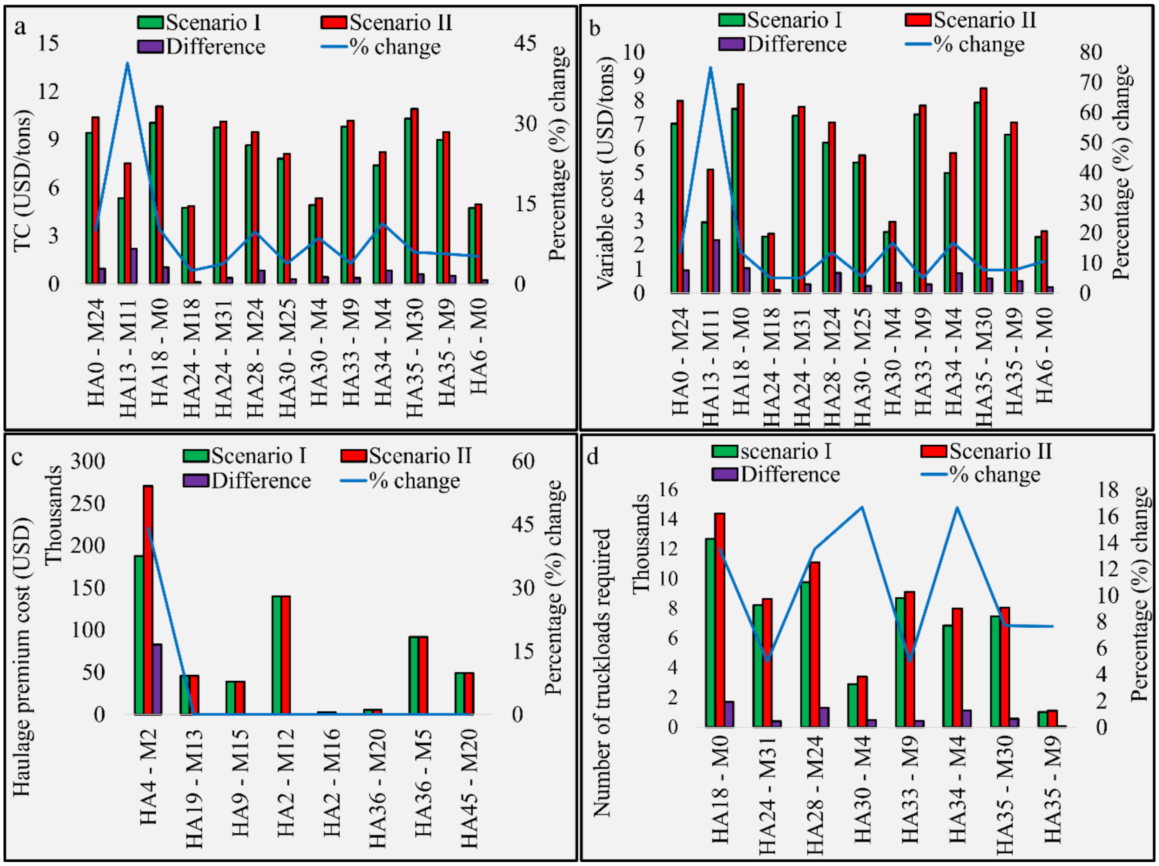

Figure 3.5 Comparison of total transportation cost (TC) per ton of softwood sawlogs transported (a), variable cost per ton of softwood sawlogs transported (b), total hauling premium cost (c), and the number of truckloads required to fulfill the mill demand for each pair affected by restricted bridges in Scenario I and II.

Only the pair HA4 – M2 had an additional haulage premium (Figure 3.5(c)). The haulage premium for this pair without considering the bridges was $187.6 thousand, and this increased to $270.3 thousand when accounting for bridges. This represented a 44.12% increase of $82.7 thousand in the haulage premium due to bridge closure or posted weight limits.

Figure 3.5 (d) displayed the number of truckloads used for transporting softwood sawlogs for the affected pairs. This analysis focused on the pairs that met three criteria: (i) present in both scenarios (ii) the same quantity of softwood sawlogs transported between them in both scenarios

(iii) utilized a different number of truckloads to transport softwood sawlogs between the two scenarios. This ensured a meaningful comparison as the pairs with varying amounts of softwood sawlogs transported would naturally have different numbers of truckloads due to the quantity difference. Eight pairs had the same amount of softwood sawlogs supplied between them, but the number of truckloads differed. Pairs HA18 - M0, HA28 - M24, and HA34 - M4 were the three most affected pairs in terms of the extra truckloads needed, 1717, 1321, and 1143, respectively. Relatively, HA30 - M4, HA34 – M4, and HA18 – M0 were the most affected pairs in terms of percentage increase in the number of truckloads, 16.68%, 16.66%, and 13.51%, respectively.

3.4.5 MODIFIED MODEL'S IMPACT ON TRANSPORTATION COST AND IT'S COMPONENTS

To rectify the problem outlined in Section 3.4.3, where sawmills 23, 27, and 29 did not receive any softwood sawlogs and sawmill 1 received only 0.81% of its demand from the collected data, sawmills 23 and 27 were initially excluded from the analysis (keeping mill id constant to ensure consistency in results) due to the unavailability of viable routes to these mills from the harvest sites. The penalty cost was then adjusted through an iterative process, following the approach of Kong et al. (2012), which entailed setting penalty costs high enough to ensure the fulfillment of mill demands. However, this strategy did not achieve the desired outcome in our case. Increasing the penalty cost did not lead to a modification in the allocation process for sawmills 1 and 29; instead, the model continued to allocate resources to other mills using the routes of 20,000 miles. Even when the distance of the unavailable route was further increased, the outcome remained unchanged. As a result, a new constraint (Equation 3.15) was introduced to the model to address the issue.

$$\sum_{i \in \boldsymbol{I}} \sum_{p \in \boldsymbol{P}} X_{ijp} \geq \alpha * d_j ;\ \forall j \in \boldsymbol{J} \qquad (3.15)$$

Equation 3.15 ensured that a minimum proportion, represented by α, of the mill's demand must be fulfilled for promoting a more balanced solution. In this case, α was set to 50%. This constraint utilized the softwood sawlogs within the internal supply system to fulfill the sawmill's demand, aiming to achieve a balanced allocation of resources and improve the overall solution. The result of the modified model is presented in Tables 3.7 and 3.8.

Table 3.7 Comparison of the amount of softwood sawlogs transported, total transportation cost (USD), transportation cost per ton of softwood sawlogs transported (USD/ton), and the number of truckloads utilized between two analyzed scenarios.

Scenarios	**Amount of transported (million tons)**	**Total TC (million USD)**	**TC per ton (USD/ton)**	**Number of truckloads required (in thousand)**
Scenario I	12.06	100.70	8.35	448.70
Scenario II	12.06	104.79	8.69	461.11
Difference in scenarios I and II	0	4.09	0.34	12.41
Percentage (%) change between scenarios I and II	0	4.07	4.07	2.77

Table 3.8 Breakdown of total transportation cost into its components and comparing them between two analyzed scenarios.

Scenarios	**Total TC (million USD)**	**Total FC (million USD)**	**Total VC (million USD)**	**Total hauling premiums (million USD)**
Scenario I	100.70	28.82	71.17	0.70
Scenario II	104.79	28.82	75.18	0.78
Difference in scenarios I and II	4.09	0	4.01	0.08
Percentage (%) change between scenarios I and II	4.07	0	5.63	11.67

Table 3.7 presents the impacts of restricted bridges on optimal routes, revealing an additional cost of $4.09 million due to the presence of these bridges along the optimal routes. This addition corresponds to an increase of $0.34 per ton of softwood sawlogs transported or a 4.07% rise in transportation cost. Table 3.8 demonstrated that the majority of the transportation cost is attributed to variable cost, followed by the fixed cost, and then the hauling premiums in both scenarios. In scenario I, the fixed, variable, and hauling premiums accounted for 28.63%, 70.68%, and 0.69% of the total cost. In scenario II, these proportions changed to 27.51%, 71.74%, and 0.75%, respectively. Restricted bridges along the shortest optimal path did not impact the fixed cost, but did affect the variable cost and hauling premiums. Specifically, the

variable cost and the hauling premiums increased by 5.63% and 11.67% respectively when the bridges were either closed or had lower weight limits imposed.

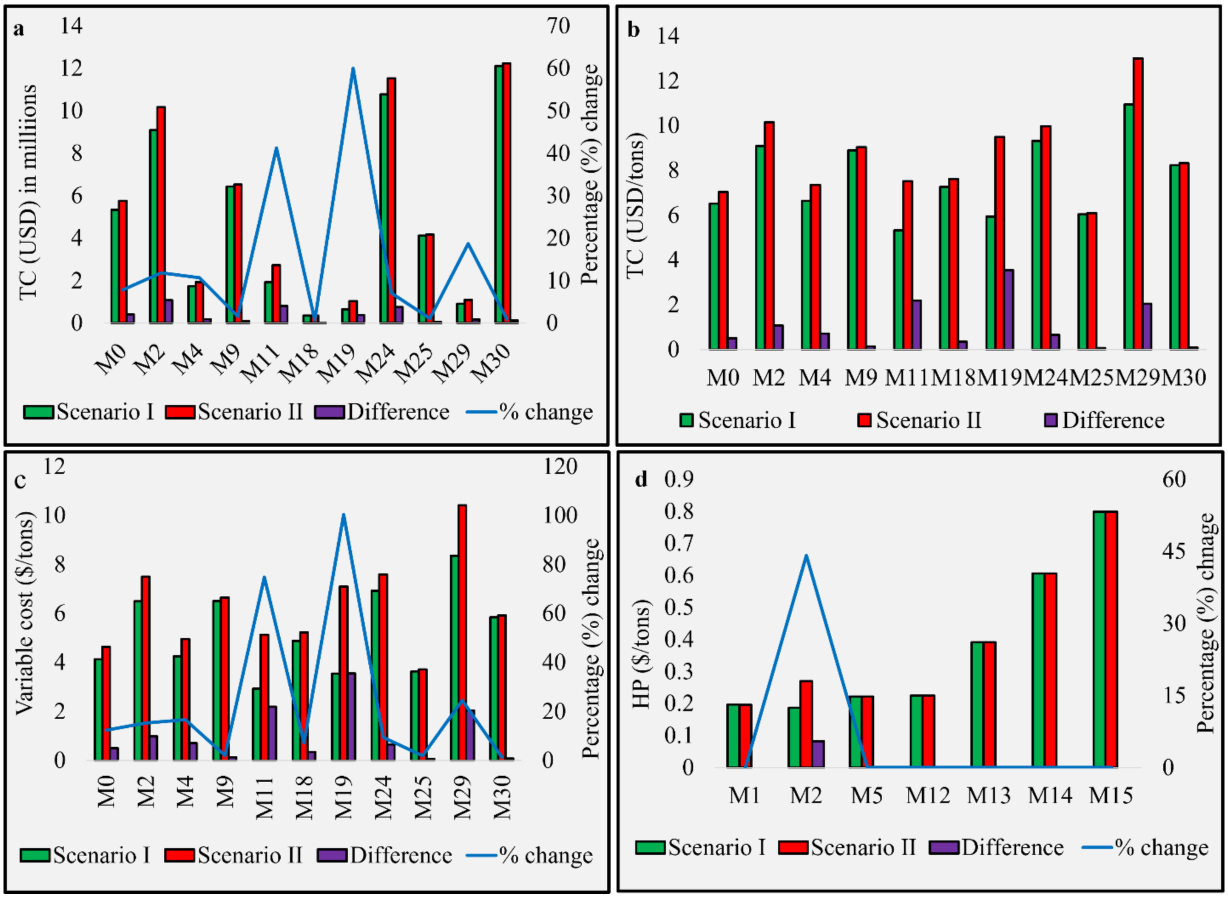

Figure 3.6 Comparison of total transportation cost (TC) (a), TC per ton of softwood sawlogs transported (b), variable cost (VC) per ton of softwood sawlogs transported (c), and total hauling premiums (HP) per ton of softwood sawlogs transported (d) for sawmills affected by restricted bridges.

Figure 3.6 (a) illustrates that 11 out of 30 mills (36.67%) experienced increased transportation costs due to restricted bridges. Sawmills 2 (Weyerhaeuser, Philadelphia), 11 (Canfor Corp, Hermanville), and 24 (Biewer Lumber, Newton) were the top three affected by additional transportation costs, $1.08 million, $800 thousand, and $762 thousand, respectively.

Sawmills 19 (King Lumber Company, Forest), 11, and 29 (Hankins Lumber, Grenada) had the greatest percentage increases in transportation costs between the two scenarios of 59.96%, 41.27%, and 18.72%, respectively. Figure 3.6 (b) depicts Sawmill 19, Sawmill 11, and Sawmill 29 being most affected by additional transportation costs per ton at $3.56, $2.20, and $2.05 per ton of softwood sawlogs transported, respectively. The breakdown of transportation cost per ton into fixed, variable, and haulage premium costs was conducted to analyze the changes in these costs for both scenarios. The total fixed cost remained unchanged in both scenarios. Sawmills 19, 11, and 29 had the highest increase in variable cost per ton of softwood sawlogs transported in scenario II, with additional costs of $3.55, $2.19, and $2.05, respectively. They also had the greatest percentage increments of 100.37%, 74.89%, and 24.54%, respectively (Figure 3.6(c)). Sawmills 1 (Weyerhaeuser, Mangolia), 2 (Weyerhaeuser, Philadelphia), 5 (Interfor Corporation, Bay Springs), 12 (Rex Lumber, Brookhaven), 13 (Seago Lumber, McComb), 14 (Magnolia Lumber Co Inc., Fernwood), 15 (W L Byrd Lumber, Fernwood), 16 (Lincoln Lumber Co., Brookhaven), 20 (Georgia-Pacific Company, Taylorsville), and 29 (Hankins Lumber, Grenada) incurred hauling premium costs as shown in Figure 3.6(d). Among them, only Sawmill 2 experienced an even greater hauling premium, which amounted to a 44.41% increase in the hauling premium due to restricted bridges of $0.08 per ton transported. Mill 15 had the highest per-ton haulage premium of $0.80/ton, followed by mill 14 ($0.60/ton) and mill 13 ($0.39/ton).

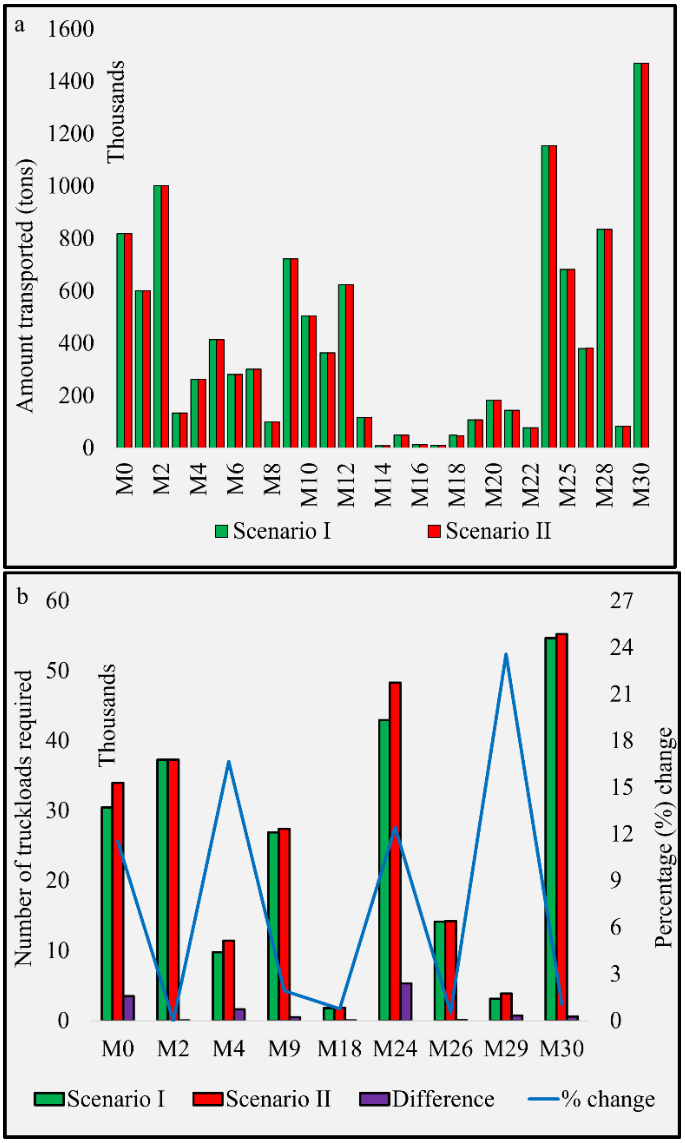

Figure 3.7 Comparison of the amount of softwood sawlogs transported for each sawmill (a) and the number of truckloads required to transport those softwood sawlogs to the respective mills (b) in scenario I and II.

Every sawmill received a certain amount of softwood sawlogs (Figure 3.7 (a)). The proportion of fulfilled demand is depicted in Figure 3.8. Figure 3.7 (b) compares the number of truckloads required to transport the softwood. The top three sawmills with the highest increase in required truckloads were Sawmills 24 (Biewer Lumber, Newton), 0 (Weyerhaeuser, Bruce), and

4 (Bazor Lumber, Quitman), with additional loads of 5347, 3517, and 1631, respectively. Sawmills 29, 4, and 24 had the highest percentage increases in truckloads required of 23.58%, 16.67%, and 12.44%, respectively (Figure 3.7(b)).

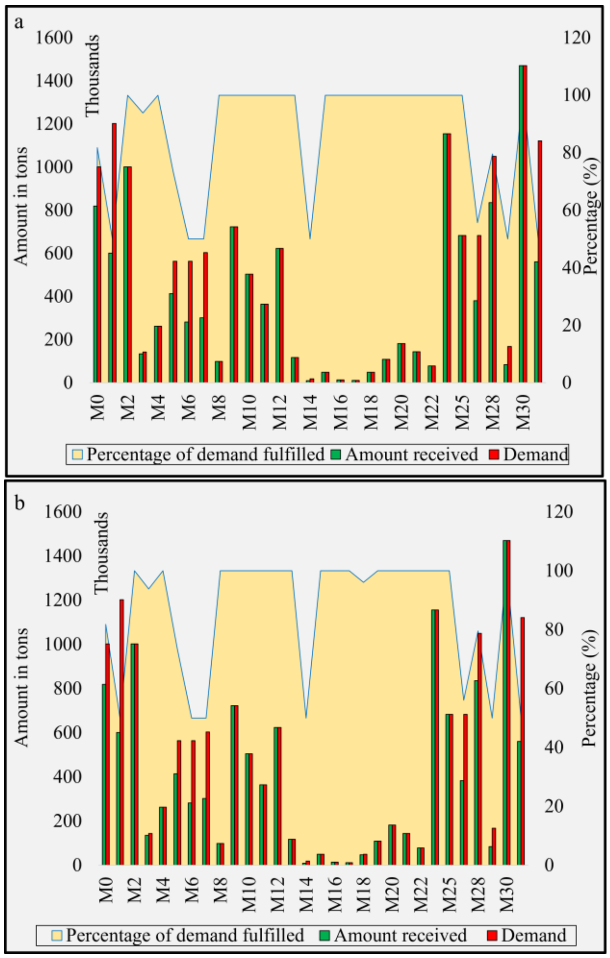

Figure 3.8 Sawmill demand, amount of softwood sawlogs received by them, and percentage of their demand fulfilled in both scenarios.

Figure 3.8 (a) and (b) presents the proportion of sawmills' demands fulfilled in the scenario I and II, respectively. In Scenario, I, Sawmills 1 (Weyerhaeuser, Mangolia), 6 (Hankins Inc, Ripley), 7 (Hankins Lumber, Elliott), 14 (Magnolia Lumber Co Inc., Fernwood), 29

(Hankins Lumber, Grenada), and 31 (Idaho Forest Group, Lumberton) had 50% of their demand fulfilled. Sawmills 26 (Hood Industries Inc., Silver Creek), 5 (Interfor Corporation, Bay Springs), 28 (Mission Forest Products, Corinth), 0 (Weyerhaeuser, Bruce), and 3 (Littrell Lumber, Luca) had fulfillment rates of 55.7%, 73.4%, 79.5%, 81.8%, and 93.8%, respectively. The remaining sawmills had their entire demand satisfied. In the second scenario, the proportion of demand fulfilled changed for only two mills. Sawmill 26 experienced a 0.28% increase in satisfied demand compared to Scenario I, reaching 56.01% demand realized. Sawmill 18 (Rogers Lumber Corporation, Columbia) experienced a 3.96% decrease in demand fulfillment, with a realized demand of 96.03% in the second scenario.

3.4.6 MODIFIED MODEL'S IMPACT ON TRANSPORTATION COST FOR INDIVIDUAL AFFECTED PAIR

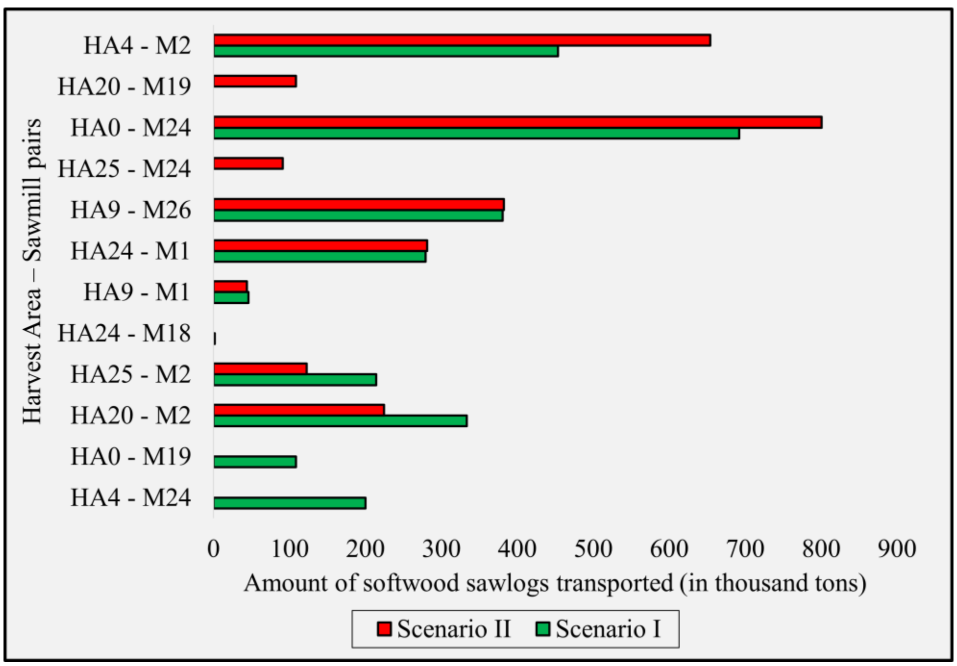

Figure 3.9 Comparison of softwood sawlogs allocation between the pairs exhibiting varying allocation between the two scenarios.

Figure 3.9 illustrates the softwood sawlogs allotment between pairs in the two scenarios. In scenario II, the amount of transported softwood sawlogs decreased for the pairs HA9 – M1, HA25 – M2, HA20 – M2, and HA24 – M1. Conversely, there was an increase in softwood sawlogs allocation in scenario II for pairs HA9 – M26, HA4 – M2, and HA0 – M24. Pairs HA4 – M24 and HA0 – M19 had softwood sawlogs transportation only in the first scenario, while pairs HA25 -M24 and HA20 – M19 had softwood sawlogs transportation for the second scenario only.

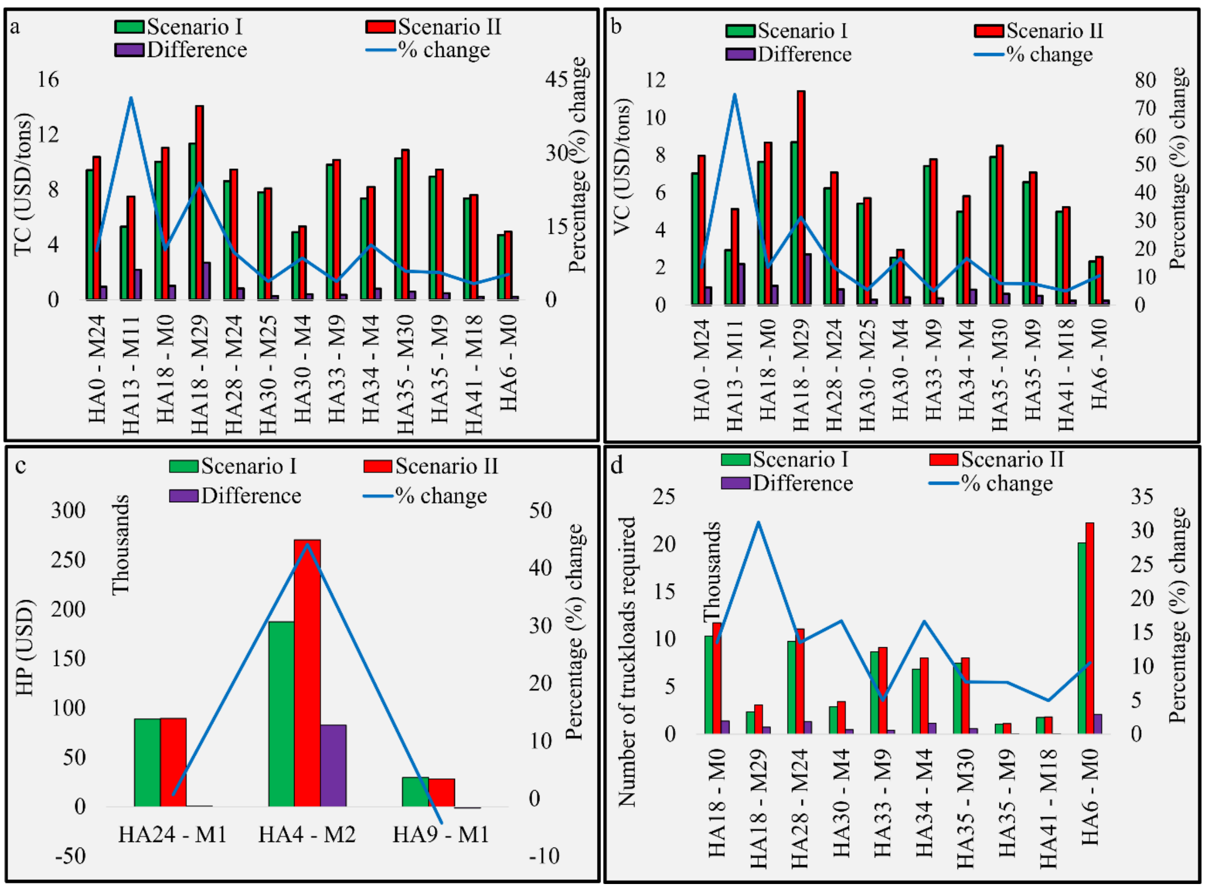

Figure 3.10 Comparison of total transportation cost (TC) per ton of softwood sawlogs transported (a), variable cost per ton of softwood sawlogs transported (b), total hauling premium cost (c), and number of truckloads required to fulfill the mill demand for each pair affected by restricted bridges in Scenario I and II.

Figure 3.10 (a) compares the total transportation cost per ton of softwood sawlogs transported between the two scenarios. Thirteen pairs of harvest areas and sawmills had additional transportation costs per ton transported, among which the pairs HA18 – M29, HA13 – M11, and HA18 – M0 experienced the highest additional cost per ton in scenario II compared to scenario I. Those values were $2.72/ton, $2.19/ton, and $1.03/ton, respectively. In terms of percentage change, HA13 – M11, HA18 – M29, and HA34 – M4 were the most affected pairs, experiencing increases of 41.27%, 23.93%, and 11.26%. A total of five pairs showed a percentage increase of over 10%. Figure 3.5(b) demonstrates the variable cost per ton of softwood sawlogs transported for the affected pairs in both scenarios. HA18 – M29 had the highest additional variable cost of $2.71/ton, followed by HA13 – M11 and HA18 – M0, with an additional cost of $2.19/ton and $1.03/ton, respectively. Pairs HA13 – M11, HA18 – M29, and HA30 – M4 experienced the greatest percentage increase in variable cost of 74.89%, 31.24%, and 16.68%, respectively. The hauling premium increased for HA4 – M2 by $82.7 thousand and for HA24 – M1 by $618, while it decreased for HA9 – M1 by $1250 (Figure 3.5 (c)). This represented a 44.12% increase for HA4 – M2 and 0.69% for HA24 – M1, and a 4.20% decrease for HA9 – M1. The haulage premium decreased for HA9 – M1 in scenario II due to a lower amount of softwood sawlogs transported to this pair compared to scenario I. Figure 3.5 (d) identified the number of truckloads used for transporting softwood sawlogs for the affected pairs. Ten pairs had the same amount of softwood sawlogs supplied between them but differed in required number of truckloads. Pairs HA6 – M0, HA18 – M0, and HA28 – M24 were the three requiring the greatest number of extra truckloads needed, 2120, 1397, and 1321, respectively. Similarly, HA18 – M29, HA30 – M4, and HA34 – M4 were the most affected pairs in terms of percentage increase in the number of truckloads, 31.24%, 16.68%, and 16.66%, respectively.

3.4.7 SENSITIVITY ANALYSIS

Sensitivity analysis was conducted to determine the parameters that impacted the transportation costs the most (Figure 3.11). The model was re-executed for both scenarios by varying each parameter by ± 10% from its base value while keeping other parameter values unchanged at their base values. The outputs (amount transported and the required number of truckloads) were then utilized in the mathematical formula mentioned in Section 3.3.2 to calculate the transportation cost.

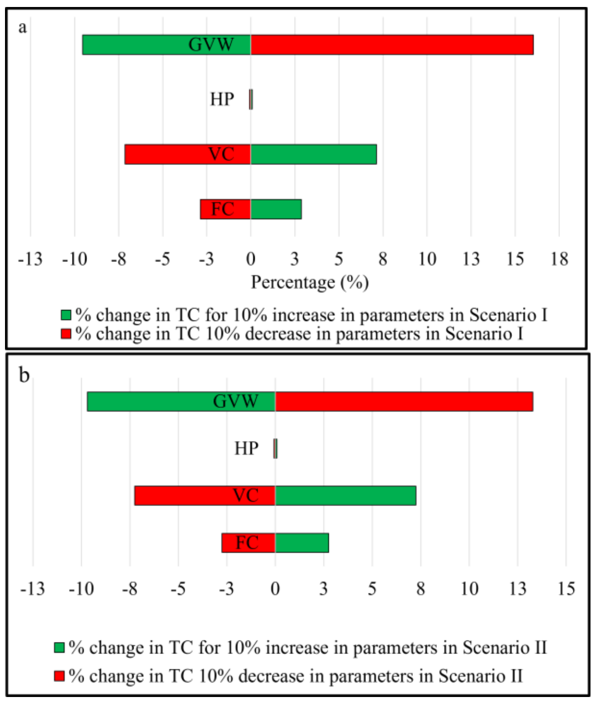

Figure 3.11 Sensitivity analysis of the total transportation cost by varying GVW, HP, VC, and FC by ± 10% from their baseline values. The analysis is conducted for both scenario I (3.11 (a)) and scenario II (3.11 (b)). Longer bar lengths indicate a greater impact of the respective parameter on transportation costs and vice versa.

In Figure 3.11, the red bar represents the effect of a 10% decrease in parameters, whereas the green bar represents the effect of a 10% increase. The parameter with the greatest impact on transportation costs was GVW, followed by VC, FC, and HP. Factors VC, FC, and HP have a direct relationship with transportation cost, while GVW has an inverse relationship. In scenario I, a 10% increase in VC, FC, and HP increased transportation costs by 7.14%, 2.86%, and 0.07%, respectively. However, a 10% increase in GVW reduced transportation costs by 9.55%. Conversely, reducing VC, FC, and HP by 10% also reduced transportation costs by 7.14%, 2.86%, and 0.07%, respectively. Nevertheless, reducing the maximum allowable GVW by 10% raised the transportation cost by 16.04%. In scenario II, a 10% increase in VC, FC, and HP led to an increase in transportation cost by 7.25%, 2.75%, and 0.07%, respectively, but a 10% increase in GVW decreased the transportation cost by 9.69%. On the other hand, a 10% decrease in VC, FC, and HP caused a 7.25%, 2.75%, and 0.07% percentage decrease, respectively, in transportation costs. However, a 10% decrease in GVW raised the transportation cost by 13.28%.

3.5 DISCUSSION

This study emphasized the need to incorporate bridge weight limits in an optimization model to minimize transportation costs in Mississippi's logging industry. A transportation cost minimization model was developed and tested under two scenarios: one considering restricted bridges along the shortest route between the harvest sites and sawmills, and one without accounting for these restrictions. The objective was to assess the impact of restricted bridges on the cost of transporting softwood sawlogs between the resource base and processors in Mississippi. Restricted bridges along optimal routes within the study area increased transportation costs by $4.09 million, a 4.07% rise in total cost, or $0.34 per ton of softwood sawlogs transported.

The breakdown of transportation costs showed that the variable costs occupied the largest proportion in both scenarios, followed by fixed costs and hauling premiums. This emphasized the significance of variable costs on overall transportation expenses. It is worth noting that the variable costs and hauling premiums increased by 5.63% and 11.67%, respectively, when bridges had weight restrictions. However, the study found that bridge restrictions did not have any impact on fixed costs. Approximately 37% of the analyzed mills experienced increased transportation costs due to restricted bridges. Sawmill 2 (Weyerhaeuser, Philadelphia) incurred an additional cost exceeding $1 million, totaling $1.08 million. Sawmill 19 (King Lumber Company, Forest) experienced about a 60% increase in transportation costs due to these restrictions.

In the first scenario, 448,702 truckloads were used to transport 12.06 million tons of softwood sawlogs, utilizing full payload capacity. In the second scenario, the number of truckloads increased to 461,112, a 2.77% increase compared to the first scenario. This resulted in an additional 12,410 truckloads hauling at lower than the allowable Gross Vehicle Weight (GVW). These findings aligned with Reddish et al. (2011), who observed that less than 5% of log truck loads across the US South were underloaded by more than 10% of the legal maximum GVW.

In scenario II, the amount of softwood sawlogs transported decreased for pairs HA9 - M1, HA25 - M2, HA20 - M2, and HA24 - M1, all of which had no restricted bridges. However, there was an increase in softwood sawlogs allocation for pairs HA9 - M26, HA4 - M2, and HA0 - M24. Pairs HA9 – M26 and HA4 – M2 had no restrictions. Surprisingly, despite a restricted bridge with a posted weight limit of 37 tons on the HA0 - M24 route, the amount of softwood sawlogs transported increased for this pair. Further investigation revealed that the model had to choose between transporting softwood sawlogs between HA0 - M24 and HA4 - M24 to balance distribution for sawmill 24 (Biewer Lumber, Newton) while minimizing overall transportation costs. Since HA4 - M24 had a closed bridge along it, the model preferred HA0 - M24 and increased the volume transported between the HA0 - M24 pair. Similarly, HA20 - M19 transported only in scenario I, even though no restricted bridges were present along the routes for this scenario. The reason behind this decision might be to minimize overall transportation costs while fulfilling each sawmill's demand.

Sawmills 23 (Tri-State Lumber Co., Fulton), 27 (Vicksburg Forest Products LLC, Vicksburg), and 29 (Hankins Lumber, Grenada) did not receive any softwood sawlogs from the harvest site data collected. Sawmill 1 (Weyerhaeuser, Mangolia) had a mere 0.81% of its demand fulfilled, while Sawmill 6 (Hankins Inc, Ripley) had 48.43% of its demand fulfilled from the data collected. The slack variable simulated the demand from shadow harvest sites, that exist mathematically, but are not present in the collected data. This indicates the sampling problem in the FIA database. In future works, incorporating real-time data by utilizing remote sensing technologies and satellite imagery might help address this issue.

The sensitivity analysis showed that GVW had the greatest impact on transportation costs, followed by VC, FC, and HP. This finding is consistent with Grebner et al. (2005), which showed that reducing truck GVW limits by 6.4 tons in Mississippi resulted in increased hauling costs for both used and new trucks. For new trucks, the costs ranged from $2.38 to $7.68 per ton in 2005 (equivalent to $3.73 to $12.05 in constant 2023 USD). For used trucks, the increase ranged from $1.46 to $4.93 per ton in 2005 (equivalent to $2.29 to $7.73 in constant 2023 USD) (U.S. Bureau of Labor Statistics 2023).

3.6 CONCLUSION, IMPLICATIONS, AND FUTURE WORK

The developed MILP optimization model effectively accounted for bridge weight limits in minimizing transportation costs between harvest areas and sawmills. The analysis was carried out under two different scenarios – the first scenario did not account for restricted bridges along the shortest optimal routes between the harvest sites and the sawmills, while the second scenario accounted for those restrictions. The analysis demonstrated that restricted bridges along optimal routes led to an additional transportation cost of $4.09 million, representing a 4.07% increase in total transportation cost of $0.34 per ton of softwood sawlogs. Variable costs constituted the largest proportion of transportation costs, followed by fixed costs and hauling premiums in both scenarios. The presence of restricted bridges resulted in a 5.63% increase in variable costs and an 11.67% increase in hauling premiums, while fixed costs remained unaffected.

Approximately 37% of the analyzed mills experienced increased transportation costs due to restricted bridges, with Sawmills 2 (Weyerhaeuser, Philadelphia), 11 (Canfor Corp, Hermanville), and 24 (Biewer Lumber, Newton) being the most affected in terms of additional costs. These mills incurred additional costs amounting to $1.08 million, $800 thousand, and $762 thousand, respectively. Ten mills incurred hauling premium costs, among which Sawmill 2 experienced a 44.41% increase in hauling premium because of the presence of restricted bridges. In the second scenario, Sawmills 24 (Biewer Lumber, Newton), 0 (Weyerhaeuser, Bruce), and 4 (Bazor Lumber, Quitman) experienced the highest increase in required truckloads to transport the same amount of softwood, with additional loads of 5347, 3517, and 1631, respectively.

Thirteen pairs incurred additional transportation costs per ton in scenario II as compared to scenario I. Among these pairs, HA18 – M29, HA13 – M11, and HA18 – M0 had the highest additional costs of $2.72/ton, $2.19/ton, and $1.03/ton. A total of five pairs showed a percentage increase of over 10% between these scenarios. HA18 – M29 incurred the highest additional variable cost of $2.71/ton, followed by HA13 – M11 with $2.19/ton, and HA18 – M0 with $1.03/ton. In scenario II, the hauling premium for HA4 – M2 increased by $82.7 thousand (44.12% increase) and $618 for HA24 – M1 (0.69% increase), while for HA9 – M1 it decreased by $1250 (4.20% decrease). The decrease in hauling premium for HA9 – M1 in scenario II is attributed to the lower amount of softwood sawlogs transported for this pair compared to scenario I. Ten pairs had identical amounts of softwood sawlogs supplied between them, but utilized a different number of truckloads. Among them, HA6 – M0, HA18 – M0, and HA28 – M24 stood out as the most affected pairs, requiring additional truckloads of 2120, 1397, and 1321, respectively.

GVW had the greatest impact on the transportation cost, followed by VC, FC, and HP. VC, FC, and HP exhibited a direct relationship with transportation cost, while GVW demonstrated an inverse relationship. In scenario I, a 10% increase in VC, FC, and HP increased transportation costs by 7.14%, 2.86%, and 0.07%, respectively, and vice versa. Conversely, a 10% increase in GVW led to a 9.55% decrease in transportation costs, while a 10% decrease in GVW raised the transportation cost by 16.04%. In scenario II, a 10% increase in VC, FC, and HP resulted in transportation cost increases of 7.25%, 2.75%, and 0.07%, respectively, and vice versa. However, a 10% increase in GVW decreased transportation costs by 9.69%, while a 10% decrease in GVW raised the transportation cost by 13.28%.

The findings highlight the importance of accounting for bridge weight limits in developing transportation cost minimization optimization models in the forestry sector. This variable is more important in Mississippi because of the presence of many closed and posted bridges. The presence of restricted bridges along the optimal routes increased transportation costs. Variable costs had the greatest contribution to transportation costs, followed by fixed costs and hauling premiums. The study revealed that GVW was the parameter with the greatest impact on the transportation cost, emphasizing the need for considering weight limitations in the optimization model. These findings provide valuable insights for decision-makers in the forestry sector, helping them make informed decisions regarding transportation route planning, bridge maintenance, and investment in efficient vehicles.

Location theory states that industries strategically locate themselves where they can be most profitable (Aguilar 2009). Therefore, processing mills are located in rural places near timberlands because of roundwood’s low value to weight ratio. The roads linking the two require upkeep like any other public good. In rural areas, though, it is often challenging for local governments to maintain basic living standards. This phenomenon is evident in Mississippi, a state with abundant natural resources, and yet it is economically poor. In an economically poor state like Mississippi, the decision-makers face the challenge of prioritizing either infrastructure development or socio-economic development to enhance living standards. Decisions like lowering bridge weight limits instead of upgrading the bridges to full capacity might appear insignificant to the local economy at first glance, but they have long-term economic impacts. Lowering bridge weight limits force longer hauling distances for fully loaded trucks, which increases the hauling cost and, in return, decreases profit. This increased transportation cost subsequently lowers the stumpage prices, leading to a decrease in timberland values and tax revenue. The decrease in timberland values and tax revenues will ultimately affect the state’s economy in the future.

The study found that restricted bridges along the optimal routes increased the transportation cost by $4.09 million (4.07% increase), or $0.34 per ton of softwood sawlogs transported, for transporting 12.06 million tons of pine sawlogs. Scaling this to the total 15.09 tons of pine sawtimber harvested in 2021 (Measells and Auel 2022), the increase in transportation cost due to bridge restriction amounts to $5.13 million. It's important to note that the impact of bridge restrictions extends beyond pine sawtimber in the forestry sector as other products like hardwood sawlogs, pine chip-n-saw, pine and hardwood pulpwood, poles, crossties, and pine and hardwood chips are also transported from the harvest site to the processing mills. When accounting for all these products, the bridge restrictions impact on the forestry sector's transportation cost is even greater.

Another implication of this study extends beyond the forestry industry to encompass the farming sector and agricultural products. Collectively, agriculture and natural resources generated $9.72 billion for Mississippi's economy in 2022, with broiler chickens, soybeans, and timber being the state's most valuable agricultural commodities (Mississippi State University Division of Agriculture, Forestry, and Veterinary Medicine 2022). If low-weight bridges impact the farm and forestry complex just one percent, then $98.2 million is being diverted from the complex to pay additional freight charges. To summarize, the constraints imposed by the bridge restrictions impact all the businesses dependent on logistics and transportation, making this one of the major problems that require immediate attention. Overlooking this problem today can lead to more serious economic consequences in the long run.

The developed model focused on transportation cost minimization between harvest sites and sawmills by using bridge weight restriction information, demand and supply, and distance between the harvest areas and the processing mills. Future research could focus on developing optimization models that also incorporate harvest schedules and vehicle scheduling into the aforementioned information to improve the model's efficiency. In conclusion, this study highlighted the importance of considering bridge weight limits while developing a transportation cost minimization model to determine the impact of restricted bridges on softwood sawlogs transportation costs in the forestry sector.

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APPENDIX A

DESCRIPTION OF DATA USED IN RESEARCH ALONG WITH THEIR SOURCE AND PURPOSE

Table A.1 Name and sources of data collected

Datasets	Source
US Road datasets	• Tigerline road shapefile downloaded from the United States Census Bureau website: https://www2.census.gov/geo/tiger/TGRGDB22/
US Bridge datasets	• Mississippi Office of State Aid Road Construction: https://www.osarc.ms.gov/Docs/idx/idx-x.html?https://www.osarc.ms.gov/Docs/data/Br-x.htm • U.S. Department of Transportation Federal Highway Administration: https://www.fhwa.dot.gov/bridge/nbi/ascii2021.cfm • Mississippi Department of Transportation (MDOT) • https://mdot.ms.gov/portal/posted_bridges
GPS location of sawmills	• Mississippi Forestry Commission (MFC): https://www.mfc.ms.gov/ • RISI mill asset database: https://www.lib.ncsu.edu/databases/risi-mill-asset-database
Harvest site for the sawmills	• Forest Inventory and Analysis National Program (FIA) DataMart website: https://apps.fs.usda.gov/fia/datamart/CSV/datamart_csv.html