Removing Supply-Chain Bottlenecks in the Sawmilling Sector: Optimal Routing for Softwood Sawmill Supply Chain for Strategic Repair of Roads and Bridges

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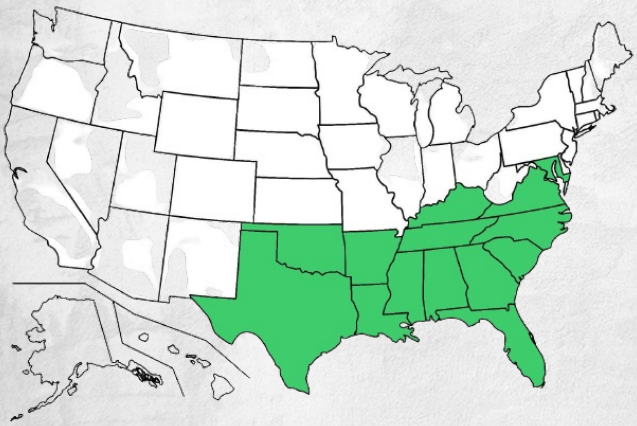
Introduction



Annual timber harvest is heavily skewed to the Southern United States.

- **Transportation costs**
  - 40 – 45% of logging operational cost (Audy et al., 2022)
- **Mississippi timber's 2021 gate value**
  - Total → $1.12 billion
  - Stumpage → $ 537 million
  - Harvest and transportation → $590 million (52%) (Measells & Auel, 2022)

Hauling truck transporting timber from the harvest sites.
Photo credit: Eric McConnell

3

Objective

Investigate the impact of bridge weight limits on the transportation costs of Mississippi's forestry sector.

4

Rationale

- Closed or posted bridges in Mississippi → over 3,000 (ARTBA, 2023; MDOT, 2023)
- Impact of these bridges on transportation cost in the forestry sector is yet to be explored.

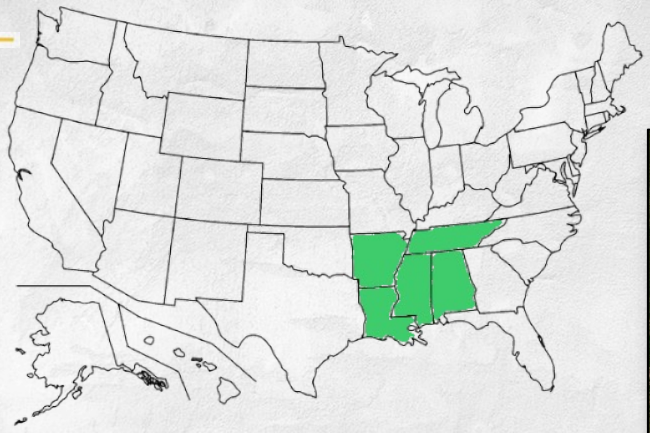
5

Methodology

Study Area

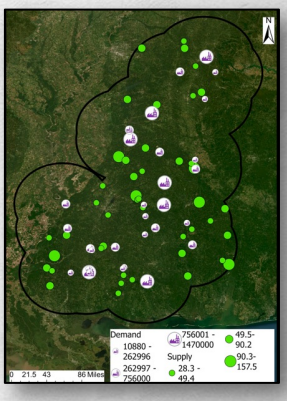
States →

Size → 40.4 million acres



Data Sources

- Harvest site location and supply availability:
  - USDA Forest Service's FIA database for years 2010 – 2020
- Softwood sawmill location and demand:
  - Mississippi Forestry Commission (MFC)
  - Resource Information Systems Inc. (RISI) mill asset database

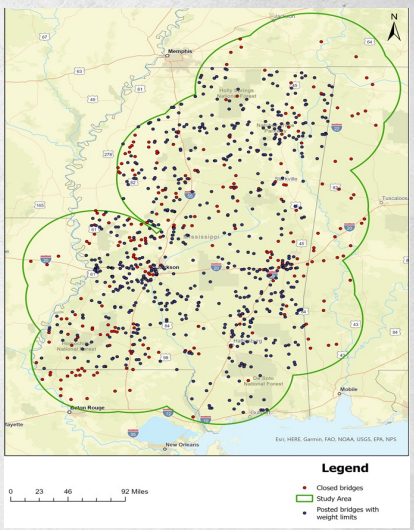


Study area with harvest sites (green circles) and softwood sawmills (blue industry-like icon).

6

Bridge data description

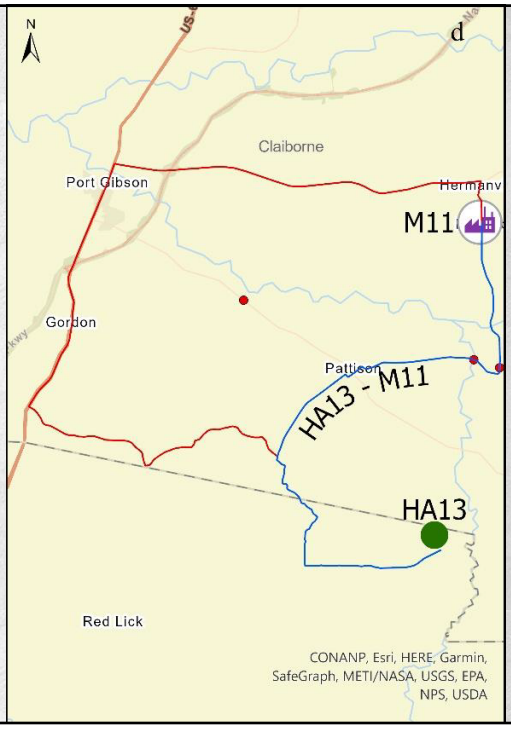
Bridge Category	Total
Closed	269
Posted	2,752
Posted with weight limits	693
Selected restricted bridges	962



Closed (red dots) and posted bridges with weight limits (blue dots) in the study area selected as restricted bridges for data analysis.

7

- Bridges
  - Mississippi Department of Transportation (MDOT)
  - Mississippi Office of State Aid Road Construction
  - U.S. Department of Transportation Federal Highway Administration
- Roads
  - United States Census Bureau
  - MDOT
- Road network analysis layer
  - ArcGIS online



8

Data Analysis

- **Identifying log trucking routes between the harvest sites and softwood sawmills.**
  - Software → ArcGIS Pro
  - Algorithm → Dijkstra's shortest path algorithm
  - Cutoff distance: 57 miles

Supply chain modeling

- Model → Mixed Integer Linear Programming (MILP) model
- Software → python
- Solver → GUROBI OPTIMIZATION
- Objective → Minimizing roundwood transportation costs along the shortest and alternative identified routes.

9

Transportation Cost Calculation

Transportation Cost (TC):

$$TTC = \sum TFC + \sum TVC + \sum THP$$

Total Fixed Cost (TFC):

$$TFC\ (\$) = FC\ (\$/tons)\ * Amount\ transported$$

Total Variable Cost (TVC):

$$TVC\ (\$) = VC\ (\$/\text{ton/mile}) * Distance * Payload\ capacity * Number\ of\ truckloads$$

Total Hauling Premiums ($):

$$THP = HP * Amount\ transported$$

Hauling Premium ($):

$$HP = VC + 50\% * VC * (Distance - 50)$$

- FC ($/tons) : $2.39
- VC ($/ton/mile) : $0.17

10

Decision Variables

Sets:

$\boldsymbol{I}$	Set of harvesting sites
$\boldsymbol{J}$	Set of mills
$\boldsymbol{P}$	Set of paths between the harvesting sites and mills

Parameters

s_i	Supply availability at harvest sites
d_j	Demand at mill
d_{ijp}	Distance of the paths from harvest sites to mills
ξ_{ijp}	Fixed cost (FC) ($/ton) of using a truck between harvest sites to mills
c_{ijp}	Variable cost (VC) ($/ton/mile) of transporting softwood between harvest sites to mills
β_{ijp}	Fraction of weight reduction due to the presence of a bridge along the path
π_j	Penalty cost ($/ton) of unsatisfied demand at mills
v^{cap}	Truck capacity

Decision Variables

Z_{ijp}	Number of truckloads transported between harvesting site and the mills → integer
X_{ijp}	Amount of softwood (in tons) transported between harvesting site and the mills → real number
U_j	Unsatisfied demand at mill → real number

11

Objective function

Penalty cost ($)

$$Minimize: \sum_{i\in I}\sum_{j\in J}\sum_{p\in P}(\xi_{ijp}Z_{ijp} + c_{ijp}d_{ijp}X_{ijp}) + \sum_{j\in J}\pi_j U_j \quad (1)$$

FC ($) VC ($)

s.t:

Supply availability restrictions:

$$\sum_{j\in J}\sum_{p\in P} X_{ijp} \le s_i;\ \forall i \in I \quad (2)$$

Capacity restrictions:

$$X_{ijp} \le v^{cap}(1-\beta_{ijp})Z_{ijp};\ \forall i \in \boldsymbol{I}, j \in \boldsymbol{J}, p \in \boldsymbol{P} \quad (3)$$

$$Z_{ijp} \le \left\lceil \frac{d_j}{\max\{1, v^{cap}(1-\beta_{ijp})\}} \right\rceil;\ \forall i \in \boldsymbol{I}, j \in \boldsymbol{J}, p \in \boldsymbol{P} \quad (4)$$

Demand satisfaction restrictions:

$$\sum_{i\in I}\sum_{p\in P} X_{ijp} + U_j = d_j;\ \forall j \in \boldsymbol{J} \quad (5)$$

Demand fulfillment restrictions:

$$\sum_{i\in I}\sum_{p\in P} X_{ijp} \ge \alpha * d_j;\ \forall j \in \boldsymbol{J} \quad (6)$$

Non-negativity restrictions:

$$X_{ijp} \in \mathbb{R}^+;\ \forall i \in \boldsymbol{I}, j \in \boldsymbol{J}, p \in \boldsymbol{P} \quad (7)$$

$$Z_{ijp} \in \mathbb{Z}^+;\ \forall i \in \boldsymbol{I}, j \in \boldsymbol{J}, p \in \boldsymbol{P} \quad (8)$$

$$U_j \in \mathbb{R}^+;\ \forall j \in \boldsymbol{J} \quad (9)$$

12

Execute model for

Scenario I:

- Derived shortest optimal routes permissible within the state's legal Gross Vehicle Weight (GVW) of 84,000 lbs (prior to July 1, 2023) on the state highway, with the purchase of a harvest permit.
- Not accounting for bridge weight limits → $'\beta_{ijp}'$ = 0
- Only uses shortest log trucking routes

Scenario II:

- Rerouting trucks to find alternative routes compliant with state's legal GVW when encountering low-weight bridges on the shortest optimal routes.
- Considers bridge weight limits → $'\beta_{ijp}'$ = fraction of weight reduction due to the bridge weight limits
- Utilizes both shortest and alternative log trucking routes

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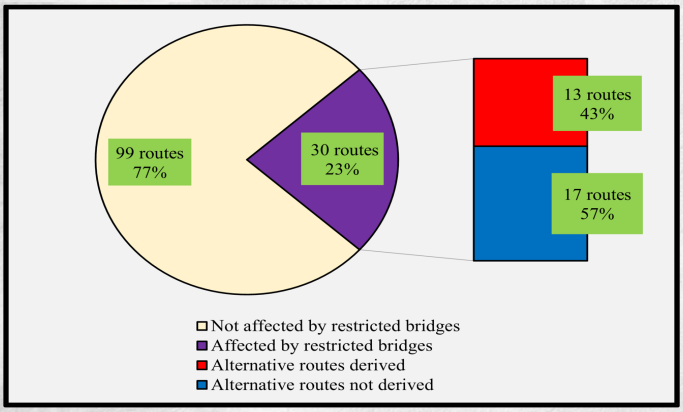
13

Results



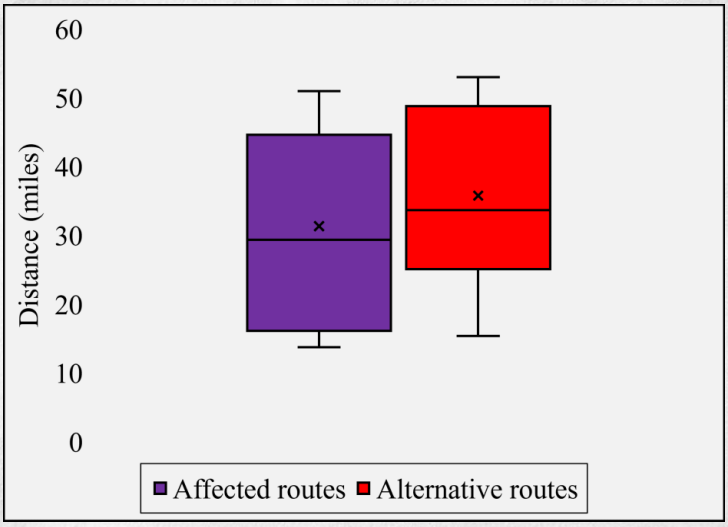
Number of derived shortest optimal, affected and alternative routes.

Affected routes → shortest optimal routes with restricted bridges along them.

No feasible routes found from harvest sites to:

- Sawmill 23 (Barge Forest Products, Macon)
- Sawmill 27 (Vicksburg Forest Products, Vicksburg)

14



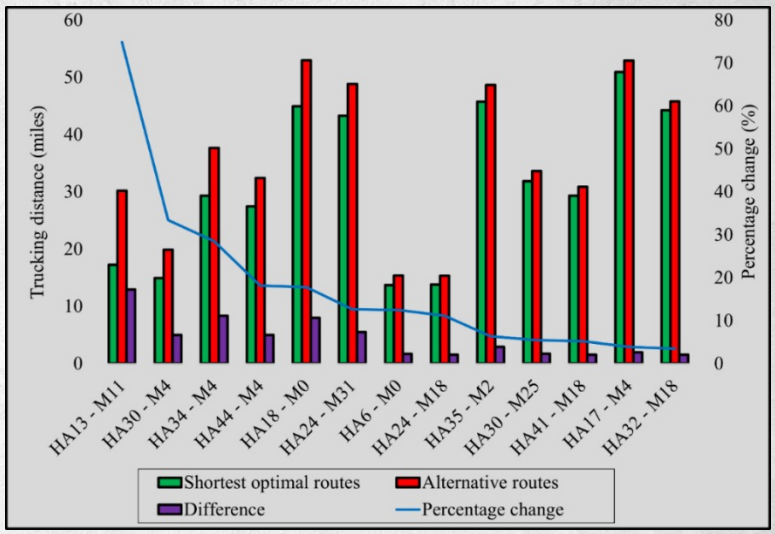
Box and whisker plot comparing 13 alternative routes to their corresponding affected routes.

15

Shortest Optimal Distance
Median: 29.3 miles
Avg: 31.3 miles
Std. Dev: 13.5 miles

Alternative Routes
Median: 33.6 miles
Avg: 35.7 miles
Std. Dev: 13.4 miles

Percent Change
Median: 12.4%
Avg: 17.9%



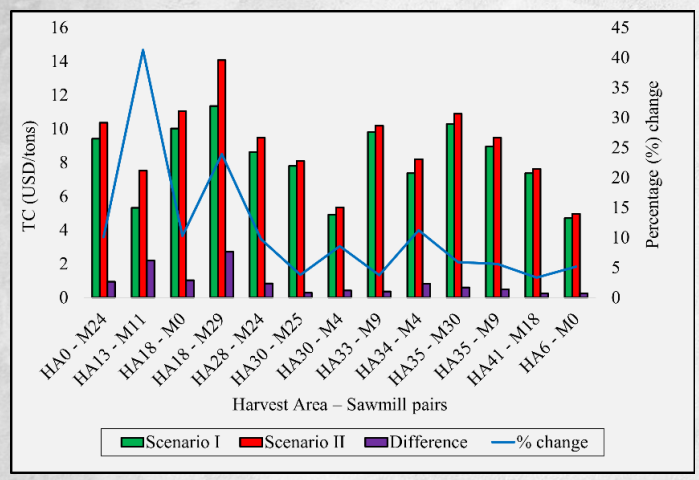
Comparison of trucking distances and their percentage changes for the shortest optimal routes between Harvest site – Sawmill pairs that has restricted bridges along the route.

16

Difference in minimum **transportation** cost between scenario I and II

Scenarios	TC per ton (USD/ton)	Total TC (million USD)	Total FC (million USD)	Total VC (million USD)	Total hauling premiums (million USD)	Number of truckloads required (in thousand)
Scenario I	8.35	100.70	28.82	71.17	0.70	448.70
Scenario II	8.69	104.79	28.82	75.18	0.78	461.11
Difference in scenario I and II	0.34	4.09	0	4.01	0.08	12.41
Percentage change between scenario I and II	4.07% ↑	4.07% ↑	0% =	5.63% ↑	11.67% ↑	2.77% ↑

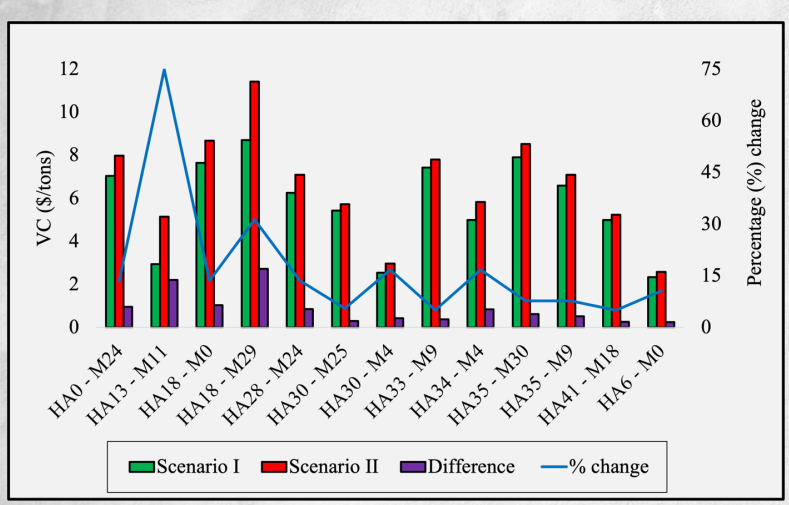
17



Scenario-wise Comparison of total transportation cost (TC) per ton of softwood transported for each pair affected by restricted bridges.

- Additional transportation costs ($/tons) due to restricted bridges → 13 pairs
- Additional Costs per ton (Scenario II vs. Scenario I):
  - (HA18 – M29): $2.72/ton
  - (HA13 – M11): $2.19/ton
  - (HA18 – M0): $1.03/ton
- Highest Percentage Increase (Scenario II vs. Scenario I):
  - (HA13 – M11): +40%
  - (HA18 – M29): +25%
  - (HA34 – M4): +10%

18

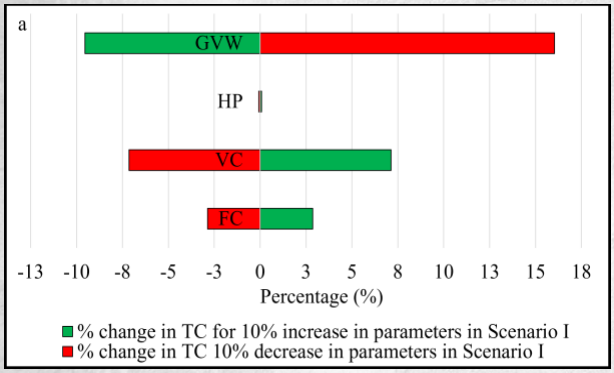


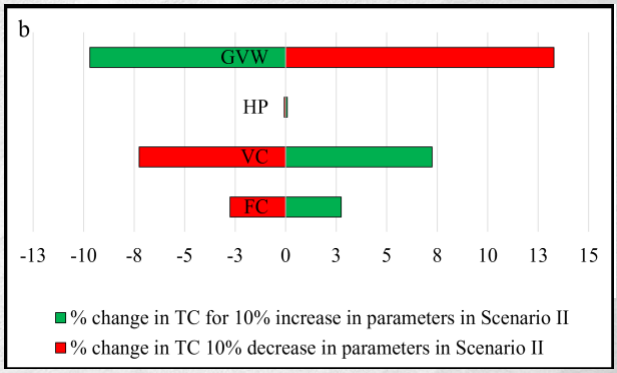
Comparison of Variable cost per ton of softwood transported for each pair affected by restricted bridges for analyzed scenario.

- Highest additional VC ($/ton) due to restricted bridges:
  - (HA18 – M29): +$2.71/ton
  - (HA13 – M11): +$2.19/ton
  - (HA18 – M0): +$1.03/ton
- Highest percentage increase in VC due to restricted bridges:
  - (HA13 – M11): +75%
  - (HA18 – M29): +30%
  - (HA30 – M4): +15%

19

How does variation in different sub-costs influence total transportation costs





- 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 (a) and scenario II(b). Longer bar lengths indicate a greater impact of the respective parameter on transportation costs and vice versa.

20

Discussion

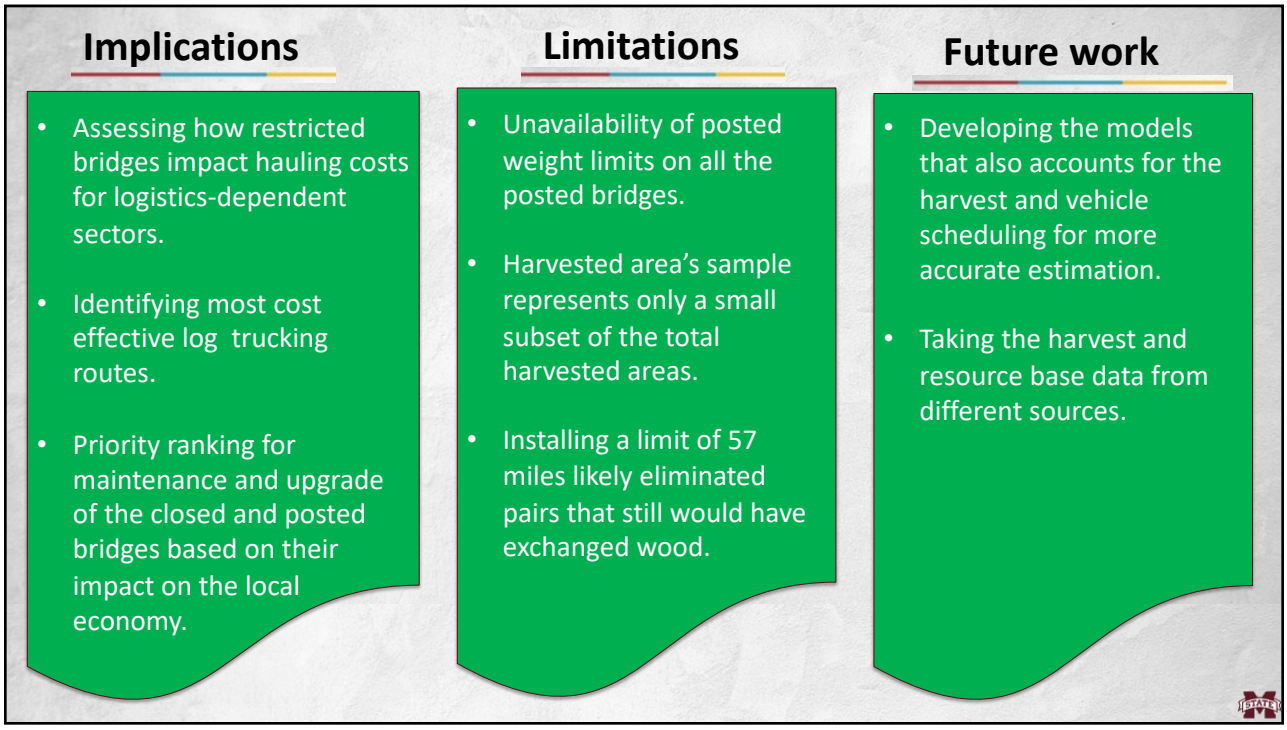
- GVW → Greatest impact on transportation cost.
- In second scenario, 2.77% additional trucks operated below the allowable GVW limit.

21

Key Findings

- About 23% of the identified shortest optimal routes connecting harvest sites and softwood sawmills had restricted bridges along them.
- Around 37% of the mills experienced increased transportation costs due to restricted bridges.
- Restricted bridges led to a 4.07% transportation cost increase, amounting to $0.34/tons; from $8.35 to $8.69.
- GVW had the greatest impact on the transportation cost, followed by VC, FC, and HP.

22


Implications
Assessing how restricted bridges impact hauling costs for logistics-dependent sectors.
Identifying most cost effective log trucking routes.
Priority ranking for maintenance and upgrade of the closed and posted bridges based on their impact on the local economy.
Limitations
Unavailability of posted weight limits on all the posted bridges.
Harvested area's sample represents only a small subset of the total harvested areas.
Installing a limit of 57 miles likely eliminated pairs that still would have exchanged wood.
Future work
Developing the models that also accounts for the harvest and vehicle scheduling for more accurate estimation.
Taking the harvest and resource base data from different sources.

23