Bayesian Inference Framework for Intermodal Transportation Network Design

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Motivation

Intermodal freight transportation is becoming more popular.

Move to intermodal is driven by lower cost of rail transportation, less carbon emissions per ton per mile.

Increasing rail utilization will require expanding existing rail terminals or building new ones.

Terminal design requires the consideration of many complicated, coupled variables.

Motivation

Design considerations

- Service node locations
- Existing rail terminal locations
- Estimated freight demand
- Cost of highway transportation
- Cost of rail transportation
- Capacity of rail terminals
- Cost of building and maintaining terminals

Method

The ultimate objective is to rank proposed terminal locations based on utility to the network and allow the network designer to make an informed decision.

Freight demand must be routed through the network.

In previous work, this is done using optimization.

Our method uses Bayesian inference to perform the freight demand routing and generate a Bayesian evidence value that can be used to rank proposed terminal locations.

By using Bayesian inference, potential terminals can be evaluated while including variances in cost, terminal capacity, and freight demand estimates.

Method

Bayesian inference uses Bayes' Theorem to compute posterior probabilities.

$$\underbrace{p(\mathbf{x}|\mathbf{d},\mathbf{c},\mathbf{T},\mathbf{k})}_{\substack{\text{Posterior}\\ \mathrm{P}(\mathbf{x})}} \propto \underbrace{p(\mathbf{x}|\mathbf{d},\mathbf{k})}_{\substack{\text{Prior}\\ \pi(\mathbf{x})}}\,\underbrace{p(\mathbf{T},\mathbf{c}|\mathbf{x},\mathbf{k})}_{\substack{\text{Likelihood}\\ \mathrm{L}(\mathbf{x})}}$$

The prior probability enforces that the routing scheme meets the demand requirements.

The likelihood is determined by the cost of the routing scheme and whether or not the routing exceeds terminal capacity constraints.

Method

$$x_1 + x_2 + x_3 + \cdots + x_N = x_{sum}$$

$$x_{sum} \sim \mathcal{N}(\mu, \sigma_d)$$

$$\log L = -\frac{1}{\sigma_C^2} Q_C^2 - \frac{1}{\sigma_T^2} Q_T^2$$

$$Q_C^2 = \sum_{n=1}^{N} \sum_{m=0}^{M} c_n^m x_n^m + \sum_{k=1}^{K} F_k$$

$$Q_T^2 = \sum_{k=1}^{K} \Delta T_k^2, \;\; \text{with } \Delta T_k^2 = \begin{cases} (t_k - T_k)^2 & : t_k > T_k \\ 0 & : t_k \leq T_k \end{cases}$$

Method

$$Z = \int \pi(\mathbf{x}) L(\mathbf{x}) \, \mathrm{d}\mathbf{x}$$

Direct integration is impossible, so we use a Markov-chain Monte Carlo (MCMC) method, nested sampling, to evaluate the evidence.

Very briefly, this involves iterating over ever-smaller portions of the prior mass constrained by increasing likelihood values.

$$\xi(\mathcal{L}) = \int_{L(\mathbf{x}) > \mathcal{L}} \pi(\mathbf{x}) \, \mathrm{d}\mathbf{x}$$

$$Z = \int_0^1 \mathcal{L}(\xi) \, \mathrm{d}\xi$$

Test case

The kind of historical intermodal transportation data we need is not freely available, so we instead invented a test case that attempts to be realistic.

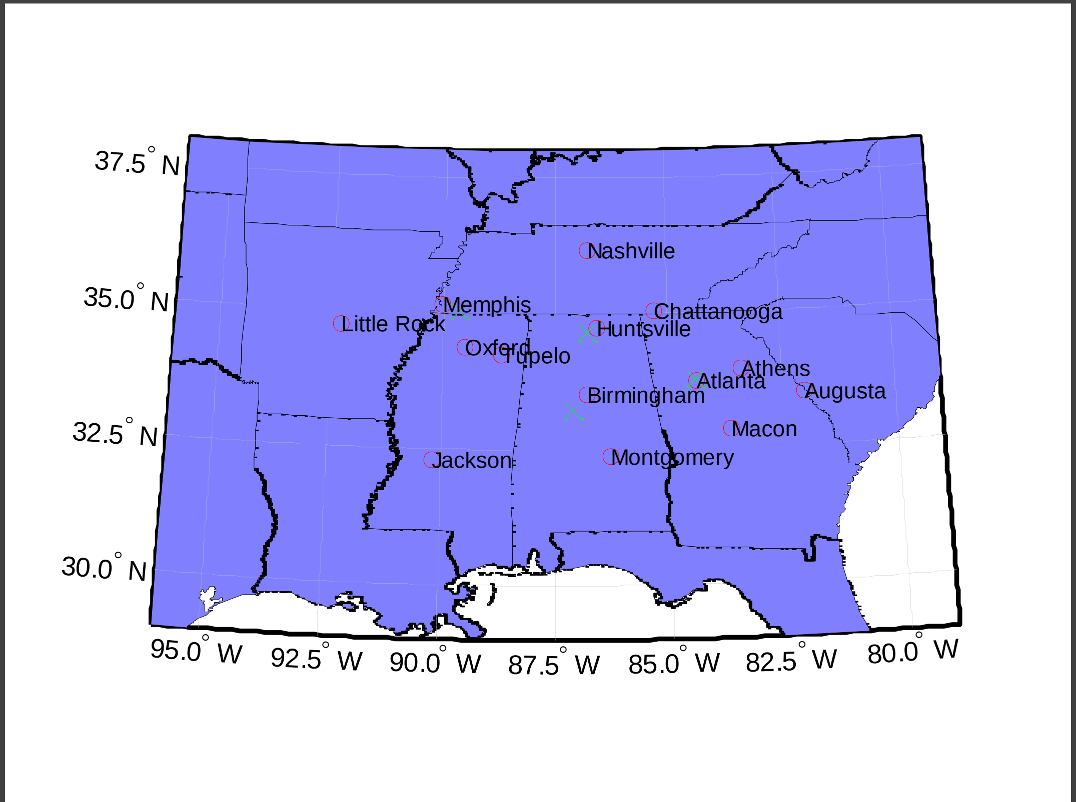
We consider 14 cities and 4 existing rail terminals in five states (Mississippi, Alabama, Tennessee, Arkansas, and Georgia). The rail lines and terminals are all part of the existing Norfolk Southern intermodal freight network.

We consider freight demand originating from four cities (Nashville, Memphis, Birmingham, and Atlanta) and arriving at each of the other cities in the network. The amount of freight demand coming from these cities is proportional to their populations.

The proportion of the demand coming from one city going to another city is proportional to the destination city's population as a percentage of the total population of all the cities in the network.

Test case

Terminal capacities and fixed costs are proportional to the population of the nearest large city.



O – Service node (city)
X – Rail terminal

Test case

Terminal	Capacity (tons)	Fixed cost ($)
Memphis	168,370	159,280
Huntsville	47,219	44,671
Birmingham	54,491	51,552
Atlanta	114,050	107,890

Each additional test case:

Terminal	Capacity (tons)	Fixed cost ($)
Chattanooga	96,349	96,800
Meridian	37,187	37,361

Results

Three configurations tested: no terminals added, one added near Chattanooga, and one added near Meridian.

The proposed Chattanooga terminal absorbs much of the demand that is normally routed unimodally from Nashville, so its cost is noticeably lower.

The Meridian terminal isn't very well-placed, so its utility to the network is minimal.

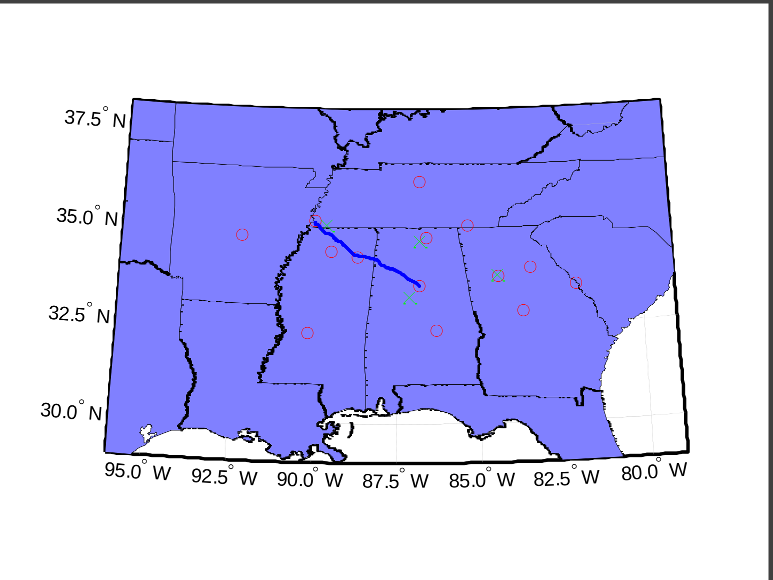
Additional Terminal	Cost ($)	Log-Evidence
None	4,002,900	-4.0033E+10
Chattanooga	3,820,600	-3.8221E+10
Meridian	3,912,300	-3.9125E+10

Configuration	Cost stdev	Demand stdev	Cost	logZ	Demand error
Nothing added	36340	370	4.58E+06	-4.8611	8.42%
Chattanooga	36340	370	4.34E+06	-1.1708	9.07%
Meridian	36340	370	4.45E+06	-5.7067	9.22%

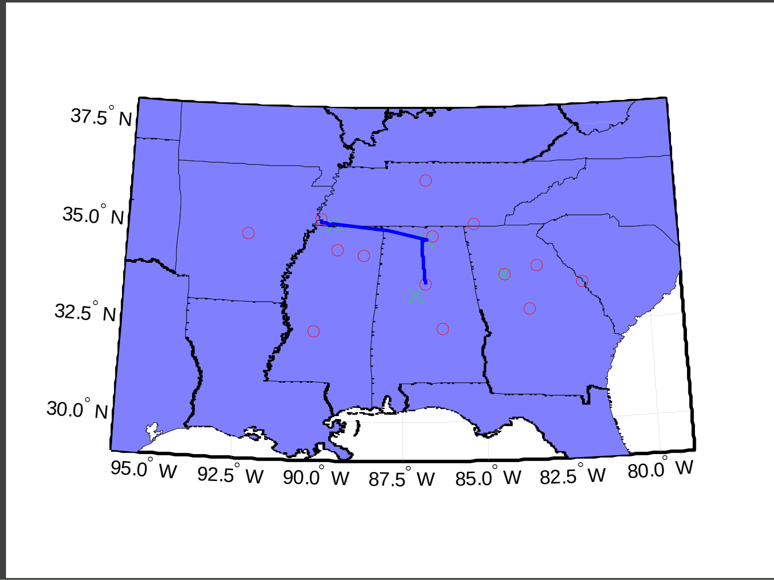
Results

Total demand from Birmingham to Memphis: 4480 tons

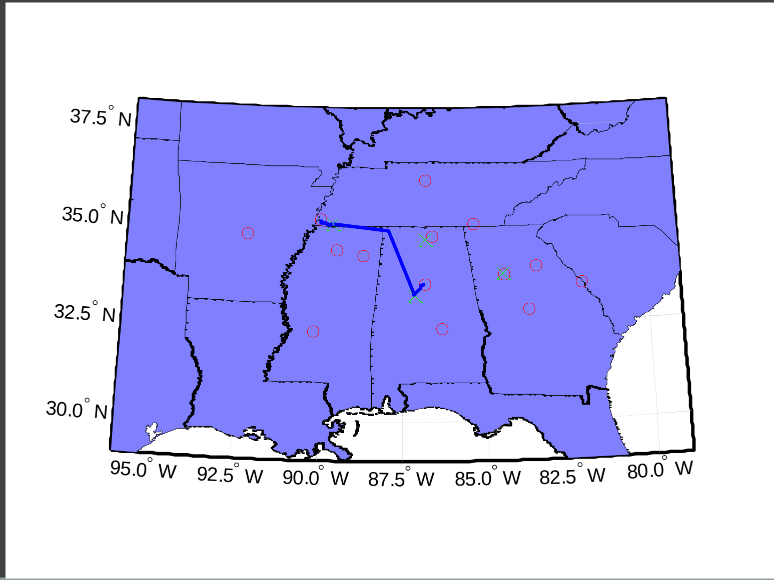
5.3 tons, 23.9 $/ton



34.2 tons, 17.45 $/ton



4440 tons, 13.47 $/ton

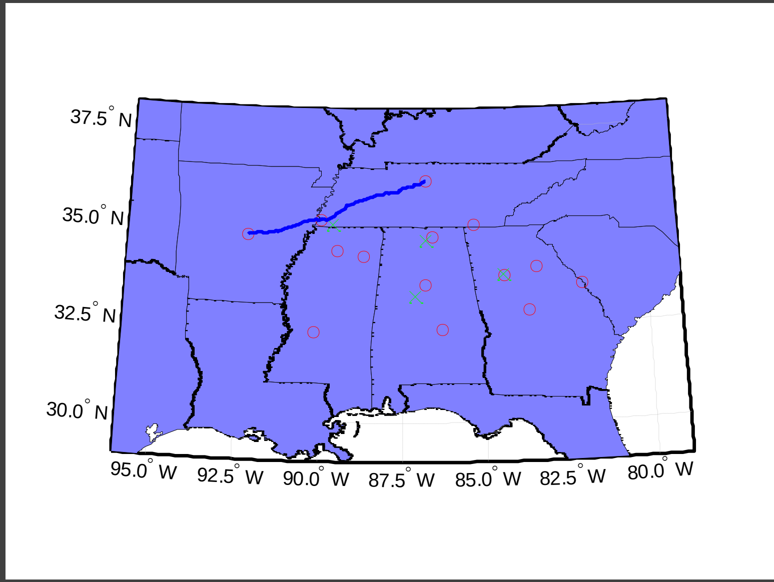


Results

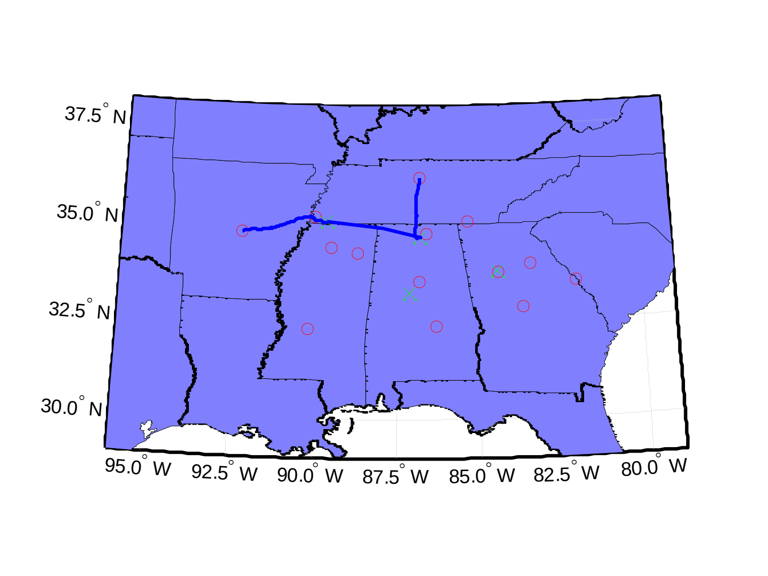
Total demand from Nashville to Little Rock: 4432 tons

Note that most of the demand is routed along more expensive unimodal path. This is due to tight capacity constraints near Nashville, and the cost difference being very small.

3485 tons, 34.9 $/ton



947.1 tons, 33.88 $/ton



Conclusion

Intermodal freight transportation is growing in popularity.

We have developed a Bayesian inference-based method to route freight demand through a network and produce a single-number measure (the Bayesian evidence) of a network design's "goodness."

The method routes demand as expected.

Terminal locations with obviously high utility are ranked highly, while those that are obviously not very useful are ranked lowly.

Future work

Examine the effects of different variance values.

Try configurations with more and less capacity-constrained terminals

Develop further metrics to show that the Bayesian evidence works well as a measure of a design's goodness.

Acknowledgment

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