A Model to Design a National High-Speed Network for Freight Distribution

Russell D. Meller, Ph.D.
Kevin R. Gue, Ph.D.

MBTC-2087

July 2008

A Model to Design a National High-Speed Network for Freight Distribution

Jennifer A. Pazour [1]
Russell D. Meller, Ph.D. [1]
Kevin R. Gue, Ph.D.[2]
Letitia M. Pohl [1]

[1]Department of Industrial Engineering, University of Arkansas, Fayetteville, AR 72701, USA
[2]Department of Industrial & Systems Engineering, Auburn University, Auburn, AL 36849, USA

Executive Summary for
"A Model to Design a National High-Speed Network for Freight Distribution"

The United States has a significant problem with highway congestion, with an estimated cost of $7.8B in lost productivity annually. To alleviate congestion issues, it is often recommended that the United States should build and encourage more high-speed passenger rail. However, since passenger traffic shares our highways with freight traffic, an alternative to alleviate congestion issues is to remove freight traffic from our highways through the development of a national high-speed network for freight distribution. In addition to reducing congestion on our highways, a high-speed freight network utilizing, say, Maglev technology, would also afford benefits in terms of fuel-efficiency and lower emissions, both of which are highly important given the unprecedented cost of fuel and the importance placed on environmental and "green" initiatives.

The objective of our research is to explore the maximum impact of instituting a high-speed rail network for freight distribution. In our research we utilize the results of technology feasibility tests indicating that freight in such a system will move approximately two to three times faster than freight distributed via the nation's highways. However, we do not consider the cost of using either mode of transportation, leaving the economics of developing a network for future consideration. Instead, we address designing a high-speed rail network for freight distribution and analyze its maximum impact on the current highway system, assuming the freight that benefits the most from the network will use the network. Thus, our goal is to determine the high-speed freight network with the maximum benefit in terms of improved freight transit times and decreasing the number of highway miles driven to move the freight. We formulate our problem as a multi-modal network design problem and present an uncapacitated network design problem with a post-processing step for the capacity constraint to construct such a network.

As a case study application of our model, we evaluate the impact of a high-speed freight network on our nation's highways with data from the Federal Government's Commodity Flow Survey as well as a major truckload carrier. For the technology parameters, we utilize current and expected values from the primary producer of Maglev technology. We create a traffic load model that examines how various amounts of investments in high-speed rail leads to a reduction in freight transit times, which then leads to a reduction in the amount of truck traffic on the highways. Since the technology is evolving, an important result of our work is that the network developed with our models is shown to be relatively robust to changes in the speed of the technology. We use our models to create a potential implementation plan of a high-speed network in the United States, one that evolves with increasing technology investment.

The results of our work show that, with sufficient capacity and associated investment, a high-speed network for freight distribution will have a significant impact on freight transit times and highway congestion, with the potential to address many of the challenges facing transportation today. For example, a 20,000-mile network (approximately half of the U.S. interstate highway system) that utilizes current Maglev technology parameters and proposed 6-minute headways would make it advantageous for a majority of the freight traffic to utilize the high-speed network. And although such a network would require a significant investment of $760B - $2.8T (using current cost estimates of $38M - $140M per mile), this investment would lead to an estimated 38% reduction in overall freight transit times. And perhaps more importantly to the public, would precipitate a net 78% decrease in the annual total truck highway miles driven.

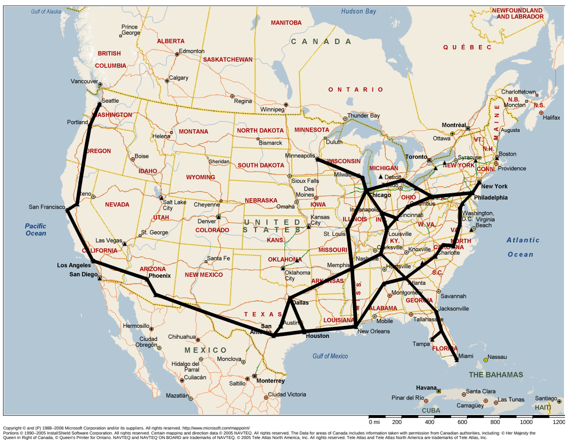
Implementation Plan for a National High-Speed Network for Freight Distribution

(a) 500 Miles

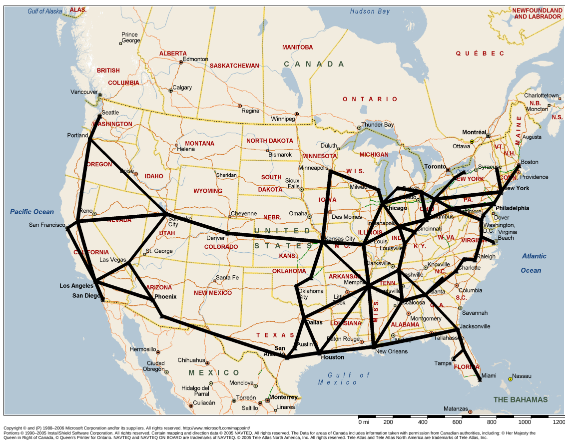
(b) 1,000 Miles

(c) 2,500 Miles

(d) 5,000 Miles



(e) 10,000 Miles



(f) 20,000 Miles

A Model to Design a National High-Speed Network for Freight Distribution

Contents

High-speed rail is often touted as a way to reduce congestion on the United States' highways by removing passenger car traffic. But reducing the amount of freight traffic would also reduce highway congestion. So, given the advances in high-speed rail, the potential exists for developing a national high-speed network for freight distribution. We present an uncapacitated network design problem with a post-processing step for the capacity constraint to construct such a network that considers highway traffic and transit times. We apply our models with data from a major truckload carrier and the U.S. Census to serve as a potential case study. We find that with sufficient capacity, a high-speed network for freight distribution will have a significant impact on freight transit times and highway congestion, with the potential to address many of the challenges facing transportation today.

1. Introduction

In many areas of the country congestion on the interstate and rural transportation networks is significant, with billions of dollars per year in lost productivity, stalled cargo, or wasted fuel associated with this congestion [34]. Today's U.S. interstate highway system carries an average of 10,500 trucks per day per mile and this figure is predicted to increase to 22,700 trucks per day per mile by 2035 [17], due to an increasing demand for goods and services as well as an increase in international trade. There are more than 3.4 million trucks currently on the road [28], and commercial truck travel has doubled over the past two decades [16]. In addition, it is predicted that the number of cars and trucks on the road will quadruple by the year 2050 [37] and freight will double in volume over the next 20 years [28]. It is also anticipated that 82% of those shipments will travel over a road [28]. Over the last 30 years, 550% more truck traffic miles were logged annually while lane miles of roadways have increased by only 6% [28]. It is clear that the current interstate and rural transportation network cannot handle such volume efficiently (i.e., without even more significant delays in transit).

Because truck traffic is often concentrated on major routes connecting population centers, ports, border crossings, and other major hubs of activity [16], high-speed rail systems, which are generally defined as systems where the train travels in excess of 100 mph, are potentially an attractive alternative to reduce congestion on the nation's highway system. Today's speed record is held by the Yamanashi Maglev Test Line in Japan, achieving a top speed of 361 mph [12]. With speeds expected to increase in the future, we ask, why not explore the potential benefits of high-speed rail technologies in the U.S. for freight transportation? Due to the predicted speed advantage, such a network could be commercially attractive for freight distribution even on a network that is significantly smaller than the current interstate highway system. If such a network is well-utilized, highway congestion and its associated costs and negative impacts could be significantly reduced.

Even though high-speed rail has not been studied much in the academic logistics literature, it has received a lot of attention from other sources. Congress has heard testimony, funded studies, and written reports [24, 23, 27]. High-speed rail has been covered in press journals, with it making the cover of the December 2007 issue of *Popular Mechanics* [29]. Various transportation leaders have commented on the critical need for a national strategy [23]. In fact, one such leader has dubbed the term "Interstate II," which is a vision for a high-speed network between various cities that is similar to the current interstate highway system [11].

It is clear that if it is economically-viable and technologically-feasible to build a high-speed rail system, it would have an overall, positive impact on the nation's transportation situation. What is less clear is the specific impact in terms of truck highway miles reduced or freight transportation times on the new, hybrid network. Also, less clear is whether a system of high-speed rail lines (point to point) or an integrated network would be more efficient. We explore this latter question in the next section, which ultimately provides motivation for modeling the problem as a network design problem.

1.1 Impact of a Single High-Speed Rail Alignment

In this section we consider building only a single high-speed alignment, which is defined as a sequence of edges connecting two major cities. Each edge must have exactly one city in common with its predecessor in the sequence and no cities may be visited more than once.

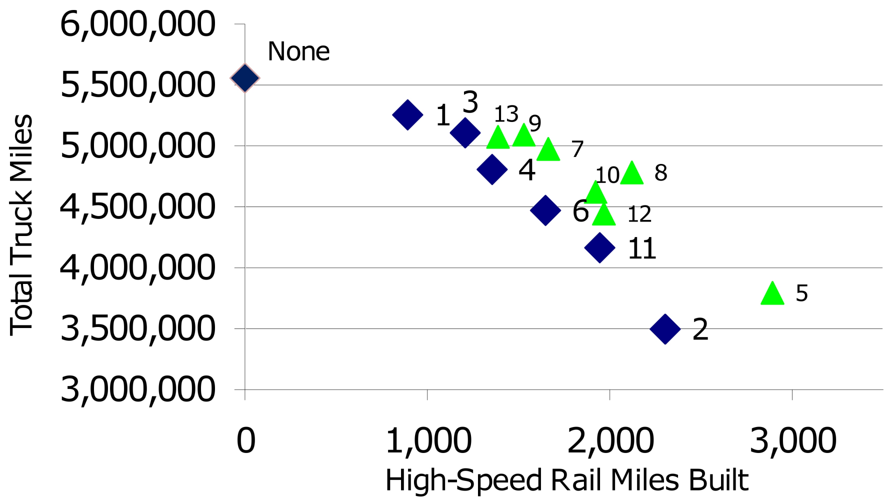
What impact would this high-speed alignment have on reducing congestion and decreasing shipment times? Which two end-point cities should be connected with high-speed rail for maximum impact? As will be discussed later in Section 2, this is the approach taken in most papers that look at public transit system design.

For now let us assume that we have built a descriptive model that evaluates various high-speed rail alignments that connect major cities as shown in Table 1. Assume we have a trucking company that delivers freight throughout the continental United States. When no high-speed alignments are available, the trucking company drives a total of 5,555,730 truck miles and takes 111,115 hours to deliver all the freight demanded. Evaluating the different high-speed alignments on both their ability to reduce truck miles on the highway and to reduce the total travel time against the amount of high-speed rail built, we develop an efficient frontier of alignments for the trucking company, which we present in Figure 1.

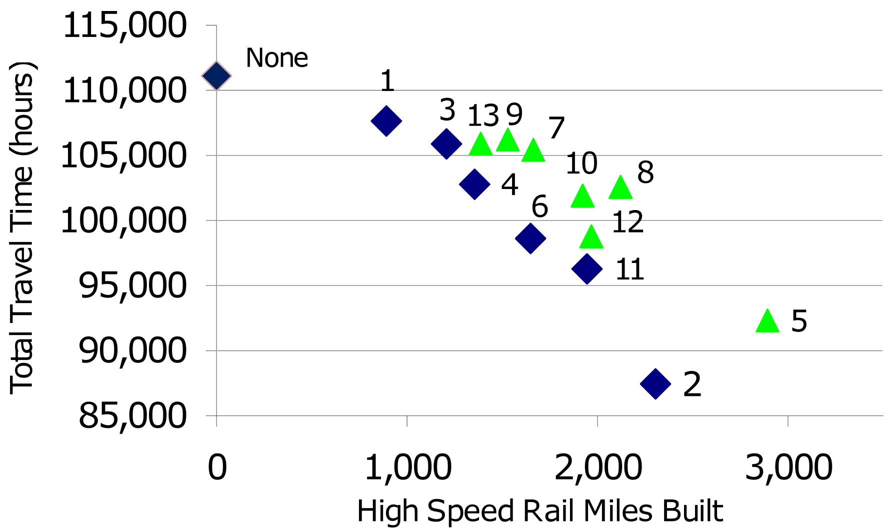
Table 1: Possible High-Speed Rail Alignments

1	Atlanta	New York City
2	Chicago	Los Angeles
3	Los Angeles	Seattle
4	Houston	Minneapolis
5	San Fransisco	Greensboro
6	Dallas	New York City
7	Seattle	Minneapolis
8	Seattle	Dallas
9	Miami	Detroit
10	Miami	Minneapolis
11	San Fransisco	Houston
12	San Fransisco	Minneapolis
13	Detroit	Tampa

From Figure 1 we can see that (g) the impact on total truck miles or (h) the total travel time in the system is inversely correlated to the length of the high-speed rail system constructed. For example, alignment 1 (Atlanta–New York City) reduces the total truck miles in the system by 301,190 miles and only requires building 892 miles of high-speed rail, whereas alignment 2 (Chicago–Los Angeles) increases the miles of high-speed built to 2,304



(g) Reducing Total Truck Miles



(h) Reducing Total Travel Time

Figure 1: Efficient Frontier of High-Speed Alignments Connecting Major U.S. Cities by Evaluating the Total High-Speed Rail Miles versus (g). the Total Truck Miles and (h). the Total Travel Time

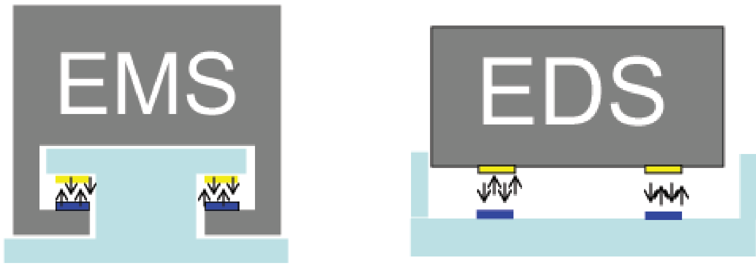
miles, but also increases the reduction in total truck miles to over 2 million miles. A similar impact on the total travel time can be seen in Figure 1(b), where the maximum reduction in total travel time by alignment 2 (Chicago-Los Angeles) is 23,670 hours, which is a reduction of 21.3% over the current system.

Now that we have illustrated that a significant reduction in truck miles and travel time is possible with a single alignment, we believe this motivates further study on a high-speed rail network. A network is a generalized version of an alignment as we are not restricted to only connecting two major cities, but can place high-speed rail anywhere in the network (i.e., a hub-and-spoke network or many point-to-point lines are possible in a network whereas they are not in an alignment). But before we address the modeling aspects of doing so, we will first discuss the high-speed rail technology with the greatest potential in terms of speed – magnetic levitation. Although there are many challenges to be addressed with respect to applying this technology to freight distribution, we believe an overview of this technology will motivate consideration of other high-speed technologies for rail distribution. As far as the subsequent optimization models are concerned, the speed and weight limit of the high-speed rail system are merely parameters, and thus, independent of the actual high-speed rail technology implemented.

1.2 Maglev Technology

Magnetic levitation (Maglev) uses electromagnetic forces to lift, propel and guide a vehicle over a specially designed guideway. There are two basic types of Maglev systems: electromagnetic suspension (EMS) and electrodynamic suspension (EDS). EMS uses electromagnetic attraction to provide levitation, while EDS levitates the vehicle by electromagnetic repulsion. Figure 2 graphically illustrates the different levitation techniques.

The two leading countries in the development of Maglev trains are Germany (EMS technology) and Japan (EDS technology). Transrapid 08, the current German Maglev design, has received extensive testing at a full-scale test track in Emsland, Germany. The German



(a) EMS (attraction) (b) EDS (repulsion)

Figure 2: Comparison of Two Maglev Technologies: (a) EMS and (b) EDS

design is the first and only operational high-speed Maglev system operating from downtown Shanghai, China to the new Shanghai airport in Pudong. The 19-mile system, inaugurated in 2002, has reportedly demonstrated high reliability and availability (99.9%), with low operating costs [36]. In a record run in November 2003, the train reached 311 mph (501 km/h). The Central Japan Railway Company (JR Central) has also developed a series of high-speed Maglev test vehicles. The current experimental vehicle is the MLX01, which is undergoing testing and demonstration at the Yamanishi Maglev Test Line, which extends 42.8 km between Sakaigawa and Akiyama [31]. The MLX01 is currently the fastest Maglev train, having achieved 361 mph (581 km/h) in December 2003. As the current technology stands, an 81.5-foot Maglev car can carry a payload weight of 67.24 tons and a freight train can be composed of 18 – 20 cars which can travel an average of 112 mph [9]. This is equivalent to carrying 78 TEU's [9].

There is interest in the U.S. in high-speed Maglev systems for passenger transportation. It should be noted that a freight transportation network is not seriously considered without a parallel passenger system [9], which provides the opportunity to utilize the network strictly for passengers during busy rush hour periods and increase the use for freight during night time hours. The U.S. Maglev Deployment Program was created in 1998 and is managed by the Federal Railroad Administration (FRA), a unit of the Department of Transportation. The objective of the program is to demonstrate the feasibility of high-speed Maglev in commercial passenger service for a relatively short line (approximately 40 miles). Four Maglev projects are in the planning stages, with all proposing to employ the German Transrapid system [15]:

- a 39-mile project between the Baltimore, MD airport and Washington D.C.;
- a 54-mile project in Pittsburgh, PA;
- a 269-mile project between Las Vegas, NV and Anaheim, CA; and
- a 55-mile project in Los Angeles, CA.

Construction costs for Maglev technology are currently about 50% higher than those of other high-speed train technology. The largest cost is in the guideways and should decrease with improvements in the technology [25]. Maglev technology has a lower operating cost when compared to airplanes, automobile, and high-speed rail, as it utilizes significantly less energy per passenger mile [26]. Also, because it levitates without friction, there is lower maintenance costs associated with vehicle and track corrosion [26]. Even though the actual cost of building this technology will vary with the location and features, the average cost per mile of a double track system for the Los Angeles project is estimated at around $140M [33] and the proposed Colorado Maglev project from the Denver International Airport to the Eagle County Airport is estimated around $38M per mile [2]. The Los Angeles estimate includes structural costs, earthwork, stations, parking facilities, operation and maintenance facilities, guideway, power supply, sound walls, safety fencing, landscaping, Maglev vehicles, roadway improvements, traffic control, contingencies, project implementation, and envionmental mitigation [33]. Detailed cost estimation and analysis is beyond the scope of this research, and yet we acknowledge that there is a significant cost component associated with this technology. For detailed cost estimation and analysis of specific projects see [2, 33]. For example, if we use the Los Angeles estimates, a 2,000 mile Maglev system would cost $280 billion dollars, which is equivalent to around 2% of the 2007 national gross domestic product [22]. Even though this is significant, traditional rail infrastructure will require nearly $200 billion over the next 20 years to maintain existing infrastructure and to accommodate freight growth [20].

The rest of the paper is organized as follows. The next section reviews the relevant literature and in Section 3, we discuss what a nationwide high-speed rail distribution network would look like and how it might impact transit times and highway travel. In Section 4, we present our methodology which includes an uncapacitated network design problem with a post-processing step for the capacity constraint and improve the solvability of the uncapacitated network design model in Section 5. An application with data from a major truckload carrier and the U.S. Census is provided in Section 6 as a potential case study. Conclusions and future research are presented in the final section.

2. Literature Review

2.1 Network Design Problem

In developing a model to determine a high-speed network for freight distribution, we solve the Network Design Problem (NDP), which has long been recognized as one of the most difficult and challenging problems in transportation [40]. It is concerned with the selection of arcs in a network in order to satisfy flow requirements between origin-destination pairs [13]. Its objective is to optimize a given system performance measure while accounting for the route choice behaviors of network users [18]. The NDP has been applied to diverse applications including transportation, capital investment decision making, vehicle fleet planning, communications, and distribution [3, 21].

The NDP is capable of considering the system-wide interactions between design decisions and how these decisions affect the operations of a transportation network. In particular, the models can consider trade-offs between various design alternatives, finding a balance between increased costs and resulting improvements in the system's operation [21]. In our work, the model balances the costs of building a high-speed rail infrastructure with the added benefits of the speed of the system. In our work of adding high-speed arcs to an existing highway network, we solve the Discrete Network Design Problem (DNDP), which focuses on the addition of new links to an existing uncapacitated transportation network with given demand from each origin to each destination [18].

In service network design problems, the NDP is extended to include additional service scheduling requirements and are generally modeled using NDP formulations with additional nodes for time and space mappings [39]. For an overview of service network design for freight distribution consult [39], which reviews tactical planning problems in the literature that have been applied to real-world problem instances for long-distance freight distribution. Capicated network design problems enforce capacity limits on the added arcs. This leads to a more difficult problem to solve and can pose considerable algorithmic challenges [14].

Our DNDP of adding high-speed arcs to an existing highway network can be modeled, in general, as a mixed-integer program and in particular, as a bi-level linear program, where bi-level programming represents the special case of multi-level programming with two levels [38]. Control over the decision variables is partitioned among the levels, but a decision variable on one level may affect the objective function of other levels [38]. In our problem, the higher-level decision is where to add high-speed rail arcs, while the lower-level decision is the shortest path problem from each origin to destination for a given network. The shortest path problem is affected by the placement of high-speed rail arcs in the network. That is, the objectives of the two levels are in conflict with each other as the higher-level decision is to minimize costs by building the fewest high-speed rail arcs, while the lower-lever decision is to minimize travel time for each network user by building the most high-speed arcs. The bi-level program balances the two objectives.

2.2 Multi-Modal Network Design

A fundamental difference between our work and other academic work in the multi-modal literature is that we are adding a parallel mode that is much faster than the existing mode. Almost all inter-modal work currently looks to add rail as a cheaper, but slower option to move freight.

Much research has been conducted on the planning of a rapid transit system and a thorough survey of optimization methods for the planning of rapid transit systems is provided in [19], which highlights the use of powerful local search methods capable of producing good quality single transit line locations, exact methods for fine tuning stations location, and proposed measures to assess the overall quality of a rapid transit configuration. No analytical method capable of solving the rapid transit network design problem to its entirety is cited in [19], because all known methods apply to the location of an alignment, as opposed to the design of a multi-line network. Due to the computational difficulty of designing a multi-modal network, numerous heuristics have been proposed. A multi-modal approach to the location of a single rapid transit line is applied in [7] and is the methodology we applied in Section 1.1. A mathematical model and a two-phase heuristic for the location of a rapid transit alignment in an urban setting is presented in [6]. Viewing [6] as a building block for the multi-line network design problem, [8] extends the single alignment algorithm to include the case of several intersecting alignments. Finally, in [30], the authors develop a two-phase heuristic to solve the multi-objective problem for integrated transit network design in a multi-modal network. Estimations of refined transit demand between origin, destinations, and inter-modal transfer locations is processed in phase 1, while the actual transit routes are built in phase 2.

3. Problem Statement

The objective of this research is to explore the impact of creating a high-speed rail network for freight distribution. We assume in our research that a high-speed rail network is technologically feasible, with a given speed advantage over highway travel, and we address constructing the most efficient high-speed rail network for freight distribution and analyze its impact on the current highway system. We model this problem by first starting with a developed national highway network between various cities. This network can be thought of as the current state of the interstate highway system in our country and is used as the framework for the potential high-speed network. That is, because of the large capital expenditures of high-speed rail infrastructure, it would not be economically feasible to build a high-speed rail network that mirrors the current highway system in length and size. Therefore in our analysis, we ask the question, where in this transportation network should links be added for high-speed rail? Interesting similar work by Bhaskaran and Turnquist [4] answers the question of where in the United States should multiple facilities be located to minimize transportation distance and maximize demand coverage.

We model the development of a high-speed network to move freight using a mixed-integer program. The main inputs to the model include a set of cities and a set of arcs between the cities. These cities were chosen to represent a national network based on their involvement in today's freight market. Parameters to the model include a distance matrix, flow matrix, average velocity for truck and high-speed travel, and a budget constraint. The distance matrix uses distances between all cities in the network and was based on data obtained from a United States atlas [32]. The flow matrix that represents the amount of freight that is shipped between origin-destination pairs is assumed to be a fixed, deterministic value. The average velocity for truck and high-speed rail travel is assumed to be a constant value, and we did not model the congestion in and around metropolitan areas. We use total miles of high-speed built as a surrogate for costs in our budget constraint. In order to compare high-speed rail to the current interstate highway system when displaying results we assume one mile of high-speed rail is equal to two tracks allowing for travel in both directions. Because high-speed rail for freight distribution is currently in the development stage, there is a substantial level of uncertainty associated with the potential speeds and capacity. We do not explicitly model the time associated with this freight transfer, but instead handle it by adjusting the average velocity of the high-speed rail mode. To accommodate these uncertainties, we vary the speed and capacity of the high-speed network in our analysis.

After high-speed rail arcs are added to our network, we analyze the impact these additional high-speed arcs would have on the current highway system. After addressing capacity issues, we create a traffic load model to answer questions like the following: To what extent does the existence of the high-speed rail arcs lead to a reduction in the amount of truck traffic and its associated freight transit time, realizing that trucks may drive out of their way in some cases to access the higher speed arcs? To answer this question, we assume that the preferred route was the shortest total travel time (over the inter-modal network) from origin to destination, which implies that if a high-speed rail arc connected two cities, the shipment would use the high-speed arc for travel between the two cities given there is adequate capacity to do so. This assumption implies that we are modeling from a users' perspective, assuming that operators will make a selfish decision, taking the route associated with the shortest travel time. We do not conduct a cost analysis when deciding if freight will utilize the high-speed network and yet acknowledge that cost will be a significant issue in determining what mode of transit is appropriate. We decide to make this modeling assumption because if a high-speed network is not feasible when the network is free to use, then it will definitely not be when we incorporate cost implementations. Finally, we compare different high-speed networks in terms of the miles of truck travel on the highway and the total travel time.

4. Methodology

In the real system, there will be capacity constraints associated with the high-speed rail technology. We consider two options for incorporating capacity into our analysis: modeling it directly or modeling it as a post-processing step. In Section 4.1 we present a capacitated network design model, which models capacity directly and in Section 4.2 we present an uncapacitated network design model with a post-processing step for capacity.

4.1 Capacitated Network Design Problem

The following model has as its objective to minimize the total time required to accomplish a set of trips between city pairs, called origin-destination (O-D) pairs, by choosing the optimal location of high-speed rail lines. The cities are represented as nodes, connected by a network of existing highways and potential high-speed guideways. The connections between nodes (cities) are represented by directed links, called arcs. The network is symmetric in that the distance from city i to city j is the same as the distance from city j to city i. Each arc is either a highway or high-speed line and has a length equal to the distance to travel that arc. The model determines which high-speed arcs should be added and the shortest path between all O-D pairs over the resultant inter-modal network. The network is connected (there is a path between every pair of nodes) and planar, which implies there is not necessarily an arc between every pair of nodes. The set of node pairs that have an arc between them is defined as A below.

Sets:

N	nodes, $i, j, k, o, d = 1, \ldots, n$
A	arcs, $(i, j) \in A$
O	origins, $o = 1, \ldots, n$
D	destinations, $d = 1, \ldots, n$
OD	all O-D pairs, $(o, d) \in OD, o \neq d$
M	modes, $m = T$ (truck), H (high-speed rail)

Parameters:

d_{ij}	distance from node i to node j
f^{od}	units transported between origin o and destination d
v^m	average velocity of mode m
t_{ij}^m	time to traverse arc (i, j) when mode m is used ($t_{ij}^m = d_{ij}/v^m$)
L	the total high-speed rail miles built in the network
c_{ij}	capacity of high-speed rail arc (i, j) in tons per unit of time

Variables:

$$Z_{ij} = \begin{cases} 1 & \text{if high-speed rail is used from } i \text{ to } j, \\ 0 & \text{otherwise} \end{cases}$$

$$z_{ij}^{od} = \begin{cases} 1 & \text{if arc } (i,j) \text{ is used in the high-speed rail mode for the } (o,d) \text{ trip}, \\ 0 & \text{otherwise} \end{cases}$$

$$x_{ij}^{od} = \begin{cases} 1 & \text{if arc } (i,j) \text{ is used in the truck mode for the } (o,d) \text{ trip}, \\ 0 & \text{otherwise} \end{cases}$$

y^{od} time to traverse the shortest path between origin o and destination d

w^{od} percent of flow that uses high-speed rail between origin o and destination d

Model:

$$\min \sum_{(o,d)\in OD} f^{od} y^{od} \tag{1}$$

$$s.t. \quad y^{od} = \sum_{(i,j)\in A} (t_{ij}^T x_{ij}^{od} + t_{ij}^H z_{ij}^{od}), \qquad \forall (o,d) \in OD \tag{2}$$

$$z_{ij}^{od} \leq Z_{ij}, \qquad \forall (i,j) \in A, (o,d) \in OD \tag{3}$$

$$Z_{ij} = Z_{ji}, \qquad \forall (i,j) \in A \tag{4}$$

$$x_{ij}^{od} + z_{ij}^{od} \leq 1, \qquad \forall (i,j) \in A, i \neq j \tag{5}$$

$$\sum_{(i,j)\in A} d_{ij} Z_{ij} \leq 2L \tag{6}$$

$$\sum_{(i,o)\in A} (x_{io}^{od} + z_{io}^{od}) - \sum_{(o,j)\in A} (x_{oj}^{od} + z_{oj}^{od}) = -1, \qquad \forall (o,d) \in OD \tag{7}$$

$$\sum_{(i,d)\in A} (x_{id}^{od} + z_{id}^{od}) - \sum_{(d,j)\in A} (x_{dj}^{od} + z_{dj}^{od}) = 1, \qquad \forall (o,d) \in OD \tag{8}$$

$$\sum_{(i,k)\in A} (x_{ik}^{od} + z_{ik}^{od}) - \sum_{(k,j)\in A} (x_{kj}^{od} + z_{kj}^{od}) = 0, \qquad \forall (o,d) \in OD; \tag{9}$$

$$\forall k \in OD, k \neq o, k \neq d \tag{10}$$

$$\sum_{(o,d)\in OD} f^{od} z_{ij}^{od} w^{od} \leq c_{ij} \qquad \forall (i,j) \in A \tag{11}$$

$$Z_{ij} = \{0,1\} \qquad \forall (i,j) \in A \tag{12}$$

$$z_{ij}^{od} = \{0,1\} \qquad \forall (o,d) \in OD, (i,j) \in A \tag{13}$$

$$x_{ij}^{od} = \{0,1\} \qquad \forall (o,d) \in OD, (i,j) \in A \tag{14}$$

$$0 \leq w^{od} \leq 1 \qquad \forall (o,d) \in OD \tag{15}$$

The objective, (1), is to minimize the total time required to accomplish a set of trips between *O-D* pairs, which is the product of the number of trips and the travel time between each *O-D* pair, for all pairs. The travel time for each *O-D* pair, y^{od}, is the sum of the arc travel times for the arcs used in that trip, as represented by (2). For each arc used in an *O-D* trip, the time to traverse that arc will depend upon the travel mode used. The variables Z_{ij} designate if high-speed rail is available, which determines if high-speed is used for travel as shown in (3). An arc must be used for the same mode in both directions (4), and only one mode can be used, as ensured in (5). The total miles of high-speed rail built is constrained to a maximum value in (6) and is multiplied by 2 because we assume 1 mile of high-speed rail is equal to 2 tracks allowing for travel in both directions.

The shortest path between pairs is determined with a minimum cost network flow formulation, where the total flow on each arc, for each mode, x_{ij}^{od} and z_{ij}^{od}, is either zero or one. The shortest path from o to d is along arcs where either $x_{ij}^{od} = 1$ or $z_{ij}^{od} = 1$. Constraints (7), (8) and (9) are balance equations that enforce conservation of flow at each node, where the origin has a supply of one, the destination has a demand of one, and all other arcs in the path (transshipment nodes) have zero supply/demand. In (7) we ensure that the flow on arcs coming into node o minus the flow on arcs coming out of node o will be -1 (i.e., there will be flow on only one arc out of o). Likewise, (8) ensures that there will be flow on only one arc into the destination, node d. All other nodes in the path from nodes o to d will have conservation of flow — one arc in and one arc out — as shown in (9).

Capacity is enforced using a multi-dimensional knapsack constraint is represented in (11), where the total weight for any *O-D* pair that utilizes the high-speed arc must be less than the capacity on each high-speed rail arc. Because capacity is related to to where high-speed rail arcs are placed in the network and how demand is routed through this network this is a non-linear constraint; i.e., z_{ij}^{od} and w_{ij}^{od}, both decision variables, are multiplied in (11). Finally, boundaries on each of the variable types are enforced in (12)–(15).

We assume that if a high-speed rail arc is built, freight will be shipped in both directions along the high-speed arc and therefore only concerned with where to place undirected high-speed arcs. Our model can be formulated with undirected arcs by restricting the node and edges to $i < j$, eliminating (4) and adding constraints. If reformulated in this way, the resulting model is a non-linear program, which is even more intractable than the proposed model. Therefore, we did not investigate this formulation further and the remainder of the paper uses directed arcs in the analysis. It is noted that we do refer to edges in the remainder of the paper, and an undirected edge between two cities consists of the two directed arcs between the two cities.

The primary advantage in modeling capacity directly is in obtaining an optimal solution to the design of a capacitated high-speed network. Unfortunately, this approach generates a non-linear model because directly enforcing capacity constraints leads to quadratic interactions, which increases the complexity of the problem. It should also be noted that the uncapacitated network design problem (which we present in the next section) is itself computationally difficult to solve (i.e., a 53-city network problem can take days to solve).

4.2 Uncapacitated Network Design Problem with a Post-Processing Step for Capacity

A second alternative would be to solve an uncapacitated network design problem and enforce capacity constraints in a post-processing step. This alternative does not result in a provably optimal solution, but does allow for a more tractable model. The uncapacitated network design problem is represented by (1) – (9) and (12) – (14).

In the post-processing step we address the capacity constraints on the high-speed rail network by developing a multi-dimensional knapsack formulation. The knapsack problem analogy here is that we wish to add flows (items) to capacitated arcs (knapsacks). In the post-processing step we use the inter-modal network developed in the uncapacitated model as an input. Therefore, we know where high-speed rail arcs are built and the new set, A', denotes this high-speed network (i.e., if $Z_{ij} = 1$, then arc (i, j) is in A'). We are only concerned with the capacity of the high-speed network and assume the highway system has infinite capacity. In order to enforce capacity, we need to know how freight is routed through the inter-modal network. Therefore, the routing decision variables z_{ij}^{od} are now considered as parameters. There is a benefit associated with using high-speed rail for each O-D pair and is calculated by (16) as follows:

$$b^{od} = u^{od} - y^{od}, \tag{16}$$

where u^{od} is the time it takes to travel between O-D pairs on a network with no high-speed rail and is determined by solving for y^{od} in our uncapacitated model with no high-speed rail arcs added (i.e., $L = 0$). The decision in this model is to determine which O-D pairs should use the high-speed network. We assume an O-D pair either uses the shortest path utilizing the inter-modal network as developed in the uncapacitated model or does not use the high-speed rail network at all. In other words, if the O-D pair is unable to use one high-speed rail arc due to a capacity constraint, it also does not use any other high-speed rail arcs. A more detailed consideration of this decision is left for future research.

Sets:

A'	high-speed rail arcs subject to $Z_{ij} = 1$ from (4.1)–(4.9), $(i, j) \in A'$
OD	all O-D pairs, $(o, d) \in OD, o \neq d$

Parameters:

b^{od} benefit of utilizing the high-speed rail network between origin o and destination d

f^{od} units transported between origin o and destination d in tons per unit of time

z'^{od}_{ij} is set to 1 if *O-D* pair uses high-speed rail arc (i,j) subject to $z^{od}_{ij} = 1$ from (4.1)–(4.9); 0 otherwise

c_{ij} capacity of high-speed rail arc (i,j) in tons per unit of time

Variables:

w^{od} percent of flow that uses high-speed rail between origin o and destination d

Post Processing Model:

$$\max \sum_{(o,d)\in OD} b^{od} f^{od} w^{od} \tag{17}$$

$$\text{s.t.} \sum_{(o,d)\in OD} f^{od} z'^{od}_{ij} w^{od} \le c_{ij} \qquad \forall (i,j) \in A' \tag{18}$$

$$0 \le w^{od} \le 1 \qquad \forall (o,d) \in OD \tag{19}$$

The objective, (17), is to maximize the total benefit of using the high-speed network. The multi-dimensional knapsack constraint is represented in (18), where the total weight for any *O-D* pair that utilizes the high-speed arc must be less than the capacity on each high-speed rail arc. Finally, a boundary on the range of w^{od} is enforced in (19). Because integrality is not enforced, some *O-D* pairs will utilize the high-speed network for some of their demand, but not necessarily all of it. Given the scope of the problem, this is believed to be a reasonable representation.

O-D pairs that do not have to drive out of their way to access the high-speed network should have the largest benefit in utilizing the high-speed rail network. The next remark shows that the manner in which we calculate benefit correctly models this relationship.

Remark 1 (The proof is provided in Appendix C)

For each high-speed rail arc, the O-D pairs that will gain the most benefit from utilizing high-speed arc (i, j) are the ones whose unique shortest path with $L = 0$ has $x_{ij}^{od} = 1$ and the shortest path with $L > 0$ has $z_{ij}^{od} = 1$.

4.3 Modeling Trade-Offs

Obviously there is a trade-off between tractability and validity in developing a model for a high-speed network for freight distribution. On one hand, we want to develop a model of high validity that holds for the real system. On the other hand, we want a model that is tractable and allows for analysis to help decision makers evaluate the impact of a high-speed network. To balance this trade-off, we solve the uncapacitated network design problem where we determine the inter-modal network, and in the post-processing step, we enforce capacity constraints on the high-speed arcs. In this modeling process, we determine the flow of freight through the network and evaluate the impact on travel times and highway congestion.

Multi-dimensional knapsack problems are known for being tractable for large problem and we have further increased the tractability by relaxing integrality on the w^{od} variables. Therefore, the post-processing step solves large problems very quickly (i.e., in seconds). This is not the case for the uncapacitated network design model, and therefore we present our efforts on improving the solvability of that formulation in the next section.

5. Improving the Solvability of the Network Design Problem

The runtime associated with the uncapacitated network design model is fairly significant. Therefore, in order to solve larger problem instances, we conducted an experimental design to improve the solvability of our formulation by analyzing and comparing various solution frameworks. This experimental design was conducted on a 30-city, 126-arc network using U.S. Census flow data [1] with various levels of L. Therefore, when we discuss average solve time, we are discussing the average solve time of various L values over this specific data set. The instances in our experimental design was solved by using CPLEX 10.1 and were ran on a Dell Optiplex GX620 PC with an Intel Pentium D Dual-Core processor at 3.2GHz and with 2.0 GB of RAM and Microsoft Windows XP Professional Version 2002 as the operating system. The data set used in this analysis is provided in Appendix B. Figure 3 provides an overview of our experimental design process, which we fully discuss below.

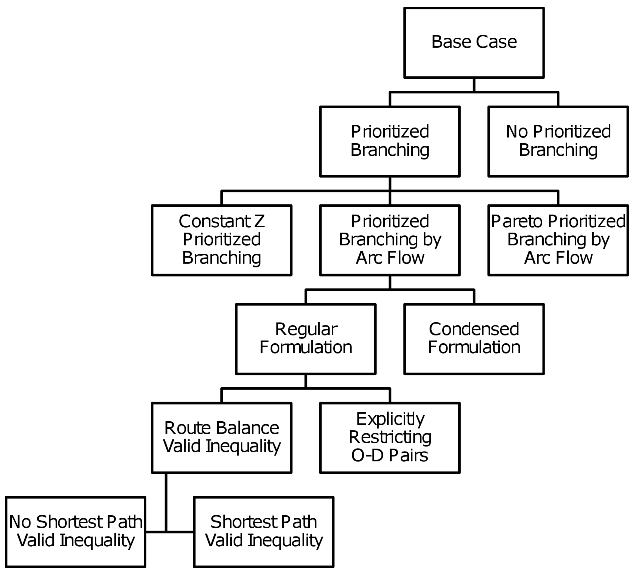


Figure 3: Experimental Design for Improving the Solvability of the Formulation

The base case for our experimental design was computationally difficult to solve and often for large networks does not find an optimal solution due to a lack of memory. For our small, 30-city network all instances solved to optimality and the average solve time was

37.35 minutes. This motivated us to look at alternative solution approaches. We begin by exploiting the bi-level nature of our problem by implementing prioritized branching on the Z_{ij} variables. The decision of where to place high-speed rail has a direct impact on the lower-level decision of determining the shortest paths for each O-D pair. This branching scheme allowed us to solve more complex problems more quickly by reducing the number of branch and bound nodes needed to solve the problem to optimality. This also alleviated some of our memory problems, as we prevent our branch and bound trees from expanding, which required a large number of unexplored branch data to be stored.

We experimented with three types of prioritized branching in which we denote P1, P2, and P3. In P1, we assigned branching priority to the Z_{ij} variables, instead of branching on the fractional variable that is closest to an integer value. In this solution framework, each Z_{ij} variable was given the same priority and a branching direction was not explicitly denoted. In P2, we not only assigned branching priority to the Z_{ij} variables, but also ranked them on the amount of flow demand traveled on each arc. To determine the flow demand on each arc, we ran the model with $L = 0$. We also explicitly denoted the branch direction toward 1 (i.e., the $Z_{ij} = 1$ branch should be explored prior to the $Z_{ij} = 0$ branch). In P3, we applied the Pareto principle to our branching scheme. In this case, we continued to rank the Z_{ij} variables in terms of flow demand, but denoted their branch direction as follows. The top 20% of the arcs had a branch direction towards 1, while the bottom 40% had a branch direction towards 0. The remaining arcs were not provided with a branch direction.

Prioritized branching on the Z_{ij} variables provided substantial improvement over the base case (the average solve time was reduced from 37.35 minutes to less than 5 minutes). Because there was no statistical difference between the three branching priority's solve times, we test the remaining solvability improvement approaches with all three branching schemes.

The next solution approach was to formulate our problem as compactly as possible by eliminating the y_{od} variables and by combining multiple constraints into condensed constraints. To handle this approach, we replaced (1) and (2) with (20), as shown below:

$$\sum_{(ij)\in A}\sum_{(od)\in OD} f^{od} d_{ij}(x_{ij}^{od}/v^T + z_{ij}^{od}/v^H). \tag{20}$$

The condensed formulation reduced the number of constraints, but in general increased the solve time (from an average of 3.78 to 3.87 minutes). In fact, for every instance that took over 1 minute to solve, the original formulation with branching schemes P1 and P2 were superior in terms of computational time. Using branching scheme P3, the original formulation was superior in all but one instance when the solve time exceeded 1 minute. Therefore, we continued to use the initially proposed formulation in the remaining solution frameworks.

In order to tighten our formulation, we added (21) and (22) to our model:

$$\sum_{(ij)\in A}\sum_{(od)\in OD} x_{ij}^{od} = x_{ji}^{do}, \tag{21}$$

$$\sum_{(ij)\in A}\sum_{(od)\in OD} z_{ij}^{od} = z_{ji}^{do}. \tag{22}$$

These route-balance valid inequalities, (21) and (22), exploited the symmetric nature of our distance matrix. For any *O-D* pairs, the shortest path from an origin to a destination must be the same as a shortest path from a destination to an origin. These valid inequalities were only appropriate if each city was considered both an origin and a destination. Where this was not the case, we assigned $f^{od} = 0$. An experimental design was undertaken to determine which provides the most benefit in terms of computational time: explicitly restricting all *O-D* pairs to have positive demand flow or adding (21) and (22) to the formulation.

For our instances, the route balance valid inequalities provided a more significant impact over reducing the number of *O-D* pairs. The average solve time with the valid inequalities was 1.41 versus 1.91 minutes with the reduced *O-D* pairs. In fact, for all instances that took over 1 minute to solve, the model with the valid inequality always solved in a shorter amount of time. It should be noted that adding the route balance valid inequalities to the base case does not produce as impressive results as providing a branching priority. Therefore, branching priority is needed to solve networks of a reasonable size regardless if the route balance valid inequalities are added.

We can further tighten our formulation by adding the following valid inequality (23) to our model:

$$y^{od} \leq u^{od} \;\; \forall (od) \in OD. \tag{23}$$

This valid inequality states that the shortest path utilizing high-speed rail for any *O-D* pair is at least as fast as the time it takes to travel without any high-speed rail. Adding this valid inequality did not improve the solvability of our formulation, as it increased the solve time for every problem instance, and also increased the average solve time from 1.41 to 2.43 minutes.

In general, the most computationally-efficient solution approach consisted of prioritized branching on Pareto ranked Z_{ij} values and using route balance valid inequalities. The mean and standard deviation of the solve time for the various solution frameworks are provided in Table 2. Implementing this formulation provided a 97% reduction in average solve time over the base case. The detailed results of our experimental design are provided in Appendix B. In the next section, we apply what we learned from this experimental design to an application with representative data sets.

6. Continental United States Application

For our experiments, we consider an application of our model with data from the Continental United States, basing the flow matrix on past shipment histories. We obtained representative data sets of freight flow between *O-D* pairs in the continental United States from two separate sources, the 2002 Commodity Flow Survey [1] and J.B. Hunt Transport Services,

Table 2: Experimental Design on the Uncapacitated Network Design Formulation

Formulation	Average Solve Time (mins)	Standard Deviation Solve Time (mins)
Base Case	37.35	82.77
Prioritized Branching (P1)	4.70	8.18
Ranked Prioritized Branching (P2)	3.31	4.99
Pareto Prioritized Branching (P3)	3.34	5.01
Average Branching	3.78	6.12
Condensed Formulation + P1	4.95	8.54
Condensed Formulation + P2	3.35	5.02
Condensed Formulation + P3	3.33	4.93
Average Condensed Formulation	3.87	6.28
Valid Inequality (21) and (22) + P1	1.57	2.33
Valid Inequality (21) and (22) + P2	1.37	1.79
Valid Inequality (21) and (22) + P3	1.29	1.60
Average Valid Inequality (21) and (22)	1.41	1.89
Explicit O-D Pairs + P1	1.91	2.72
Explicit O-D Pairs + P2	2.14	3.50
Explicit O-D Pairs + P3	1.65	2.16
Average Explicit O-D Pairs	1.91	2.78
V.I. (21), (22), and (23) + P1	2.75	4.17
V.I. (21), (22), and (23) + P2	2.31	3.11
V.I. (21), (22), and (23) + P3	2.25	2.89
Average V.I. (21), (22), and (23)	2.43	3.39

Inc. (J.B. Hunt) [5]. The 2002 Commodity Flow Survey (U.S. Census) is undertaken through a partnership between the Bureau of the Census, the U.S. Department of Commerce, the Bureau of Transportation Statistics, and the U.S. Department of Transportation. This survey produces data on the movement of goods in the United States in truckload, less than truckload, and parcel form. The data from the Commodity Flow Survey are used by public policy analysts and for transportation planning and decision-making to assess the demand for transportation facilities and services, energy use, and safety risk and environmental concerns. The number of tons of shipment from O-D pairs was provided in this data set. The second data set was obtained from one of the largest transportation logistics companies in North America, J.B. Hunt, which is headquartered in Lowell, AR. They focus on the transport of full truckload freight to a diverse group of customers throughout the continental United States, Canada and Mexico. Their business operations are primarily organized through three business segments that include dry van, inter-modal and dedicated contract services. J.B. Hunt provided general bid history data for a one-year period. As J.B. Hunt is the largest U.S.-based truckload carrier, they believe their bid data represents a typical distribution of truckload demand. Units of shipment for the J.B. Hunt bid data are in 53-foot inter-modal containers.

The Commodity Flow Survey was used to estimate the yearly total tons of freight transported by truck over the nation's highways (5,271,589,000 tons). Freight transported within a city was deemed irrelevant to our study and therefore disregarded. Of the data provided by this study, 12% denoted freight transported between two large cities, for example San Antonio, Texas to Detroit, Michigan. The remaining 88% of the data reported was highly aggregated (i.e., the remainder of Texas to the remainder of Michigan). We develop a 53-city, 192-arc network that is represented in Figure 4 with 579,838,000 tons of freight assumed to be transported through this network. This data set represents 91% of the city-to-city data or 11% of the yearly total. We assume that the aggregated freight is equally as likely to use the high-speed rail as the more concise data and therefore inflate the 53-city, 192 arc network data in our capacity analysis to create a representative data set of the entire yearly tons of freight transported by truck.

The J.B. Hunt data is provided in 53-foot trailers but to protect proprietary information, we convert the data supplied in trailers to tons and compare it to the CFS data. A 97-city, 406-arc network is developed using the flow data from J.B. Hunt, which assumes that 285,989,006 tons of total freight is being transported through the network. The total flow of material provided by J.B. Hunt was 336,388,613 tons and our 97-city network encompasses 85% of this data. The remaining 15% did not aggregate well, but we take this into account for our capacity analysis later. This data set encompasses approximately 6.5% of the yearly total tons estimated from the Commodity Flow Survey. Figure 5 shows the network map of this data set. For our analysis, we also develop a 50-city, 198-arc network which assumes 144,051,254 tons of freight is being transported through the network. This is 2.7% of the yearly total tons estimated from the Commodity Flow Survey. Data sets denoting the cities, distances, and demands used in the analysis for both data sets are provided in Appendix B.

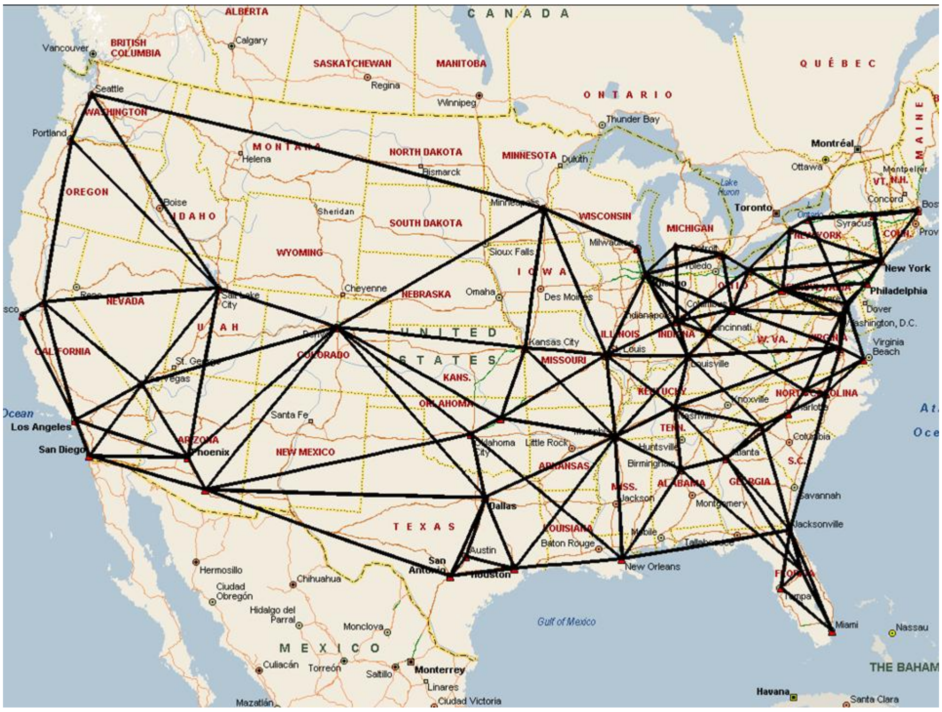


Figure 4: U.S. Census Network

We compare the two data sets statistically to decide if both need to be considered in our analysis of the potential of a high-speed rail network. First, we note that it is difficult to directly compare the two data sets in terms of total flow as one is from a single company's perspective for truckload freight and one from a national perspective of all types of freight. Therefore, we understand that some scaling must be performed. Once that is done, a comparison of the coefficient of variation (CV) illustrates that the U.S. Census data set (CV = 2.9) has more variation in the *O*-*D* pair demands than the J.B. Hunt data set (CV = 1.7), which is expected since there is more variation in the type of freight considered in the U.S. Census data. Thus, to further illustrate this we compare the common *O*-*D* pairs with a positive flow of freight and divide the flow data into five value ranges as a percentage of the mean as described in Table 3. For example the freight from Detroit to Los Angeles was 230%

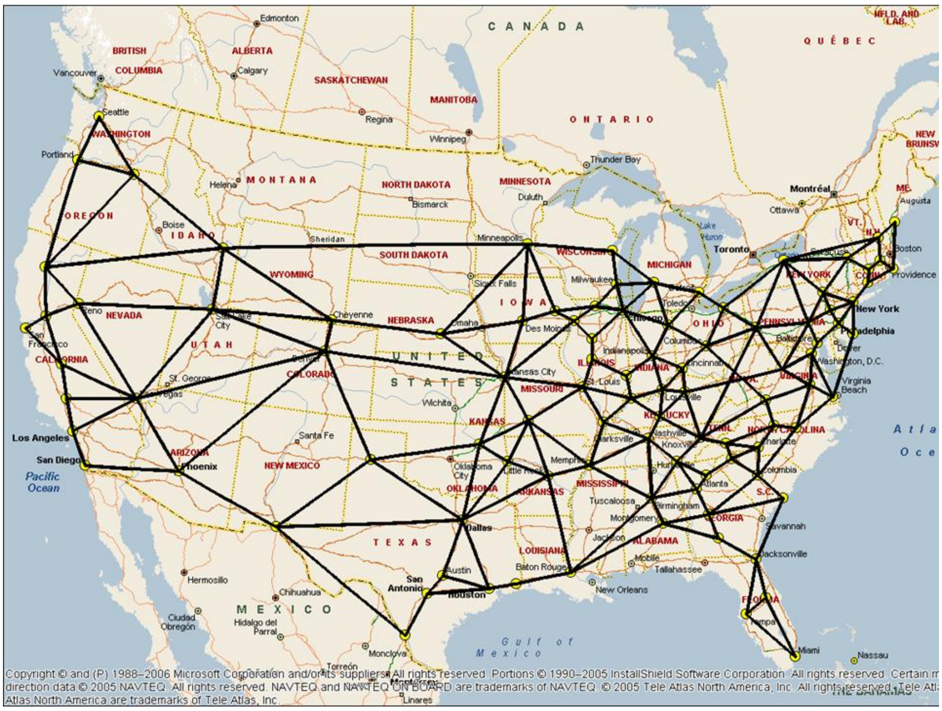


Figure 5: J.B. Hunt Bid History Network

Table 3: Statistical Value Ranges

	Value Range as a Percentage of the Mean
1	0% to 10%
2	10% to 50%
3	50% to 150%
4	150% to 500%
5	500% and up

of the mean for the J.B. Hunt data set (Value Range 4) and only 130% of the mean for the U.S. Census Data set (Value Range 3). The *O-D* flow data for J.B. Hunt and U.S. Census fell in the same value range only 41% of the time. Therefore, we conclude that statistically, the two data sets are not very similar, which is our justification in analyzing both data sets separately to see if the high-speed rail networks developed are the same or different.

Designing and optimizing a national high-speed network for freight distribution would lead to a reduction of truck traffic on the current highway system as well as a decrease in travel times to deliver products across the country. Therefore we next optimize the network with the provided data to illustrate the impact of a high-speed rail network on the time shipments spend in transit and the amount of highway miles traveled (by trucks). These impacts are first analyzed in an uncapacitated network in Section 6.1 and next with capacity constraints enforced in Section 6.2.

6.1 Uncapacitated Analysis

As discussed in Section 1, delays caused by highway congestion represent a major cost to motorists in lost wages and wasted fuel. Furthermore, congestion has steadily worsened over time because the population of drivers, number of vehicles, and travel volume continues to increase at a faster rate than system capacity [35]. Also, the variability in speeds and size of trucks and passenger vehicles on the highway system has led to safety issues and loss of life. In fact, one in eight traffic fatalities results from a collision involving a truck and being involved in a collision with a truck is nine times more likely to cause fatal injury to the driver of the passenger vehicle [28]. Another advantage of removing freight traffic would be a lower maintenance costs for our current highway system since one 80,000-pound tractor trailer can do as much damage to 1 mile of interstate as 9,600 passenger cars [28]. Another obvious benefit of high-speed rail is the ability to ship products with increased speed. The shift in focus to customer service, lean manufacturing techniques, and just-in-time practices has heightened interest in time-sensitive shipments. In general, improvements and additions of high-speed alternatives will induce changes in the traffic flow and safety over the national network. Therefore, we analyze our models to determine the impact of adding high-speed rail on the current highway system by comparing the following two performance measures on various high-speed rail networks:

1. Truck Miles: the total number of miles traveled by trucks on the current highway system to transport freight across the network,

$$\text{Truck Miles} \equiv \sum_{(i,j)\in A} \sum_{(od)\in OD} d_{ij} x_{ij}^{od} f^{od}.$$

2. Total Travel Time (TTT): the total time in hours to transport all freight across the network,

$$\text{TTT} \equiv \sum_{(od)\in OD} f^{od} y^{od}.$$

We assume that one trailer is equivalent to one truck and the data sets are converted from ton miles to truck miles.

By solving our model with different values for total miles of high-speed rail built, (L), we can gain insight into how various high-speed networks could affect highway congestion and the timeliness of freight distribution. In the initial analysis, we use $v^T = 50$ mph and $v^H = 150$ mph (i.e., high-speed rail is 3 times faster than the current highway system). We present the results of a J.B. Hunt data set with 50 cities and 198 arcs and the full U.S. Census data set (53 cities, 192 arcs) in Figure 6. This traffic load model tells a "story" in that it provides a visual reference in which to compare total truck miles and travel times of various high-speed networks.

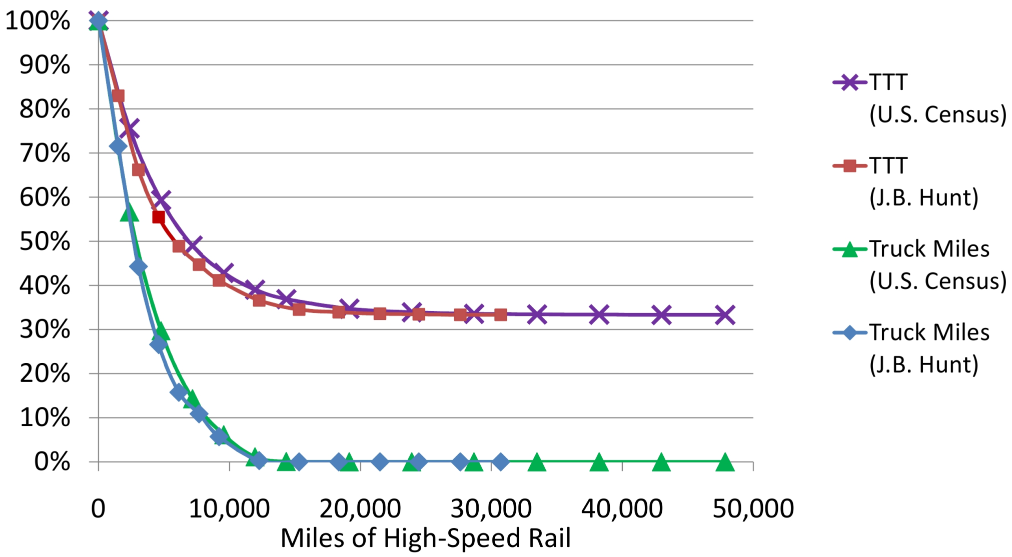


Figure 6: An Uncapacitated Traffic Load Story for the U.S. Census and J.B. Hunt Data Sets

From this analysis, one can see the ultimate trade off of high-speed rail: as the miles of high-speed rail increases, the total truck miles and total travel time decreases. This raises the question of how much capital is necessary to achieve a certain benefit in terms of decreased shipment times and highway congestion. As a frame of reference, the Interstate Highway System is made up of 47,000 miles of highway, but is only 1% of the total U.S. highway miles [17]. For example, using the J.B. Hunt data set, if approximately 3,000 miles of high-speed rail were built, it would decrease total truck miles to 66% of the current transportation network with no high-speed rail. The U.S. Census data provides similar results; if around 2,400 miles of high-speed rail are built, the total truck miles are reduced to 57% and the total travel time is reduced to 76% of the current highway network with no high-speed rail. These numbers are best-case scenario, as it is assumed that the high-speed network is uncapacitated. The issue of capacity will be addressed in the next section.

After analyzing the two statistically-different data sets, the overall benefits in terms of total truck miles and travel time reduction are similar. That is, the curves for the two data sets are extremely similar and illustrate that regardless of the source of the demand data, comparable national benefits will be related in terms of reduction in the total truck miles and total travel time. Even though the overall benefits are similar, the actual networks (i.e., where high-speed rail is built) vary with the *O-D* demand provided by the different data sets. For example, the roughly 4,500-mile high-speed rail networks using J.B. Hunt and U.S. Census flow demand are depicted in Figure 7. Even though both high-speed networks have a comparable number of arcs (40 versus 42 arcs) and "look," they share only 5 edges (Sacramento to Los Angeles, Los Angeles to Phoenix, Birmingham to Atlanta, Birmingham to Nashville, and Chicago to Indianapolis). The high-speed networks continue to vary in structure for different values of L.

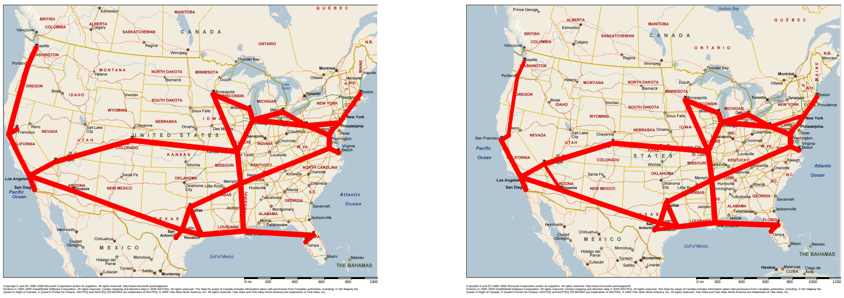
The high-speed networks developed in our model are dependent on the values of v^T and v^H but the actual solutions are fairly robust. That is, even though varying the value for v^H may impact where high-speed rail is built, the overall changes in the networks are small. For example, a 30-city U.S. Census network was ran twice, once with v^H equal to 150 mph and once with v^H equal to 400 mph. The percent difference in the miles of high-speed rail built varied by approximately 7% yet the actual networks "looked" very similar. For example,

(a) U.S. Census

(b) J.B. Hunt

Figure 7: The Contrast Between the 4,500 Mile High-Speed Networks for U.S. Census and J.B. Hunt Data Sets

Figure 8 shows the different networks developed for the two velocity parameters. Much of the variation in networks can be traced to the slack in (6), our maximum miles of high-speed rail constraint. When this constraint was tight, our model produced high-speed networks that were not sensitive to the value of v^H. Due to the robustness of our solutions, we use the high-speed network developed with $v^T = 50$ mph and $v^H = 150$ mph in our capacity analysis.



(a) $v^H = 150$ (b) $v^H = 400$

Figure 8: The High-Speed Rail Networks for the U.S. Census 30-City Network for $v^H = 150$ mph and $v^H = 400$ mph

Due to the high cost of these systems, it is likely a high-speed network will be implemented in phases throughout a planning horizon of many years. In order to create our implementation plan, we assume that a 20,000-mile network will be built in 6 phases. In order to arrive at an optimal network, we restrict our set of possible high-speed rail arcs in all phases to the set of high-speed arcs that were obtained in the optimal 20,000-mile network. We then solve our model sequentially for increasing values of L ($L = 500$, 1,000, ..., 20,000), ensuring that the arcs built for the previous value of L are selected for the current value of L. Therefore, although the complete network is optional, the solution for each phase may not be. The resulting implementation plan is illustrated in Figure 9.

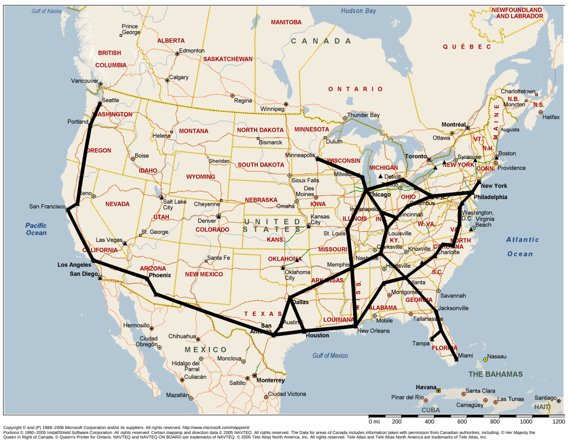
In the next section we analyze the sensitivity of the factors that determine capacity and freight transit times. Results from the uncapacitated model are referred to as "no cap. limit" in the next section's graphs. Also, because the uncapacitated and capacitated results are so similar, we only present the U.S. Census Data set in the next section's experiments.

(a) 500 Miles

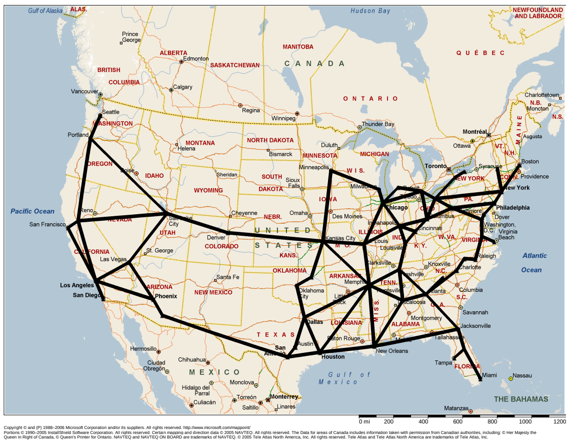
(b) 1,000 Miles

(c) 2,500 Miles

(d) 5,000 Miles



(e) 10,000 Miles



(f) 20,000 Miles

Figure 9: Implementation Plan

6.2 Capacity Analysis

We define capacity as a function of the speed, length, and weight limit of the high-speed vehicle. Because our freight data represents one year's worth of demand, we determine the number of tons per year that each high-speed arc is capable of transporting. To represent the total freight transported across the continental United States, we inflate our data sets to total yearly freight volumes by multiplying each *O-D* pair by a factor (i.e., 9.09 for the 53-city U.S. Census data, 36.60 for the 50-city J.B. Hunt network, and 18.43 for the 98-city J.B. Hunt network). We assume that the high-speed rail operates 24 hours a day, 7 days a week and we use an utilization factor, ρ, to adjust for capacity restrictions in the system. We vary the speed of the vehicle (s), distance between vehicles (ℓ), and weight limit(ω), in our analysis. The capacity of a high-speed arc is then calculated using (24), as shown below:

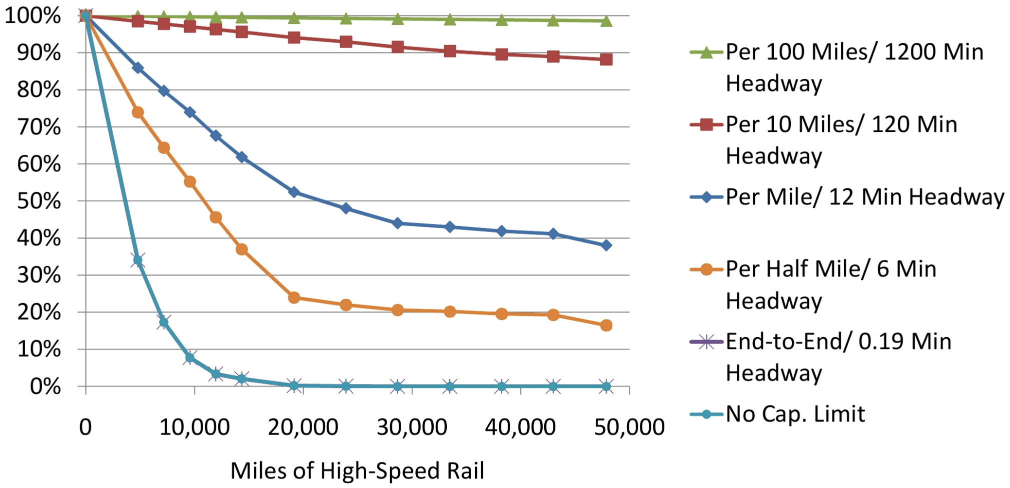
$$c_{ij} = \frac{s \text{ miles}}{\text{hour}} \times \frac{5280 \text{ feet}}{\text{mile}} \times \frac{24 \text{ hours}}{\text{day}} \times \frac{365 \text{ days}}{\text{year}} \times \frac{1 \text{ vehicle}}{\ell \text{ feet}} \times \frac{\omega \text{ tons}}{\text{vehicle}} \times \rho. \tag{24}$$

After talking to experts who have implemented and designed the only fully-operational Maglev system, Transrapid International [9], we are able to estimate the impact of a high-speed rail network using current technology parameters. The current average speed of the operational Maglev system is 110 mph and we reduce this value to 100 mph in our analysis. This reduction accounts for two, one hour delays for transfer times in a 2,000 mile trip. The experts believe that in order for a Maglev system to be viable for freight, the transfer times would need to be reduced to very short times (around 10 minutes or less) to ensure high utilization to justify the expensive infrastructure. We use the current weight limit of 67.24 tons per 81.5-foot vehicle [10] and a utilization factor of 0.80. We then vary the distance between vehicles in our analysis. A theoretical upper bound on capacity for a given speed and capacity limit would be to position vehicles end-to-end. This upper bound is not practically achievable, and therefore to represent a more realistic situation, we also analyze the capacity if the technology could support ℓ equal to 0.5 mile, 1 mile, 10 miles, or 100 miles.

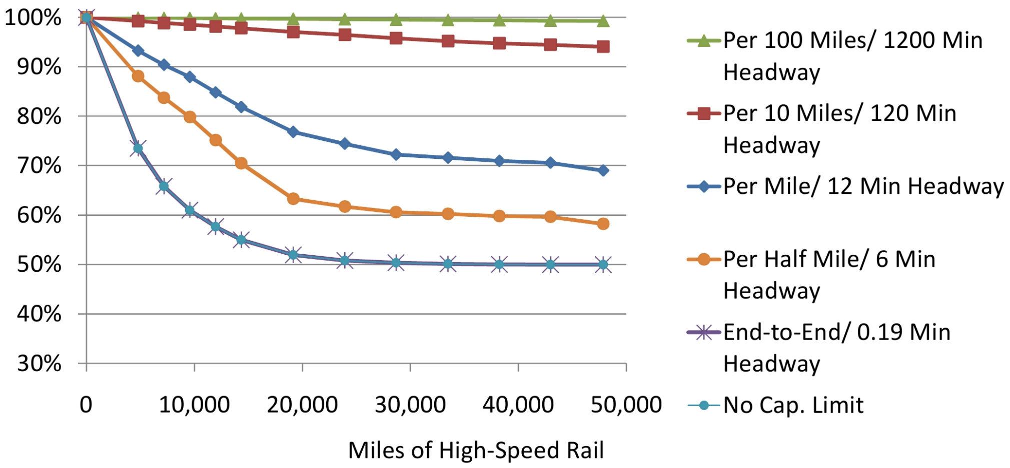
Headway, which is a terminology common in the train industry, denotes the time between head cars of a train. Therefore, the distance between vehicles can also be denoted in terms of headways. We assume that a train is composed of 20 cars and therefore ℓ equal to 0.5 miles is equivalent to a 6 minute headway. Feasibility studies have been conducted that a Maglev freight system could handle 20 car trains with 5 to 10 minute headways [9]. Looking at capacity from another perspective, ℓ equal to 1 mile is equivalent to a system with 1 car per mile. For example, a 2,000-mile network, would require 2000 cars. Similar calculations can be performed for various high-speed networks and distance-between-vehicles values.

Figure 10 illustrates the impact of a high-speed rail network on (a) the total truck miles and (b) the total travel time for various assumptions on ℓ. This figure also suggests that up to 20,000 miles of high-speed rail, the increase in high-speed rail miles provides significant reductions in total truck miles and total travel time. However, after 20,000 miles the marginal savings for each additional mile is low. In summary, in the case when high-speed vehicles can travel positioned end-to-end at the higher speed and weight limit, the high-speed network can be considered sufficient to handle today's freight volumes. However, since this is not achievable, capacity will always be a concern of a system with a limited budget. It should be noted that capacity could be increased by building multiple lanes of parallel high-speed rail but is not thought to be realistic with a limited budget.

Next, assuming that the technology will increase in the future in terms of speed and weight capacity, we examine the impact of high-speed rail utilizing future technology paramters. We use a v^H equal to 150 mph, which assumes an average high-speed velocity of 160 mph and accounts for two, one-half hour breaks in a 2,000 mile trip. We continue to assume a utilization factor of 0.80 and a weight limit of 67.24 tons [9]. In Figure 11, the allowable distance between each vehicle is varied and the impacts on highway congestion and travel time are shown. As technology improves, the potential benefits of a high-speed network increase.

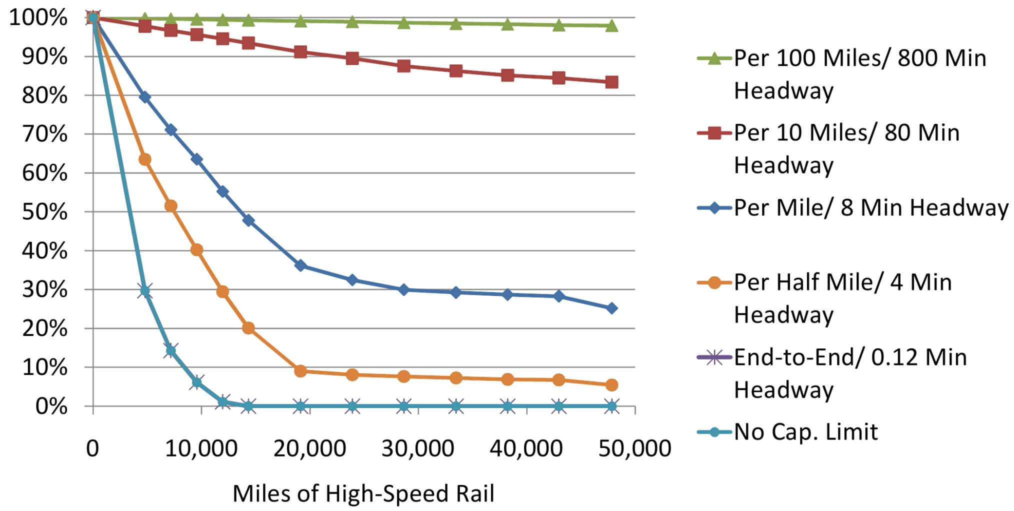


(a) Total Truck Miles

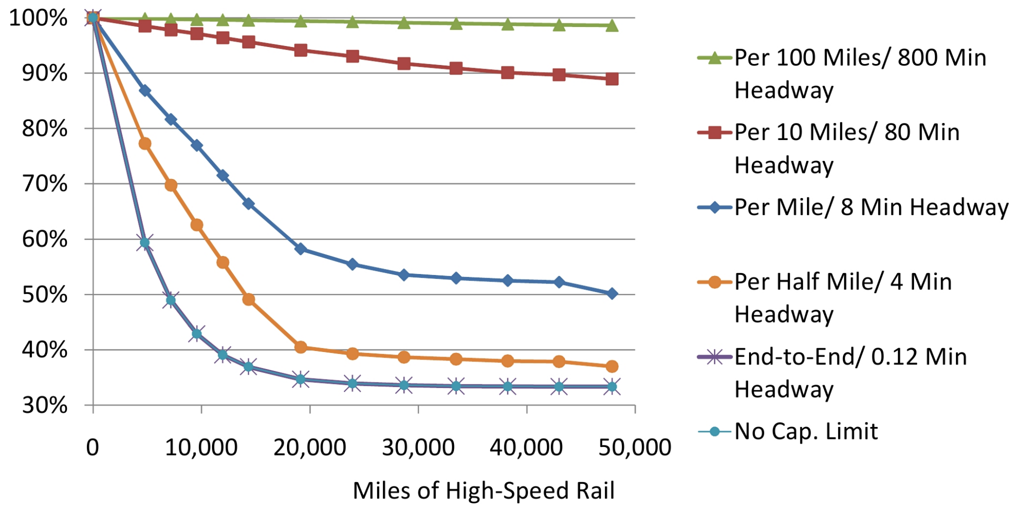


(b) Total Travel Time

Figure 10: A Traffic Load Story with the Current Average Speed and Weight Limit (U.S. Census Full Data Set)



(a) Total Truck Miles



(b) Total Travel Time

Figure 11: A Traffic Load Story with the Future Average Speed and Weight Limit (U.S. Census Full Data Set)

7. Conclusions & Future Research

In summary, we developed a model that takes into account a faster, but more expensive alternative to transport freight through a network by solving an uncapacitated network design problem. We then enforce capacity constraints in a post-processing step. Our model is capable of analyzing the effect of a high-speed network on the current highway system by evaluating performance measures on highway congestion and freight transit times. We improve the solvability of our uncapacitated network design formulation and reduce the solve time of a 30-city network by 97%. Representative data sets were applied to our model to illustrate the potential advantage of a national high-speed rail network for freight distribution.

It is clear that — with sufficient capacity — a high-speed network for freight distribution will have an impact on highway congestion and freight transit times and has the potential to address many of the challenges facing transportation today. However, providing adequate capacity in the high-speed rail system is a very challenging issue that will need to be addressed before the full benefits reported here can be realized on a national perspective. That said, if freight does indeed double as expected in the next 20 years, our current transportation infrastructure will not be able to handle the load. Therefore, even with limited capacity, high-speed rail may be the only feasible option.

As this research considered issues related to developing a high-speed rail network for freight distribution from a strategic perspective, future research should be conducted from tactical and operational perspectives. This includes focusing more on exact estimates of transfer times and capacities, as well as determining the logistics and actual implementation of such a system. Additionally, operational trade-offs should be explored, such as determining whether joining cars together like a traditional train or sending individual high-speed cars would be more cost beneficial. Operational questions, such as the following should be answered. Is there an optimal speed for a high-speed network? Is there an optimal headway? What is the best way to increase capacity in a network by adjusting headways? What is the best way to schedule freight and passenger cars given that both will likely utilize the network and will have different demands and peak hours? Also, further effort should be directed at improving the solvability of the uncapacitated network design problem to solve larger networks (i.e., our 98-city J.B. Hunt network that remains unsolved).

We examined the design of a high-speed rail network as a deterministic problem, whereas in reality, the existence of a high-speed rail network would itself affect and influence the demand around this technology. For example, companies may locate near the high-speed rail network and could change the business structures of transportation companies. Therefore, future research should examine a high-speed rail network taking into account dynamic and shifting demand structures.

High-speed rail should provide options and opportunities to expand our current national freight distribution and should not be thought of as a replacement for traditional railroads or highways, but instead as another mode of available transportation. It is our hope that this study will aid in the conversation about providing additional capacity in our nation's transportation network through high-speed rail.

References

[1] "2002 Economic Census Transportation: 2002 Commodity Flow Survey," Technical Report EC02TCF-US, U.S. Department of Transportation, Bureau of Transportation Statistics (2004).

[2] Anisimow, V., Wilson, J. R., Womack, W. C., Kaye, R. J., Akhil, A. A., Paananen, O. H., Covan, J. M., and Munoz, D., "Urban Maglev Technology Development Program: Colorado Maglev Project Final Report," Technical Report CO-26-7002, U.S. Department of Transportation, Federal Transit Administration (2004), http://www.dot.state.co.us/publications/maglev/maglevfinal.pdf.

[3] Balakrishnan, A., Magnanti, T. L., and Wong, R. T., "A Dual-Ascent Procedure for Large-scale Uncapicated Network Design," *Operations Research*, 37, 716–740 (1989).

[4] Bhaskaran, S., and Turnquist, M., "Mutliobjective Transportaiton Considerations in Multiple Facility Location," *Transportation Research Part A*, 24A, 139–148 (1900).

[5] Brewer, M., "Information Systems Manager, J.B. Hunt Transport, Inc.," (November 15, 2006), Personal Communication.

[6] Bruno, G., Gendreau, M., and Laporte, G., "A Heuristic for the Location of a Rapid Transit Line," *Computers & Operations Research*, 29, 1–12 (2002).

[7] Bruno, G., Ghiani, G., and Improta, G., "A Multi-Modal Approach to the Location of a Rapid Transit Line," *European Journal of Operational Research*, 104, 321–332 (1998).

[8] Bruno, G., and Laporte, G., "An Interactive Decision Support System for the Design of Rapid Public Transit Networks," *ABI/INFORM Complete*, 40, 2, 111–118 (2002).

[9] Budell, R., "Transrapid International, Berlin, Germany," (June 10, 2008), Personal Communication.

[10] "Build Maglev - Restore the National Transportation Grid," (1993), http://american_almanac.tripod.com/maglev2.htm.

[11] Carmichael, G. E., "It's Time for Interstate II," (1999), http://www.varprail.org/Interst2.htm.

[12] CNN, "Japan's Maglev Train Sets Record," (December 3, 2003), http://edition.cnn.com/2003/WORLD/asiapcf/east/12/03/japan.maglev.ap/.

[13] Costa, A., "A Survey on Benders Decomposition Applied to Fixed-Charge Network Design Problems," *Computers and Operations Research*, 32, 1429–1450 (2003).

[14] Crainic, T. G., "Service Network Design in Freight Transportation," *European Journal of Operational Research*, 122, 272–288 (2000).

[15] "FRA Website, Maglev Deployment Program description," (Retreived January 26, 2006), http://www.fra.dot.gov.

[16] "Freight Facts and Figures 2006," Technical Report FHWA-HOP-07-033, U.S. Department of Transportation (2006).

[17] "Future Needs of the U.S. Surface Transportation System," Technical Report ISBN: 978-1-56051-368-1, American Association of State Highway and Transportation Officials (2007).

[18] Gao, Z., Wu, J., and Sun, H., "Solution Algorithm for the Bi-Level Discrete Network Design Problem," *Transportation Research Part B*, 39, 479–495 (2005).

[19] Gilbert Laporte, Juan A. Mesa, F. A. O., "Optimization methods for the planning of rapid transit systems," *European Journal of Operational Research*, 122, 1–10 (2000).

[20] Kavinoky, J. F., "Condition of Our Nation's Infrastructure and Proposals for Needed Improvements," Testimony before the senate banking, housing and urban affairs committee, U.S. Chamber of Commerce (2008).

[21] Magnanti, T., and Wong, R., "Network Design and Transportation Planning: Models and Algorithms," *Transportation Science*, 18, 1–55 (1984).

[22] "National Economic Accounts: Current-dollar and "Real" GDP," (Retreived April 7, 2008), `http://www.bea.gov/national/index.htm#gdp`.

[23] "National Policy and Strategies Can Help Improve Freight Mobility," A Report to the Ranking Member, Committee on Environment and Public Works, U.S. Senate GAO-08-287, United States Goverment Accountability Office (2008).

[24] "National Cooperative Highway Research Program Report 586: Rail Freight Solutions to Roadway Congestion, Final Report and Guidebook," Technical report, Transportation Research Board of the National Academies (2007).

[25] Okumura, F., and Hashimoto, S., "Railway Technical Research Institute (RTRI) Maglev System Development Department Yamanashi Maglev Test Line," (1996), `http://www.wtec.org/loyola/scpa/09_12.htm`.

[26] "The Pennsylvania Project: High Speed Maglev," (Retreived April 7, 2008), `http://www.maglevpa.com/index.html`.

[27] Pott, C., "How a Critical Commerce Corridors Program Will Improve the Performance of Our Transportation System," Testimony before the national surface transportation and policy revenue study commission, American Road and Transportation Builders Association (2007).

[28] Potts, C., "America's Transportation Network: Developing the Vision for Tomorrow," *Better Roads*, 77, 3, 36–42 (2007).

[29] Quain, J., "Fast Track," *Popular Mechanics*, 184, 89–93 (2007).

[30] Quentin Wan, Hong Lo, C.-W. Y., "Optimal Integrated Transit Network Design," In *Applications of Advanced Technology in Transportation: Proceedings of the Seventh*

International Conference on Applications of Advanced Technology in Transportation, volume 7, 7, 736–743 (2002).

[31] "Railway Technical Research Institute (RTRI) Website, Tokyo, Japan," (February 2, 2004), `http://www.rtri.or.jp/rd/maglev/html/english/maglev_frame_E.html`.

[32] *Rand McNally 2000 Road Atlas: United States, Canada, Mexico*, Rand McNally (2000), ISBN:9780528841262.

[33] "Southern California Association of Governments Maglev Deployment Program: Refined Cost Estimates," Technical report, Lockheed Martin - Integrated Systems and Solutions and IBI Group (2006).

[34] "Transportation Invest in Our Future: America's Freight Challenge," Technical Report ISBN: 978-1-56051-372-8, American Association of State Highway and Transportation Officials (2007).

[35] "United States Department of Transportation Report on Highway Congestion," (February 3, 2002), `http://www.dot.gov/PerfPlan2004/mobility_congestion.html`.

[36] U.S. Department of Transportation, F. R. A., "Report to Congress: Costs and Benefits of Magnetic Levitation," (2005), `http://www.fra.dot.gov/downloads/RRdev/maglev-sep05.pdf`.

[37] "Vision 2050: An Integrated National Transportation System," Technical report, The Federal Transportation Advisory Group (2001), available at http://scitech.dot.gov.

[38] Wen, U.-P., and Hsu, S.-T., "Linear Bi-level Programming Problems A Review," *Operations Research Society*, 42, 125–133 (1991).

[39] Wieberneit, N., "Service Network Design for Freight Transportation: A Review," *OR Spectrum* (2007).

[40] Yang, H., and Bell, M., "Models and Algorithms for Road Network Design: A Review and Some New Developments," *Transport Reviews*, 18, 257–278 (1998).