A Model to Design a National Maglev Network for Freight Distribution

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ABSTRACT: Maglev technology 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 Maglev technology, the potential exists for developing a national Maglev network for freight distribution. In this paper we report on an optimization-based approach to determine where to add Maglev arcs in the United States, given budget constraints and freight demands. This is modeled as an uncapacitated network design problem to set the network and then a post-processing step is used to determine which freight will utilize the network for a given capacity constraint. An economic argument based on transit times is used to make this determination. As performance measures, we calculate the reduced transit times for freight as well as the resulting reduction in freight traffic on the highway network. We have applied our models with data from the U.S. Census Commodity Flow Survey 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

The United States has a significant problem with highway congestion, with billions of dollars per year in lost productivity, stalled cargo, or wasted fuel associated with this congestion [10]. 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 [5], 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 [7], and commercial truck travel has doubled over the past two decades [5]. In addition, it is predicted that the number of cars and trucks on the road will quadruple by the year 2050 [12] and freight will double in volume over the next 20 years [7]. It is also anticipated that 82% of those shipments will travel over a road [7]. Over the last 30 years, 550% more truck traffic miles were logged annually while lane miles of roadways have increased by only 6% [7].

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 Maglev network for freight distribution. In addition to reducing congestion on our highways, a Maglev freight network 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.

Because truck traffic is often concentrated on major routes connecting population centers, ports, border crossings, and other major hubs of activity [4], Maglev systems are potentially an attractive alternative to reduce congestion on the nation's highway system. In fact, technology feasibility tests have indicated that Maglev systems have the potential to move freight approximately two to three times faster than freight distributed via the nation's highways. With speeds expected to increase in the future, we ask, why not explore the potential benefits of Maglev 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.

It is clear that if it is economically viable and technologically feasible to build a Maglev 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 freight transportation times and truck highway miles reduction on the new, hybrid network. Also, less clear is whether a system of Maglev lines (point to point) or an integrated network would be more efficient.

2 PROBLEM STATEMENT

The objective of this research is to explore the impact of creating a Maglev network for freight distribution. Utilizing the results of Maglev technology feasibility testing, we address constructing the most efficient Maglev 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 Maglev infrastructure, it would not be economically feasible to build a Maglev 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 Maglev be added in parallel?

We model the development of a Maglev 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 directly connected cities. These cities were chosen to represent a national network based on their involvement in today's freight market. Parameters to the model include an arc-based distance matrix, an origin-destination flow matrix, average velocities for truck and Maglev, 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 [8]. The flow matrix that represents the amount of freight that is shipped between origin-destination pairs (O-D pairs) is assumed to be a fixed, deterministic value. The average velocities for truck and Maglev travel are assumed to be a constant values, and we did not model the congestion in and around metropolitan areas. We use total miles of Maglev built as a surrogate for costs in our budget constraint. In order to compare a Maglev system to the current interstate highway system when displaying results we assume one mile of Maglev is equal to two tracks allowing for travel in both directions. Because Maglev 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.

After Maglev arcs are added to our network, we analyze the impact these additional Maglev 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 Maglev arcs lead to a reduction in freight transit times and the resulting amount of truck traffic, 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 Maglev 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-benefit analysis when deciding if freight will utilize the Maglev 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 Maglev network is not feasible when the network is free to use, then it will definitely not be when we incorporate user costs. Finally, we compare different Maglev networks in terms of the miles of truck travel on the highway and the total travel time.

For more details on the mathematical modeling of this problem, please see [6].

3 CONTINENTAL UNITED STATES APPLICATION

3.1 Data

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 a representative data set of freight flow between O-D pairs in the continental United States from the 2002 Commodity Flow Survey [1]. The 2002 Commodity Flow Survey is undertaken through a partnership between the U.S. Bureau of the Census, the U.S. Department of Commerce, the U.S. 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 O-D pair data was provided in terms of tons of shipments.

3.2 Results

We analyze our models to determine the impact of adding Maglev arcs to the current highway system by comparing the following two performance measures on various Maglev networks:

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

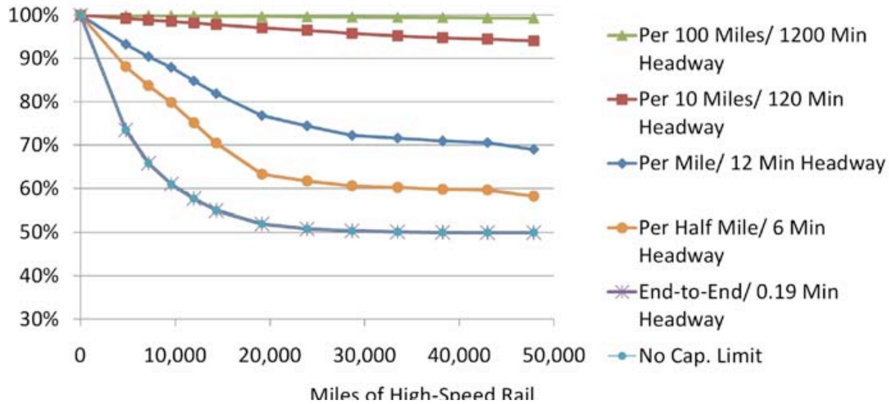
2. Total Truck Miles: the total number of miles traveled by trucks on the current highway system to transport all freight across the network.

After talking to experts who have implemented and designed the only fully-operational Maglev system, Transrapid International [3], 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 [3] 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 the distance between vehicles 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 if the distance between vehicles is equal to 0.5 miles, this is equivalent to 6-minute headways. Feasibility studies have been conducted that a Maglev freight system could handle 20 car trains with 5 to 10-minute headways [2].

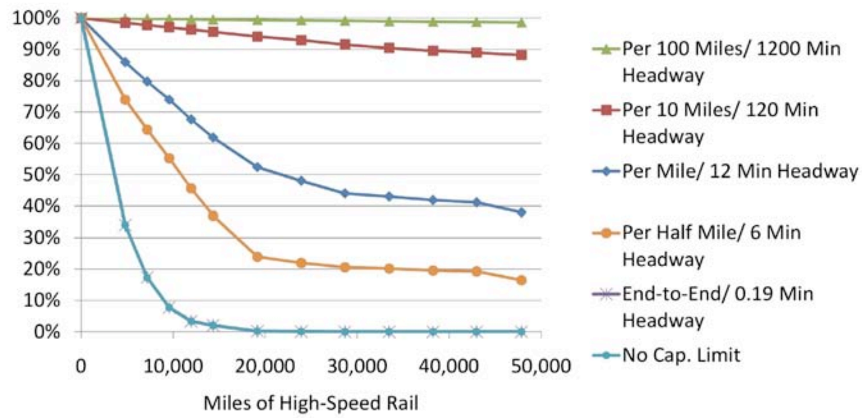
Figure 1 illustrates the impact of a Maglev network on (a) the total travel time and (b) the total truck miles for various headway assumptions. For example, a 20,000-mile network with 6-minute headways would lead to an estimated 38% reduction in overall freight transit times. And perhaps more importantly to the public, would precipitate a net 78% decrease in the annual total truck highway miles driven. This figure also suggests that up to 20,000 miles of Maglev, the increase in Maglev 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. Also, in the case when Maglev vehicles can travel positioned end-to-end at the higher speed and weight limit, the Maglev 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 Maglev tracks 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 Maglev utilizing future technology parameters. We input a Maglev velocity equal to 150 mph, which assumes an average Maglev velocity of 160 mph and accounts for two, 30-minute 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 [2]. In Figure 2, 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 Maglev network increase. For example, a 20,000-mile network with 6-minute headways reduces the total travel time by 60%, and the total truck miles on the highway by over 90%.

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 Maglev miles built (i.e., 500, 1,000, … 20,000), ensuring that the arcs built for the previous value of Maglev miles

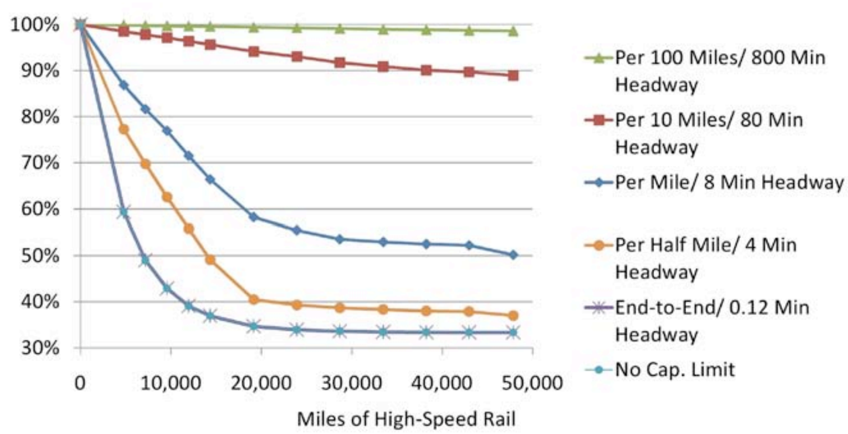


(a) Total Travel Time



(b) Total Truck Miles

Figure 1: A Traffic Load Story with the Current Average Speed and Weight Limit



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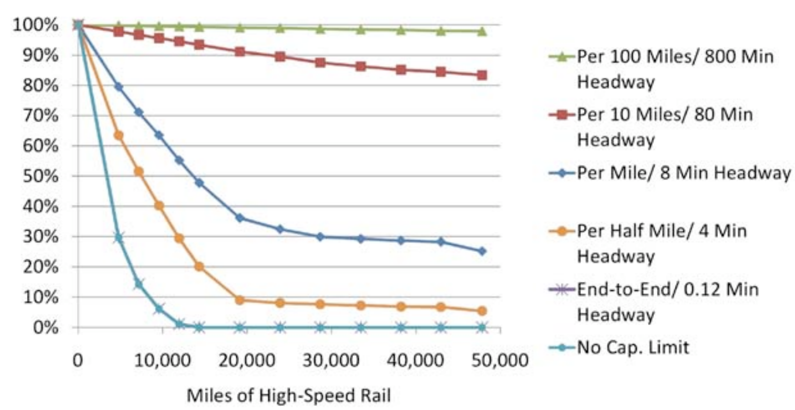

(b) Total Truck Miles

Figure 2: A Traffic Load Story with the Future Average Speed and Weight Limit

(a) 500 Miles

(b) 1,000 Miles

(c) 2,500 Miles

(d) 5,000 Miles

(e) 10,000 Miles

(f) 20,000 Miles

Figure 3: Implementation Plan

are selected for the current value. Therefore, although the complete network is optimal, the solution for each phase may not. Detailed cost estimation and analysis is beyond the scope of this research, yet we acknowledge that there is a significant cost component associated with this technology. For example, if we use the Los Angeles estimates ($140M per mile), a 20,000-mile Maglev system would cost $2.8T [9]. The resulting implementation plan is illustrated in Figure 3.

4 CONCLUSIONS

It is clear that, with sufficient capacity, a Maglev network for freight distribution would have an important impact on freight transit times and, as a result, reduced highway congestion, having the potential to address many of the challenges facing transportation today. For example, a 20,000 mile network utilizing current speed and weight limitations with 6-minute headways 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. However, providing adequate capacity and investment in the Maglev 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, a Maglev network may be the only feasible option.

A Maglev system 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 Maglev technology.

5 REFERENCES

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