Northeast Corridor Mass Transportation System Analysis

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Abstract—This paper addresses the need for a high-speed rail improvement between the Washington DC metro region and the New York City metro region. This need for improved transit infrastructure is increasingly urgent, due to the growing backlog of critical infrastructure projects along the Northeast Corridor. This problem limits the ability of currently available mass transportation systems to meet the demand for high speed transportation. To address this need, a cost-to-benefits analysis has been conducted on Maglev, a new Acela fleet, and a new High-speed rail system. Based on this analysis, the team has recommended the new Acela fleet for the Northeast Corridor.

INTRODUCTION

In 19th century, the United States of America (USA) led the revolution on highway construction and expansion of the aviation industry. However, the United States is currently lagging behind in key aspects of mass transportation, such as high-speed rail. In addition, the overall transportation infrastructure is no longer competitive and needs up to $302 billion for repair [1].

This project addresses this critical need of the country by focusing its scope on the Northeast Corridor (NEC), which is the busiest rail corridor in the USA [2]. The NEC intercity transportation infrastructure is currently at or near capacity for all high-speed transit options, and is therefore no longer responding to the growing population need. Travel along the Northeast Corridor (Washington DC to New York City) is limited to four main options: Bus, Train, Car, and Plane. Of these four options, only Plane and Train offer high-speed intercity transit. Between these two travel options, the total number of available high-speed transit seats has been decreasing over the past decade. At the same time, the NEC population has continued to grow by approximately 2.5% annually. These two metrics (Available High-Speed Seats & Population) suggest that the NEC is currently moving towards a future where high-speed travel will be too saturated and/or expensive for the greater NEC population by 2030 (Figure 1) [3] [4].

Figure 1. Available High-Speed Seats and Moveable Population

The decrease in available high-speed passenger seats is largely attributable to the decreasing size of airplanes operating along the route. This reduced plane size is especially concerning, considering that the average load factor has been increasing during this time.

This project aims to identify a cost-effective design alternative that will provide additional high-speed transit capacity for the Northeast Corridor.

PROBLEM AND NEED STATEMENT

The current high-speed transportation options on the Northeast Corridor, air, automobile, and rail, are struggling to provide reliable high-speed intercity transit. Available air travel capacity is being artificially restricted, while rail travel still lags behind air in terms of speed and travel time. Therefore, there is a need for high-speed transportation along the Northeast Corridor.

STATEMENT OF WORK

To address the need for high-speed transportation on the northeast corridor, the team analyzed the limitations of the current transportation systems and evaluated different high-speed future design alternatives. The team examined the existing Air, Rail, and Automobile transit modes, and we explored three new design alternatives: New High-Speed Rail (HSR), Maglev, & Improved Acela Express (Amtrak). Table 1 shows the requirements set to achieve for each design alternative.
<table>
<thead>
<tr>
<th>Req. ID</th>
<th>Requirement Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>The System shall Operate at or below 70% Capacity.</td>
</tr>
<tr>
<td>2</td>
<td>The system shall deliver passengers in 90 minutes.</td>
</tr>
<tr>
<td>3</td>
<td>The system shall adhere to federal transportation regulation set by the Department of Transportation (DOT).</td>
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</tbody>
</table>

Table 1. System Requirements

STAKEHOLDERS

The main stakeholders for the new transit system are the passengers, corridor population, competitors, regulatory agencies and the government. All of the stakeholders (Figures 2 & 3) are affected by the new transit system.

DESIGN ALTERNATIVES

There are three design alternatives in this project, as well as a no-build alternative. These design alternatives consist of evaluating Acela’s new fleet, foreign high-speed rails, and Maglev. Throughout the world, HSR technology has had half a century to mature and HSR systems are currently in operation in many countries. The first HSR began operation in 1964. In contrast, Maglev represents a newer technology which is still under development and still requires empirical evidence on safety and operation cost. The first Maglev train was inaugurated in 2002 and started a commercial operation in 2003.

For each of the three alternatives, a specific trainset was chosen for study. The French Alstom trainset was chosen for Acela, ICE3 trainset for wheel-on-rail high-speed design, and the electromagnetic suspension system for Maglev. The French Alstom train, also known as Avelia liberty, is capable of traveling up to 350 km/h (217 mph) and is 15% lighter than current Acela Trainset. For its operation on the NEC, Avelia Liberty will run at 160 mph. The Maglev design is capable of traveling up to 450 km/h (280 mph) and is, by far, the fastest train around the world.

The first design alternative we consider is an all-new high-speed rail trainset and track. There are many models of high-speed trains around the globe, but for the purpose of this study we narrow our scope to the German ICE 3 trainset. First introduced in 2000, this trainset has seen many variations, some under the name ICE 3 and some under the name Velaro. This study considered the variation known as Velaro D. The maximum speed of this trainset is 300 km/h (186 mph) and uses advanced three-phase asynchronous motors designed without wearing parts. Moreover, the Velaro D rolling stock has earned a reputation of reliability, dependability, energy-efficiency, and safety [5]. The team estimated that for every mile on the NEC, it would cost $164 million per mile with a total capital
cost of $37 billion and a yearly operation cost of $570 million.

The second design alternative is to build a Maglev (Magnetic Levitation) train and track that would operate separately from all the rail on the corridor. There are two main technologies of Maglev such as the Electromagnetic Suspension technology (EMS) developed by Germany and the Electrodynamic Suspension technology (EDS) developed by Japan. Thus far, the team has focused on EMS because of limited availability of reliable data sources for EDS technology implementation. The EMS is electronically controlled electromagnets, and it is magnetically conductive (usually steel) track. Moreover, the onboard suspension that is placed under the track is energized to generate the electromagnetic field through the mutual attraction between the electromagnet and the vehicle is suspended on the rail. In order to implement this, the capital cost is estimated at $64 billion with $282 million per mile cost and with an operating cost of $460 million.

As of April 2018, the Baltimore-Washington Superconducting Maglev Project (BWSMP) is working with the Federal Railway Administration as well as the Maryland Department of Transportation to develop a plan to implement Maglev on the Northeast Corridor. Unfortunately, this plan only extends from Washington DC to Baltimore and for this project, the scope extends between DC-NYC.

The third alternative is to build a new high-speed rail line and populate it with Amtrak’s new Acela Express fleet (dubbed the Avelia Liberty). This fleet has already been commissioned and is expected to be in service starting 2021. The current Acela fleet has been in service since 2000. During the lifetime of this fleet, there have been several issues with the safety and performance of the design. The new Acela Fleet promises substantial upgrades to both capacity and top speed, but the manufacturer has not published expected travel times for the new trainset.

All three design alternatives are environmentally friendly compared to other modes of transportation considered in this study (Air and Automobile). They pollute 3 to 10 times less CO₂ than automobiles and take about 3.5 times less land than automobile road networks. HSR and Acela’s land consumption at grade is about 16 m² whereas Maglev land consumption is 11.5 m². Furthermore, Maglev trains consume less energy and produce less CO₂ pollutants than high-speed rail from speed of 200 km/h (Breimeier, 2004) [6].

The train must perform its functions in routine circumstances as well as unexpected circumstances with little variation performance. HSR is supported by a mechanical system and its support can be maintained in case of power outage. For weather conditions, such as strong winds do not have great impact on Maglev system since Maglev system wraps around its guide way.

Safety is one of the major concerns when passengers choose a mode of transportation. For maglev system, it is technically impossible for it to collide with another maglev train since only one train can be in each drive control zone. Also, for HSR, a collision of two high-speed trains is extremely improbable due to advanced control system that are designed specifically to prevent such incidents.

The cost of these alternatives described above are the results of many studies from different authors and base on capital cost from Florida and California High Speed Rail projects. Based on this research outlined above, one can observe that it costs more to implement HSR or Maglev system than to improve the current Amtrak system.

**UTILITY ANALYSIS**

This utility involves measuring the performance of Avelia Liberty Trainset built by the French Alstom, ICE 3 train built by Siemens, and Maglev EMS technology developed by Germany. The evaluation of these trains is based on the manufacture published documents, research done by variety of authors and the input from the project sponsor. Although, the Maglev train has different type of travel speed ranging from 300 – 450 km/h (186 - 280 mph), only Maglev with a speed of 450 km/h (280 mph) will be considered. The team on this project considers that choosing a Maglev system with the same speed as that of HSR will not be a fair comparison. This utility function considers 7 categories that are evaluated based on 27 characteristics as shown in below Table 2.

Based on stakeholders and sponsors of this project consideration, the 7 categories and the 27 characteristics were identified, and they represent an exhaustive list of what should be considered in system design evaluation.

The Georgia Tech study by Dominik Ziemke [6], was the primary foundation in developing these weighting factors. Ziemke has conducted survey with variety of organizations concerned with high-speed rails such as associations and agencies, engineering and consulting firms, and national agencies. Finally, the utility is calculated based on the survey results from these agencies and the use of multi-criteria decision-making approach where the weighting factors are then combined with the benefit values based on each train performance.
Table 2: Utility Function Characteristics

Based on survey data from the study, average importance was developed for each criteria and the weighting factor was calculated by dividing system average importance by the total sum of average importance. By multiplying attribute utility values that was found earlier by the weight factor, the overall utility of the system is found.

The utility value for each category is shown below in a hierarchy diagram.

![Utility Hierarchy](image)

Figure 4. Utility Hierarchy

The Utility vs. Cost graph in Figure 5 shows that high-speed rail has the highest utility followed by Acela and Maglev. However, since cost is an important factor when choosing an alternative, the highest capital cost of Maglev ($64 billion) and its system maturity inferiority makes it an unattractive choice. The next highest utility over the cost alternative is Acela with 0.031 for it marginal utility. The next highest utility over the cost alternative is the high-speed rail with utility over cost of 0.021. Since Acela has the highest utility over the cost, the recommended system is Acela.

![Utility vs. Cost](image)

Figure 5: Utility vs. Cost

METHOD OF ANALYSIS AND RESULTS

To calculate the frequency of service and overall capacity needed from a new rail system and assess how it responds to increasing demand due to population growth, the team designed a simulation program that consists of three parts. The first part of the simulation was programmed using Java and modeled the usage of current intercity transit modes based on passenger choice. The second part of the simulation received passenger demand as an input and modeled the frequency of service of each design alternative. The third part received frequency of service as an input and modeled the system capacity of each design alternative.

Each part of the simulation was calculated for each design alternative considered. Since listing each result is beyond the scope of this paper, this section will focus on results specific to the new Acela system. To achieve the original simulation assessment goal, simulation requirements were developed and are listed in Table 3.

<table>
<thead>
<tr>
<th>Req. ID</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>The simulation shall compute the demand for automobile, rail, and plane travel along the Northeast Corridor.</td>
</tr>
<tr>
<td>2</td>
<td>The simulation shall simulate travel along the rail system until the predicted demand has been met or there is no additional capacity available during the unit time along the route.</td>
</tr>
<tr>
<td>3</td>
<td>The simulation shall simulate frequency of service and capacity of the recommended rail system.</td>
</tr>
</tbody>
</table>

Table 3: Simulation Requirements

In the first part of the simulation, passenger demand is predicted using a multinomial logit model. The utilities for this model are taken from research that was previously conducted by Moeckel et al. and published by the Transportation Letters [7]. These utility functions consider in-vehicle travel time, out-of vehicle travel time, and cost of trip. Passengers are modeled as having one of three reasons for traveling (business, personal, or commute), and their likelihood of picking a mode is dependent on a weights matrix associated with each trip purpose that encompasses each of the aforementioned mode specific variables. With this model, the team simulated each design alternative to get projections of ridership.

Part 1 receives NEC travel population and year as input and produces demand for each mode of transportation considered. Of the variables considered, expected travel time, travel time within the origin and destination city, driver’s license status, trip purpose, and origin-destination city pairs were varied.
Variables that remained static were cost to travel, distance between city pairs, and expected in-vehicle travel time along interstate highways, train tracks, and plane routes. This process is simplified and shown in Figure 6, where Amtrak is defined as the new Acela system.

In the second part of the simulation, Amtrak’s projected growth from its daily demand of passengers is taken into consideration. Each design alternative was simulated to determine the system capacity and the projected growth of ridership on the corridor.

For the projected growth starting at year 1 of operation of the new Acela system, a conservative yearly ridership of 12 million was used to calculate this projection throughout the system life-cycle of 50 years with 3% annual growth derived for the NEC population growth estimation.

The daily frequency of service chosen for this simulation is 18 hours a day (6 am – 12 am). MATLAB was used to calculate the frequency of service as the population growth to meet the predicted demand.

The number of seats and the size of each train was assumed to remain constant throughout the system life-cycle.

Once the frequency of service was calculated in part 2, it was used as an input to calculate the expected system capacities. These are the daily and yearly capacity of our system, which are defined as the number of trains needed for operation, and the potential growth projection. The system output then is used to calculate the economic feasibility of the design alternative chosen.

To achieve the remainder of this simulation’s objective, the actual number of passengers that were able to be transported was calculated based on frequency of service, expected demand, and system capacity. “Passenger transported” was represented as a binary value that aims to represent whether a passenger was transported based on three independent variables, which are calculated during Parts 1, 2, and 3 of the simulation. This equation is listed below:

\[
\text{Passenger Transported} = \text{Mode Choice} \times \text{Frequency of Service} \times \text{System Capacity}
\]

After “passenger transported” was calculated for each passenger, the total number of passengers moved via rail was incremented and stored using the equation below.

\[
\text{total passengers transported} = \sum \text{(passenger transported)}
\]

COST AND BREAK-EVEN ANALYSIS

In order to evaluate the cost and the break-even point, first, the team has evaluated the railway market on the NEC and its future ridership forecast through Java simulation. Lastly, MATLAB code was constructed to generate break-even point of each design. This analysis used the inputs from the Java simulation and the cost break down of each design alternative.

The rail market evaluation from our Java simulation estimates that the demand for the new Acela system will grow from 3 million annually to 18 million passengers annually. The current average round trip from DC - NY is estimated at $193, but for our cost analysis simulation, this cost is set at $200. For the 50 years life-cycle of the system, a 4% interest value of money was set which is derived from the California Rail project. Using, the Net Present Value calculation, and the annual equivalence the present graph shown in Figure 10 was generated.
This figure shows that, with a capital cost of $25 billion, and annual operating cost of $570 million, the system will reach a break-even point in year 1 of operation.

Using the same ridership cost, interest rate and population demand of 18 million for the other alternative design, the HSR which has a $37 billion capital, and maglev capital cost of $64 billion have a different break-even point of 18 years and 44 years respectively.

**VERIFICATION AND VALIDATION**

The testing of the mission requirements was done via simulation and inspection of the design alternatives. This testing procedure is outlined below.

<table>
<thead>
<tr>
<th>M.R. ID</th>
<th>Measurement</th>
<th>Test Procedure</th>
<th>Pass/Fail Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>MR. 1</td>
<td>Comparison of Actual Simulation Result to Upper</td>
<td>Vehicle capacity is simulated over time.</td>
<td>Capacity &lt; 70%</td>
</tr>
<tr>
<td></td>
<td>Bounds (70% Capacity)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MR. 2</td>
<td>Comparison of Actual Result to Upper Bound (90)</td>
<td>In-vehicle travel time is calculated using</td>
<td>Passenger Travel Time &lt;= 90 minutes</td>
</tr>
<tr>
<td></td>
<td></td>
<td>simulation.</td>
<td></td>
</tr>
<tr>
<td>MR. 3</td>
<td>Comparison of Actual result to regulations</td>
<td>Analyze the proposed system design to see that</td>
<td>Federal transportation regulations are met</td>
</tr>
<tr>
<td></td>
<td></td>
<td>regulatory requirements are fulfilled.</td>
<td></td>
</tr>
</tbody>
</table>

**Table 4. Mission Requirements**

Of these design alternatives, only the new Acela fleet met all specified requirements and is therefore the only design alternative that can be verified.

The simulation was tested via analysis. The test procedure is outlined in Table 5.

<table>
<thead>
<tr>
<th>Req. ID</th>
<th>Eval Type</th>
<th>Test Procedure</th>
<th>Pass/Fail Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Analysis</td>
<td>Compare the amount of demand for each system from the</td>
<td>Comparison should be a 95% match.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>simulation with the historical data.</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Analysis</td>
<td>Compare the predicted demand to the estimated system</td>
<td>Predicted Demand &lt;= Capacity</td>
</tr>
<tr>
<td></td>
<td></td>
<td>capacity.</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Analysis</td>
<td>Compare the minimum headway time requirement and</td>
<td>Min simulated time &gt;= min safe time of 5 min</td>
</tr>
<tr>
<td></td>
<td></td>
<td>route capacity of the rail system.</td>
<td></td>
</tr>
</tbody>
</table>

**Table 5. Mission Requirement Test Plan**

To verify the simulation results from part 1, the team used historical demand data for each mode of transportation. In the below figure, historical demand data for transportation along the NEC is shown in Figure 11 while the simulation output is shown in Figure 12. Because the simulation output matched the historical demand data within 5%, the predicted demand did not exceed available capacity, and the frequency of service did not exceed safety standards, the simulation was able to be verified. Therefore, the team proceeded to use this simulation to predict demand for each design alternative considered.
For the simulation validation, the team used the current Acela ridership and its frequency of service. With these inputs, MATLAB generated a yearly passenger moved along the new Acela system of 3,219,300 for a load factor of 70% and a yearly passenger of 3,449,250 for a load factor of 75%. Comparing these with the historical data of 3,489,311 under the average load factor of 69% from Acela, it can be concluded that the approach taking for this calculation is accurate. Validation was achieved via testing and debugging of the simulation. Extensive tests were run on all three parts of the simulation to ensure accurate results.

RESULTS AND CONCLUSIONS

The economic health of the NEC is directly tied to its transportation system. The present research is devoted to evaluating the critical infrastructure needs of this system so that a mitigation plan may be recommended. The research is twofold: an analysis of the current transit alternatives and infrastructure as well as a cost-benefit analysis of the proposed design alternatives (Maglev, HSR, Acela). From this research, the team proposes an improvement to the existing high-speed rail travel alternative (Acela Express). This design alternative is expected to be able to meet the transit capacity needed to ensure continued operation of the Northeast Corridor transportation system while effectively minimizing cost as shown in the simulation.

The simulation shows that a new Acela system will alleviate congestion from both automobile and air transportation. This means that demand for this new Acela system is expected to increase significantly. The team has noted that this increase is likely an overestimation. This could be because the travel time for a new Acela system is greatly reduced by 42%. The other transportation options that are currently available take about 3 to 4 hours or more to travel from DC to NYC. Weights taken from the research conducted by Moeckel et al. suggest that travel time is one of the most important factors when a passenger considers a mode of transportation [7].

Because the frequency of service needed to meet demand was below the new Acela system capacity, the team concluded that all simulated passengers who demanded transportation via the new Acela system are theoretically able to be transported.

ACKNOWLEDGMENTS

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REFERENCES


