Cambridge Grand Junction Transit Implementation: Alternatives, Scheduling, Cost, and Performance

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Submitted to the Department of Civil and Environmental Engineering in Partial Fulfillment of the Requirements for the Degree of

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ABSTRACT

The Grand Junction railroad lies at the heart of East Cambridge adjacent to the Kendall Square business district and the Massachusetts Institute of Technology campus. Over the last one hundred years the railroad has gone through substantial changes – from an important freight corridor to having just a few train movements per day. The recent purchase of the railroad by the Commonwealth of Massachusetts, planned relocations of existing freight yards, and future corridor improvements have made it possible to consider the addition of passenger services on the Grand Junction. Rising employment, population, and the congestion of the existing commuter rail facilities necessitate exploration of existing means to alleviate capacity.

This study is part of larger study that explores the addition of passenger transit services on the Grand Junction with the goal of increasing frequency and capacity to the west along the Worcester/Framingham main line. The topics of this paper are service alternatives, scheduling, cost and performance. The study outlines all possible alternatives that are then screened for final analysis. Commuter rail and diesel multiple unit (DMU) services are the alternatives quantitatively analyzed. A schedule model estimates the maximum frequency, based on existing constraints, to be five trains per hour. Marginal cost modeling shows that based on estimated demand levels, DMU trains may be a more financially viable option for Grand Junction service. This conclusion is backed up by performance comparison of DMUs and commuter trains, showing that DMUs in the configurations proposed are quieter, more fuel efficient, and would likely have a smaller traffic impact along the densely populated Grand Junction corridor. A substantial and detailed study of DMU service along the Grand Junction is recommended.

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1 Introduction

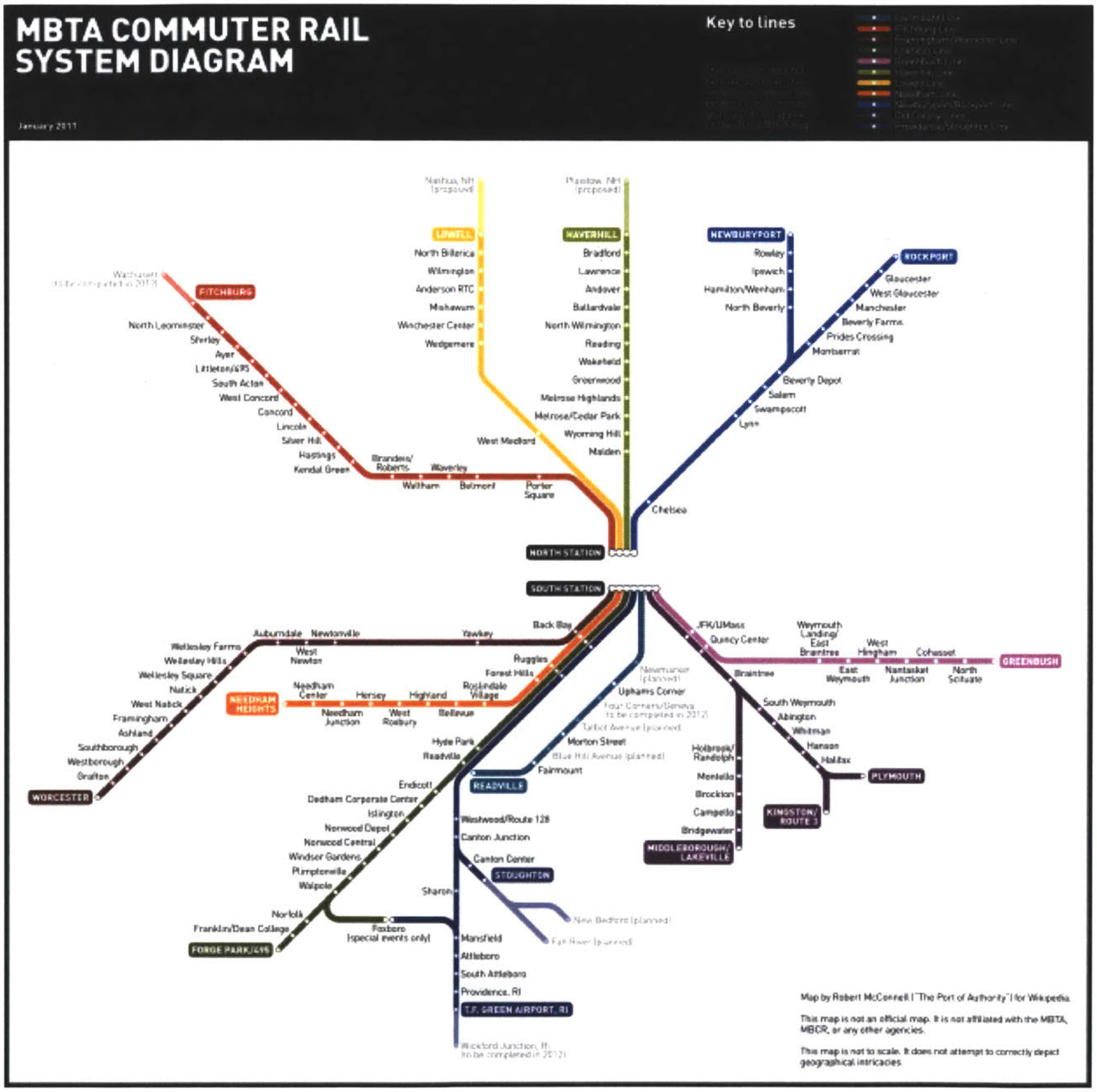
The Boston metropolitan area has one of the oldest and largest public transportation systems in the United States, operated by the Massachusetts Bay Transportation Authority (MBTA). Part of this system is the regional commuter rail network, operated under contract to the MBTA by the privately-held Massachusetts Bay Commuter Railroad Company (MBCR). The commuter rail network is made up of almost 400 miles of rail track on 11 separate lines, bringing close to 55,000 passengers daily into downtown Boston (Central Transportation Planning Staff, 2010). Four of the commuter rail lines terminate at North Station and seven terminate at South Station, as seen in the system map below. With an increase in population, development, job growth, and urbanization expected in the future, ridership on all transit will inevitably increase. Increasing commuter rail transit capacity to meet these future needs can be done by expanding the capacity of existing stations or making efficient use of existing infrastructure.

Expansion of the large downtown stations, namely South Station, is likely to be a capital intensive and lengthy project. Moreover constraints at Back Bay often cause additional delays for trains to and from the west, so that even improvements at South Station beyond those required for Amtrak, the Fairmount Line, Old Colony Line, and other southern lines may not provide additional capacity for trains to Worcester and points west. This study examines the possibility of improving commuter rail service to the west by using the available infrastructure as a short term alternative to terminal station expansion and a long term complement to such expansions.

One shortfall of the commuter rail network that can be seen by looking at the map in Figure 1 is the lack of a north-south connector – the network is essentially two separate systems, one for the north and one for the south.. Passengers that begin their trips in the south and terminate in the north, or visa-versa, must transfer downtown to the MBTA rapid transit network, bus, auto, or another mode to complete their journey. The lack of connection also means that forecasted increases in demand must be dealt with separately. The only connecting infrastructure east of Worcester between the north and south is the Grand Junction railroad. The goal of this study is to examine the possible alternatives for using the Grand Junction railroad to improve passenger service from the west (areas from Brighton and Newton out to Framingham and Worcester) to Cambridge and downtown Boston. The primary motivations for this study are rising employment, congestion at the South Station and Back Bay rail facilities, and improving transit services to Cambridge by using this existing facility.

This thesis is part of a larger study, titled *Grand Junction Transit Service Implementation* that also includes ridership estimation and data on rising employment and population in Kendall Square. The elements that this thesis focuses on are alternatives analysis, schedule modeling, and cost modeling. An in-depth analysis on the demand modeling and ridership analysis for the proposed project can be found in a thesis by Adam Bockelie and James Dohm (Bockelie & Dohm, 2012).

Figure 1: Boston Commuter Rail Network



Map by Robert McConnell ("The Port of Authority") for Wikipedia.

This map is not an official map. It is not affiliated with the MBTA, MBCR, or any other agencies.

This map is not to scale. It does not attempt to correctly depict geographical intricacies.

2 Background

The Grand Junction is an 8.5 mile long corridor that stretches from the Beacon Yard in Allston through east Cambridge to Chelsea in the north of Boston. It was opened in 1855 by the Grand Junction & Depot Company to serve a variety of factories and warehouses in the newly industrialized east end of Cambridge, (City of Cambridge, 2006). Some of the customers that relied on the freight services along the corridor included rubber goods manufacturers, stone cutters, soap manufacturers, and meats companies. Post World War II, however, saw the rise of service and technologies industries in the area, drastically decreasing the demand for freight along the Grand Junction until its present state where there is no significant freight service along the route in east Cambridge.

The railroad has gone through a multitude of owners, finally ending up in the hands of the Commonwealth of Massachusetts and under the control of the MBTA (City of Cambridge, 2006). MIT acquired property rights over and under a portion of the right of way, but the MBTA acquired the operation rights from CSX, subject to requirements to continue allowing freight service to operate. This means that the MBTA also controls dispatching, making it easier to schedule passenger train movements along the Grand Junction.

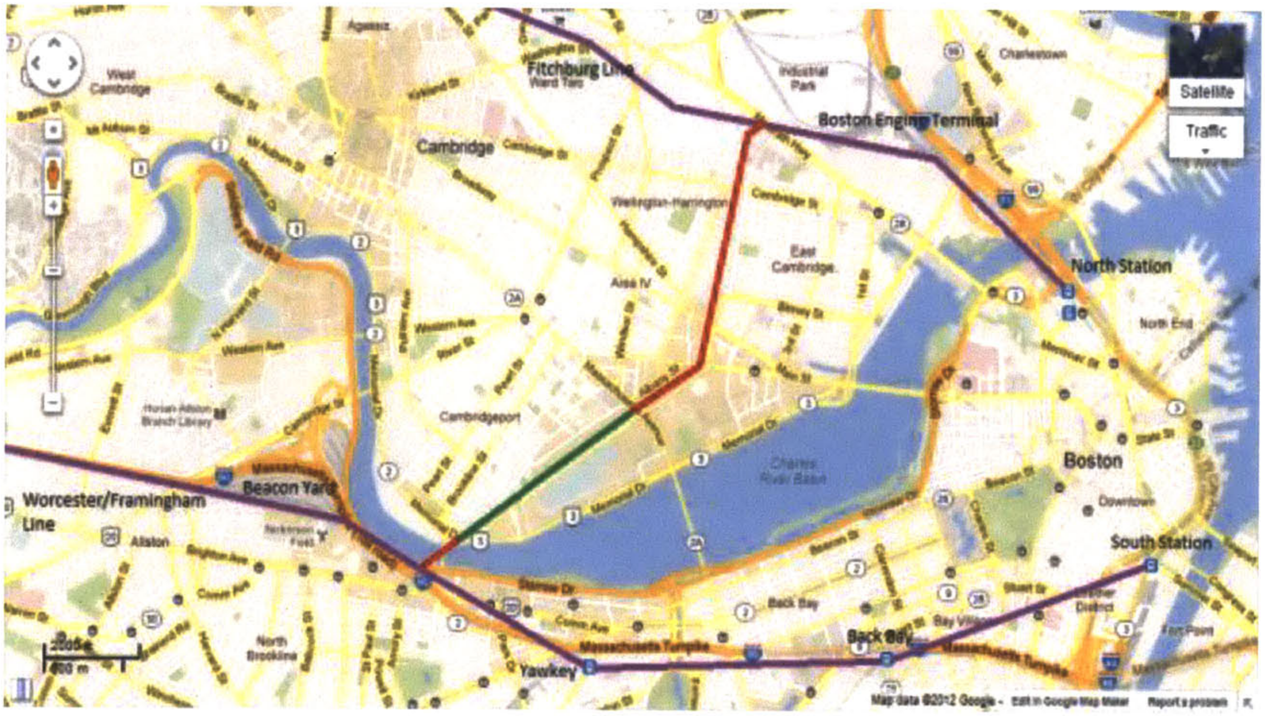
Decreasing demand for freight traffic and increasing demand for transit, coupled with the Commonwealth purchase, have opened the door for possible passenger service expansions along the Grand Junction corridor. Such a service could provide many short term benefits and be a complement to future improvements to the commuter rail network. To better understand the feasibility of such an expansion, the current state of Grand Junction railroad, restrictions, and existing traffic along it should be reviewed.

2.1 Existing Conditions

A two mile portion of the Grand Junction tracks runs through the heart of Cambridge adjacent to the MIT campus, Kendall Square, and residential areas in North Cambridge. To the west the Grand Junction connects to the Worcester/Framingham commuter rail tracks and crosses the Charles River under the BU Bridge into Cambridge. The tracks make six at-grade crossings along the two mile stretch, crossing Massachusetts Avenue, Main Street, Broadway Street, Binney Street, Cambridge Street and Medford Street. Along with these roadway crossings, the tracks have several pedestrian only crossings – both marked ones and ones that are illegally used purely for convenience by students. In the east the tracks cross the Fitchburg mainline at a diamond interchange and go into the Boston Engine Terminal (BET) before joining the other tracks and leading into North Station.

The physical condition of the tracks is a reflection of corridor's diminishing importance over the last half century. The corridor used to feature sections with multiple track segments, but is now largely a single track corridor. A single track splits from Beacon Yard in the west crossing over the Charles River. The bridge was built to hold two tracks but the current configuration of the Massachusetts Turnpike and Soldiers Field Road constrain the connection to a single track in the turn. The radius of the turn limits trains to 10 mph in this segment. The double tracks starts at the western end of Cambridge after the bridge crossing and continue until Massachusetts Avenue where the rails merge into a single track. This single track continues until the Grand Junction connects into the BET in the east. The single track turn here runs very close to a bridge abutment of the McGrath Highway and the turn radius also limits trains to 10 mph. Figure 2 shows a schematic of the double track portion in green, the single track portion in red, and existing commuter lines in purple.

Figure 2: The Grand Junction in Cambridge



Further physical constraints exist on the corridor because of the zoning and adjacent land ownership. Where the entire corridor used to be zoned for industrial use, many portions are now residential areas, commercial buildings, and institutional buildings such as those of MIT. The proximity of houses and businesses constricts the right of way. For example, the single track portion of the Grand Junction runs under two MIT buildings: the cogeneration power plant and building 46, where the rail right-of-way is constrained to 60 feet. In addition, further east the railroad hugs the sides of several commercial buildings with little room to expand.

The physical state of the already constrained corridor is also an issue impacting future services. The Grand Junction lacks the necessary train signals and safety devices that would allow proper everyday use. Table 1 summarizes the safety barriers and flashers that exist at each crossing.

Table 1: Grand Junction Intersection Safety Features (City of Cambridge, 2006)

Location	Width of Road Crossing	Safety Features
Massachusetts Avenue	4 lanes	Flashing signals
Main St.	2 lanes	Flashing signals
Broadway St.	4 lanes	Flashing signals
Binney St.	2 lanes	Flashing signals
Cambridge St.	2 lanes	Flashing signals and gates
Medford St.	2 lanes	Flashing signals and gates

The rails along the tracks are not continuous and welded and vary in condition. The current conditions limit most operations to around 10 miles per hour and trains must stop and blow their whistles before the at-grade crossings where there are no gates. The starting, stopping, and federally mandated whistle blowing at unprotected intersections creates noise that many residents complain about. Furthermore, buses that cross these unprotected intersections are required to stop at the crossing before proceeding, causing some traffic delay.

Many of these conditions do not pose a major problem for rail operations as current traffic along the Grand Junction is very low. The tracks see between four and six train movements a day, mostly non-revenue moves of MBTA equipment between the northern and southern service yards, including transfers of coaches, freight cars, and locomotives. There is a daily freight service that serves the Chelsea produce market and the occasional circus train that stops near the MIT campus. The double track section between Massachusetts Avenue and the BU Bridge is also used to store overflow cars from Beacon Yard when necessary.

In order to propose feasible introduction of passenger rail service along the corridor it is necessary to establish some simplifying assumptions for the future. For the purposes of this study the following was assumed:

- Single and double track segments remain in Cambridge remain as they are.
- Planned signal, rail, track bed, and safety improvements will be carried out by the MBTA regardless of service introduction and will not be analyzed. These will allow slightly higher speeds and more efficient service along the Grand Junction.
- The interlocking connections to the Worcester/Framingham and Fitchburg lines will be optimally designed to provide seamless travel from those lines onto the Grand Junction. Their design and configuration is beyond the scope of this analysis.

2.2 North and South Station Capacity

A significant constraint on any commuter rail service expansions is the capacity of North and South Station to handle additional trains. Ridership is expected to increase on the Worcester/Framingham line, as well as all southern lines, but according to a White Paper from Technical Report Number 5 – Operations Study assessing the capacity of the two downtown terminals, additional trains would overburden South Station (Boston's Passenger Rail Operational Capacity White Paper).

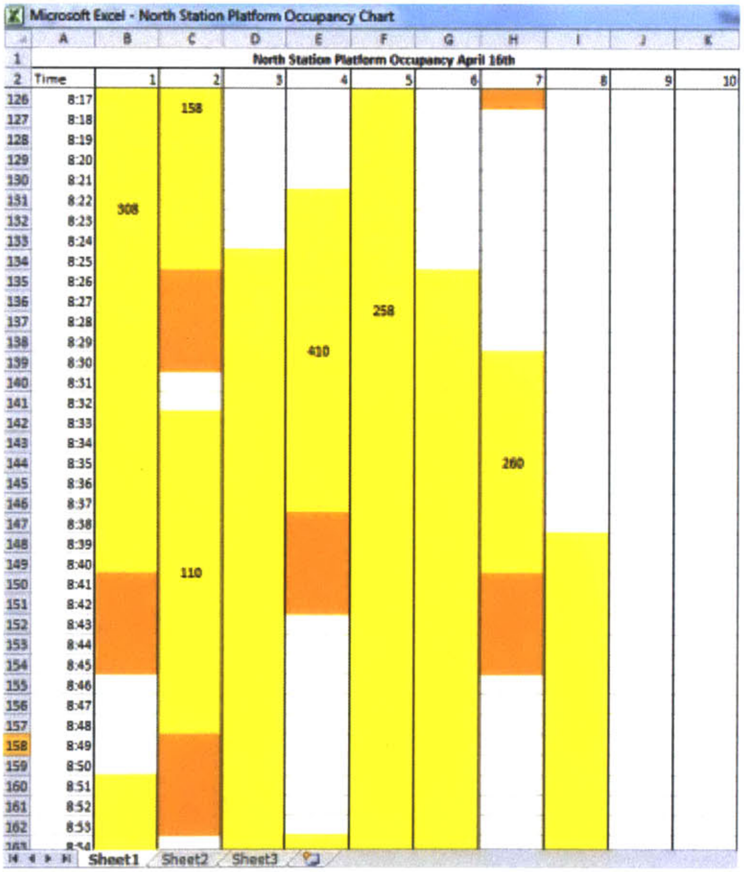
South Station currently has 13 tracks of varying station platform lengths. Three of those tracks are used for Amtrak service (White & O'Conner, 2001). The MBTA projects that by 2020 ridership in the south will be over 74,000 (Boston's Passenger Rail Operational Capacity White Paper). To deal with the forecasted increase in demand a proposal for South Station expansion is being investigated but this project will be difficult, expensive and time consuming. It is prioritized by the State and will offer a long term solution when complete for most of the network, but as described in Section 1, western lines may experience fewer of the benefits of expansion.

North Station currently has 10 tracks. Two additional tracks can be put into service by taking over an MBTA easement from the Spaulding Rehabilitation Hospital (White & O'Conner, 2001). The MBTA projects that northern ridership in 2020 will a bit over 51,000 (Boston's Passenger Rail Operational Capacity White Paper). This lower ridership compared to the South means that fewer trains are required to service North Station, something that was confirmed using a typical weekday train schedule. A platform occupancy chart was created based on the following:

- All trains have access to every platform, although some platform management is done
- At least 5 min must pass between a train departing a platform and another arriving
- Any house moves (trains going out of service) remain at platform for 15 min
- Arrivals were optimized to reduce the number of occupied platforms at any given time

Using these assumptions, it is feasible that under the current operations, one platform remains unused in the AM peak period. The schedule is a simplification of real operations but illustrates that there is some available capacity at North Station to handle additional train movements. The availability of capacity at North Station is also confirmed in the White Paper (Boston's Passenger Rail Operational Capacity White Paper).

Figure 3: North Station Sample Platform Occupancy (yellow - scheduled time, orange - buffer time)



Keeping in mind these capacity constraints, all efforts should be geared toward easing the congestion at South Station and Back Bay while meeting transit demands to downtown Boston and Cambridge. Even with the substantial investments, efforts, and time slated to improve South Station and Back Bay terminal capacities, any Grand Junction service moving passengers from the west through Cambridge into North Station stands as a desirable complement for the near and long term future of the entire commuter rail system.

3 Previous Corridor Plans

The addition of passenger services in the Grand Junction corridor has been previously considered by MassDOT and the MBTA. The purpose of this section is to briefly review those studies.

3.1 The Urban Ring

The MBTA Urban Ring project proposes circumferential transit services (primarily bus) that link destinations outside of downtown Boston. The areas it would cover are East Cambridge, Somerville, Chelsea, East Boston, South Boston, Roxbury, LMA, and Brookline. The Urban Ring project has three phases. Phase 1, which has been partially implemented, includes expansion of crosstown buses between some of the destinations. Phase 2 proposes the addition of bus rapid transit services to create the circumferential routes and Phase 3 implements rail to the most heavily traveled corridors in order to provide improved service to the maximum number of passengers. The Urban Ring had some planned service along the Grand Junction corridor serving Kendall Square but many of its sections traveled on existing roads. Phases 2 and 3 of the project have not been implemented and the project is on indefinite hold due to funding problems. The Urban Ring had a high projected ridership and remains the benchmark for ridership that the City of Cambridge uses when weighing possible Grand Junction alternatives.

3.2 Mass DOT Grand Junction Commuter Rail Proposal

Mass DOT conducted a study proposing the addition of commuter rail service from the Worcester/Framingham line to North Station along the Grand Junction corridor. That study laid the foundation for much of this proposal. Mass DOT proposed the addition of a maximum of three peak period train sets consisting of six car trains and a station at Kendall Square, assuming the existing infrastructure remained largely as is. That study concluded that the addition of Grand Junction service would increase Worcester line demand by up to 300 passengers compared to the same service increase on the line to South Station, which would be impossible to implement without the aforementioned expansion of South Station capacity. The study met heavy opposition from Cambridge residents who were against the idea of large trains passing through the dense urban area. As part of the study Mass DOT modeled traffic delays, passenger delays, auto diversions, and air quality improvements to demonstrate the possible merits and issues with a Grand Junction service. Ultimately, based on the results of the study and community opposition, the state suspended pursuing Grand Junction service in the near future, choosing instead to focus on expansion of South Station.

3.3 Cambridge Community and Bike Path

In 2006 the city of Cambridge completed a feasibility study for a Rail-with-Trail (RWT) corridor in the Grand Junction (City of Cambridge, 2006). The city proposed a community path sharing the rail right-of-way with the existing traffic and configuration. The path configuration was also explored under the scenario of having a one way bus service as part of the Urban Ring. Community support is very high for a pedestrian and bike path along this corridor as the city has chosen to move toward sustainable forms of transportation. The proposed community path would complement the Vassar Street cycle path and allow access to more parts of eastern Cambridge. The proposed community bike path would be 10-12 ft wide and must be separated from the centerline of the railroad by 10-25 ft. There are certain areas, such as under MIT building 46, where the existing right of way may not allow enough room for a bike path and an expansion of existing rail infrastructure such as a double track station. The addition of a community path is currently on hold but any proposals for Grand Junction service will need to include it because of community support for such infrastructure.

3.4 No-Build Scenario

Most commuter demand is for downtown Boston and the financial district area around South Station so a no-build scenario is possible as a future alternative. This scenario would maintain existing freight traffic along the tracks and complete only the scheduled MBTA safety improvements along the Grand Junction. No capital expenditures beyond this would be required. In a no-build scenario the following factors will likely influence future plans for the area: population and employment growth in Kendall and Boston, transit system congestion, limited parking in Kendall and Boston and limited transit access to Kendall.

4 Alternative Creation

The first step in the project analysis was to create a full list of possible alternatives along the corridor. The only restriction made in this initial list was that each alternative had to use the Grand Junction right-of-way and connect passengers coming from the west to North Station and downtown via the Kendall Square and MIT area of Cambridge. Passenger service could be routed straight into North Station but considering the number of jobs in the Kendall Square area, all of the alternatives include a station in the Kendall area. Additionally, a station in the area of Beacon Yard, near the Boston University campus, is also included in the alternatives. This second station offers transfer services, further described for each alternative and provides another center of demand for future transit. Station locations are described in more detail in Section 7.

The initial alternatives were qualitatively assessed based on cost, passenger capacity, noise, vibration, and the ease with which they could be introduced. The list below enumerates the initial options with a short description of each, including basic improvements or changes that would be necessary along the existing Grand Junction corridor in order to facilitate their introduction, followed by an assessment of the initial alternatives.

4.1.1 Commuter rail expansion

The first service alternative that was examined for this study was the addition of commuter rail trains along the Grand Junction from Worcester/Framingham into North Station. This alternative was the focus of the study completed by Mass DOT. Locomotive hauled trains would be added to the Worcester/Framingham line and routed along the Grand Junction corridor to North Station. Diesel push-pull configurations are comparatively inexpensive and dominate US regional rail systems because most tracks lack the overhead catenary supply required for electrified service. The ubiquity of these types of vehicles means that the cheapest and easiest way to add passenger service to a commuter rail system is simply the introduction of additional conventional train sets.

The train consists considered in this study would be around six coaches long (a mix of bi-level and single level cars) pulled by a locomotive. This is the basic setup for most train consists in the MBTA commuter rail network and commuter rail networks around the United States. Accepting the assumptions, made about the future of the corridor, the only addition necessary to introduce commuter rail service along the Grand Junction would be the construction of new stations at Beacon Yard and Kendall/MIT.

4.1.2 Diesel Multiple Unit

Diesel multiple units (DMUs) are the second heavy rail service alternative that was considered. DMUs are self-propelled coach cars that do not require separate locomotives. DMUs are popular outside of the United States: they are often quieter, smaller, more economical, and offer better performance in certain configurations when compared to push-pull locomotive configurations. As with the commuter rail alternative, station construction would be the only corridor improvement necessary beyond the assumed improvements. The biggest obstacle to introduction of DMUs is Federal Railway Administration (FRA) regulations on crash worthiness.

The connection to the Worcester line and the Fitchburg line means that any equipment moving along the Grand Junction must comply with crash worthiness requirements for freight trains and large passenger trains. There are only a few FRA compliant DMU vehicles, one sold by US Railcar. For the DMU service alternative a long route service and a short route service will be considered. The long service will be from Worcester to North Station and the short service will be from Auburndale, in Newton, to North Station. The long service will be interspersed with the current commuter rail operations, while the short service will offer transfers by being scheduled to minimize transfer times for passengers wishing to go to Cambridge or North Station. Both alternatives will include stops at BU and Kendall/MIT to capture the existing demand in Cambridge and possible future demand in Allston. A BU station would also offer transfers to the Green Line and in the case of a short line service it will provide an additional transfer point for passengers on the existing mainline services. Figures 4 and 5 illustrate the two options with the new stations shown by yellow circles.

Figure 4: Long Route DMU Service

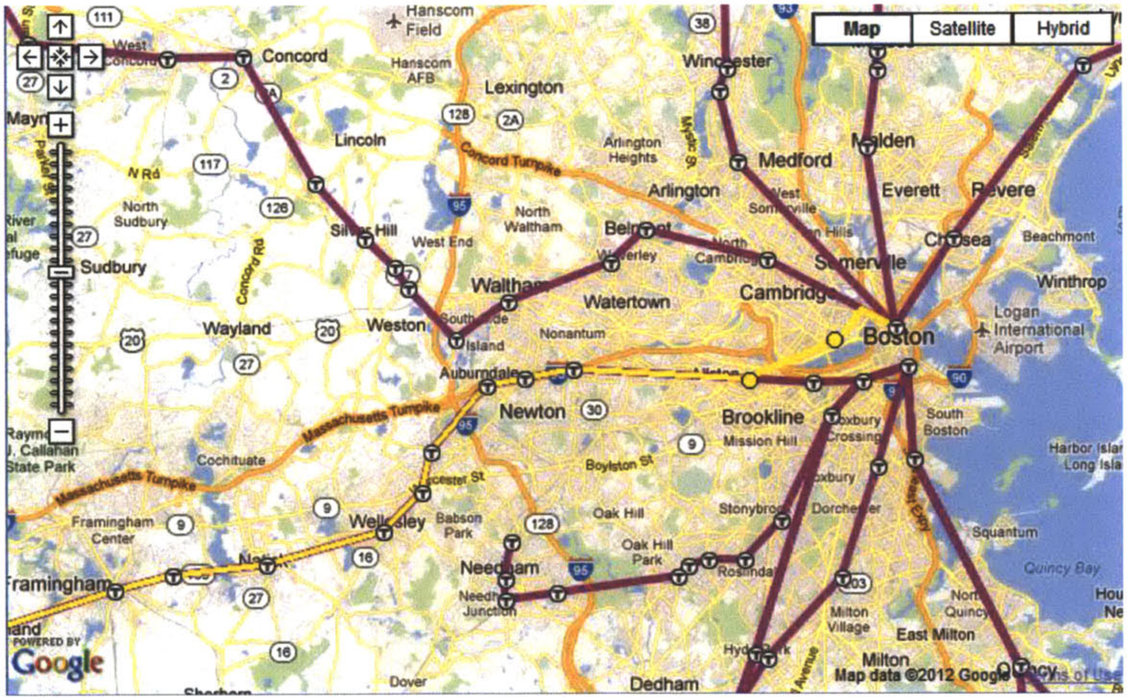
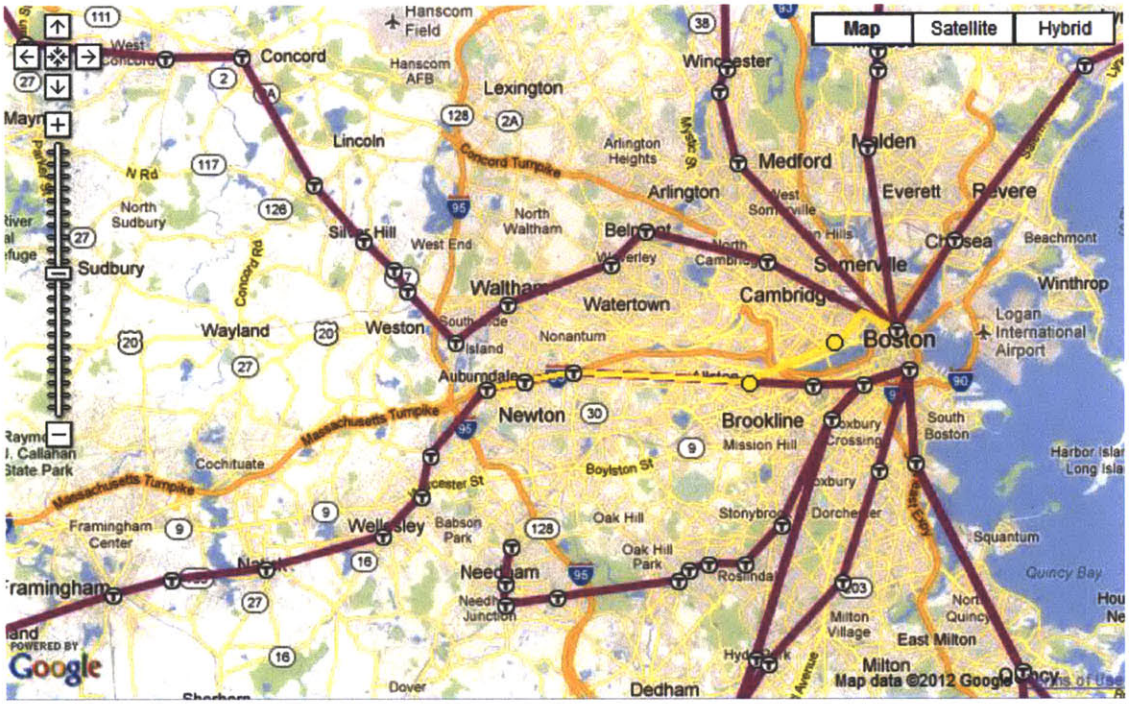


Figure 5: Short Route DMU Service



4.1.3 Non-compliant Diesel Multiple Units

All DMUs that do not comply with FRA collision regulations are referred to as "non-compliant DMUs". These vehicles are lighter, smaller, and quieter than FRA compliant DMUs. They have smaller passenger capacity but better performance characteristics. Several non-FRA compliant services are legal and exist in the United States, a notable example being the New Jersey River Line in Figure 6. Non-FRA compliant service requires strict time separation from heavy equipment or alternative service arrangements to ensure safety. Existing deadhead moves and the produce freight service must remain on the Grand Junction so the introduction of non-compliant service would be possible only with dedicated tracks or time-of-day separations. Dedicated tracks would require a large capital investment and time share agreements would be very difficult to implement because of the existing connection with the busy Worcester and Fitchburg lines. Considering these limitations, only a short route service from Auburndale to North Station or a shuttle service from Beacon Yard to North Station was considered. Stations would be built at Beacon Yard and Kendall as in the previous alternatives.

Figure 6: Non-FRA Compliant DMU on NJ RiverLine

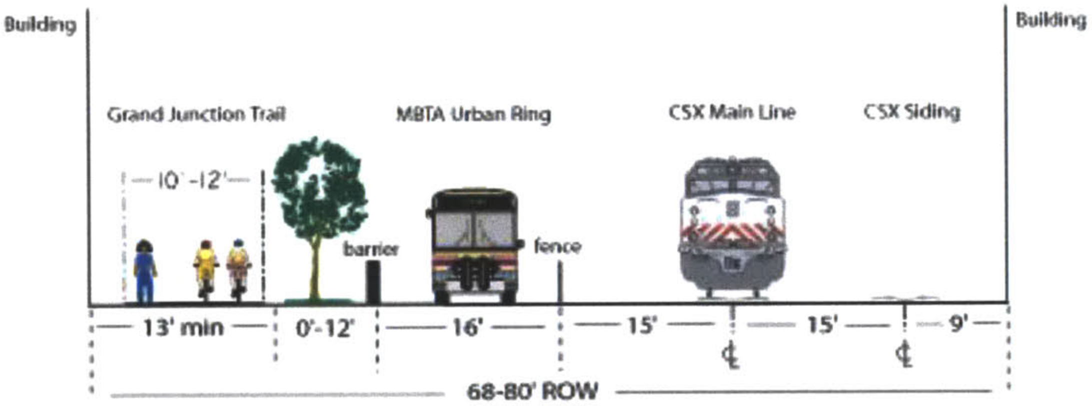
4.1.4 Electrified Light Rail Service

An alternative to heavy commuter rail and DMU operation on the Grand Junction would be electrified light rail. This could be a spur of the Green Line from Lechmere or a separate line using tram cars. Electrification of the Grand Junction would provide a quiet, locally pollution free passenger service and would be possible through a third electric rail or overhead catenary. Light rail vehicles also offer superior performance in terms of acceleration and ride quality to almost any other mode of public transportation. The improved start-stop performance a light rail system means it could have more than one stop and have a smaller impact on road traffic at crossings. On the downside, a third rail power system would create many safety issues at grade crossings and overhead catenary will be expensive to build. With the existing freight use having to continue throughout the foreseeable future and FRA rules governing mixed rail traffic, electrification at this time would require dedicated tracks paralleling the freight line. Having a two way light rail track with station platforms and a single heavy rail line may be expensive or impossible in some areas given the physical constraints that exist on the Grand Junction, and would preclude any consideration of a community path sharing the right-of-way.

4.1.5 Bus Rapid Transit

Bus rapid transit, or BRT, has been gaining popularity around the world as an inexpensive alternative to rail transit. Typical characteristics of BRT include exclusive bus ways, signal priority, and off-bus fare collection. This alternative would be similar to the Silver Line, primarily using a combination of adjacent Vassar and Albany St. dedicated lanes with some use of Grand Junction right of way. The goal with BRT would be providing a service that is not impacted by road congestion, is much quieter than most train services, and provides faster access than regular bus service to commuters. There are many flexible options with BRT but a short service from Auburndale to North Station in order to keep it comparable to the rail alternatives was considered. The BRT route would travel on existing roads and highways and cross the Charles River along the BU Bridge then use a combination of Vassar St, Albany St. and portions of the Grand Junction in dedicated lanes until Lechmere. It could either terminate here or make its way all the way into North Station or Sullivan Square. The BRT alternative would have multiple stations in the Grand Junction corridor. To accommodate buses, portions of the corridor would have to be paved adjacent to the rail tracks where the right-of-way would be shared by the bus and existing freight traffic. The width of the Grand Junction corridor would also preclude the possibility of two-way bus traffic and the existing operations. If the right-of-way was shared between one-way BRT, a community path, and existing freight traffic an alignment such as the one pictured in Figure 7 would be possible.

Figure 7: Example BRT Right-of-Way in Grand Junction corridor



4.1.6 Tunnel

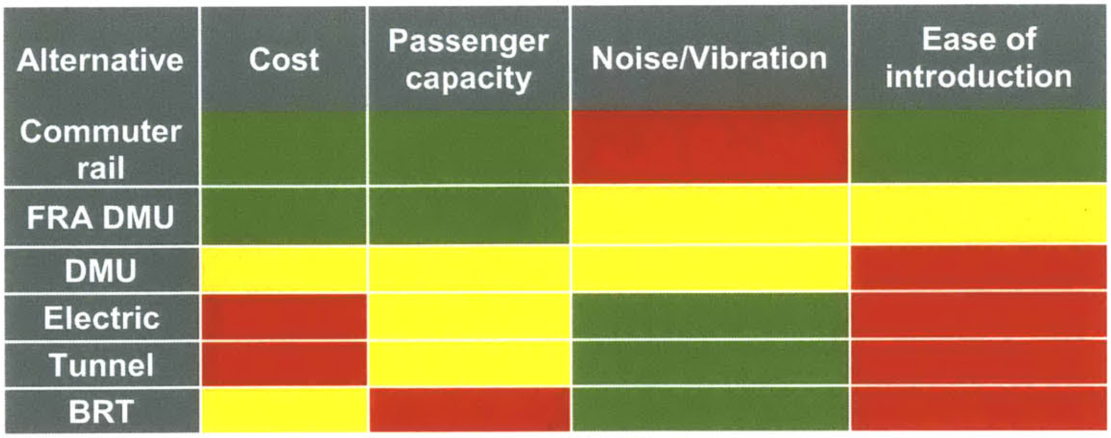
An ultimate solution to increase passenger transit services to Cambridge and Boston would be to depress the Grand Junction railroad into a tunnel. This alternative would solve many of the issues with pollution, vibration, noise, traffic impact, and capacity that the other alternatives only placate. A tunnel would most likely be electrified but could be used by commuter trains or DMUs with proper ventilation. Placing the tracks underground would allow double track service on the entire corridor – the tracks would go underground after crossing under the BU Bridge and come up at the eastern end to join the Fitchburg line or Green Line, depending on whether commuter rail type service or rapid transit is used in the tunnel. This alternative would have an underground station at Kendall/MIT. Depressing the tracks into a tunnel would resolve almost all the difficult implementation issues that have been raised in this corridor but would be a massively expensive undertaking accompanied by significant disruptions. A project of this size would run in the hundreds of millions of dollars and take a significant amount of time to complete.

4.2 Screening of Initial Alternatives

The next step in the alternative selection process was to screen the list to a few alternatives that could be analyzed in our demand model and quantitatively assessed. In Table 2, each alternative is qualitatively compared to the others in several categories and assigned a color depending on how it compares. Green represents very good estimated performance, yellow marginal, and red poor. The factors analyzed were:

- Cost – how much any necessary capital improvements would cost (beyond the assumptions stated) and if a new fleet is required, would it require expensive vehicles.
- Passenger capacity – this category is based on potential vehicle size, with commuter trains and FRA compliant DMU cars having the most seated capacity per vehicle.
- Noise/vibration – the Grand Junction is located in a dense residential area so noise and vibration reduction are paramount to gaining community acceptance. Locomotive whistles, vehicle size, engine noise, and horsepower are the strongest indicators in this category. Large vehicles, such as locomotives, are considered much worse than smaller ones, such as buses.
- Ease of introduction – the goal of this performance measure is to see which of the alternatives could be introduced in the shortest time frame. Good performance is estimated as having few capital improvements, vehicle acquisitions, and shorter implementation times.

Table 2: Initial Screening of Alternatives



Alternative	Cost	Passenger capacity	Noise/Vibration	Ease of introduction
Commuter rail	🟩	🟩	🟥	🟩
FRA DMU	🟩	🟩	🟨	🟨
DMU	🟨	🟨	🟨	🟥
Electric	🟥	🟨	🟩	🟥
Tunnel	🟥	🟨	🟩	🟥
BRT	🟨	🟥	🟩	🟥

Electrification and tunneling would require substantial capital improvements in the corridor so they are the worst performers in the cost category. BRT would require some corridor improvements to allow bus service so it receives marginal scores. Non-compliant DMU service would require purchase of an expensive new fleet, but because of non-compliance it would also require possible investments in corridor improvements and new rail track if new traffic is to be physically separated from the current traffic. The FRA compliant DMUs and commuter rail would only require the purchase of new vehicles and fewer capital improvements..

In the passenger capacity category, FRA compliant DMUs and commuter trains score very well because they have very similar capacities. The other rail options have smaller vehicles with fewer seats so they score marginally. BRT is bus service, which may be frequent but has a much smaller seating capacity than most trains.

With high residential density along the Grand Junction, it is important that the selected service alternative minimizes negative impacts along the corridor. Noise and vibration are detrimental to the community and can create community backlash. Electrification for light rail, tunneling, and BRT would all have minimal noise and vibration impacts (not considering construction) because the vehicles will be buses with small engines or electrically driven trains. BRT service could be introduced on Vassar and Albany without conflicting with the Grand Junction. All DMUs score better than commuter trains because they tend to use smaller diesel engines and consist of shorter trains. In the final category, commuter rail and compliant DMUs score higher than all the other alternatives because they would cause fewer scheduling conflicts and require the least new construction. The FRA compliant DMU service is yellow because the purchase of vehicles would take time and maintenance staff would have to be trained to work on the new fleet. Non-compliant DMUs would cause scheduling conflicts because of the necessary temporal or physical separation and cannot be seamlessly introduced with existing commuter rail and freight operations. The other alternatives would require significant corridor improvements that would be time consuming and would delay the introduction of passenger services.

In addition to the constraints established in the table it is important to consider the types of riders that would be serviced by each alternative and how each alternative meets the established goals of this study. BRT service, as proposed here or as part of the Urban Ring, could be introduced on adjacent streets without conflicting with Grand Junction traffic, even if commuter trains or DMUs are added. BRT service would not relieve any capacity constraints on the commuter rail network which serves passenger that usually travel longer distances. Similarly, electrified light rail service would not serve long distance commuters or relieve congestion and could be introduced to the corridor parallel to heavy rail. Therefore the BRT and light rail alternatives could be separate and additive to Grand Junction service in the future. The tunnel alternative can be eliminated based on the costs and effort required and the non-compliant DMU services would fall in a similar situation with the light rail alternative – it is viable even with long distance commuter rail service added on the corridor.

4.3 Final Alternatives Selection

Based on the screening criteria established and analyzed the list of alternatives was narrowed to commuter rail service and FRA compliant DMU service. A long and short service option for DMUs is maintained producing the three alternatives for quantitative analysis listed below:

1. Expansion of commuter rail services by adding Worcester to North Station service
2. Long route FRA compliant DMU service from Worcester to North Station
3. Short route FRA compliant DMU service from Auburndale to North Station

Several service configurations were analyzed for each alternative including varied frequency and travel times. These are crucial inputs to the demand model necessary to develop a ridership estimate for the service.

5 Schedule Model

5.1 Schedule Model Formulation

In order to provide a realistic plan for the addition of passenger services along the Grand Junction, a model to provide possible schedules for the three final alternatives was developed. This model was used to generate the maximum possible frequencies, which are essential to estimating the ridership for the service, and to estimate the marginal operating costs of providing each service based on those frequencies.

To create a realistic model, the physical constraints outlined in the earlier sections, such as the extensive single track portions, and as well as the performance characteristics of commuter train and DMUs were considered. The train model is spreadsheet-based and uses basic kinematic equations to model the speed, acceleration, and position of the trains (see Figure 8). The inputs for the model were the length of railroad segment between stations, L; the initial position of a stopped train along the segment, A; train speed, V; final position along the segment, B; and acceleration. For acceleration values the model uses two approaches: for commuter trains acceleration and decelerations based on kinematic equations and field data (described later) were assumed, and for DMU operations a table of accelerations (seen in Table 3) provided by US Railcar was used (Schaefer, 2012)

Figure 8: Schedule Model Formulation

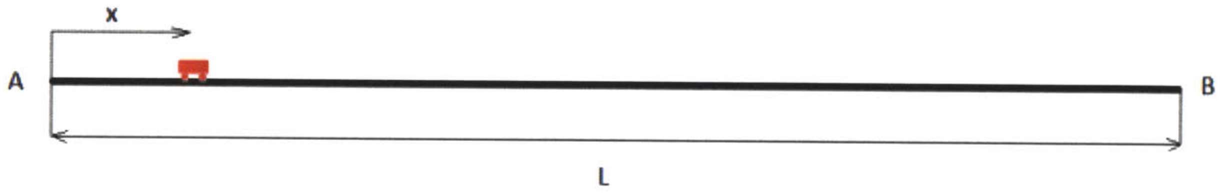


Figure 8 above illustrates the model of a single track, where x(t) is the position of the train at certain time t and A and B are consecutive stations along the rail line. Deriving this position is crucial to creating frequencies and schedules that minimize trains waiting to enter the single track portions of the Grand Junction. To derive the position of the train with acceleration ($\ddot{x}$) and velocity ($\dot{x}$) were considered as defined here:

$$\dot{x} = \frac{dx}{dt} \qquad (1)$$

$$\ddot{x} = \frac{d^2x}{dt^2} \qquad (2)$$

If acceleration is a constant, α, then

$$\ddot{x} = \alpha \qquad (3)$$

And if the equation is integrated, the result is the velocity with respect to time, where v_0 is the initial speed at point A:

$$\dot{x} = \alpha t + v_0 \qquad (4)$$

With one more integration, position equation is obtained:

$$x = \frac{1}{2}\alpha t^2 + v_0 t + x_0 \qquad (5)$$

Applying zero as the initial velocity and position, v_0 and x_0, the equation that determines the position of the train when it is accelerating in segment L can be derived:

$$x = \frac{1}{2}\alpha t^2 \qquad (6)$$

And the speed at a time t is:

$$v = \alpha t \qquad (7)$$

Regulations and track conditions limit the maximum speed along parts of the track. From a field data collection study described later on values for v_{max} were calculated along the Worcester/Framingham mainline. For areas on the Grand Junction v_{max} is determined by track conditions. The value for speed allows derivation of the time and distance required to reach this speed as:

$$t_{acel} = \frac{v_{max}}{\alpha} \qquad (8)$$

$$x_{accel} = \frac{1}{2}\frac{v_{max}^2}{\alpha} \qquad (9)$$

When the train reaches the maximum allowable speed along the track section it will continue to travel at that constant speed, advancing a distance of x_c:

$$x_c = v_{max} t_c \qquad (10)$$

As the train approaches B, it will start to decelerate at constant acceleration $-\beta$. Using (5), and two new initial conditions:

$$x = -\frac{1}{2}\beta t^2 + v_0 t + x_0 \qquad (11)$$

$$v_0 = v_{max} \qquad (12)$$

$$x_0 = 0 \qquad (13)$$

$$v = -\beta t \qquad (14)$$

The length needed for deceleration until the train stops:

$$x_{decel} = \frac{1}{2}\frac{v_{max}^2}{\beta} \qquad (15)$$

And the time needed for it to stop at B:

$$t_{decel} = \frac{v_{max}}{\beta} \qquad (16)$$

Therefore, the total time and distance from A to B should be:

$$t_{AB} = t_{accel} + t_c + t_{decel} = \frac{v_{max}}{\alpha} + t_c + \frac{v_{max}}{\beta} \qquad (17)$$

$$L = \frac{1}{2}\frac{v_{max}^2}{\alpha} + v_{max}t_c + \frac{1}{2}\frac{v_{max}^2}{\beta} \qquad (18)$$

From (17) the time spent at constant velocity, t_c, is:

$$t_c = \frac{L - \frac{1}{2}\frac{v_{max}^2}{\alpha} - \frac{1}{2}\frac{v_{max}^2}{\beta}}{v_{max}} \qquad (19)$$

And then, t_{AB} can be calculated:

$$t_{AB} = t_{accel} + t_c + t_{decel} = \frac{v_{max}}{\alpha} + \frac{L - \frac{1}{2}\frac{v_{max}^2}{\alpha} - \frac{1}{2}\frac{v_{max}^2}{\beta}}{v_{max}} + \frac{v_{max}}{\beta} \qquad (20)$$

As mentioned earlier, v_{max} will be determined by the type of the train or the characteristics of the railroad. Usually, but not in all cases along the track, A and B will be separated by a distance that allows the train to reach the speed v_{max}. In cases where the distance between stations, L, is not long enough it was assumed that the train will accelerate up to a maximum speed v_{max}^* that will be lower than v_{max}, and then decelerate immediately. This case happens when:

$$L < \frac{1}{2}\frac{v_{max}^2}{\alpha} + \frac{1}{2}\frac{v_{max}^2}{\beta} \qquad (21)$$

In this case, v_{max}^* can be calculated using:

$$L = \frac{1}{2}\frac{v_{max}^{*2}}{\alpha} + \frac{1}{2}\frac{v_{max}^{*2}}{\beta} \qquad (22)$$

Where,

$$v_{max}^* = \sqrt{\frac{2L}{\frac{1}{\alpha}+\frac{1}{\beta}}} \qquad (23)$$

And therefore, the time needed for the train to go from A to B in the case where L is too short for maximum speed will be:

$$t_{AB} = t_{accel} + t_{decel} = \frac{v_{max}^*}{\alpha} + \frac{v_{max}^*}{\beta} \qquad (24)$$

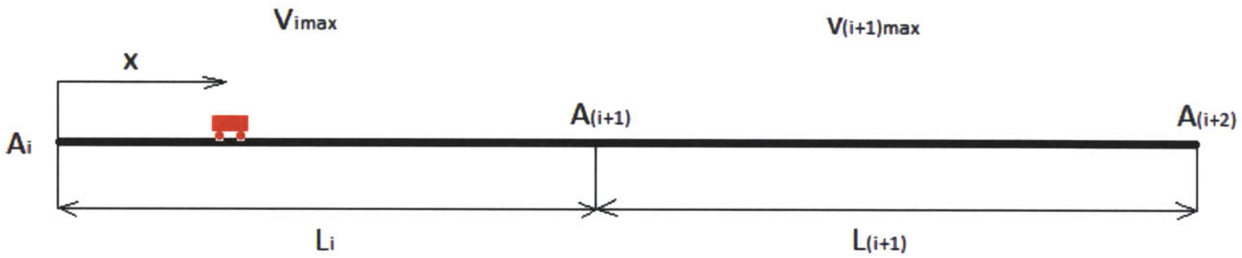
So t_{AB} will be:

$$t_{AB} = \sqrt{2L(\frac{1}{\alpha} + \frac{1}{\beta})} \qquad (25)$$

To create a full model of the entire route for each alternative the previous equations are considered over consecutive stages, creating a formulation of the total time needed for a train to complete a trip. An illustration of this can be seen in Figure 9. Over the entire trip length the following simplifying assumptions were initially made:

- Acceleration and deceleration values are the same on all stages of the journey.
- The length of every stage, L_i will be enough to reach the maximum speed assigned to that stage, v_{imax}.
- Train will start running at A_i at a time t_i.
- Train will stop at point $A_{(i+1)}$ for a time $t_{stop(i+1)}$, the dwell time.

Figure 9: Schedule Model Formulation



The time to reach the first station will be:

$$t_{(i+1)} = \frac{v_{imax}}{\alpha} + \frac{L_i - \frac{1}{2}\frac{v_{imax}^2}{\alpha} - \frac{1}{2}\frac{v_{imax}^2}{\beta}}{v_{imax}^2} + \frac{v_{imax}^2}{\beta} \qquad (26)$$

And therefore, the time to complete the entire two stage journey illustrated above will be:

$$t_{(i+2)} = t_{(i+1)} + t_{stop(i+1)} + \frac{v_{(i+1)max}}{\alpha} + \frac{L_{(i+1)} - \frac{1}{2}\frac{v_{(i+1)max}^2}{\alpha} - \frac{1}{2}\frac{v_{(i+1)max}^2}{\beta}}{v_{(i+1)max}^2} + \frac{v_{(i+1)max}^2}{\beta} \qquad (27)$$

Equation 27 is the basis for the spreadsheet model and it easily allows prediction of the behavior of trains along any route. In the case of DMUs when accelerations are not calculated using the equations above, but rather pulled from the US Railcar (See Table 3), the formulation is slightly different. The acceleration table displays the time and distance needed to reach different speeds in various single level powered car-coach car configurations. Therefore, for a given speed v_i, the table will return a value of time t_i and distance x_i. The model assumes constant decelerations for DMUs.

The equations for time in each stage that result from using the acceleration table are:

$$t_{(i+1)} = t_{imax} + \frac{L_i - x_{imax} - \frac{1}{2}\frac{v_{imax}^2}{\beta}}{v_{imax}^2} + \frac{v_{imax}^2}{\beta} \qquad (28)$$

$$t_{(i+2)} = t_{(i+1)} + t_{stop(i+1)} + t_{(i+1)max} + \frac{L_{(i+1)} - x_{(i+1)max} - \frac{1}{2}\frac{v^2_{(i+1)max}}{\beta}}{v^2_{(i+1)max}} + \frac{v^2_{(i+1)max}}{\beta} \qquad (29)$$

Where x_{imax} and t_{imax} are distance and position taken from the acceleration table corresponding to the value of v_{imax} in segment one. The same is true for second segment where $x_{(i+1)max}$ and $t_{(i+1)max}$ correspond to $v_{(i+1)max}$.

Table 3: DMU Acceleration Table

Projected Acceleration Performance of Various Single-Level DMU Consists

Assumes: Modified Davis equation for train resistance
Dry, level, tangent track
Two 600 hp Detroit Diesels, Two Voith T212bre transmissions, Two Voith KE553 final drives
36-inch wheels
Fully loaded single level power car, 190,000 pounds
Fully loaded single level trailer car, 158,250 pounds

	One Power Car		One Power Car One Trailer Car		One Power Car Two Trailer Cars		Two Power Cars One Trailer Car		Two Power Cars Three Trailer Cars	
Speed (mph)	Time (seconds)	Distance (miles)	Time (seconds)	Distance (miles)	Time (seconds)	Distance (miles)	Time (seconds)	Distance (miles)	Time (seconds)	Distance (miles)
46.0	35.5	0.2711	67.7	0.5310	104.0	0.8300	50.2	0.3869	83.6	0.6566
47.0	36.9	0.2901	70.7	0.5695	108.8	0.8927	52.3	0.4135	87.2	0.7035
48.0	38.5	0.3102	73.8	0.6105	113.9	0.9599	54.4	0.4418	91.0	0.7533
49.0	40.0	0.3315	77.0	0.6543	119.3	1.0321	56.6	0.4717	94.9	0.8064
50.0	41.7	0.3542	80.4	0.7010	124.9	1.1098	58.9	0.5033	99.0	0.8628
51.0	43.4	0.3782	84.0	0.7509	130.9	1.1932	61.3	0.5368	103.3	0.9228
52.0	45.2	0.4044	87.8	0.8055	137.4	1.2859	63.8	0.5730	107.9	0.9883
53.0	47.1	0.4322	91.8	0.8643	144.3	1.3865	66.5	0.6115	112.7	1.0584
54.0	49.1	0.4612	95.9	0.9256	151.3	1.4917	69.2	0.6514	117.6	1.1310
55.0	51.1	0.4912	100.2	0.9893	158.6	1.6018	71.9	0.6925	122.5	1.2063
56.0	53.1	0.5223	104.5	1.0556	166.1	1.7171	74.6	0.7350	127.6	1.2843
57.0	55.1	0.5546	108.9	1.1248	173.8	1.8378	77.4	0.7789	132.7	1.3652
58.0	57.2	0.5882	113.4	1.1968	181.7	1.9643	80.3	0.8243	138.0	1.4490
59.0	59.4	0.6230	118.0	1.2719	189.9	2.0970	83.2	0.8712	143.3	1.5360
60.0	61.6	0.6591	122.7	1.3502	198.3	2.2364	86.1	0.9197	148.8	1.6261
61.0	63.8	0.6966	127.6	1.4319	207.0	2.3828	89.1	0.9697	154.3	1.7195
62.0	66.1	0.7356	132.6	1.5173	216.0	2.5370	92.1	1.0215	160.0	1.8164
63.0	68.4	0.7761	137.7	1.6065	225.4	2.6994	95.2	1.0749	165.8	1.9170
64.0	70.8	0.8184	143.0	1.7001	235.1	2.8713	98.3	1.1303	171.7	2.0216
65.0	73.3	0.8624	148.5	1.7984	245.3	3.0537	101.5	1.1877	177.8	2.1306
66.0	75.8	0.9085	154.2	1.9017	256.0	3.2478	104.8	1.2472	184.1	2.2442
67.0	78.4	0.9565	160.1	2.0105	267.2	3.4546	108.1	1.3089	190.5	2.3626
68.0	81.1	1.0068	166.2	2.1254	279.0	3.6759	111.5	1.3730	197.1	2.4862
69.0	83.9	1.0595	172.6	2.2468	291.5	3.9135	115.0	1.4395	203.9	2.6153
70.0	86.7	1.1148	179.3	2.3754	304.7	4.1695	118.6	1.5086	210.9	2.7504
71.0	89.7	1.1728	186.2	2.5119	318.9	4.4465	122.3	1.5805	218.1	2.8918
72.0	92.8	1.2338	193.5	2.6571	334.0	4.7474	126.1	1.6552	225.5	3.0399
73.0	95.9	1.2981	201.2	2.8119	350.3	5.0762	129.9	1.7330	233.2	3.1952
74.0	99.3	1.3658	209.3	2.9775	368.1	5.4380	133.9	1.8140	241.2	3.3584
75.0	102.7	1.4375	218.0	3.1560	387.6	5.8419	138.0	1.8986	249.6	3.5305
76.0	106.4	1.5138	227.2	3.3493			142.2	1.9872	258.2	3.7125
77.0	110.9	1.6104	240.1	3.6238			147.2	2.0935	269.2	3.9448
78.0	115.9	1.7185	255.1	3.9466			152.6	2.2088	281.2	4.2031
79.0	121.2	1.8337	271.4	4.3031			158.1	2.3289	293.7	4.4756
80.0	126.8	1.9566	289.4	4.7000			163.7	2.4541	306.7	4.7638
81.0	132.7	2.0884	309.4	5.1466			169.6	2.5846	320.4	5.0691
82.0	138.9	2.2300	331.8	5.6555			175.6	2.7208	334.7	5.3931
83.0	145.6	2.3828	357.6	6.2452			181.8	2.8631	349.7	5.7379
84.0	152.7	2.5486					188.2	3.0119	365.6	6.1056
85.0	160.4	2.7294					194.8	3.1676		
86.0	168.8	2.9279					201.7	3.3309		
87.0	177.9	3.1475					208.8	3.5022		
88.0	188.0	3.3921					216.2	3.6820		
89.0	199.2	3.6671					223.9	3.8710		
90.0	211.8	3.9805					231.9	4.0697		

5.2 Excel Implementation

The formulas described were entered into Microsoft Excel to create the full model. Excel was chosen mainly because it easily accessible and operable. The application does not require programming expertise which makes it easy to explain to anyone reviewing the proposed alternatives. The Excel model is easy to program and expand using the stage by stage formulation described and also allows the creation of simple visuals that organize the results. The schedule, frequency, and travel time results from Excel are readily compatible with most other packages and allowed for seamless integration into the demand model.

5.3 Model Inputs

To apply the model to the Worcester/Framingham mainline and the Grand Junction the following variables were input:

- Distance between stations, corresponding to L
- Departure time from station A, t_A
- The maximum speed on each segment, v_{max}
- The acceleration of the trains, α
- The deceleration of the trains, β
- Dwell times at each station

The distance between stations was taken from Googlemaps. The departure time can vary and is an easy input to change depending on the chosen frequencies. To determine the last four variables for each segment and station, field data were collected. V_{max} will be the same for all alternatives and is based on track characteristics observed; accelerations were measured to correctly model commuter train performance; and dwell time estimates were applied to all alternatives with slight adjustments for each.

5.4 Data Collection

Data collection on the Worcester line was performed using a Marathon Windows Phone 7 Application using the Samsung Focus Flash internal GPS unit. An Android based application was used to verify the speeds from the GPS application after processing the data. The GPS application recorded data points every four seconds and provided the following information:

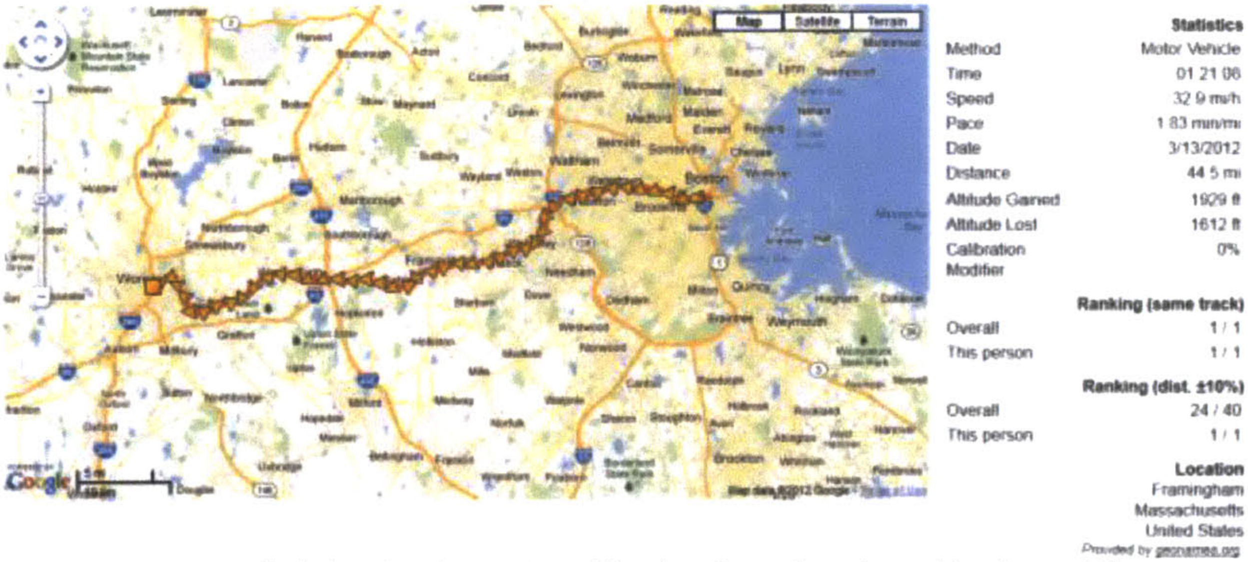
- Coordinates: Longitude, Latitude.
- Altitude (feet).
- Altitude Valid (true or false), depending on GPS data reliability.
- Distance (cumulative, in meters).
- Heading (0-360°)
- Speed (m/s)
- Time (local time. hh:mm:ss)

- Time interval (time elapsed between two measures, in seconds)
- Speed (mph)
- Distance (cumulative, in miles)
- Total time (cumulative elapsed time, hh:mm:ss)

The data collection was performed by riding a Tuesday morning train from South Station to Worcester. The train stopped at Back Bay, Wellesley Farms, Wellesley Hills, Wellesley Square, Natick, West Natick, Framingham, Ashland, Southborough, Westborough, Grafton, and Worcester. The data recorded for the South Station-Back Bay-Wellesley Farms section of the trip is useless for the purposes of this study because large portions of it were underground limiting GPS availability and because no stops occurred that are relevant to the proposed alternatives. The rest of the journey, however, provides enough accelerations, decelerations, and speeds to generate the necessary inputs for the spreadsheet model.

To verify that all the position data was accurate from the GPS, the application has an online system that maps the coordinates collected. Figure 10 shows the positions recorded during the trip.

Figure 10: Map of GPS Data

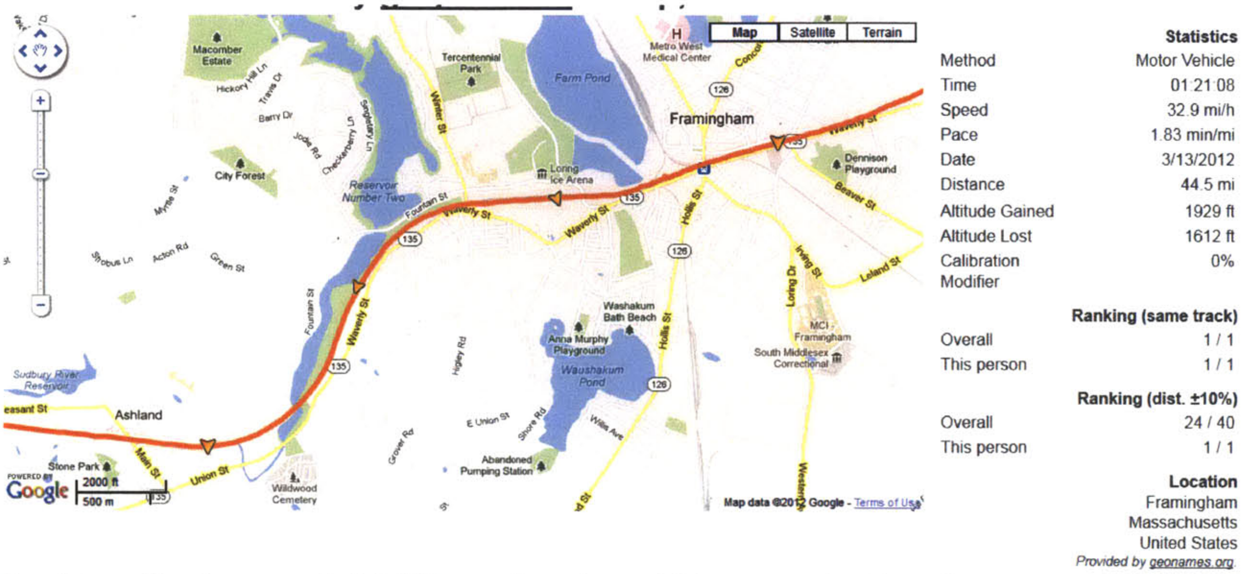


	Statistics
Method	Motor Vehicle
Time	01 21 06
Speed	32 9 mi/h
Pace	1 83 min/mi
Date	3/13/2012
Distance	44 5 mi
Altitude Gained	1929 ft
Altitude Lost	1612 ft
Calibration Modifier	0%
	Ranking (same track)
Overall	1 / 1
This person	1 / 1
	Ranking (dist. ±10%)
Overall	24 / 40
This person	1 / 1
	Location
	Framingham Massachusetts United States

Provided by geonames.org

A more detailed view in Figure 11 verifies that the path registered by the mobile application GPS is the same as the Worcester line mapped in Google. In addition, speed data was checked throughout the trip using a second mobile application for real time speed – the values from both phone applications were a close match. This confirms that all the other data collected by the application can be safely used to derive the model inputs.

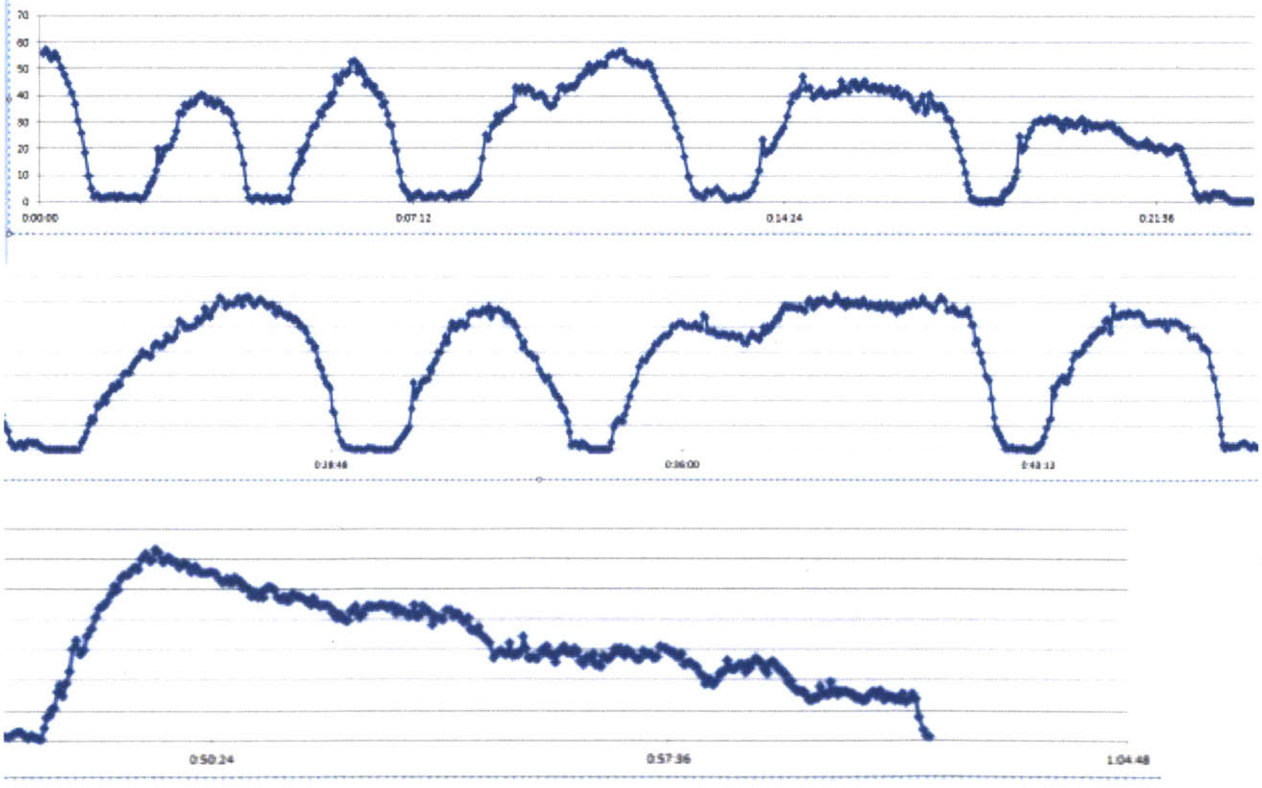
Figure 11: Close-up map of GPS Data Points



	Statistics
Method	Motor Vehicle
Time	01:21:08
Speed	32.9 mi/h
Pace	1.83 min/mi
Date	3/13/2012
Distance	44.5 mi
Altitude Gained	1929 ft
Altitude Lost	1612 ft
Calibration Modifier	0%
	Ranking (same track)
Overall	1 / 1
This person	1 / 1
	Ranking (dist. ±10%)
Overall	24 / 40
This person	1 / 1
	Location
	Framingham Massachusetts United States
	Provided by geonames.org

The data collection recorded 1,239 sample points which are graphed in a time vs speed plot in Excel, depicting the entire journey ending in Worcester, as shown in Figure 12.

Figure 12: Time vs Speed Plot of GPS Data



Station locations are very obvious in the graph. The maximum speed inputs for the model, the acceleration and deceleration values for commuter trains, and the estimated dwell times were derived from this graph.

5.4.1 Maximum Speed

To create an accurate model, the maximum speed along every track segment on the Worcester/Framingham mainline was estimated based on the GPS results. While the DMU alternatives' different acceleration characteristics from conventional push-pull operations were considered, the model will assume that maximum speeds along the track are the same for both. MBTA commuter trains have a speed limit of 60 mph along any track, but they often don't reach this speed for several reasons. First, the distance between consecutive stations may not be sufficient for a train to accelerate to 60 mph then safely decelerate to enter the following station. Second, geometric characteristics of particular segments of track such as curves may limit the actual possible speed despite the higher speed limit.

From the dataset of time and speed collected by GPS the maximum speed reached in an interval between two stations was selected and this was assigned as v_{max} for that segment. The corresponding travel times based on these speeds are later verified by comparing the model travel time estimates to the travel time registered by the GPS application. Table 4 shows the maximum speeds for each segment on the Worcester/Framingham mainline that was input into the spreadsheet model.

Table 4: Maximum Speeds (mph) by Segment

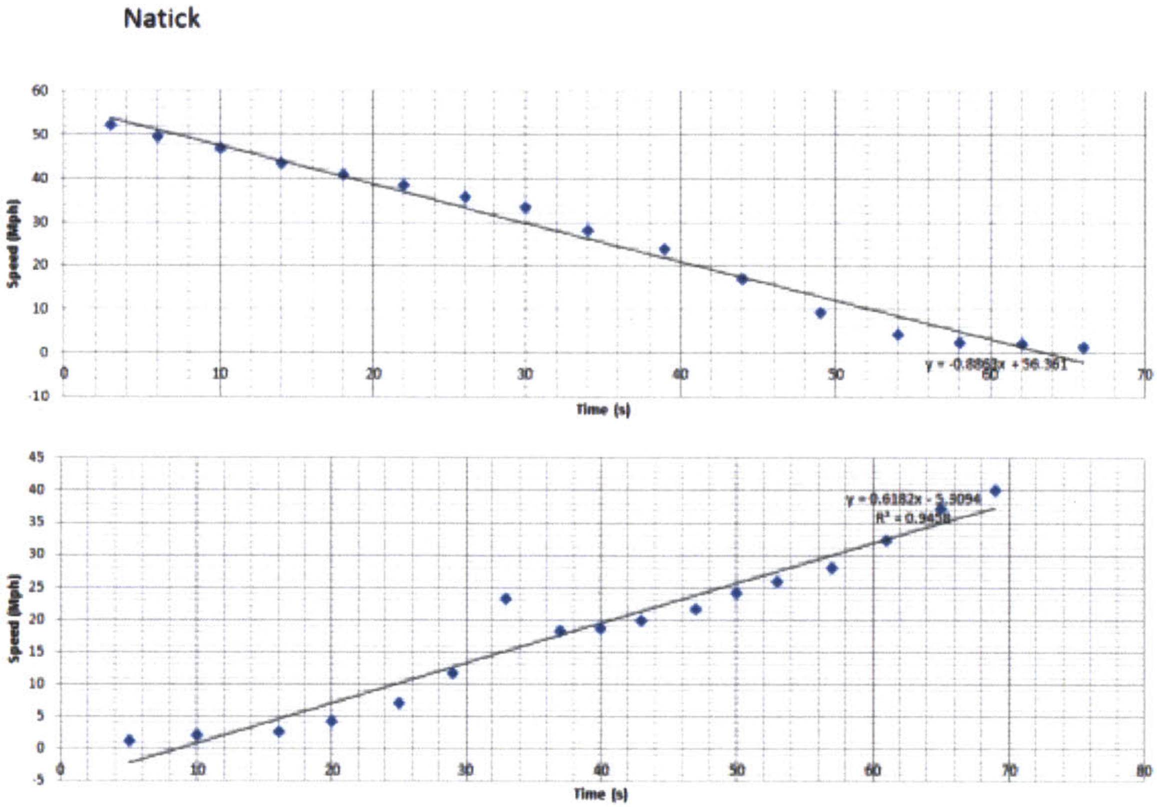
Worcester-Grafton	23-57
Grafton-Westborough	55
Westborough-Southborough	57
Southborough-Ashland	55
Ashland-Framingham	50
Framingham-West Natick	30
West Natick-Natick	50
Natick-Wellesley Sq	55
Wellesley Sq-Wellesley Hills	55
Wellesley Hills-Wellesley Farms	50
Wellesley Farms-Auburndale	57
Auburndale-West Newton	50
West Newton-Newtonville	50
Newtonville-Boston University	57
Boston University-MIT	25-10
MIT-North station	25-10

As seen in Figure 12 of the entire journey, trains that approach Worcester from Grafton reduce their speed for several miles, so for the model the Worcester-Grafton segment was broken down into two with the segment closer to Worcester having a maximum speed of 23 mph and the rest of the segment having a maximum speed of 57 mph. For the Grand Junction segment between North Station and the proposed station for Boston University in Beacon Yard the maximum speeds were set at 10 mph and 25 mph. The curved sections into and out of the Grand Junction in Cambridge are limited to 10 mph due to the sharp turning radii and the estimated maximum speed along the length of the corridor is 25 mph due to the track conditions and multiple grade crossing. Along with the curves, the approach into North Station is also limited to 10 mph in the model. For the purposes of this report, these speeds offer good conservative estimates that can improve in the future. Track and signaling improvements, combined with proper vehicle performance could increase the speeds, reducing travel time and improving the service along the Grand Junction.

5.4.2 Acceleration and Deceleration

To estimate commuter train acceleration and decelerations from the GPS data the data points that corresponding to vehicle movements in and out of stations on a time vs speed chart were graphed. A linear approximation of each was extrapolated using Excel trend lines. The procedure was performed for the ten stations between Wellesley Farms and Grafton. The slope of the lines of each acceleration and deceleration chart represents the value of acceleration or deceleration for that station. Figure 13 represents an example of the acceleration and decelerations at Natick. The chart for deceleration is on top and the chart for acceleration is on the bottom.

Figure 13: Sample Acceleration/Deceleration Graph



The acceleration and deceleration values for each of the 10 stations are summarized in Table 5. The charts for each station can be seen in the appendix. Having these values allows calculation of the average acceleration and deceleration for commuter trains that can be input into the model developed in section 5.1.

Table 5: Commuter Train Acceleration/Deceleration by station

Station	Acceleration (mph/s)	Deceleration (mph/s)
Wellesley Farms	0.62	-1.03
Wellesley Hills	0.67	-0.87
Wellesley Square	0.97	-0.86
Natick	0.62	-0.89
West Natick	0.70	-0.84
Framingham	0.48	-0.87
Ashland	0.76	-0.82
Southborough	0.60	-0.57
Westborough	1.08	-1.28
Grafton	0.63	-0.96
Average	0.71	-0.90

As discussed earlier, the model inputs for acceleration and deceleration for DMUs are taken from the table supplied by US Railcar in Table 3. In segments where train speeds are less than 46 mph (the lowest provided in the table), a constant acceleration based on a linear approximation of the required time for the DMU to reach 46 mph will be used. The value of the distance required to reach that speed will be calculated using the kinematic equations developed in the model creation. The deceleration value will be a constant provided by the US Railcar. Based on this constant deceleration, corresponding stopping times and distances will be calculated using the kinematic equations.

5.4.3 Dwell Times

Over the course of the data collection trip, various dwell times were recorded. The input for commuter train dwell time is an average of all total dwell times measured during the real trip from South Station to Worcester. Dwell time on the commuter rail network is dependent on several factors including boardings, alightings, door configuration, manpower on the train, and platform configuration. Most train operations on the MBTA commuter rail network have manual door operation which means that conductors must open the doors to allow passengers to board and exit the train. This procedure takes longer when the station has a low level platform because door traps that are used in high level boardings must lifted to allow stair access. Stair access and door width does not allow for simultaneous boarding and alighting. To add to this, current coach cars have only two end doors on each car which also contributes to dwell time.

Measured dwell times varied considerably from about 20 seconds up to 1 minute and 30 seconds. Particular dwell times could not be associated to specific stops as different trips have a variety of dwell times for the same stops. The average dwell time value calculated from the dwell time data for commuter trains was 46.6 seconds. For DMUs a dwell time of 30 seconds was estimated in the schedule model. DMUs, like conventional trains, allow low and high level platform access but have a wide center door with automatic operation. The reduced dwell time benefits of the wide automatic doors will be more significant at high level platforms slated to be built in on the Worcester Line in the future. Another factor that could significantly improve dwell time and performance across the entire commuter rail network, regardless of the type of vehicle, is automatic fare collection such as the one that exists on the MBTA bus and subway network.

5.5 Validation of Model

Using the average values of acceleration and deceleration for commuter trains, the maximum speeds between each pair of stations, and the dwell time for commuter trains as inputs to the Excel spreadsheet model, it is possible to compare the model predictions of travel time to those observed in the field. The travel time between each set of stations between Wellesley Hills and Worcester was compared, and it is summarized in Table 6. Some of the predicted travel times were longer than the real times and some were shorter. The result for the model estimate was a total travel time difference of just 18 seconds between Worcester and Wellesley Hills. Considering the small differences it is concluded that the schedule model is adequate to predict commuter train performance. The model can be applied to the Grand Junction alternatives that have been proposed to derive maximum frequencies, headways, and create possible schedule alternatives.

Table 6: Validation Travel Times

Station	**Model time (mm:ss)**	**Real time (mm:ss)**	**Difference**
Worcester	14:22	14:32	00:10
Grafton	04:52	04:29	-00:23
Westborough	09:00	08:48	-00:12
Southborough	04:43	04:33	-00:10
Ashland	06:24	06:41	00:17
Framingham	04:09	04:31	00:22
West Natick	04:39	05:01	00:22
Natick	05:24	05:43	00:19
Wellesley Sq	03:30	03:08	-00:22
Wellesley Hills	03:06	03:01	-00:05
		Total difference (mm:ss)	00:18

5.6 Model Example

Figure 14: Model Example

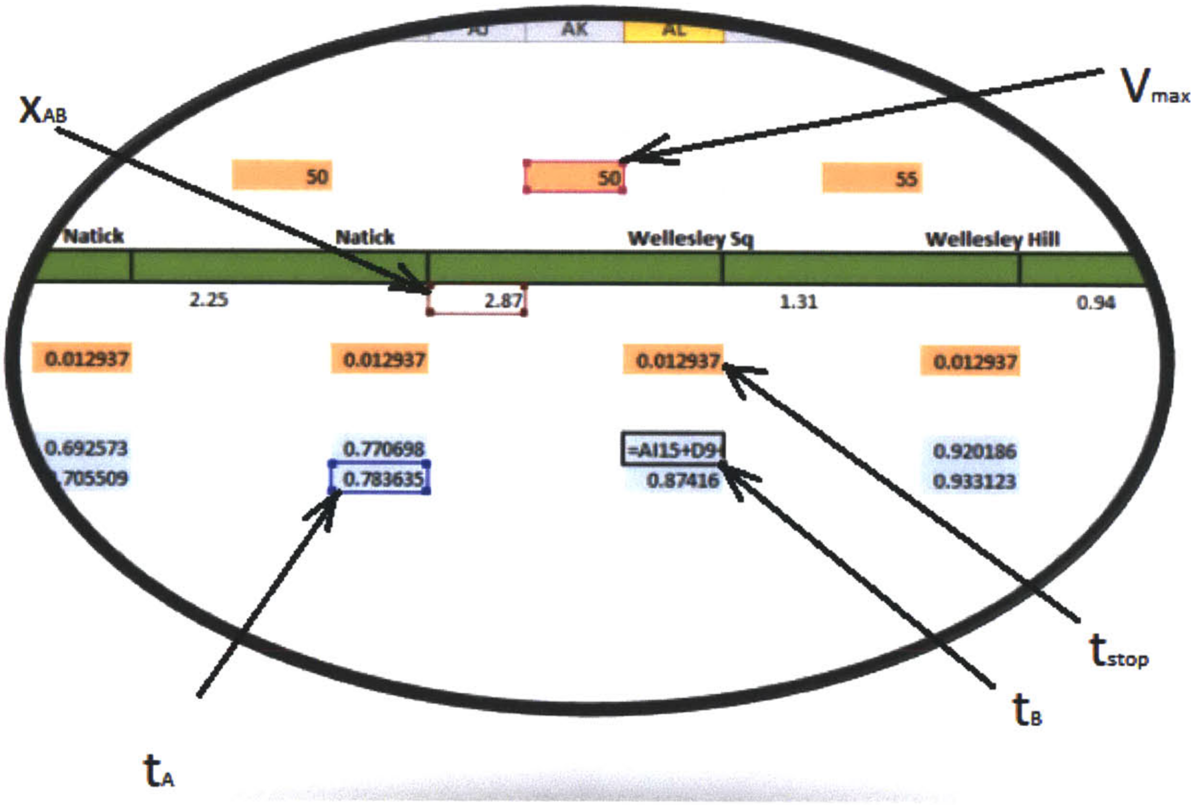


Figure 14 represents an example portion of the spreadsheet model between Natick and Wellesley Square stations. The green portion is used to visualize the double track portions of the track with each station separated by a few cells – the distance between stations is not scaled to represent actual distances but x_{ab} is the input for distance between stations. The blue cells represent the time of arrival and departure at certain station – the lower number, t_a, is the time of departure and the upper number, t_b, is the time of arrival. The dwell time, t_{stop}, is located in the red cell below the station name. All times are represented as decimal fractions of an hour. V_{max} for each segment is input above each segment in the red cell. It can be seen that the arrival time at Wellesley Square is the time when the train left Natick plus the time needed to accelerate the train, the time spent at V_{max}, and the time needed to decelerate the train.

For this particular example the acceleration and deceleration values calculated are:

Acceleration	0.58	Mph/s
Deceleration	0.85	Mph/s

Using the acceleration and deceleration values along with the kinematic equations to describe the train motion tables for time (in decimal fractions of an hour) and distance (in miles) could be obtained for a set of speeds in Table 7 and Table 8.

Table 7: Acceleration Example

Speed (mph)	Time (hr)	Distance (mi)
10	0.005	0.024
25	0.012	0.15
35	0.017	0.29
45	0.021	0.49
50	0.023	0.6
55	0.026	0.72
57	0.027	0.78

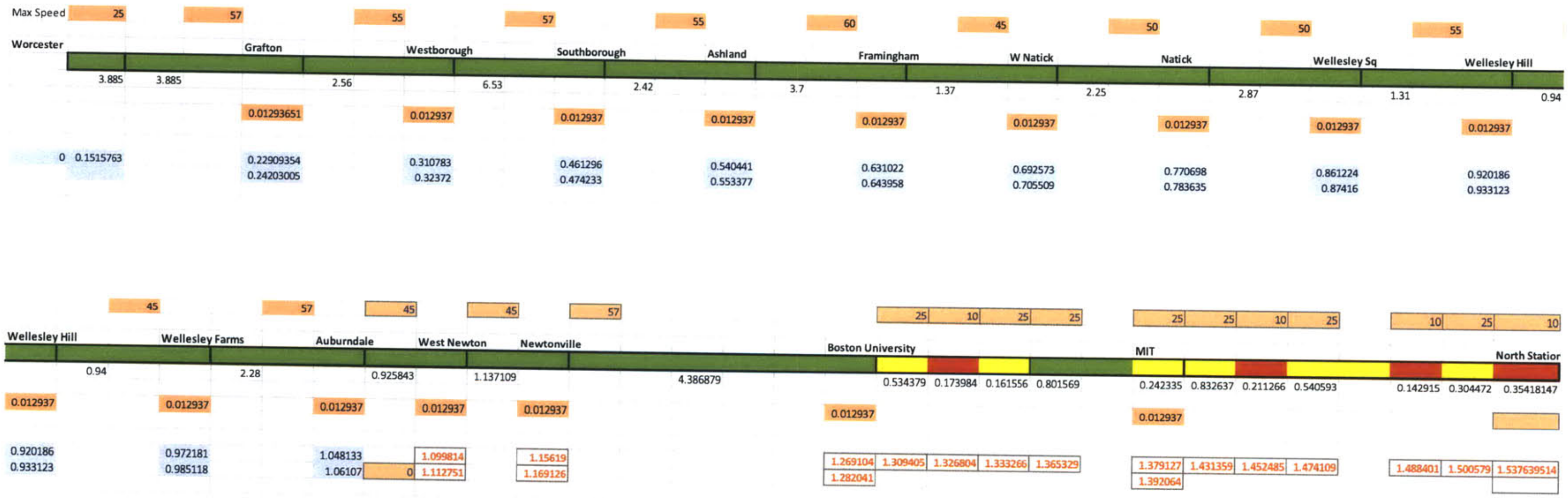
Table 8: Deceleration Example

Speed (mph)	Time (hr)	Distance (mi)
10	0.003	0.01
25	0.008	0.1
35	0.011	0.2
45	0.014	0.33
50	0.016	0.41
55	0.018	0.5
57	0.019	0.53

The inputs for this example are:
t_A = Departure time from Natick= 0.78 hr
Time required to accelerate up to 50 mph= 0.024 hr
Time required to decelerate from 50 to 0 mph= 0.016 hr
x_{AB}= Distance between Natick and Wellesley Sq= 2.87 mi
Distance required to accelerate up to 50 mph= 0.60 mi
Distance required to decelerate from 50 to 0 mph= 0.41 hr
V_{max}= 50 mph

Repeating the procedure outlined in this example for every segment of the route gives a model for the complete line. Once the complete sheet for a train line is built, the initial departure time from Worcester is added and the spreadsheet provides travel times to each station. Figure 15 shows the entire model with all the parameters shown: distances below each segment, max speeds above, dwell times in red below the stations and arrival and departure times in blue. Following the model is a discussion of the single track modeling procedures. The yellow and red portions of track in the model represent Grand Junction.

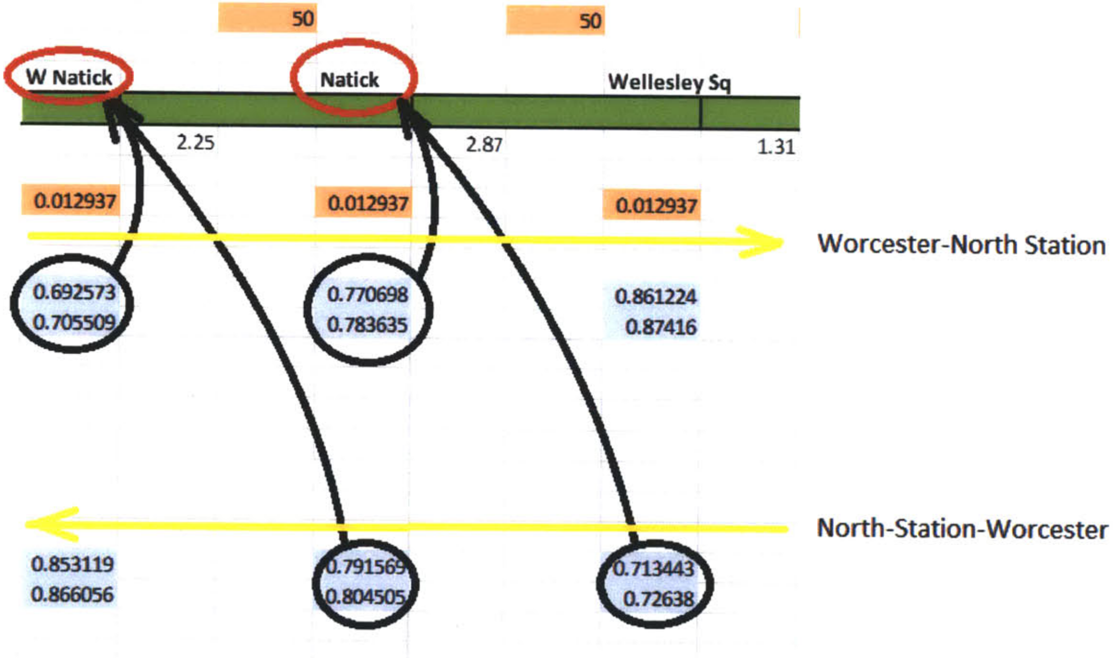
Figure 15: Schedule Model



5.7 Modeling of Grand Junction Single Track Operation

To analyze single track restriction a model that can calculate the travel times in the same line, but for two different directions simultaneously is required. This is fairly straightforward and only requires different cell references in the spreadsheet model. Figure 16 is an illustration of both directions, with the top representing the inbound Worcester to North Station direction and the bottom representing outbound trains.

Figure 16: Example of Schedule Model



The cells in blue represent the different arrival and departure times to different stations. Inbound times increase going right and outbound times increase going to the left. Black arrows represent the stations related to the time values of the blue cells. By introducing initial departure times at each terminal station, the model will predict where each train will be at a certain time. Overlap may occur in the Grand Junction and is dealt with using some "if" statements and waiting conditions.

Figure 17: Single Track Schedule Model Illustration

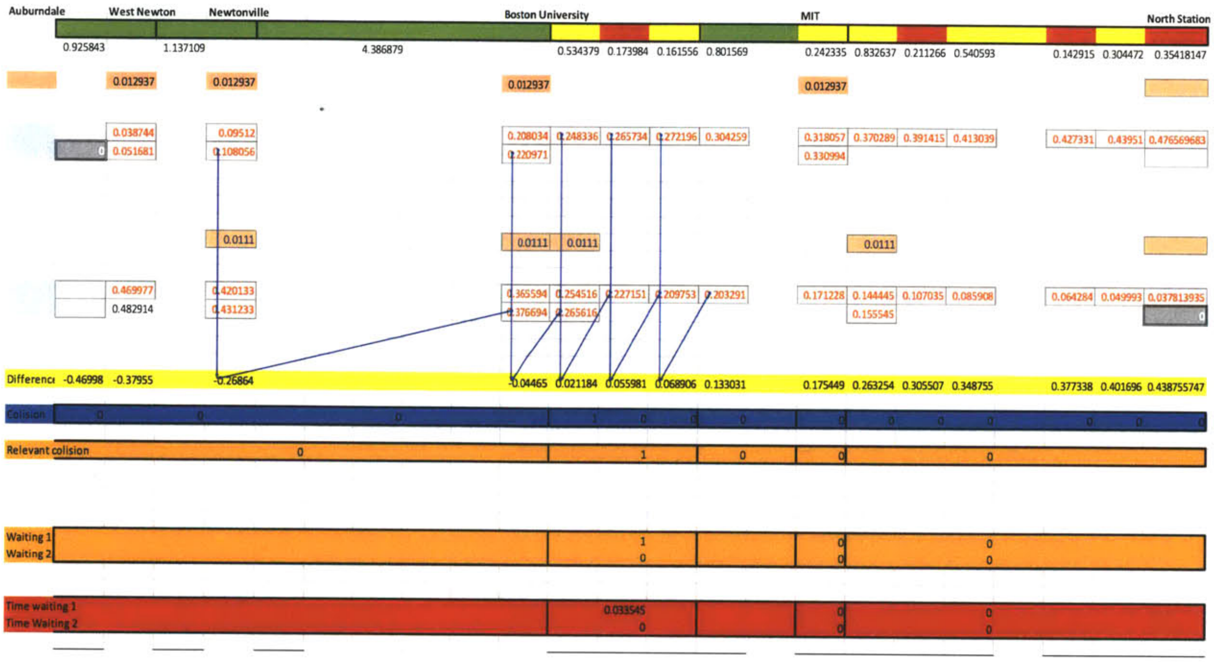


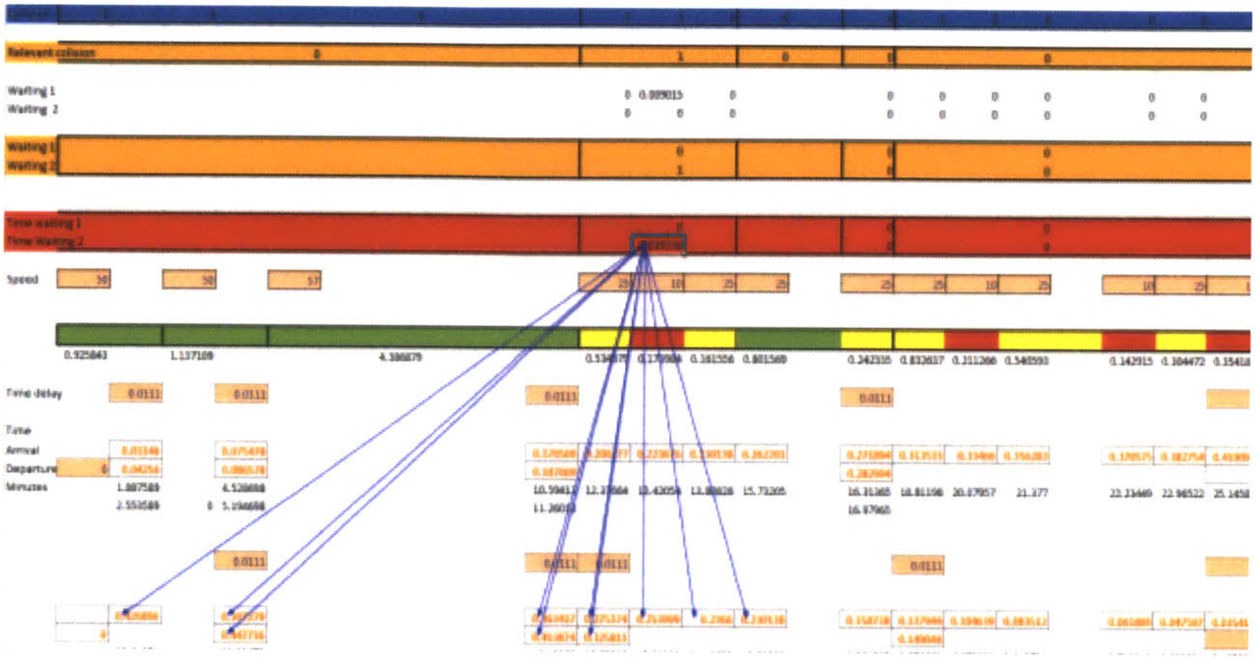
Figure 17 represents a complete line between Auburndale and North Station in both directions. On the top, stations are represented above a green-yellow-red cells line. Green color represents double track line parts, while yellow and red represent single track parts limited to a 25 and 10 mph speed limit, respectively.

The yellow cells line, labeled as "Difference", represents the difference between the time values of departure cells for the same places for trains in both directions. As it can be seen, differences are negative until they reach certain cell, where the sign turns positive. When the sign changes, it means that it is the part of the track where both trains meet. If this happens under a green portion there is no problem, since it is a double track part.

When the change of sign happens in a part of a single line track, an "if" condition will put a '1' in the blue line, labeled "Collision", under the corresponding part of the track where the collision is going to happen. Train signaling will prevent two trains from entering the single track segment in opposite direction and priority will be given to the train that goes into the single track part first.

Waiting time for the waiting trains are calculated in the red cells. It is assumed that once the track is clear it can immediately be occupied by the waiting train. All waiting time restrictions are added to the original unrestricted schedule.

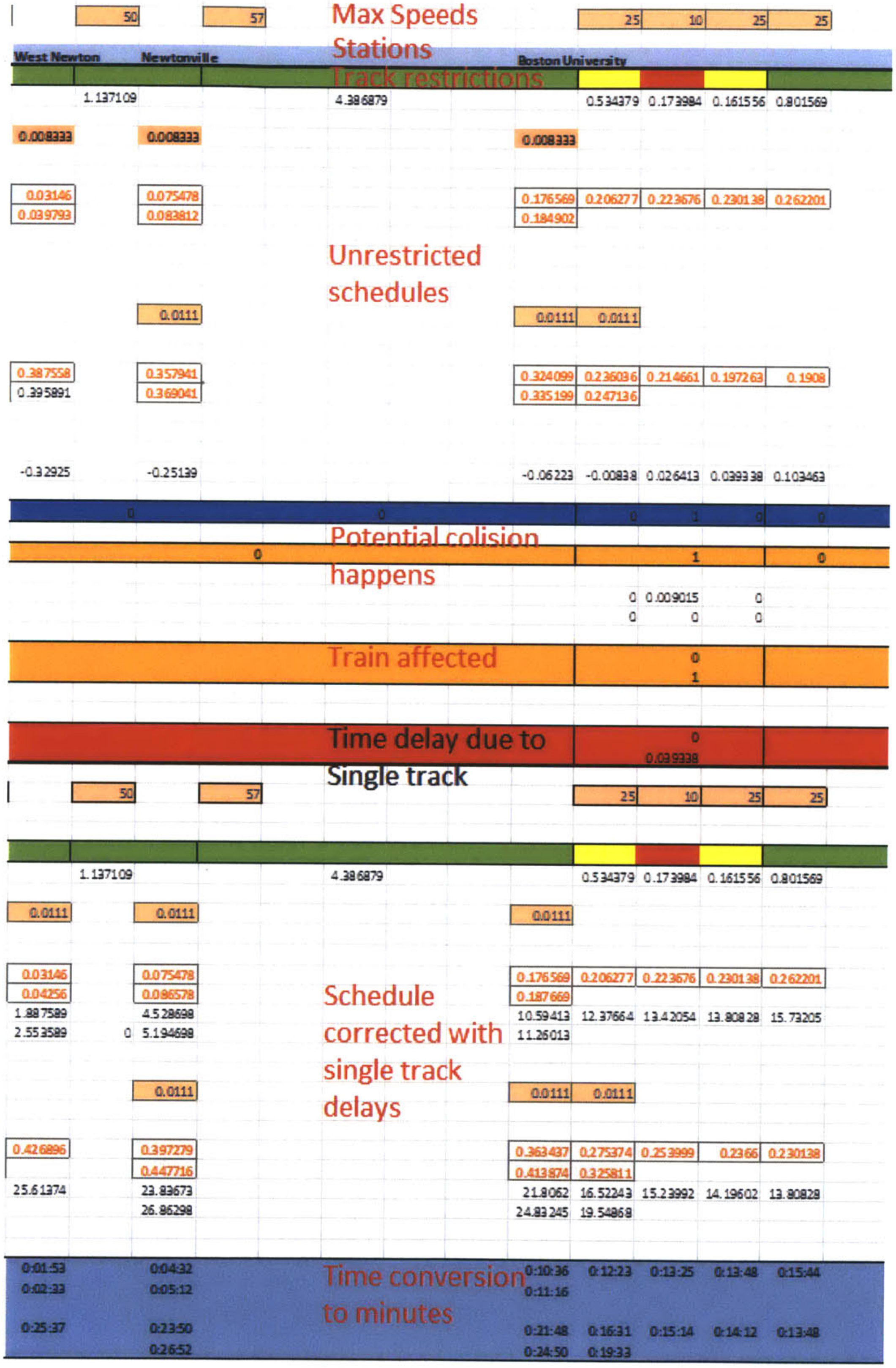
Figure 18: Illustration of Waiting Time in Model



In the example in Figure 18, it can be seen that there is a number in the second red row. It means that the outbound train has a delay due to single track restrictions, because the inbound Auburndale-NS train arrives first to a single track path.

The wait time is 0.039 hours (2 min, 20 seconds) and is added to every station in advance to indicate this delay. The complete model sheet in the single track portion of the track is therefore a two-step process, calculating unrestricted travel times which are then adjusted if a collision is predicted by the model. Wait time are added accordingly to produce the model seen in Figure 19.

Figure 19: Single Track Delay Illustration



	50		57	Max Speeds		25	10	25	25
West Newton		Newtonville		Stations	Boston University				
🟩	🟩	🟩	🟩	Track restrictions	🟩	🟨	🟥	🟨	🟩
	1.137109			4.386879		0.534379	0.173984	0.161556	0.801569
0.008333		0.008333			0.008333				
0.03146		0.075478			0.176569	0.206277	0.223676	0.230138	0.262201
0.039793		0.083812			0.184902				
				Unrestricted schedules					
		0.0111			0.0111	0.0111			
0.387558		0.357941			0.324099	0.236036	0.214661	0.197263	0.1908
0.395891		0.369041			0.335199	0.247136			
-0.32925		-0.25139			-0.06223	-0.00838	0.026413	0.039338	0.103463
	0			0		0	1	0	0
			0	Potential colision happens			1		0
						0	0.009015	0	
						0	0	0	
				Train affected			0 1		
				Time delay due to Single track			0 0.039338		
	50		57			25	10	25	25
🟩	🟩	🟩	🟩		🟩	🟨	🟥	🟨	🟩
	1.137109			4.386879		0.534379	0.173984	0.161556	0.801569
0.0111		0.0111			0.0111				
0.03146		0.075478			0.176569	0.206277	0.223676	0.230138	0.262201
0.04256		0.086578			0.187669				
1.887589		4.528698		Schedule corrected with single track delays	10.59413	12.37664	13.42054	13.80828	15.73205
2.553589	0	5.194698			11.26013				
		0.0111			0.0111	0.0111			
0.426896		0.397279			0.363437	0.275374	0.253999	0.2366	0.230138
		0.447716			0.413874	0.325811			
25.61374		23.83673			21.8062	16.52243	15.23992	14.19602	13.80828
		26.86298			24.83245	19.54868			
0:01:53		0:04:32		Time conversion to minutes	0:10:36	0:12:23	0:13:25	0:13:48	0:15:44
0:02:33		0:05:12			0:11:16				
0:25:37		0:23:50			0:21:48	0:16:31	0:15:14	0:14:12	0:13:48
		0:26:52			0:24:50	0:19:33			

6 Model Application

To determine the maximum frequencies, minimum headways, and minimum travel times the spreadsheet model is applied to the alternatives outlined in Section 4.3.

6.1 Auburndale-North Station Alternative

This alternative, referred to as the short route alternative, will have 6 stations. Auburndale, West Newton, Newtonville and North Station are existing stations and two new proposed stations are Boston University and Kendall Square/MIT. Three train consist configurations are considered, each having slightly different performance characteristics (as shown in the acceleration table provided by US Railcar in Table 3): DMUs with 2 powered cars and 1 trailer car, DMUs with 1 powered car and 1 trailer car, DMUs with 1 powered car and 2 trailer cars. All train configurations are with single level cars. It is assumed that all stations are double track including the Kendall Square/MIT station that it is currently in a single track segment.

The model was used to estimate the maximum frequencies along the route in the AM peak hours assuming that North Station has enough capacity to absorb all services to and from Auburndale. The existing Worcester line schedule is taken into account to minimize impact of the DMU service on current operations.

Several limitations become evident from the model. Since the required time for a DMU to go from Kendall to North Station is about 8-9 minutes, frequency on the entire route is limited by this portion of single track. In order to reduce the number of interruptions due to single track restrictions, terminal departure times are offset. This means that if the first train from Auburndale departed at 6:08 AM, then first train from North Station should depart at 6:13 AM. With this offset of 5 minutes, the service becomes stable and there are limited interruptions of inbound service forcing the train to wait at the Kendall Square station before moving on to North Station. The model also predicts shorter travel times in the outbound direction from North Station to Auburndale because of the track configuration. The goal of the model is to determine maximum frequencies in the two directions combined. In a real world application, outbound service may be less regular which leads to equipment movement issues and scheduling issues that are beyond the scope of this analysis.

With these restrictions, maximum service could be offered every 12 minutes in each direction. Sample inbound schedules and time space diagrams for each consist mix considered are shown below in Tables 9-11 and Figures 21-23. The predicted headways and travel times can be seen in each.

Table 9: Example Inbound DMU Schedule; 2 powered cars + 1 trailer car

Auburndale	6:08:00 AM	6:20:00 AM	6:32:00 AM	6:44:00 AM	6:56:00 AM	7:08:00 AM	7:20:00 AM	7:32:00 AM	7:44:00 AM	7:56:00 AM	8:08:00 AM	8:20:00 AM	8:32:00 AM
West Newton	6:09:46 AM	6:21:46 AM	6:33:46 AM	6:45:46 AM	6:57:46 AM	7:09:46 AM	7:21:46 AM	7:33:46 AM	7:45:46 AM	7:57:46 AM	8:09:46 AM	8:21:46 AM	8:33:46 AM
Newtonville	6:13:30 AM	6:25:30 AM	6:37:30 AM	6:49:30 AM	7:01:30 AM	7:13:30 AM	7:25:30 AM	7:37:30 AM	7:49:30 AM	8:01:30 AM	8:13:30 AM	8:25:30 AM	8:37:30 AM
Boston University	6:19:24 AM	6:31:24 AM	6:43:24 AM	6:55:24 AM	7:07:24 AM	7:19:24 AM	7:31:24 AM	7:43:24 AM	7:55:24 AM	8:07:24 AM	8:19:24 AM	8:31:24 AM	8:43:24 AM
MIT	6:25:29 AM	6:37:29 AM	6:49:29 AM	7:01:29 AM	7:13:29 AM	7:25:29 AM	7:37:29 AM	7:49:29 AM	8:01:29 AM	8:13:29 AM	8:25:29 AM	8:37:29 AM	8:49:29 AM
North station	6:42:37 AM	6:54:37 AM	7:06:37 AM	7:18:37 AM	7:30:37 AM	7:42:37 AM	7:54:37 AM	8:06:37 AM	8:18:37 AM	8:30:37 AM	8:42:37 AM	8:54:37 AM	9:06:37 AM

Figure 20: Example Time vs. Space Plot; 2 powered cars + 1 trailer car

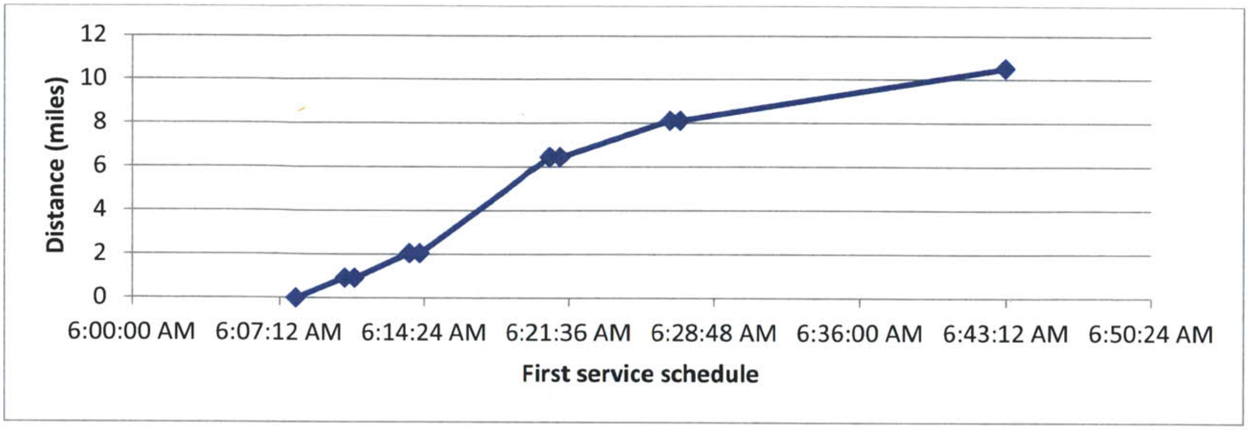


Table 10: Example Inbound DMU Schedule; 1 powered car + 2 trailer cars

Auburndale	6:08:00 AM	6:20:00 AM	6:32:00 AM	6:44:00 AM	6:56:00 AM	7:08:00 AM	7:20:00 AM	7:32:00 AM	7:44:00 AM	7:56:00 AM	8:08:00 AM	8:20:00 AM	8:32:00 AM
West Newton	6:10:02 AM	6:22:02 AM	6:34:02 AM	6:46:02 AM	6:58:02 AM	7:10:02 AM	7:22:02 AM	7:34:02 AM	7:46:02 AM	7:58:02 AM	8:10:02 AM	8:22:02 AM	8:34:02 AM
Newtonville	6:14:29 AM	6:26:29 AM	6:38:29 AM	6:50:29 AM	7:02:29 AM	7:14:29 AM	7:26:29 AM	7:38:29 AM	7:50:29 AM	8:02:29 AM	8:14:29 AM	8:26:29 AM	8:38:29 AM
Boston University	6:20:43 AM	6:32:43 AM	6:44:43 AM	6:56:43 AM	7:08:43 AM	7:20:43 AM	7:32:43 AM	7:44:43 AM	7:56:43 AM	8:08:43 AM	8:20:43 AM	8:32:43 AM	8:44:43 AM
MIT	6:26:54 AM	6:38:54 AM	6:50:54 AM	7:02:54 AM	7:14:54 AM	7:26:54 AM	7:38:54 AM	7:50:54 AM	8:02:54 AM	8:14:54 AM	8:26:54 AM	8:38:54 AM	8:50:54 AM
North station	6:42:44 AM	6:54:44 AM	7:06:44 AM	7:18:44 AM	7:30:44 AM	7:42:44 AM	7:54:44 AM	8:06:44 AM	8:18:44 AM	8:30:44 AM	8:42:44 AM	8:54:44 AM	9:06:44 AM

Figure 21: Example Time vs. Space Plot: 1 powered car + 2 trailer car

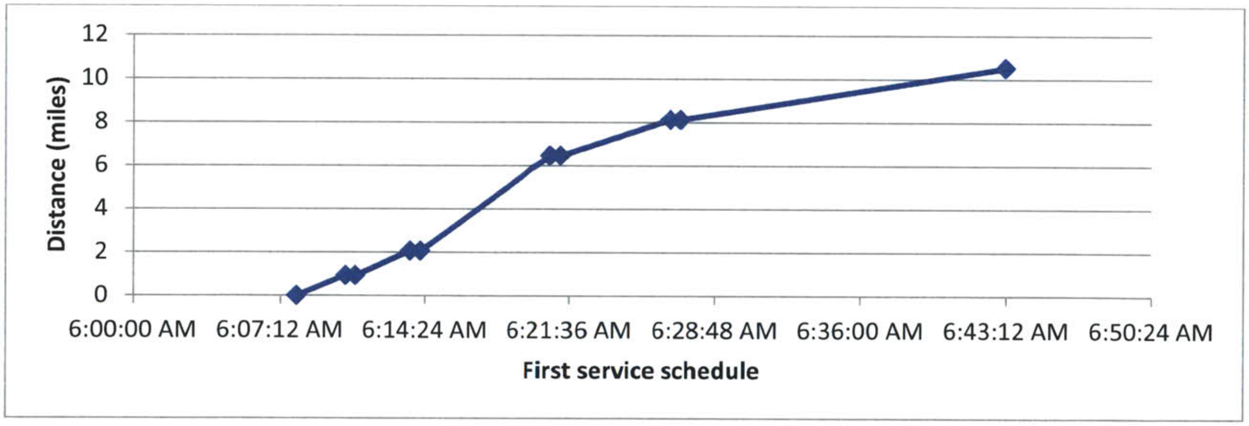
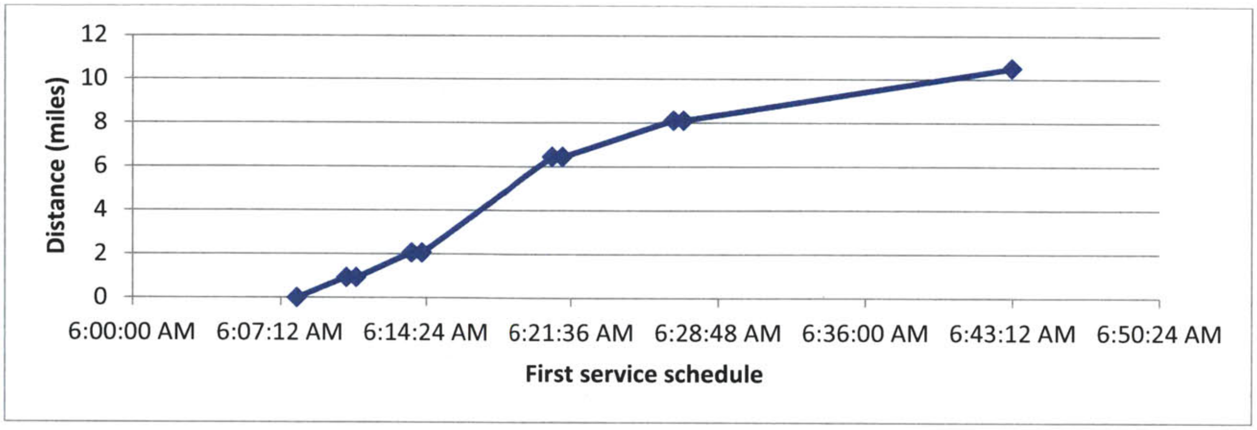


Table 11: Example Inbound DMU Schedule; 1 powered car + 1 trailer car

Auburndale	6:08:00 AM	6:20:00 AM	6:32:00 AM	6:44:00 AM	6:56:00 AM	7:08:00 AM	7:20:00 AM	7:32:00 AM	7:44:00 AM	7:56:00 AM	8:08:00 AM	8:20:00 AM	8:32:00 AM
West Newton	6:10:27 AM	6:22:27 AM	6:34:27 AM	6:46:27 AM	6:58:27 AM	7:10:27 AM	7:22:27 AM	7:34:27 AM	7:46:27 AM	7:58:27 AM	8:10:27 AM	8:22:27 AM	8:34:27 AM
Newtonville	6:13:42 AM	6:25:42 AM	6:37:42 AM	6:49:42 AM	7:01:42 AM	7:13:42 AM	7:25:42 AM	7:37:42 AM	7:49:42 AM	8:01:42 AM	8:13:42 AM	8:25:42 AM	8:37:42 AM
Boston University	6:20:14 AM	6:32:14 AM	6:44:14 AM	6:56:14 AM	7:08:14 AM	7:20:14 AM	7:32:14 AM	7:44:14 AM	7:56:14 AM	8:08:14 AM	8:20:14 AM	8:32:14 AM	8:44:14 AM
MIT	6:26:38 AM	6:38:38 AM	6:50:38 AM	7:02:38 AM	7:14:38 AM	7:26:38 AM	7:38:38 AM	7:50:38 AM	8:02:38 AM	8:14:38 AM	8:26:38 AM	8:38:38 AM	8:50:38 AM
North station	6:43:10 AM	6:55:10 AM	7:07:10 AM	7:19:10 AM	7:31:10 AM	7:43:10 AM	7:55:10 AM	8:07:10 AM	8:19:10 AM	8:31:10 AM	8:43:10 AM	8:55:10 AM	9:07:10 AM

Figure 22: Example Time vs. Space Plot; 1 powered car + 1 trailer car



Columns in red indicate a service that should be removed due to compatibility restrictions with the current Worcester-South Station scheduled services. Columns in orange indicate a service that could be delayed about 5 minutes for compatibility restrictions with the current Worcester-South Station scheduled services. These compatibility issues would be resolved in a real application to reduce delays but do not prevent the model from providing realistic travel times based on existing conditions. Lower frequency service alternatives were also calculated, the results for those are summarized in Section 6.3.

The calculated travel times from Auburndale to North Station for each consist mix were:

DMUs with 2 Power cars and 1 trailer car	34 min 37 sec
DMUs with 1 Power car and 1 trailer car	34 min 44 sec
DMUs with 1 Power car and 2 trailer cars	35 min 10 sec

Based on these travel times and the passenger capacity of each DMU, the 1 power car + 1 trailer car configuration is selected for further analysis. The total cycle time of this DMU service will be 71 minutes. The model predicts 35 minutes travel time in the inbound direction, 26 minutes in the outbound (due to the single track constraint this is shorter), and 5 minutes of layover is added at each terminal station. With this cycle time and 12 minute headways, 6 DMU trains will be required for the service. The cycle time calculation is based on the equation:

$$c = n \times h \rightarrow n = \frac{71}{12} = 5.92\ trains \rightarrow 6\ trains\ , where$$

c is the cycle time, n is the number of vehicles, and h is the headway – the answer is rounded up to the nearest number of vehicles. A lower frequency service was also calculated and summarized in Section 6.3.

Conclusions:

- There are no significant differences between the different DMU configurations, since the speeds on most segments of the Auburndale-North Station line are low, decreasing the importance of acceleration performance.

- Single track restriction is not an obstacle for a frequent service. It creates a total delay of 9 minutes for two trains in the AM peak but this delay would only affect passengers going to North Station, not Kendall. This delay could be avoided by limiting outbound service in the morning or adjusting the existing Worcester line schedules to better accommodate the new service.
- Considering the length and frequency of the alternative, further analysis will be based on a DMU consist of 1 powered car and 1 trailer car – this consist mix provides a good travel time and provides a capacity of 198 seats in two cars which is appropriate for a short route commuter service.

6.2 Worcester-North Station Alternative

The schedule model can also be applied to the Worcester-North Station line for both alternatives: Commuter rail and DMU services. Since it is a line significantly longer than Auburndale-North Station and has other MBTA and freight users that cannot be accounted for in this study, determining the maximum frequency will be based on a combination of factors. The goal again is to find the minimum number of trains that can provide the most frequent service and to estimate the travel times. Calculations will be based on the following:

- Current schedule for Worcester-North Station service will be considered for compatibility with the use of the line. This is a very conservative assumption, because if all the existing line's schedules and signals were modified more trains than predicted could be added.
- No single track restriction, since frequencies are now low enough to consider that the single track would not affect two trains simultaneously.
- Calculations were made to reach the maximum frequencies on the route during the AM peak hours assuming that North Station has enough capacity to absorb all services to and from Worcester.
- DMU dwell times are 30 seconds and commuter train dwell times are 48 seconds

6.2.1 Commuter rail results

Table 12: Example Inbound Commuter Rail Schedule - Worcester to North Station

Worcester	5:20:00 AM	5:35:00 AM	6:00:00 AM	6:25:00 AM	6:45:00 AM	8:00:00 AM	8:25:00 AM
Grafton	5:34:22 AM	5:49:22 AM	6:14:22 AM	6:39:22 AM	6:58:43 AM	8:14:22 AM	8:39:22 AM
Westborough	5:39:14 AM	5:54:14 AM	6:19:14 AM	6:44:14 AM	7:03:35 AM	8:19:14 AM	8:44:14 AM
Southborough	5:48:14 AM	6:03:14 AM	6:28:14 AM	6:53:14 AM	7:12:35 AM	8:28:14 AM	8:53:14 AM
Ashland	5:52:57 AM	6:07:57 AM	6:32:57 AM	6:57:57 AM	7:17:18 AM	8:32:57 AM	8:57:57 AM
Framingham	5:59:21 AM	6:14:21 AM	6:39:21 AM	7:04:21 AM	7:22:42 AM	8:39:21 AM	9:04:21 AM
West Natick	6:03:29 AM	6:18:29 AM	6:43:29 AM	7:08:29 AM	7:26:22 AM	8:43:29 AM	9:08:29 AM
Natick	6:08:09 AM	6:23:09 AM	6:48:09 AM	7:13:09 AM	7:31:01 AM	8:48:09 AM	9:13:09 AM
Wellesley Sq	6:13:33 AM	6:28:33 AM	6:53:33 AM	7:18:33 AM	7:36:25 AM	8:53:33 AM	9:18:33 AM
Wellesley Hills	6:17:03 AM	6:32:03 AM	6:57:03 AM	7:22:03 AM	7:39:56 AM	8:57:03 AM	9:22:03 AM
Wellesley Farms	6:20:09 AM	6:35:09 AM	7:00:09 AM	7:25:09 AM	7:43:01 AM	9:00:09 AM	9:25:09 AM
Auburndale	6:24:40 AM	6:39:40 AM	7:04:40 AM	7:29:40 AM	7:47:33 AM	9:04:40 AM	9:29:40 AM
West Newton	6:27:45 AM	6:42:45 AM	7:07:45 AM	7:32:45 AM	7:50:37 AM	9:07:45 AM	9:32:45 AM
Newtonville	6:31:06 AM	6:46:06 AM	7:11:06 AM	7:36:06 AM	7:53:59 AM	9:11:06 AM	9:36:06 AM
Boston University	6:37:51 AM	6:52:51 AM	7:17:51 AM	7:42:51 AM	8:00:43 AM	9:17:51 AM	9:42:51 AM
MIT	6:44:26 AM	6:59:26 AM	7:24:26 AM	7:49:26 AM	8:07:18 AM	9:24:26 AM	9:49:26 AM
North station	6:53:56 AM	7:08:56 AM	7:33:56 AM	7:58:56 AM	8:16:49 AM	9:33:56 AM	9:58:56 AM

The result for commuter rail is a total travel time of 1 hour, 34 minutes to North Station, seen in the example schedule in Table 12. The average frequency is one train every 31 minutes. The frequency is an average because compatibility with the existing schedule creates uneven headways. There is a service at 5:35 AM, just 15 minutes after the first service in the morning, but there is another gap of one hour and 15 minutes after 6:45 service. Eliminating these gaps will require the Worcester line schedule to be adjusted to accommodate the new service.

The travel time of 1 hour and 34 minute is predicted to be the same in the inbound and outbound directions for this service. Adding 10 minutes layover time at North Station and 15 minutes at Worcester, results in a total cycle time for the service of 213 minutes. At 31 minute headways, the number of trains required for this service will be 7. The calculation depends on the formula below, where c is the cycle time, n in the number of vehicles, and h is the headway:

$$c = n \times h \rightarrow n = \frac{213}{31} = 6.87 \; trains \rightarrow 7 \; trains$$

Future accommodation of the new service would be vital in improving the headway irregularities and increasing passenger reliability and the desirability of the service. A service with lower frequencies, longer headways, and the number of trains required is also calculated using the model and summarized in Section 6.3.

6.2.2 DMU results

The DMU combination used for Worcester-North Station was 2 single level powered cars with 1 single lever trailer car. This consist configuration has 292 seats and offers better performance characteristics than conventional trains and the larger DMU configurations that data was provided for in Table 3. The passenger capacity of this three car train can potentially be increased by using double decker coaches or DMUs but performance data for those configurations was not available for this study. The configuration was chosen considering that demand for Kendall and North Station service would likely be lower than the existing services to South Station – at least in the early stages of the service. Providing fewer seats on smaller trains would have the benefit of high occupancy levels and decreased negative impacts along the dense residential corridor in Cambridge. Based on the performance characteristics of the 2 powered cars + 1 trailer car configuration the sample schedule shown in Table 13 was generated.

Table 13: Example DMU Schedule - Worcester to North Station

Worcester	5:20:00 AM	5:35:00 AM	6:00:00 AM	6:25:00 AM	6:50:00 AM	8:00:00 AM	8:25:00 AM
Grafton	5:33:09 AM	5:48:09 AM	6:13:09 AM	6:38:09 AM	7:03:09 AM	8:13:09 AM	8:38:09 AM
Westborough	5:37:12 AM	5:52:12 AM	6:17:12 AM	6:42:12 AM	7:07:12 AM	8:17:12 AM	8:42:12 AM
Southborough	5:45:21 AM	6:00:21 AM	6:25:21 AM	6:50:21 AM	7:15:21 AM	8:25:21 AM	8:50:21 AM
Ashland	5:49:14 AM	6:04:14 AM	6:29:14 AM	6:54:14 AM	7:19:14 AM	8:29:14 AM	8:54:14 AM
Framingham	5:54:50 AM	6:09:50 AM	6:34:50 AM	6:59:50 AM	7:24:50 AM	8:34:50 AM	8:59:50 AM
West Natick	5:58:31 AM	6:13:31 AM	6:38:31 AM	7:03:31 AM	7:28:31 AM	8:38:31 AM	9:03:31 AM
Natick	6:02:22 AM	6:17:22 AM	6:42:22 AM	7:07:22 AM	7:32:22 AM	8:42:22 AM	9:07:22 AM
Wellesley Sq	6:09:45 AM	6:24:45 AM	6:49:45 AM	7:14:45 AM	7:39:45 AM	8:49:45 AM	9:14:45 AM
Wellesley Hills	6:12:26 AM	6:27:26 AM	6:52:26 AM	7:17:26 AM	7:42:26 AM	8:52:26 AM	9:17:26 AM
Wellesley Farms	6:14:43 AM	6:29:43 AM	6:54:43 AM	7:19:43 AM	7:44:43 AM	8:54:43 AM	9:19:43 AM
Auburndale	6:18:24 AM	6:33:24 AM	6:58:24 AM	7:23:24 AM	7:48:24 AM	8:58:24 AM	9:23:24 AM
West Newton	6:20:40 AM	6:35:40 AM	7:00:40 AM	7:25:40 AM	7:50:40 AM	9:00:40 AM	9:25:40 AM
Newtonville	6:24:24 AM	6:39:24 AM	7:04:24 AM	7:29:24 AM	7:54:24 AM	9:04:24 AM	9:29:24 AM
Boston University	6:30:18 AM	6:45:18 AM	7:10:18 AM	7:35:18 AM	8:00:18 AM	9:10:18 AM	9:35:18 AM
MIT	6:36:23 AM	6:51:23 AM	7:16:23 AM	7:41:23 AM	8:06:23 AM	9:16:23 AM	9:41:23 AM
North station	6:45:27 AM	7:00:27 AM	7:25:27 AM	7:50:27 AM	8:15:27 AM	9:25:27 AM	9:50:27 AM

In this case, total travel time is 1 hour, 26 minutes, 8 minutes faster than the commuter train travel time, resulting in a similar schedule to the one in Table 12. Average frequency is one DMU train every 31 minutes, the same as commuter trains – this again is governed by compatibility with the existing Worcester Line schedule.

The schedule model estimates that outbound travel times will be the same as the inbound travel times, resulting in a total running time of 172 minutes. Adding 10 minutes for layover at North Station and 15 minutes of layover at Worcester produces a cycle time of 197 minutes. With 31 minute headways as described, 7 DMU trains will be required for this service. The calculation depends on the formula below, where c is the cycle time, n in the number of vehicles, and h is the headway:

$$c = n \times h \rightarrow n = \frac{197}{31} = 6.35\ trains \rightarrow 7\ trains$$

A lower frequency service alternative is also calculated and summarized in Section 6.3.

Conclusions

- Travel times provided by DMUs and commuters differ only by 8 minutes.
- Headways for both alternatives are the same.
- Schedule modifications to existing service could dramatically increase the reliability and attractiveness of this service.

6.3 Schedule Summary

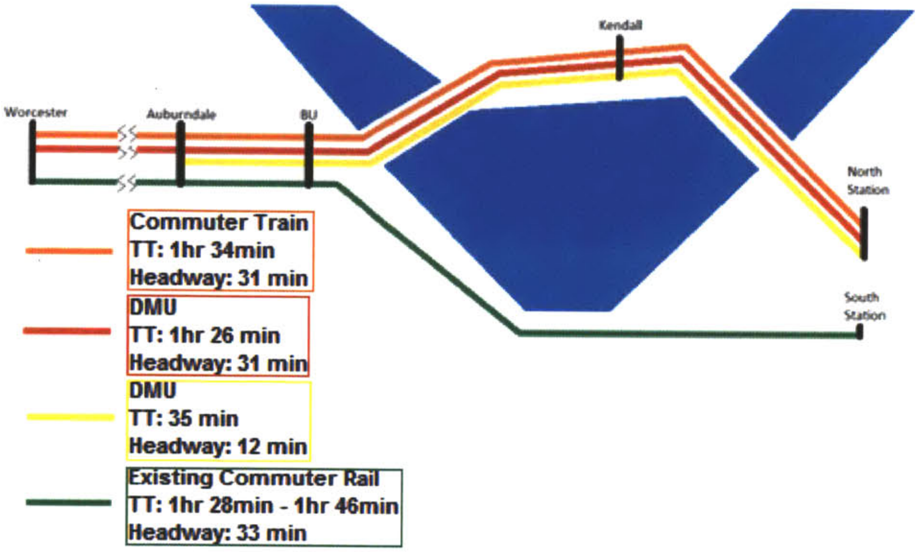
The maximum possible frequency on the short route DMU service from Auburndale to North Station is 12 minute headways with 35 min inbound travel time. For cost and demand estimation a high frequency service, requiring 6 trains, and a lower frequency service (24 minute headways), requiring 3 trains, were considered. All calculations were done as described in the previous sections.

The maximum frequency for the long route service from Worcester to North Station, for either mode, is 31 minute headways with a travel time of 1 hour 24 minutes for DMUs and 1 hour 34 minutes for conventional trains. For the cost and demand estimation a lower frequency alternatives, with 1 hour headways for DMUs and 1 hour headways for commuter trains, was considered as well. The maximum frequency service requires 7 trains, while the low frequency service requires only 4. The final alternatives are summarized in Table 14 and Figure 23 and carried forward to the cost and revenue analysis in Section 8.

Table 14: Final Alternatives for Analysis

Outbound Terminal	Train	Train Consist	# of Trains	Headway	Inbound Travel time to NS
Worcester	DMU	2 pow.+1 trailer	7	0:31	1:26
Worcester	DMU	2 pow.+1 trailer	4	1:00	1:26
Worcester	Commuter	Loco + 6 coaches	7	0:31	1:34
Worcester	Commuter	Loco + 6 coaches	4	1:00	1:34
Auburndale	DMU	1 pow.+1 trailer	6	0:12	0:35
Auburndale	DMU	1 pow.+1 trailer	3	0:24	0:35

Figure 23: Final Alternatives



7 Station Locations

7.1 Kendall/MIT Station

Figure 24: Kendall/MIT Commuter Rail Station Location

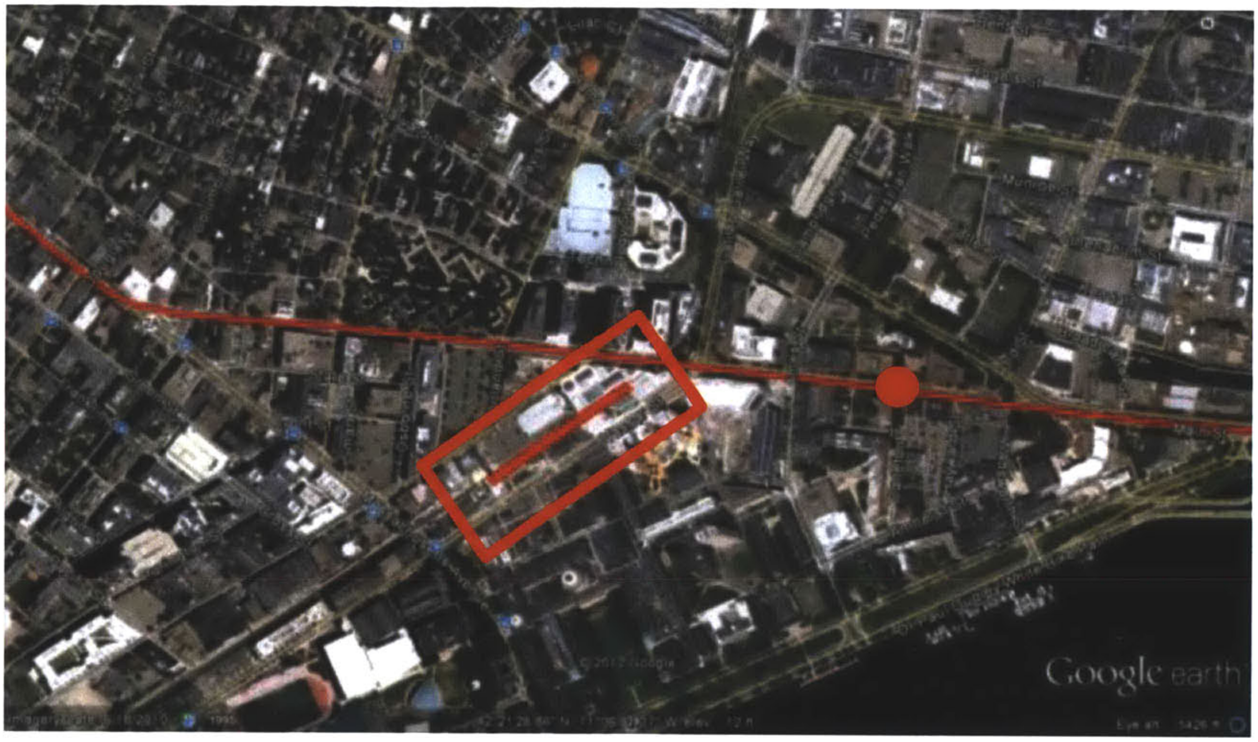


Figure 24 above shows an 850 ft. possible commuter rail station in red. Superimposed are the Red Line and the Kendall/MIT stop is the red circle. The MBTA requires all new commuter rail stations to be 850 ft. long high boarding platforms on a tangent. This is the only location that can accommodate the requirements and be in the Kendall Square business district. It also offers the shortest transfer to the red line (approximately 2 blocks) and offers access to most of MIT and the Kendall business district. Locations north of Binney Street are undesirable as they are farther away from the Red Line.

Figure 25: Kendall/MIT DMU Station Locations

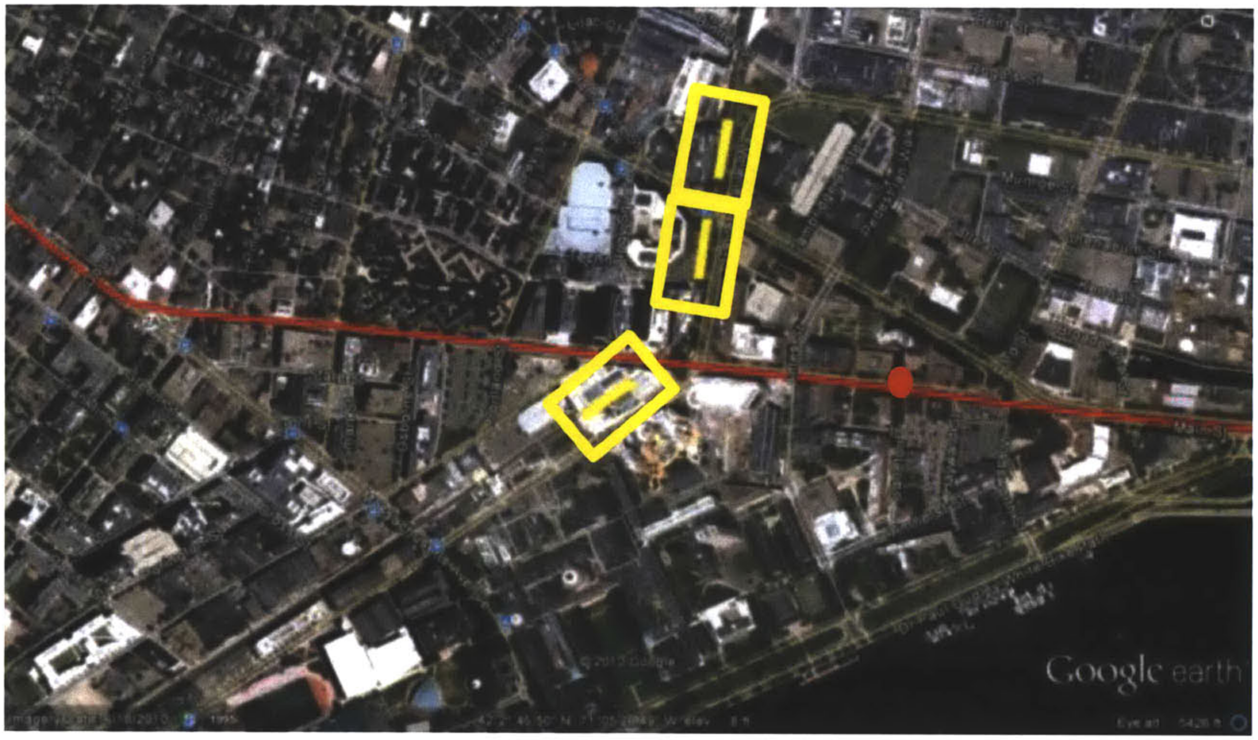


Figure 25 shows the possible DMU station locations in yellow. The longest DMU consists considered in the alternatives are three cars long and 255 ft. long so the stations above are all 300 ft. long – likely making their construction costs lower than the 850 ft. commuter rail stations. The stations would not comply with the MBTA requirements of 850ft but an exemption for DMUs would offer more flexibility in station location. The southernmost station offers a 2 block transfer from the Red Line while the other two options offer service slightly closer to Kendall Square businesses with a reasonable walking distance to the Red Line. Additionally, if future DMU service on the Grand Junction is expanded, multiple stations can be built in the corridor. It is possible to imagine a station in the east, near Cambridge Street, or one further south closer to Cambridgeport. These stations would become even more desirable if track conditions were improved to allow higher speeds and the corridor was double tracked.

7.2 Beacon Yard/Boston University Station

Figure 26: BU Station Location

Figure 26 shows an aerial image of Beacon Rail Yard, with the Green Line superimposed to the south. In red is an 850 ft. section for a possible rail station platform. The MBTA requires all new commuter rail stations be built to 850 ft. to accommodate nine car trains. There is obvious leeway with a platform of shorter length such as in the Kendall/MIT station but for this station a short length may be inappropriate. Under all scenarios this station will be served by commuter trains so it must be able to accommodate all possible train sets, making a 300 ft. platform highly undesirable as it will not accommodate long trains. It would be advantageous to have the new station be in the tangent section of the existing rail yard and as close as possible to the Green Line to facilitate possible transfers to and from rapid transit.

The proximity of this station to Boston University will also likely create new demand. The station would be within 1000 feet of many university buildings and a short walk would be very desirable for new users. In the DMU alternatives, this station will serve as a final transfer point for passengers who wish to go to Kendall or North Station. Consequently, to foster future demand, this station provides transfer access for commuter rail riders to a potential DMU service, and provides a short transfer to the Green Line with a new 850 ft. platform.

8 Cost /Revenue Analysis

Cost/revenue analysis is a very important aspect of the alternatives analysis. The three cost components that were the focus of the analysis are the capital improvements, mainly new station construction; vehicle acquisition; and marginal operational costs. The marginal operational cost analysis was done separately for the long Worcester to North Station services and the short Auburndale to North Station service, with the goal of estimating whether a service would be financially viable given a small set of cost and revenue inputs.

8.1 Capital Costs

The proposals for passenger service along the Grand Junction call for new stations to be built at BU, near the split between the Worcester mainline and the Grand Junction, and at Kendall/MIT. Station costs will vary with track configuration, platform length, amenities provided, and the condition of the existing sites. For the purposes of this study, MassDOT station construction estimates as well as judgment based on existing conditions at the proposed station locations was used to come up with station costs.

For Kendall/MIT, MassDOT estimates a construction cost of $7.5 million for a long platform commuter rail station (MassDOT, 2011). The proposed station locations are all located in the heart of the business district and near the busy MIT campus so $8.5 million is estimated here as a more conservative station price for a long platform commuter rail station. For DMU station the estimated cost is $6.5 because of the smaller platform length. The BU station will be located in the existing rail yard near heavy rail traffic which means it will likely require more extensive environmental remediation and engineering work than the station at Kendall/MIT. The platform length required there will also be longer and in order to mitigate train delays the station will have to accommodate more than two tracks to allow passing. With these considerations in mind it is estimated that the BU station will cost $12 million.

The second component of the capital expenditures for the three alternatives is vehicle acquisition costs. To be conservative it is assumed that the MBTA has no current excess rolling stock for this route so all vehicles used for the Grand Junction service will have to be new. This may not be the case in real life, but provides a solid upper bound on the vehicle acquisition costs. One train consist is added to the peak number of consists required in each scenario as a "spare" to be used in case of mechanical failure or other issues. The DMU powered car and coach car prices are provided by US Railcar and the locomotive and coach car prices are estimated from existing prices. This would give the vehicle costs outlined in Table 15 and Table 16.

Table 15: DMU Fleet Costs

	DMU	DMU Cost	Coach	Coach Cost	# of consists	Total Price
Worcester to NS – 1:00 hour headways	2	$4,500,000	1	$3,200,000	5	$61 mil
Worcester to NS – 30 min headways	2		1		8	$97.6 mil
Auburndale to NS – 12 min headways	1		1		7	$53.9 mil
Auburndale to NS – 24 min headways	1		1		4	$30.8 mil

Table 16: Commuter Train Fleet Costs

	Locomotives	Loco cost	Coach	Coach Cost	# of consists	Total Price
Worcester to NS – 1:00 hour headways	1	$5,500,00	6	$2,800,000	5	$111.5 mil
Worcester to NS – 30 min headways	1		6		8	$178.4 mil

Combining the station costs and vehicle cost for each alternative it is possible to get the total estimated capital costs listed in Table 17.

Table 17: Total Estimated Capital Costs

Mode	DMU Long	DMU Long	Loco Long	Loco Long	DMU Short	DMU Short
Headway	1 hour	31 min	1 hr.	31 min	24 min	12 min
Kendall Station	$6.5	$6.5	$8.5	$8.5	$6.5	$6.5
BU Station	$12	$12	$12	$12	$12	$12
Trains	$61	$97.6	$111.5	$178.4	$30.8	$53.9
Total	*$79.5*	*$116.1*	*$132*	*$198.9*	*$49.3*	*$72.4*

8.2 Marginal Operating Costs

Marginal operational costs are estimated from a spreadsheet tool provided by US Railcar that can be seen in the Appendix. This tool was chosen for two reasons: US Railcar is the most likely producer of potential DMUs for the Grand Junction service and since the company has experience with the technology they are capable of providing reasonable estimates for some of the inputs. The model was adapted for commuter rail. The model includes the following categories and inputs:

- Mileage/Fuel – Miles traveled, number of consists operating, round trips per consist per day, average miles per gallon, fuel price
- Expenses – Personnel costs, DMU maintenance per year, coach maintenance per year, track maintenance, loan amount and repayment, station costs, insurance, marketing, and the fuel costs from Mileage/Fuel

Some of these categories are irrelevant to the Grand Junction services proposed and have been taken out to simplify the cost estimation. For example, food will not be sold on board, so the expenses category includes personnel costs, vehicle maintenance, insurance, marketing, and fuel. Capital costs were separated (section 8.1) and the loan repayment is not included because financing is outside the scope of this analysis. Track maintenance was removed because it is assumed that maintenance activities are ongoing even without the addition of Grand Junction service. Administrative and managerial overheads are not distributed to the new service, as this was outside the scope of the marginal operating cost analysis performed for the alternatives.

For the fuel costs the model uses two values for the wholesale price of diesel: $4.25 per gallon and $5.00 per gallon. The first corresponds to the retail price of diesel in New England for March 2012 according to the US Energy Information Administration while the second value provides a reasonable future price. Having a low and high estimate provides two scenarios of what marginal operating expenses could be in the near future. Fuel consumption is summarized for each alternative in the respective sections.

The personnel cost category includes salaries for train engineers and conductors. The number of operators on each train is based on the train configuration and seating capacity. One engineer is assigned per train and MBTA rules state that one conductor must be available for each 300 seats (White & O'Conner, 2001). The conductors are responsible for ticket validation and sales and in general are only responsible for two cars – meaning that in a 3 car DMU with less than 300 total seats, 2 conductors are likely to be needed. All calculations were based on a 16 hour work day so two crews are assigned to each train to cover the working day. The manpower requirements are summarized for each alternative in the respective sections. The salary inputs for each are consistent with estimates of engineer and conductor salaries provided by MBCR (White & O'Conner, 2001).

Finally, maintenance, insurance and marketing costs are also attributed to each alternative. Insurance and marketing expenses for all operations are the default values provided by US Railcar, $1,000,000 and $100,000, respectively. DMU and coach maintenance costs are provided by US Railcar: $260,000 per DMU per year and $109,000 per coach per year all in 2011 dollars. For commuter trains, yearly locomotive maintenance is estimated to cost $200,000, while coaches cost is estimated at $100,000, based on costs found in the Fairmount Line Service Improvement report and adjusted for inflation (Jacobs, Edwards and Kelcey, 2007).

8.3 Marginal Revenues

The marginal revenues for each alternative are also based on the spreadsheet tool described in Section 8.2. The following inputs were available:

- Revenue – Passenger capacity, occupancy level, average round trip ticket price, operation days per year, food and beverage sales, and advertising

For the purposes of this study, only fare box revenue and advertising revenue were considered and estimated.

Advertising cost inputs were a combination of rates supplied by Titan360, the current advertising contractor for the MBTA, and assumed values. Average cost per advert per month is $160 dollars. An average of 30 adverts per car was assumed for all services. For train branding it is assumed $20,000 per year could be raised, which is the current price of rail wrap for a double decker car. For station signage the input was $10,000 per year – based on the two new stations at BU and Kendall having about eight 2-sheet platform advertisements each priced at $600 per advertisement.

Table 18: Current MBTA Advertising Fees

Location	Size	Fee/Unit
Rail Interior	22”x21”	$160
Platform	46”x60”	$600
Exterior Double Decker		$20,000
Exterior Single Level		$17,500

The fare box revenue is based on occupancy levels, train capacity, and average roundtrip fare so it is slightly different for each alternative. The service marginal revenues and costs are based on 260 weekdays – weekends were not included in this analysis as they will have different service and ridership characteristics than those examined here.

Occupancy levels are the most important variable in the estimated marginal revenue. The occupancy level inputs are averages over the entire operating day so three scenarios were analyzed: 40%, 35%, and 25%. To establish these benchmarks, a South Side equipment cycle chart for November 2006 was used listing the passenger counts on each train and the seating capacity. The average occupancy for Worcester/Framingham trains was 35.7% and the average for all trains was 28.4%. The 40% represents an optimistic scenario that could be pertinent to DMU service considering that the lower passenger capacities could result in higher average daily occupancy. The 35% occupancy level represents the average on the Worcester line, assuming that new service follows this trend, and 25% is a minimum, assuming that a new service will have slightly lower than network average occupancy levels. The values chosen provide a good range for a new service but could change depending on the reliability of the service and demand.

For the ticket revenue, it was assumed that commuter rail prices would be increased in July 2012 as proposed by the MBTA (CTPS, 2012). To calculate an average daily roundtrip fare, monthly zonal pass prices, listed in Table 19, were spread over 20 workdays per month (4 weeks of 5 work days) and weighted based on the number of passengers in each zone along the Worcester Line as counted by the MBTA Commuter Rail Survey (Central Transportation Planning Staff, 2010). This is deemed to be an adequate estimate, as it was observed that most passengers use monthly passes and only use commuter rail during the work week. The resulting average daily roundtrip fare using this method for the long route service alternatives is $12.50 and $8.80 for the short route alternative.

Table 19: Proposed Commuter Rail Pass Prices (CTPS, 2012)

Pass Category	Proposed
Zone 1A	$70.00
Zone 1	$173.00
Zone 2	$189.00
Zone 3	$212.00
Zone 4	$228.00
Zone 5	$252.00
Zone 6	$275.00
Zone 7	$291.00
Zone 8	$314.00
Zone 9	$329.00

The marginal operating costs and revenues for each alternative are outlined in the respective sections.

8.4 Marginal Cost/Marginal Revenue Tool Example

The spreadsheet tool incorporates the inputs outlined in Section 8.2 and Section 8.3 to calculate the marginal profits of each service. An example of how this is done is outlined here for a DMU service from Worcester to North Station with an average frequency of 31 minutes for 16 hours per day and an occupancy level of 40%.

8.4.1 Marginal Cost Calculation

The marginal cost portion is made up of personnel expenses, maintenance fees, insurance, marketing, and fuel costs.

Personnel:

	Qty	Base Salary	Burden Factor	Total Salary
Engineer per consist	1	$70,000	60%	$112,000
Conductor per Consist	2	$65,000	60%	$208,000

The inputs here are used for a DMU train consists requiring 1 engineer and 2 conductors per crew, which is doubled for the 16-hour day. A burden factor is used to multiply the base salary to a total that includes all benefits. This is typical of all transit operators. The total of $320,000 yearly cost for one consist crew is multiplied by the number of consists, 7 in this example, and doubled to account for two crews per day per consist. Total yearly personnel cost = $4,480,000

Maintenance is just the sum of yearly maintenance estimates:

$$\begin{aligned}&\$259{,}711\ x\ 2\ powered\ cars\ +\ \$108{,}398\ x\ 1\ coach\ car\\ &\quad = \$627{,}940\ per\ consists\ x\ 7\ consists\ =\ \$4{,}395{,}582\ per\ year\end{aligned}$$

Fuel cost is calculated based on the number of powered cars, fuel consumption, fuel costs, and distance traveled: (a 10% speed factor is used to account for increased fuel consumption at high speeds)

$$\begin{aligned}Round\ trips\ per\ car &= (7\ consists) x\ (4.43\ roundtrips\ per\ day) x\ (260\ days)\\ &= 8{,}063\ round\ trips\ per\ year\ for\ all\ consists\end{aligned}$$

$$\begin{aligned}Fuel\ cost &= (\frac{94\ miles}{1.90 mpg} \times\ (1+10\%))\ x\ (2\ powered\ cars)\\ &= 108\ gallons\ of\ fuel\ per\ consist\ x\ \$5.00\ per\ gallon\\ &= \$540\ of\ fuel\ per\ roundtrip\ per\ consist\\ \$540\ x\ 8{,}063\ round\ trips\ per\ year &= \$4{,}353{,}804\end{aligned}$$

Insurance of $1,000,000 and estimated marketing costs of $100,000 are added.

$$\begin{aligned}&Marginal\ cost\\ &\quad = \$4.480{,}000\ personnel + \$4{,}395{,}582\ maintenance\ +\ \$4{,}353{,}804\ fuel\\ &\quad + \$1{,}000{,}000\ insurance\ +\ \$100{,}000\ marketing\ =\ \$14{,}329{,}386\end{aligned}$$

8.4.2 Marginal Revenue Calculation

The marginal revenue portion of the spreadsheet has two parts: fare box revenue and advertising revenue.

$$\begin{aligned}&Fare\ box\ revenue\\ &\quad = passengers\ per\ consist \times\ number\ of\ round\ trips\\ &\quad \times number\ of\ consists \times average\ round\ trip\ ticket \times occupany\ level\end{aligned}$$

Example:

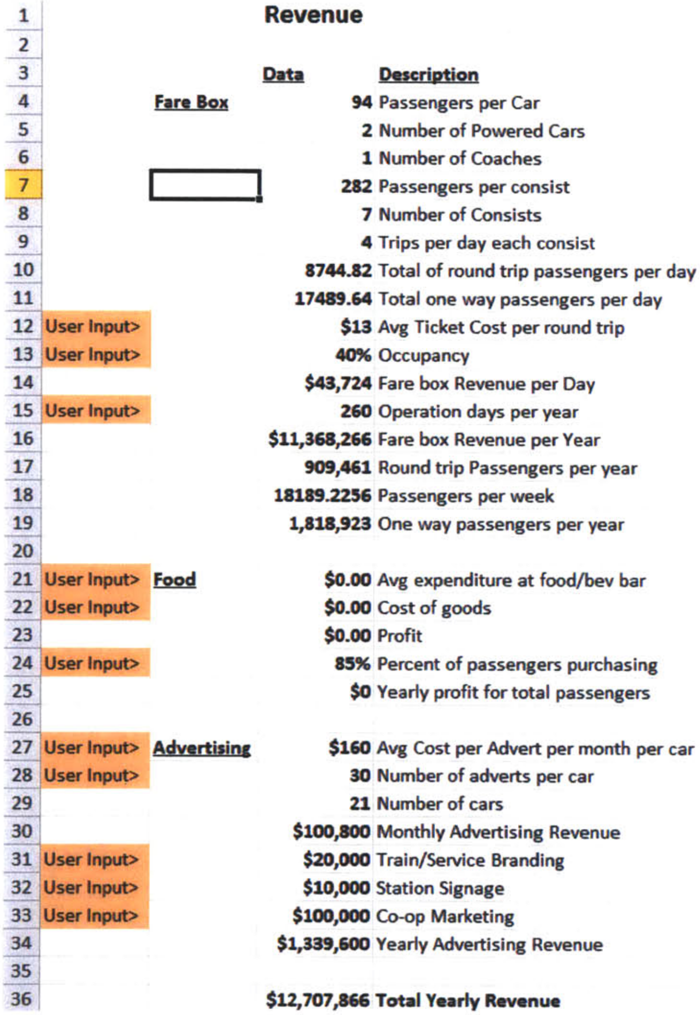
$$(282\ pax) \times (4.43\ trips) \times (7\ consists) \times (\$12.50) \times (40\%) = \$43{,}724\ per\ day$$
$$\$43{,}724 \times 260\ days = \$11{,}368{,}266\ per\ year$$

$$Advertising\ revenue = (\$160\ per\ advert)\ x\ (\#\ of\ adverts/car)\ x\ (\#\ of\ cars)$$

$$Advertising\ revenue\ = (\$160\ per\ car)\ x\ (30\ adverts\ per\ car)\ x\ (21\ cars) = \$100{,}800\ per\ month$$

Adding the $20,000 for branding, $10,000 for station signage, and $100,000 co-op marketing we get $12,707,866 per year marginal revenue seen in Figure 27. Food has been removed as can be seen.

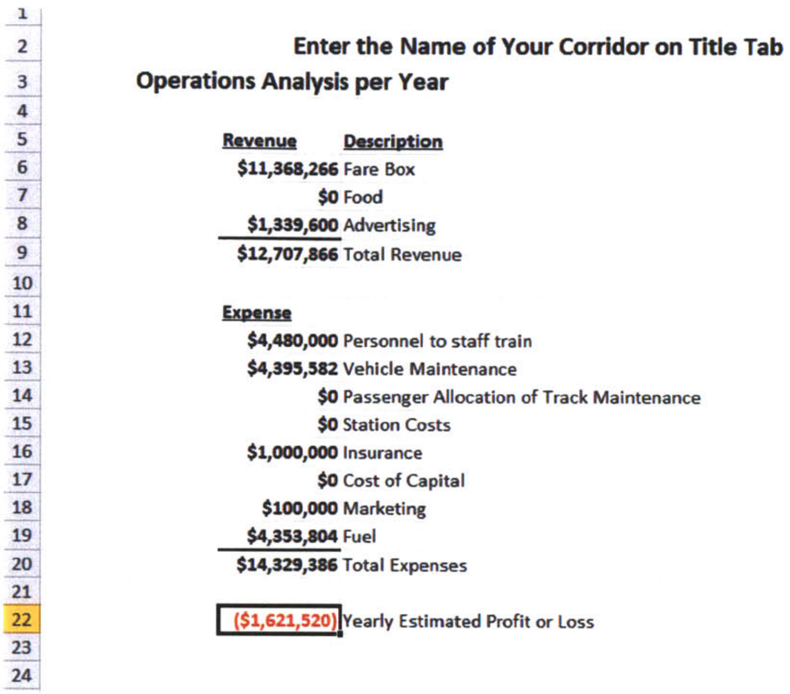
Figure 27: Marginal Revenue Example



1			**Revenue**	
2				
3			**Data**	**Description**
4		**Fare Box**	94	Passengers per Car
5			2	Number of Powered Cars
6			1	Number of Coaches
7			282	Passengers per consist
8			7	Number of Consists
9			4	Trips per day each consist
10			8744.82	Total of round trip passengers per day
11			17489.64	Total one way passengers per day
12	User Input>		$13	Avg Ticket Cost per round trip
13	User Input>		40%	Occupancy
14			$43,724	Fare box Revenue per Day
15	User Input>		260	Operation days per year
16			$11,368,266	Fare box Revenue per Year
17			909,461	Round trip Passengers per year
18			18189.2256	Passengers per week
19			1,818,923	One way passengers per year
20				
21	User Input>	**Food**	$0.00	Avg expenditure at food/bev bar
22	User Input>		$0.00	Cost of goods
23			$0.00	Profit
24	User Input>		85%	Percent of passengers purchasing
25			$0	Yearly profit for total passengers
26				
27	User Input>	**Advertising**	$160	Avg Cost per Advert per month per car
28	User Input>		30	Number of adverts per car
29			21	Number of cars
30			$100,800	Monthly Advertising Revenue
31	User Input>		$20,000	Train/Service Branding
32	User Input>		$10,000	Station Signage
33	User Input>		$100,000	Co-op Marketing
34			$1,339,600	Yearly Advertising Revenue
35				
36			$12,707,866	**Total Yearly Revenue**

Based on the example inputs for costs and revenues, this service would run an operating loss of $1,621,520, seen in Figure 28. The procedures for this example are used to calculate the marginal operating profit of each service proposed. The results for each alternative are summarized in Sections 8.5, 8.6, and 8.7.

Figure 28: Marginal Cost/Revenue Summary



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Operations Analysis per Year

Revenue	Description
$11,368,266	Fare Box
$0	Food
$1,339,600	Advertising
$12,707,866	Total Revenue
Expense	
$4,480,000	Personnel to staff train
$4,395,582	Vehicle Maintenance
$0	Passenger Allocation of Track Maintenance
$0	Station Costs
$1,000,000	Insurance
$0	Cost of Capital
$100,000	Marketing
$4,353,804	Fuel
$14,329,386	Total Expenses
($1,621,520)	Yearly Estimated Profit or Loss

8.5 DMU: Worcester to North Station

For the Worcester to North Station service the cost/revenue model is based on the three car consist of two single level powered cars and one single level coach car as described in Section 6.3. The seating capacity of this configuration is set at 282 passengers, but could change based on specific seating configurations requested by the MBTA. For the purposes of this study this capacity is considered to provide a good estimate of the costs and revenues associated with the potential Grand Junction service.

Two frequency alternatives were analyzed for the long route service: 31 minute headways and 1 hour headways – both with a cycle time of 172 minutes. For the 31 minute headway service, a total of 7 trains are required; for the 1 hour headway service, 4 trains are required. Assuming a 16 work day with first departures from the terminals around 6am and last departures around 9:30pm and no decrease in service during the off-peak hours, each consist in the low frequency service will make 4 round trips per day. In the high frequency service, six of the trains will make 4.5 roundtrips and one train will make 4 roundtrips, averaging to 4.43 round trips per train for the fleet (this was used as the input for the model).

The fuel consumption input for this service is the average miles per gallon per powered car, 1.90, as reported by the Florida Tri-Rail system which has run US railcar DMUs. For the personnel cost, one engineer and two conductors per work crew are assigned to this train configuration. All other cost and revenue inputs were as described in Section 8.2 and Section 8.3. A summary of the marginal operating costs and revenues is shown in Table 20. It is important to note that the marginal profit does not include repayments of loans or other obligations that would be associated with the capital expenditures summarized in Section 8.1.

Table 20: DMU – Worcester to North Station Marginal Cost and Revenue Summary

Headway (hr.)	Diesel Cost	RT Ticket Price	Occupancy	Marginal Revenue	Marginal Costs	Marginal Profit
1 hr.	$4.25	$12.50	40%	$6,686,800	$8,081,201	($1,394,401)
			35%	$5,953,600		($2,127,601)
			25%	$4,487,200		($3,594,001)
	$5.00		40%	$6,686,800	$8,418,161	($1,731,361)
			35%	$5,953,600		($2,464,561)
			25%	$4,487,200		($3,930,961)
0.5 hr.	$4.25	$12.50	40%	$12,707,866	$13,676,316	($968,450)
			35%	$11,286,833		($2,389,483)
			25%	$8,444,766		($5,231,549)
	$5.00		40%	$12,707,866	$14,329,386	($1,621,520)
			35%	$11,286,833		($3,042,553)
			25%	$8,444,766		($5,884,620)

In all cases for this service an operating loss is estimated. According to the demand modeling and ridership projection completed by Adam Bockelie and James Dohm, the high frequency service is estimated to serve about 2000 riders per day in the AM peak (Bockelie & Dohm, 2012). With a frequency of 6 inbound trains in the three hour AM peak providing 282 seats, it is estimated that train occupancy will be 118%, exceeding the seating capacity. The lower frequency service (3 trains in the AM peak) has a predicted ridership of about 1100 passengers and is likely to experience similar very high occupancy levels in the peak direction during the peak periods (129%). To estimate which occupancy category the service will most likely fall under, the minimum average daily occupancy level is calculated by assuming that PM peak period occupancy will be the same as AM peak period occupancy and that the 10 off peak hours will have zero ridership. Based on this assumption the *minimum* daily average occupancy levels are estimated to be 44 % and 48%, for the high and low frequency services respectively. Therefore, an occupancy level of 40% or higher, shaded in grey in Table 20, is a likely scenario for both alternatives. Additionally, in order to estimate marginal profits based on the calculated minimum daily occupancy levels, operating cost and revenues were calculated for a 50% occupancy level and summarized in Table 21. Unless zero ridership is actually observed in the off peak, these results show more realistic and likely marginal profits.

Table 21: DMU – Worcester to North Station Marginal Cost and Revenue Summary for High Occupancy

Headway (hr.)	Diesel Cost	RT Ticket Price	Occupancy	Marginal Revenue	Marginal Costs	Marginal Profit
1 hr	$4.25	$12.50	50%	$8,153,200	$8,081,201	$71,999
	$5.00		50%		$8,418,161	($264,961)
0.5 hr	$4.25	$12.50	50%	$15,549,933	$13,676,316	$1,873,617
	$5.00		50%		$14,329,386	$1,220,546

It can be seen from the estimated marginal profits in Table 20 and Table 21 that this service alternative is highly sensitive to occupancy levels. Occupancy levels of 50% and above will likely have positive operating numbers while 40% and below have operating losses. The 50% daily average is the most likely, first because of high peak period ridership, and second because the smaller DMU seating capacity means that even small off peak ridership will produce higher occupancy levels compared to conventional commuter trains which have a large capacity. High average occupancy will justify a DMU service alternative but it is important to note that, if observed, occupancy levels above 110% (estimated here) are undesirable and may lead to service changes. Such changes will have an impact on the ridership and the marginal operating profits.

8.6 Commuter Rail: Worcester to North Station

To estimate the commuter rail marginal cost and revenues the spreadsheet tool was adapted by changing the relevant inputs. Diesel fuel price, ticket price, advertising revenue, and occupancy levels were the same as the DMU alternatives but fuel consumption, consist configuration, passenger capacity, personnel, and maintenance costs were adjusted.

A fuel consumption rate of 0.36 mpg for locomotives was used for the model, taken from the Fairmount Line Service Improvement plan (Jacobs, Edwards and Kelcey, 2007). For the consist configuration, one powered locomotive and six coach cars were considered as described in Section 6.3. The passenger capacity was set to 155 per coach car to account for the mix of double and single decker cars used on most MBTA commuter trains. This provides a total capacity of 930 passengers per train which is consistent with the average of 932 seat average capacity of all south side commuter trains calculated from the South Side Equipment Cycle chart. As with the long route DMU service, two frequency alternatives were analyzed: 31 minute headways and 1 hour headways – both have a cycle time of 213 minutes. For the 31 minute headway service, a total of 7 trains are required; for the 1 hour headway service, 4 trains are required. Assuming a 16 work day with first departures from the terminals around 6am and last departures around 9:30pm and no decrease in service during the off-peak hours, each consist in the low frequency service will make 4 round trips per day. In the high frequency service, six of the trains will make 4.5 roundtrips and one train will make 4 roundtrips, averaging to 4.43 round trips per train for the fleet (this was used as the input for the model).

The personnel requirements for the commuter trains were set to one engineer and four conductors per crew and two crews for the entire work day. With a capacity of 930 seats, the MBTA requires four conductors on board. The maintenance costs for the trains were set to those described in Section 8.2. A summary of the marginal costs and revenues is shown in Table 22.

Table 22: Commuter Rail – Worcester to North Station Marginal Cost and Revenue Summary

Headway (hr)	Diesel Cost	RT Ticket Price	Occupancy	Marginal Revenue	Marginal Costs	Marginal Profit
1 hr	$4.25	$12.50	40%	$20,856,400	$13,577,280	$7,279,120
			35%	$18,438,400		$4,861,120
			25%	$13,602,400		$25,120
	$5.00		40%	$20,856,400	$14,469,600	$6,386,800
			35%	$18,438,400		$3,968,800
			25%	$13,602,400		($867,200)
0.5 hr	$4.25	$12.50	40%	$40,040,290	$23,886,490	$16,153,800
			35%	$35,353,904		$11,467,413
			25%	$25,981,131		$2,094,641
	$5.00		40%	$40,040,290	$25,615,918	$14,424,372
			35%	$35,353,904		$9,737,986
			25%	$25,981,131		$365,213

Many of the marginal profits in Table 22 are high compared to the DMU alternative but it is important to consider which are most plausible according to the estimated ridership. The ridership numbers estimated in the demand model for the commuter rail alternatives are very similar to those for the DMUs: around 2000 for the high frequency service and about half that for the low frequency service (Bockelie & Dohm, 2012). Based on this demand estimate, AM peak period occupancy for the 1 hr. headway service (3 trains in AM peak) will be 72% and 36% for the 31 min headway service (6 trains in AM peak). As with the DMU alternative, a minimum daily occupancy is calculated by assuming that the PM peak is the same as the AM peak and zero ridership is observed in the off peak. The *minimum* average daily occupancy levels for the two services will be 27% and 13.5%, respectively. In addition to this estimate, the large capacity of commuter trains will mean that even with some off peak ridership the average daily occupancy will still be low. Therefore, 25% occupancy is shaded in Table 22 as it is deemed the mostly likely occupancy level for this service.

The expected marginal profits for the highlighted scenarios are positive, except for one, but in general are lower than what is estimated as likely for the DMU alternative (see Table 21). It is important to note that the commuter trains have much larger marginal costs than DMUs due to the higher fuel consumption and staffing requirement. With a low ridership estimate and resulting low occupancy levels for the large commuter trains, the commuter rail service may be undesirable.

8.7 DMU: Auburndale to North Station

The Auburndale to North Station service would use a consist of one DMU and one coach car, having an estimated total capacity of 188 passengers. The two frequency alternatives are a high frequency service with 12 minute headways and a low frequency service with 24 minute headways. Both have a round trip cycle time of 71 minutes. For the 12 minute headway service six trains are required and for the 24 minute headway service three trains are needed.

Assuming a 16 hour workday, with first departures around 6am and last departures around 10pm from each station, each train will complete 13.5 round trips per day.

Fuel prices and occupancy levels are the same as in the other alternatives. For fuel consumption, the input is 1.90 mph as with the long DMU service. The personnel assignment for this service is one conductor and one engineer, which satisfies the MBTA requirements based on seating capacity. As with the other alternatives, two crews are assigned to cover the entire work day. In the ticket price category, $8.80 is used for the average daily fare as calculated in Section 8.3. The marginal costs and revenues for the short route DMU service are summarized in Table 23.

Table 23: DMU - Auburndale to North Station Marginal Cost and Revenue Summary

Headway	Diesel Cost	RT Ticket Price	Occupancy	Marginal Revenue	Marginal Expenses	Marginal Profit
24 min	$4.25	$8.80	40%	$7,443,933	$4,127,043	$3,316,890
			35%	$6,572,891		$2,445,848
			25%	$4,830,808		$703,765
	$5.00		40%	$7,443,933	$4,237,608	$3,206,325
			35%	$6,572,891		$2,335,283
			25%	$4,830,808		$593,200
12 min	$4.25	$8.80	40%	$14,757,866	$7,154,085	$7,603,780
			35%	$13,015,782		$5,861,697
			25%	$9,531,616		$2,377,531
	$5.00		40%	$14,757,866	$7,375,215	$7,382,650
			35%	$13,015,782		$5,640,567
			25%	$9,531,616		$2,156,401

All marginal profits listed in Table 23 are positive, but it is unlikely that this service will have very high average daily occupancy. According to the ridership estimate, the short route DMU service will have approximately 1100 and 900 passengers in the AM peak period, for the 12 minute and 24 minute headway services, respectively (Bockelie & Dohm, 2012). Based on this, the high frequency service offering maximum of 15 trains during the three hour AM peak (5 per hour), occupancy levels in the peak will be about 40% assuming uniform ridership on each train (1100 passengers divided into 15 trains is 74 passengers per train). The average occupancy for the 24 minutes headway service in the AM peak will be 64% (900 passengers divided into 7.5 peak period trains). With low off-peak ridership, it is likely that the high frequency service (12 min headways) will have average daily occupancy levels closer to 25%. It may experience higher occupancy levels because it is a service with low headways and therefore attracts more users. The low frequency service (24 min headways) will perform better and is estimated to have average occupancy of 35% but it too will likely experience lower average daily occupancy levels than the two long route alternatives.

A minimum daily occupancy level was not calculated as in the Worcester to North Station services because the headways for this service are very short compared to existing commuter rail service; therefore zero off peak ridership is highly unlikely. No existing services have similar characteristics to this alternative, so making comparisons with other off peak commuter rail ridership estimates is difficult. The most likely average occupancy estimates for each alternative are shaded in the Table 23. It is important to note that regardless of the estimate, any range of daily occupancy levels between 25% and 40% will have positive marginal profits. Given the high capital costs and uncertainty in ridership, it appears that the short route DMU service is riskier than the long route alternatives which capture a larger portion of the commuting population in the corridor.

9 Other Impacts – DMU vs Conventional Locomotives

Although DMUs and conventional push-pull train configurations would provide similar service characteristics to passengers, in terms of travel time and comfort, there are significant performance differences between the two types of configurations. These are even more pronounced when considering the alternatives proposed in this report. A study done by Jacobs Engineering's Edwards and Kelcey unit exploring the potential use of DMUs on the Fairmount Line in Boston is the source of most of the data examined. The areas of comparison considered are: speed and acceleration, fuel consumption, emissions, noise and vibration, maintenance and configuration.

9.1 Speed and Acceleration

Maximum speeds for both conventional push-pull configurations and DMUs is very similar but acceleration characteristics, as described in Section 5, can vary dramatically. DMUs, at 80 tons a piece, are much lighter than locomotives which can be over 130 tons. They have smaller engines, but with a higher horsepower/weight ratio, the DMU cars offer better performance even when coupled with an unpowered coach car. According to the Fairmont Line Service Improvements report done in 2006, a typical locomotive train has a maximum acceleration of 0.50 mph/second (Jacobs, Edwards and Kelcey, 2007). This means that the train reaches speeds of 30 mph and 60 mph in 65 seconds and 166 seconds, respectively. A mix of 50% DMU powered car and 50% coach cars (as proposed in the short route alternative) would have acceleration times of 32 seconds and 123 seconds to those same speeds (Table 3). For a set consisting of two DMUs and one coach car (as proposed in the long route alternatives) the acceleration time to 60 mph would decrease to 86 seconds (Table 3). As a result, DMUs can offer substantial time savings on some lines where high speeds can be reached, especially if there are a large number of stops.

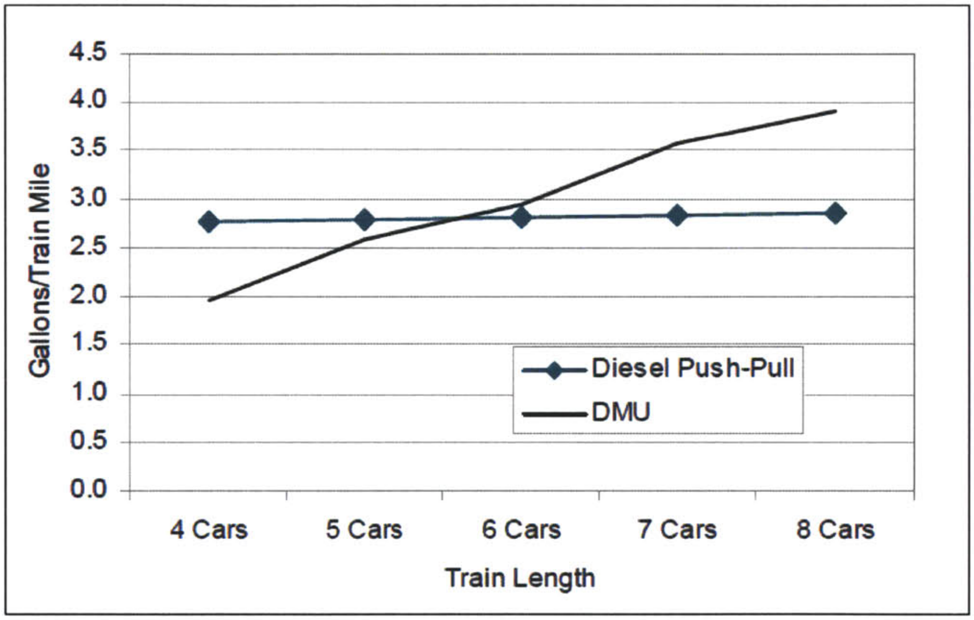
Unlike conventional train sets however, DMU performance is highly dependent on the powered car to coach car mix (Jacobs, Edwards and Kelcey, 2007). In general, a 50/50 mix of DMUs to coach cars will always provide better acceleration characteristics that a conventional train set. As train lengths and capacity requirements increase requiring longer trains the cost of a 50/50 mix DMU train will outpace the cost of a similar length conventional train. If the consist mix has less than 50 percent DMUs then it will also have acceleration performance similar or worse than a conventional train set. Therefore, as capacity requirements increase, DMUs become less desirable. For the services examined in this analysis, the capacity requirements are not very large making DMUs a viable option for the Grand Junction.

9.2 Fuel Consumption

As with acceleration, the train length and consist mix have a large impact on fuel consumption of DMUs. Fuel consumption in a push-pull configuration is largely determined by the operation of a locomotive, regardless of train length. According to the Fairmount Line Service Improvements report existing MBTA services average 2.81 gallons per revenue mile for locomotive operation (Jacobs, Edwards and Kelcey, 2007).

The estimate for fuel consumption of DMUs in the cost/revenue analysis model was 1.90 miles per gallon per powered car (~0.55 gallons per mile). This number can vary according to many factors, the most important being the length of the train and the mix of cars. Various mixes of powered cars and coaches examined in the Fairmount Line report are estimated to have fuel consumption rates between 0.60 gallons per mile to 2.2 gallons per mile – less than a traditional locomotive. Figure 29 shows the estimated fuel consumption of a 50/50 mix of coaches and powered cars for various train lengths. It can be seen that as DMU train length increases fuel consumption also increases. The DMU alternatives proposed in this study are one powered car + one trailer car and two powered cars + one trailer car – both are well below the fuel consumption levels estimated for locomotives.

Figure 29: DMU vs Locomotive Fuel Consumption (Jacobs, Edwards and Kelcey, 2007)



9.3 Emissions

DMUs and traditional locomotives emission levels are governed by different EPA standards. The emissions considered in the Fairmount report for each alternative were hydrocarbons (HC), carbon monoxide (CO), Nitrogen Oxides (NOx), and particulate matter (PM) (Jacobs, Edwards and Kelcey, 2007). As with fuel consumption, emission rates for locomotives are largely unaffected by the train length. For DMUs, emission rates are smaller due to the engine size and weight but vary depending on the train length and consist mix. Figure 30 through Figure 33 compare the various types of emissions between push-pull operations and DMUs (50/50 mix) presented in the Fairmount report. These emissions levels are for US Railcar DMUs. It can be seen that for all emissions types and train lengths graphed DMUs outperform conventional locomotives. The DMU consist lengths proposed in this study fall well within the range of low emissions seen here.

Figure 30: DMU vs Locomotive Hydrocarbon Emissions (Jacobs, Edwards and Kelcey, 2007)

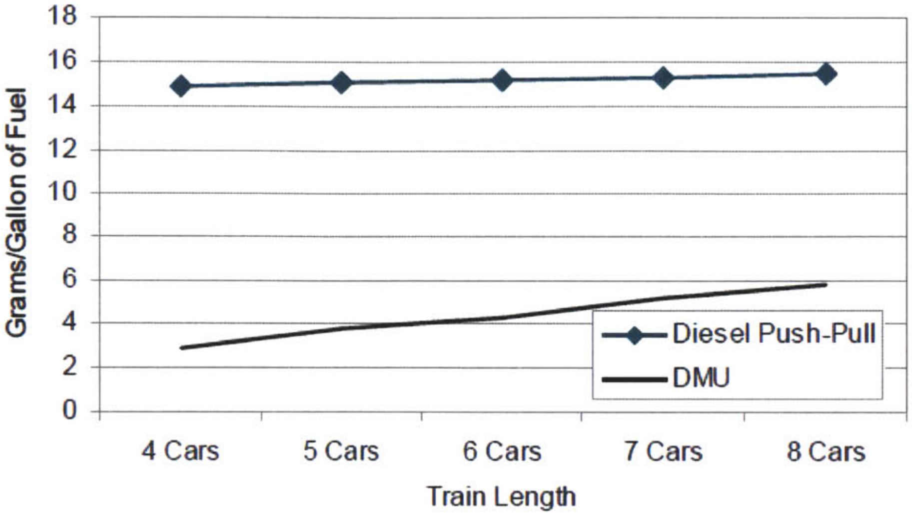


Figure 31: DMU vs Locomotive Carbon Monoxide Emissions (Jacobs, Edwards and Kelcey, 2007)

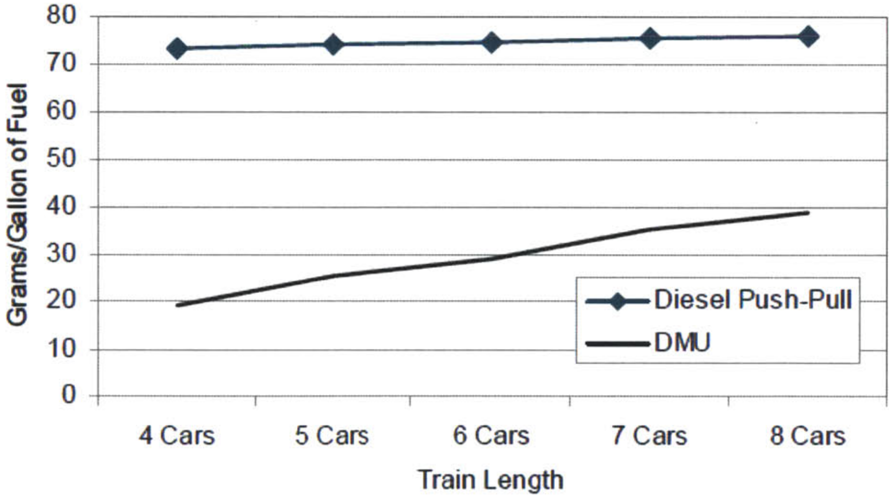


Figure 32: DMU vs Locomotive Nitrogen Oxide Emissions (Jacobs, Edwards and Kelcey, 2007)

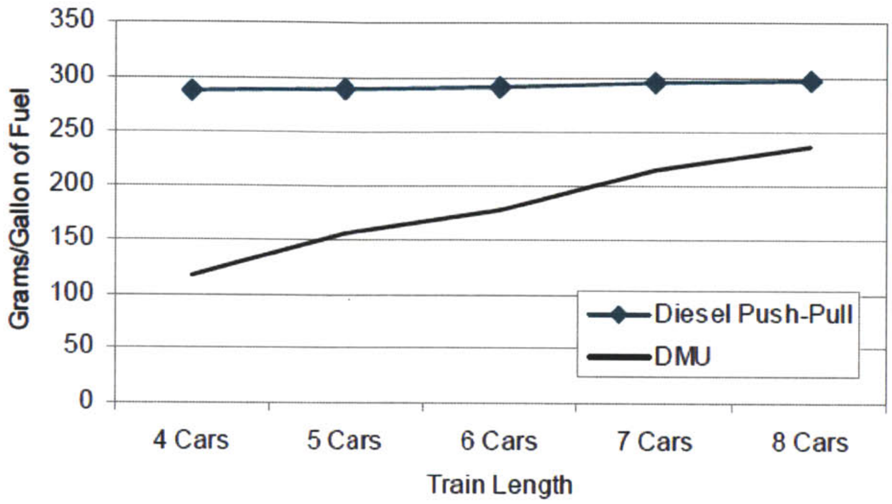
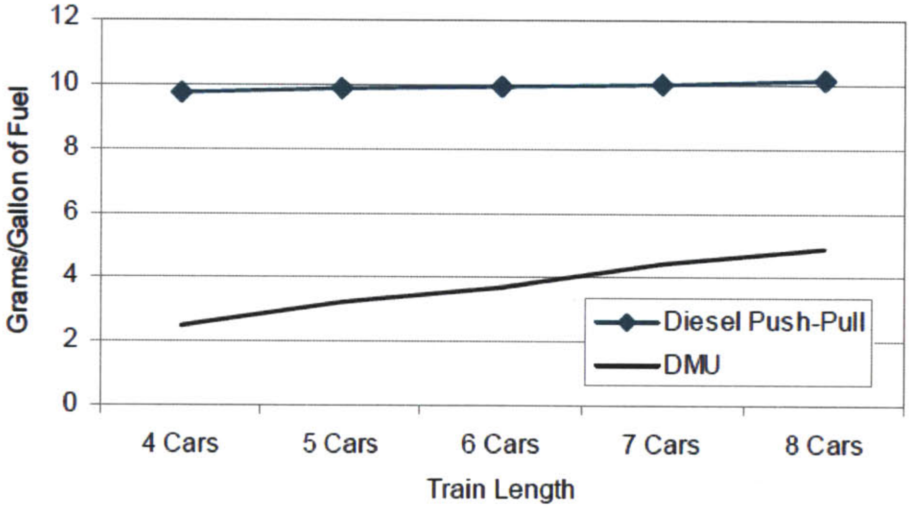


Figure 33: DMU vs Locomotive Particulate Matter Emissions (Jacobs, Edwards and Kelcey, 2007)



9.4 Noise and Vibrations

The dense urban setting of the Grand Junction requires that noise and vibrations be considered and compared. The strongest factors that differentiate DMUs and locomotives in this area are weight and engine size. US Railcar DMUs are equipped with two 600 hp engines supplying a total of 1200 hp per powered car (US Railcar). The most powered cars proposed in the alternatives would be two, giving a combined 2400 hp per train set. In comparison, current locomotives in the MBTA fleet have engines delivering upwards of 3000 hp and projected as high as 4600 hp for the newest locomotives set to join the fleet. As discusses earlier, the locomotives also weigh over 50 tons more than a single level powered DMU. The large locomotive engines area therefore louder and cause more vibrations along the line.

In addition to engine noise, locomotive whistles are a known peeve in the Cambridge area. Federal regulations state that trains must blow their whistles at train crossings. Although no info is available on the whistles of DMUs it can be assumed that they are similar in loudness. With the appropriate intersection safety measures, a whistle ban along the Grand Junction may limit any and all train whistle use.

Along with the increased noise that comes from locomotives, the large heavy trains also dramatically increase wear and tear on the tracks (White & O'Conner, 2001). Having lighter DMU trains use the corridor would decrease the need for track maintenance due to wear and tear.

9.5 Maintenance and Configuration

Maintenance of DMUs does not require specialized equipment but introducing US Railcar DMUs into the MBTA fleet would undoubtedly add complexity to the maintenance procedures. FRA requirements govern that all control cars in a fleet meet certain maintenance standards that are more stringent than those of coach cars. Control cars include locomotives, DMUs, and any car that has a control station even if it does not have on-board power (White & O'Conner, 2001). For the different DMU fleets proposed in this study, the ratio of control cars to coach cars is much higher than for the commuter rail alternatives.

Table 24: DMU vs Locomotive Fleet Mix

	DMU – Wor. To NS		**DMU – Aub. To NS**		**Loco – Wor. To NS**	
Consists	5	8	4	7	5	8
Control cars	10	16	4	7	5	8
Coach cars	5	8	4	7	30	48
Ratio	2:1		1:1		1:6	

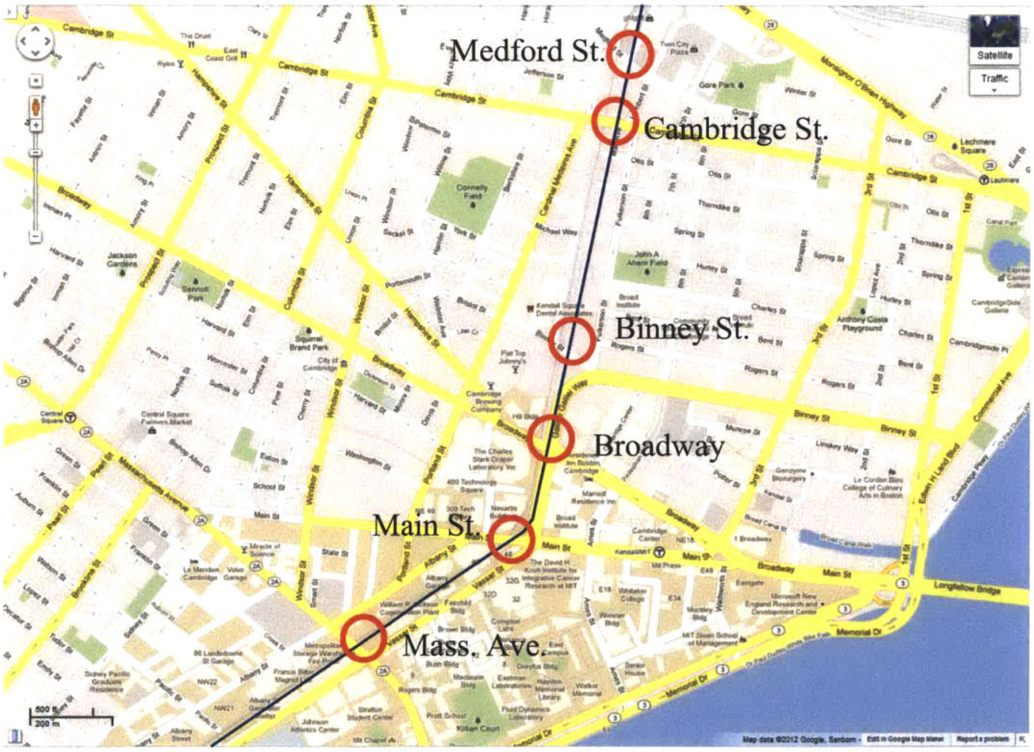
The high number of control cars means increased maintenance time per car for all DMU alternatives proposed. The smaller fleet sizes however mean a decreased load on maintenance facilities. The introduction of any new vehicles will increase the load on maintenance facilities that are running close to capacity (Jacobs, Edwards and Kelcey, 2007). Extra vehicles would require extra storage in layover and layup facilities.

Another benefit of DMUs is that train consists can easily be moved around in the off peak hours. Most of the cars in the train sets are self-propelled so if a reduction in capacity is warranted, equipment can be stored to save fuel, wear and tear, or be shifted to where it is needed without much hassle. These mid-day configuration changes are more difficult and provide fewer savings with conventional push-pull operations.

9.6 Traffic Impact

The Grand Junction railroad makes six at-grade crossings in Cambridge seen in Figure 34. Current railroad traffic has an insignificant impact on road traffic, but addition of trains along the line will create traffic delays. In accordance with safety procedures, railroad gates will be placed at every intersection and must be lowered at least 20 seconds before the arrival of a train at the intersection (White & O'Conner, 2001). With the maximum 5 trains per hour per direction (assuming equal railroad traffic in the inbound and outbound directions), ten train crossing will occur per hour equating to at least 200 seconds (3.33 minutes) of gate closures for the high frequency DMU service analyzed. Assuming that the improved barriers allow trains to pass without stopping and slowing down, the short DMU trains will clear all Cambridge intersection in about 15 seconds each. This will lead to an estimated total "gate down" time of 350 seconds (5.83 minutes) for the DMU alternatives. The long commuter train alternatives analyzed will have a maximum frequency of about four per hour (31 minute headways in each direction) and need an estimated 35 seconds to clear each intersection, resulting in a total "gate down" time of 220 seconds (3.67 minutes). The commuter train delay may be larger if trains are slowing down to enter or exit a Kendall Station and because of the slower acceleration and deceleration characteristics of locomotives. In comparison, MassDOT concluded that traffic delays due to commuter trains would be on the order of three times higher than the no build scenario – ranging from one to four and a half minutes of queuing at certain intersections (MassDOT, 2011). This analysis does not quantify intersection delay further, but it is obvious that at high frequencies DMU service will likely cause lower traffic delays in Cambridge than conventional trains.

Figure 34: Grand Junction Intersection Crossings



Station location in Kendall could also be a contributing factor to traffic delay. If the station located is near an intersection, start and stop times for trains entering and leaving the station will increase the traffic impact. As described in Section 9.1, DMUs will have slightly better performance entering and exiting the Kendall Station which would likely be located near the intersection with Main Street.

Improving gate protection at all crossings will not only decrease the delay caused by train movements but will also reduce the complexity created by requirements that all buses stop at railroad crossing. Railroad signal and traffic signal coordination could also mitigate the potential traffic problems. For example, the limiting factor of capacity at Mass. Ave in the area of the Grand Junction appears to be the existing operation at Mass Ave and Vassar Street (the intersection to the east of the railroad intersection) so it is not clear whether the addition of rail service would increase existing delays. This issue, and the traffic patterns at six intersections, would require a more thorough traffic impact analysis than has been done here or previously.

It is also important to consider bicycle and pedestrian traffic. Signalization and gates for bikes and pedestrians should be considered at the large intersections, such as Massachusetts Avenue where there is significant bike and pedestrian traffic. Fencing to restrict illegal pedestrian crossings or a pedestrian bridge could be considered as solutions to stop student crossings near the MIT Warehouse dormitory. With the addition of any train service the addition of adequate safety measures for the heavy bike and pedestrian access is of paramount importance.

10 Conclusions and Recommendations

The addition of passenger service along the Grand Junction requires careful consideration of cost, revenue, ridership, scheduling, corridor constraints, and community reaction. Any one factor alone described in this study cannot be used as a definitive measure but they describe the possibilities and future potential of using the railroad for commuter passenger service.

Considering the current capacity constraints on the southern commuter rail lines from the congestion at South Station, it is necessary to explore existing possibilities of alleviating the congestion. South Station expansion will likely happen in the future, but the increasing demand from all seven southern lines and constraints at other stations, like Back Bay, may prevent significant increased service to the west. The potential to provide up to five trips per hour to North Station via the Grand Junction is a desirable short term and medium term solution for expanding frequency and capacity to the west, improving transit access to Cambridge, and alleviating congestion at South Station. In the long term this service will complement any increases in capacity from the expansion of South Station.

10.1 Conclusions

Based on the analysis of alternatives, scheduling, performance, cost and revenue performed in this study the following conclusions can be summarized:

- The alternatives analyzed are not mutually exclusive. The goal of this study is to examine the possible alternatives for using the Grand Junction railroad to improve commuter passenger service from the west. Based on the constraints and existing conditions along the railroad, heavy rail – in the form of conventional trains or FRA compliant DMUs – is the most desirable alternative. It provides long distance service that can be most easily integrated into existing operations along the commuter rail lines but it does not eliminate the possibility of complementary light rail or BRT services such as the ones proposed in the Urban Ring in the future. Light rail and BRT would serve more inner city passengers and could either be built parallel to the heavy rail in the Grand Junction right-of-way or, in the case of BRT, the service could be on adjacent streets. Additionally, a community path can be included with most service alternatives.
- Station construction at Kendall Square would improve transit access to the budding business district and ensure some future capacity from the west. The location and length of this station is dictated by the type of service provided. A station at Boston University would provide increased commuter transit to the area from the west and in the case of DMU service would allow an additional transfer station to Kendall and North Station for both MBTA Green Line users and long distance commuters.
- Based on existing scheduling, track constraints, and station constraints up to five trains per hour can be introduced along the Grand Junction. There is the potential to handle these additional trains at North Station. With planned improvements along the Worcester mainline, the relocation of Beacon Yard to Worcester, and track improvements there is potential to increase the frequency of service from the estimated five trains per hour.

- Considering the maximum ridership of 2000 estimated for the AM peak period for a Worcester-North Station service, a DMU service is likely to have higher occupancy levels. The capital costs for this service are smaller than the comparable commuter rail alternative but provide fewer passenger seats. Marginal costs and revenues, based on high occupancy levels, suggest that a DMU service is plausible. However, with higher than predicted demand or increased future demand conventional trains are better equipped to handle the high ridership at low frequencies.
- Considering the high density urban corridor along the Grand Junction and existing public outcry against additional heavy rail service based on noise, pollution, vibrations, and worsening traffic, DMU service would be a more desirable alternative than conventional push-pull commuter trains. DMU consists proposed in this study are smaller, lighter, and quieter than conventional trains. They have superior fuel efficiency, lower emissions, and better acceleration performance than conventional trains in the configurations proposed.
- DMUs may create an undesirable maintenance issue for the MBTA because the equipment is different than conventional locomotives and coaches, but the addition of new commuter trains may also place a strain on existing maintenance capacity.
- DMU trains are more flexible than conventional equipment because the cars are self-propelled. They can more easily be decoupled and reconfigured to meet off-peak demand or moved to another line that requires higher capacity. US Railcar DMUs are compatible with conventional equipment.

10.2 Recommendations

Based on the conclusions in Section 10.1, passenger service along the Grand Junction railroad, particularly the addition of DMU trains, should be seriously considered. A more detailed study of costs, revenues, and impacts of such trains on existing services, capacity, and maintenance facilities should be conducted. Future system modifications along the Worcester Line, expansions at North Station and South Station, and expansions of MBTA rapid transit network, and road modifications near the corridor should include the possibility of adding future passenger service along the Grand Junction. Future proposals not analyzed in this study could include express service inside route 128, a new station near route 128 along the Worcester line, new signalization, or intercity rail improvements. With careful planning and integration of services, the corridor is capable of handling a combination of heavy rail, light rail, bus rapid transit and a community path. Improvements to the public transit network, possible only through careful and thorough planning, will have widespread benefits in Cambridge and the greater Boston area.

11 Bibliography

Evaluation of Variant CW-12 - DMUs on Rail From West Allston to Chelsea. (2006). Urban Ring Phase 2 RDEIR/DEIS.

Bockelie, A., & Dohm, J. (2012). *Estimating Commuter Rail Demand to Kendall Square along the Grand Junction Corridor.* MIT, Cambridge.

(n.d.). *Boston's Passenger Rail Operational Capacity White Paper.*

Central Transportation Planning Staff. (2010). *MBTA System Wide Passenger Survery.* Boston.

Central Transportation Planning Staff. (2010). *MBTA System Wide Passenger Survey - South Side Volumes.* Boston.

City of Cambridge. (2006). *Grand Junction Rail-with-Trail Feasibility Study.* Cambridge.

CTPS. (2012). *Potential MBTA Fare Increase and Service Changes in 2012: Scenario 3 Impact Analysis.*

Jacobs, Edwards and Kelcey. (2007). *Fairmount Line Service Improvements: Potential Use of DMUs.*

MassDOT. (2011). *Grand Junction Transportation Study.* Retrieved from http://www.massdot.state.ma.us/planning/GrandJunctionTransportationStudy.aspx

Nelson, D., & Duse-Anthony, Y. (2004). *New Haven Hartford Springfield Commuter Rail Implementation Study.* KKO and Associates, LLC.

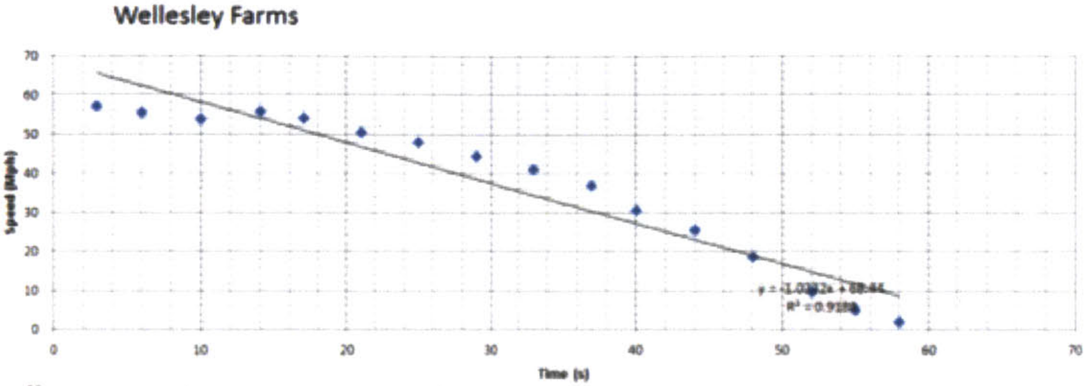
Schaefer, T. (2012, February 22). Projected Acceleration Performance of Various Single Level DMU Consists. US Railcar.

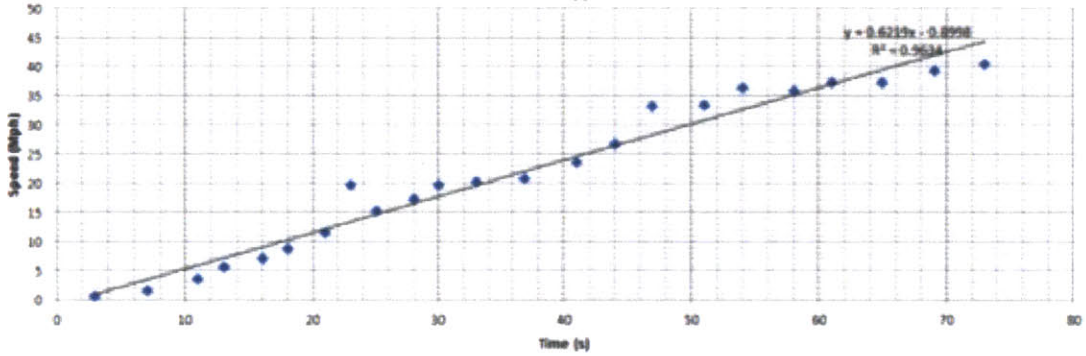
US Railcar. (n.d.). *US Railcar DMU Specs.* Retrieved from http://www.usrailcar.com/dmu-specs.php

White, J., & O'Conner, F. (2001, April 16). (S. Neov, Interviewer)

12 Appendix

Acceleration and deceleration tables





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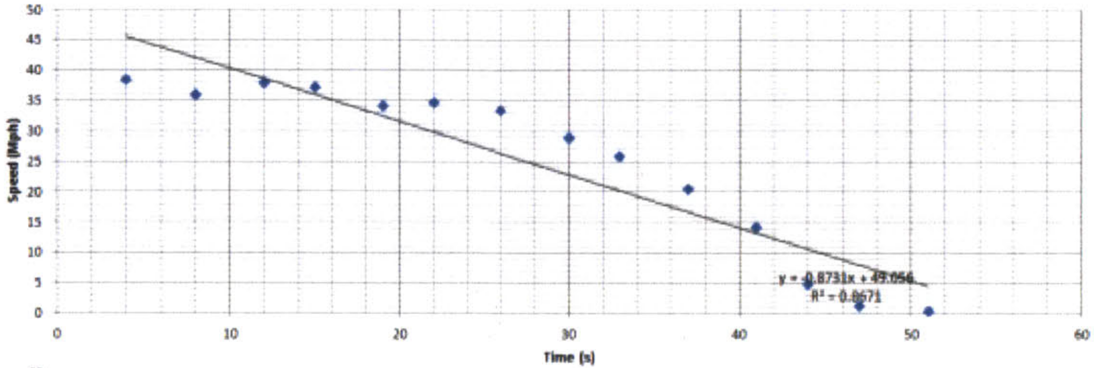

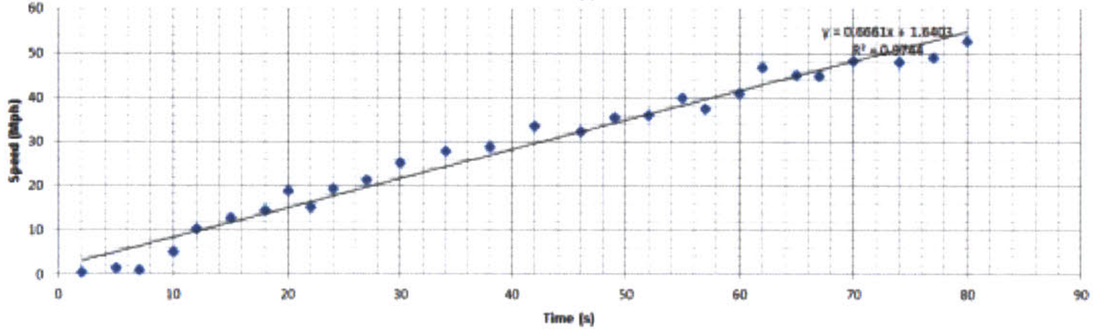

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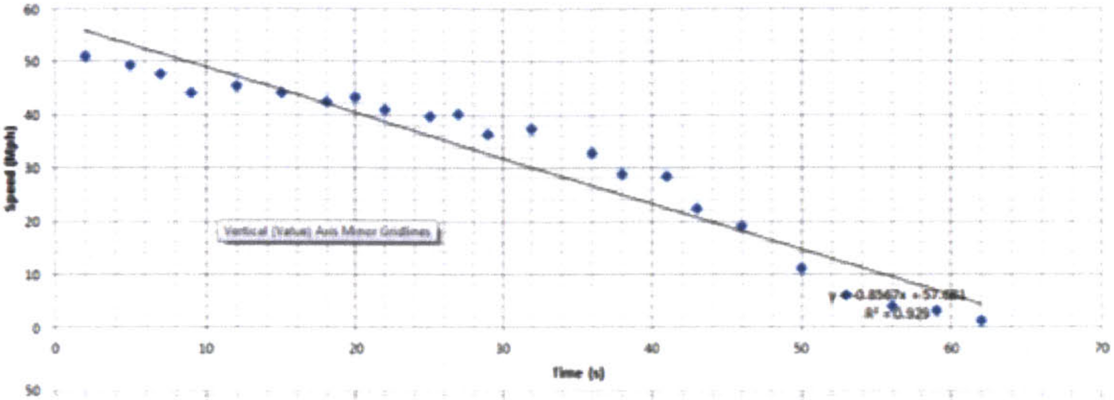

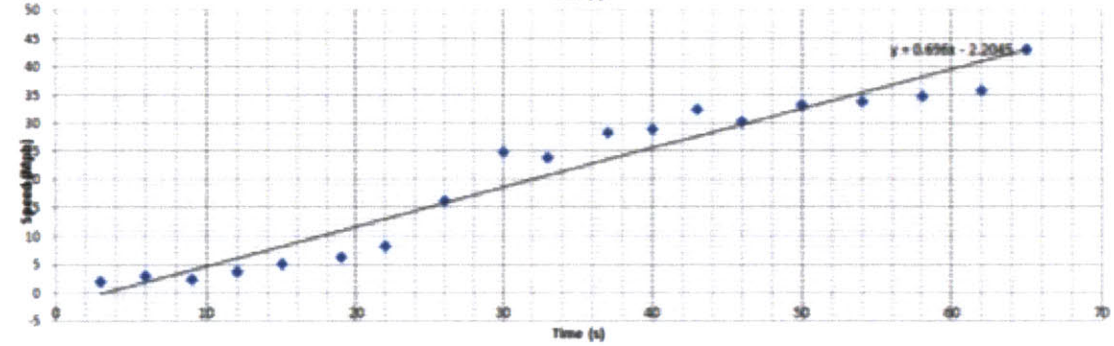

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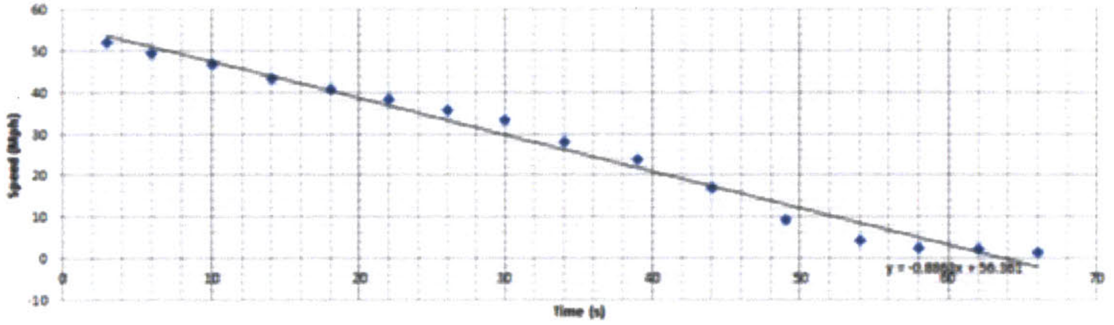

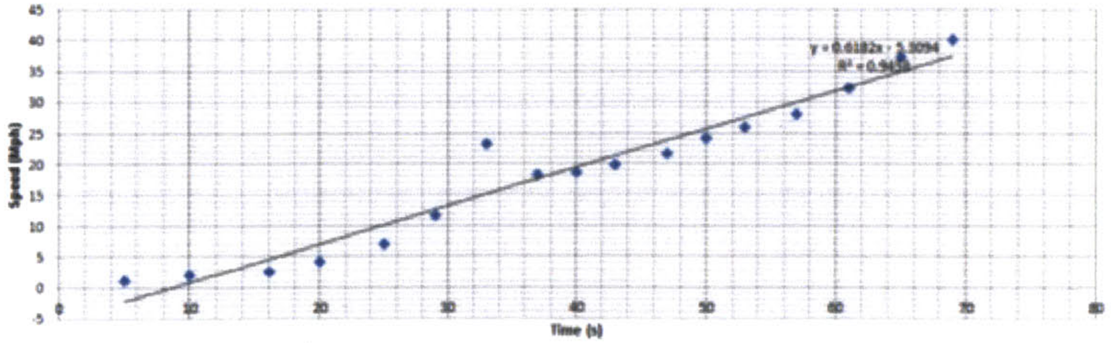

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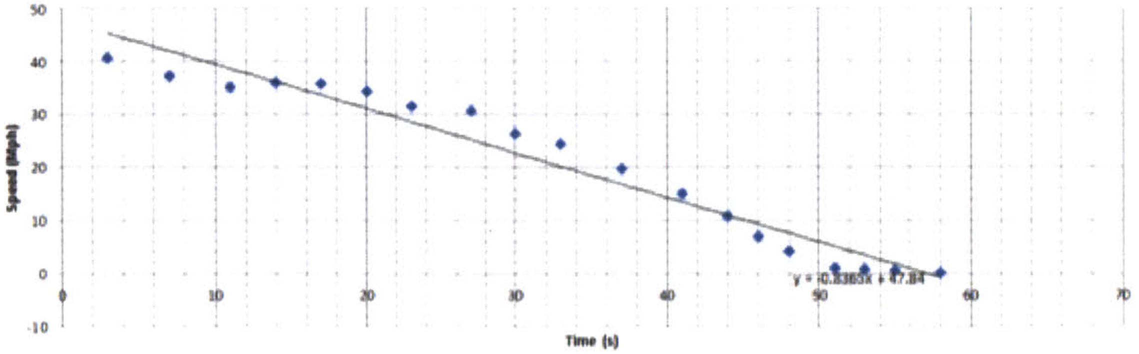

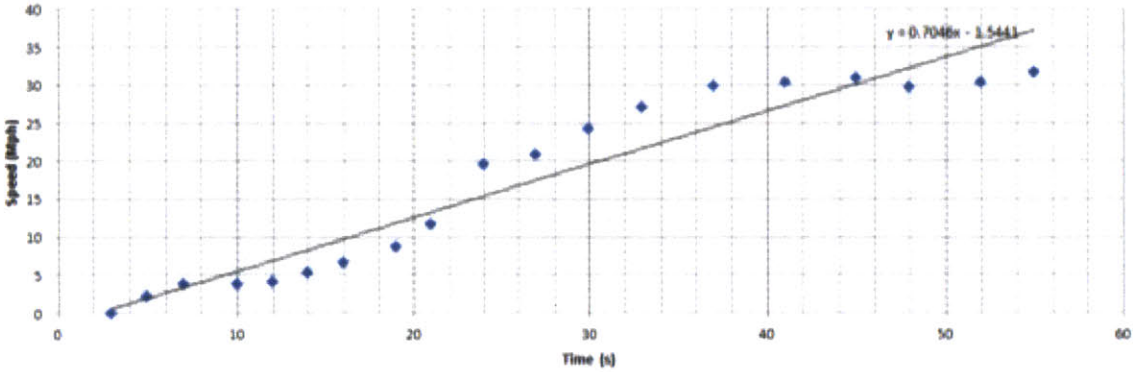

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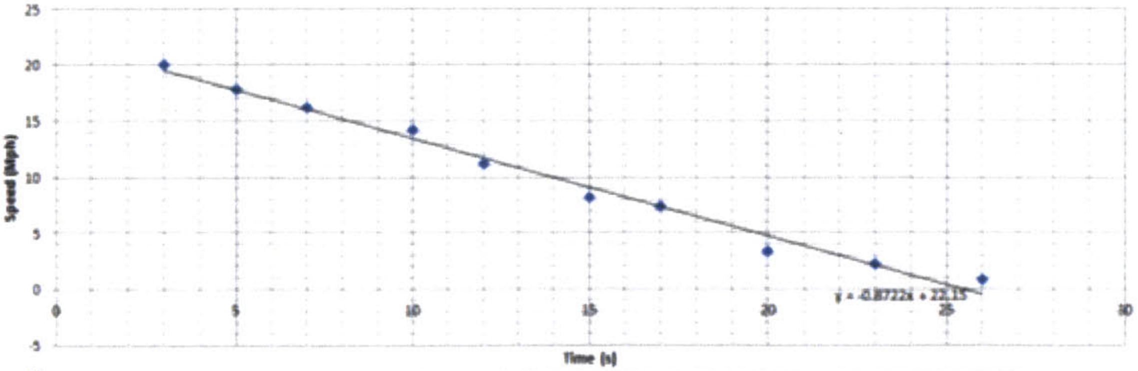

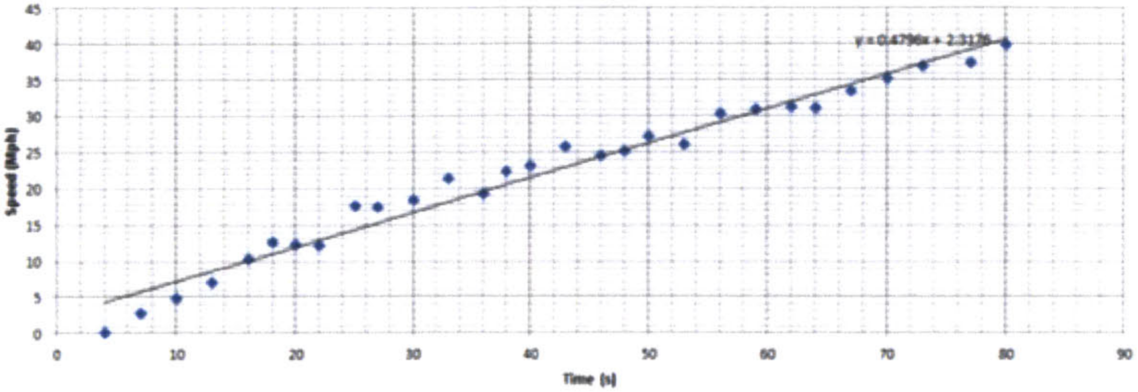

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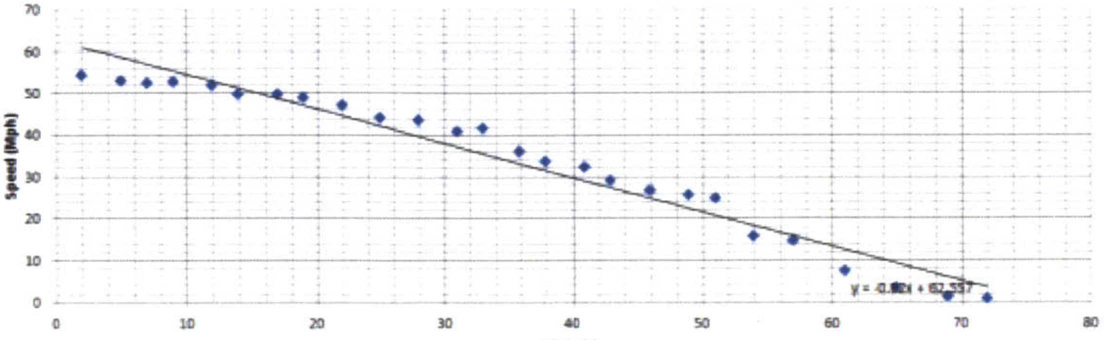

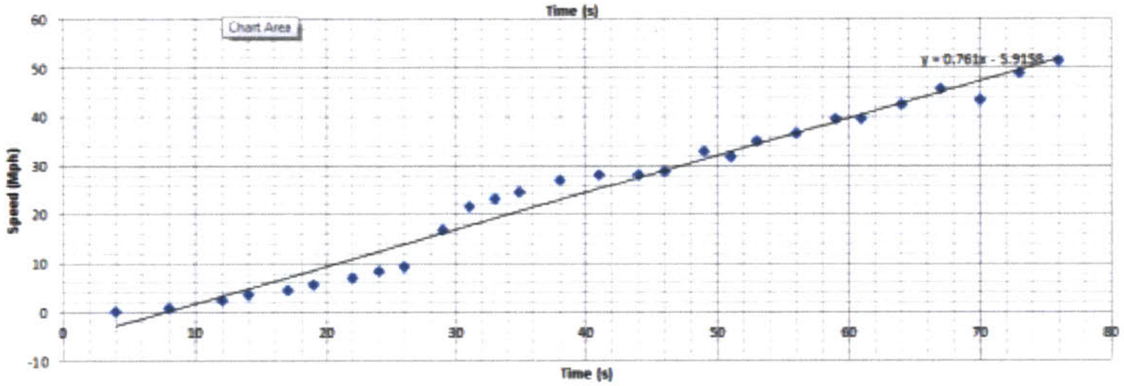

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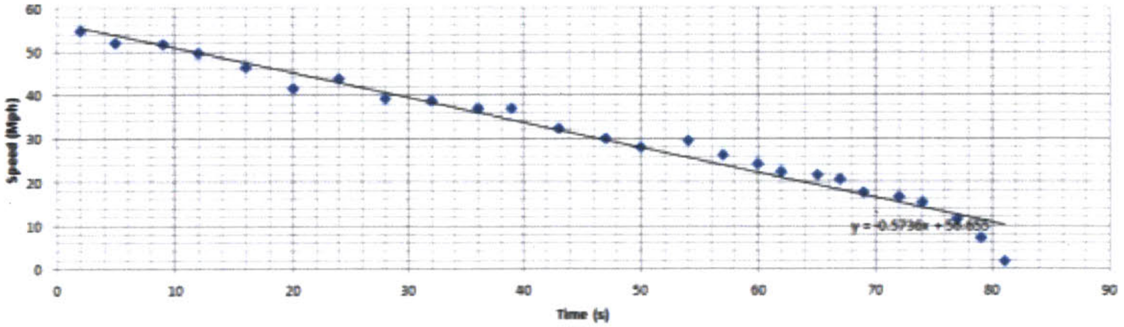

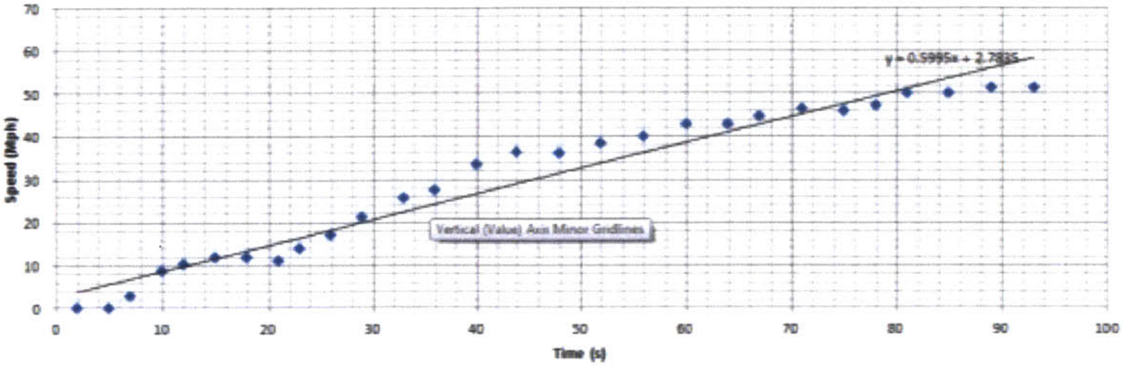

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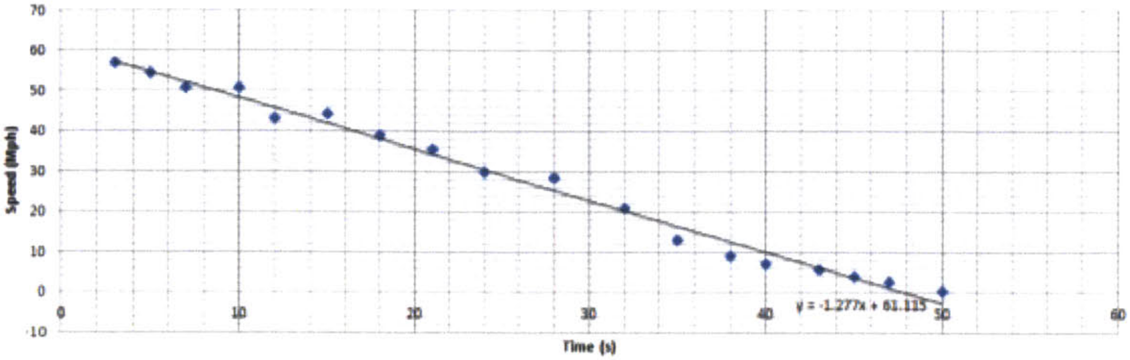

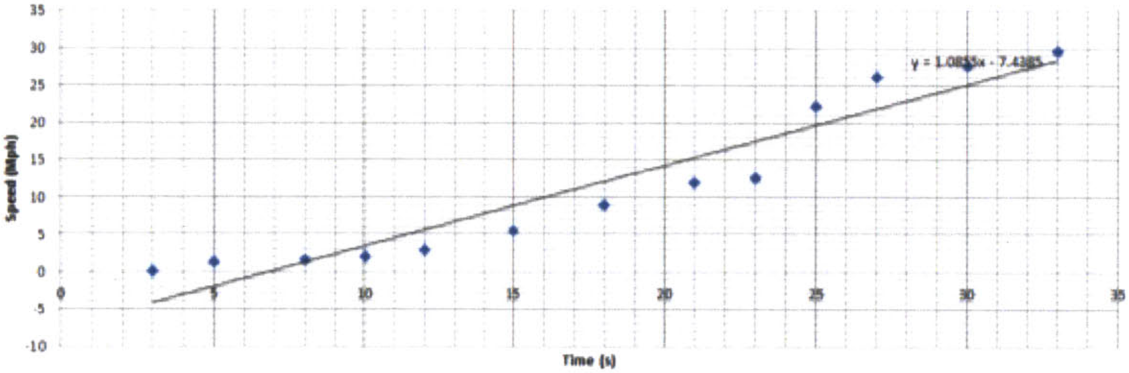

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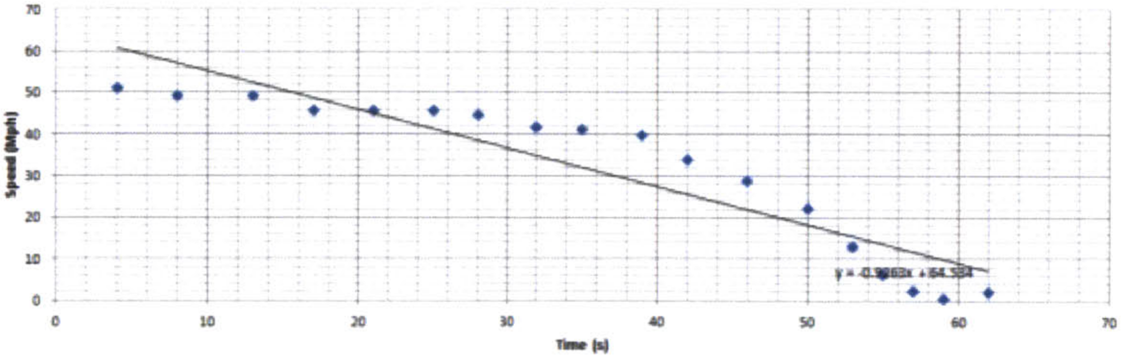
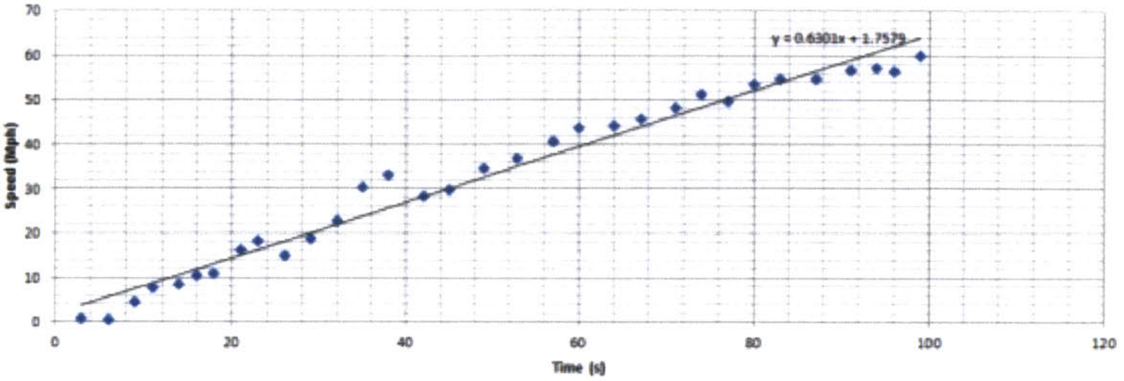
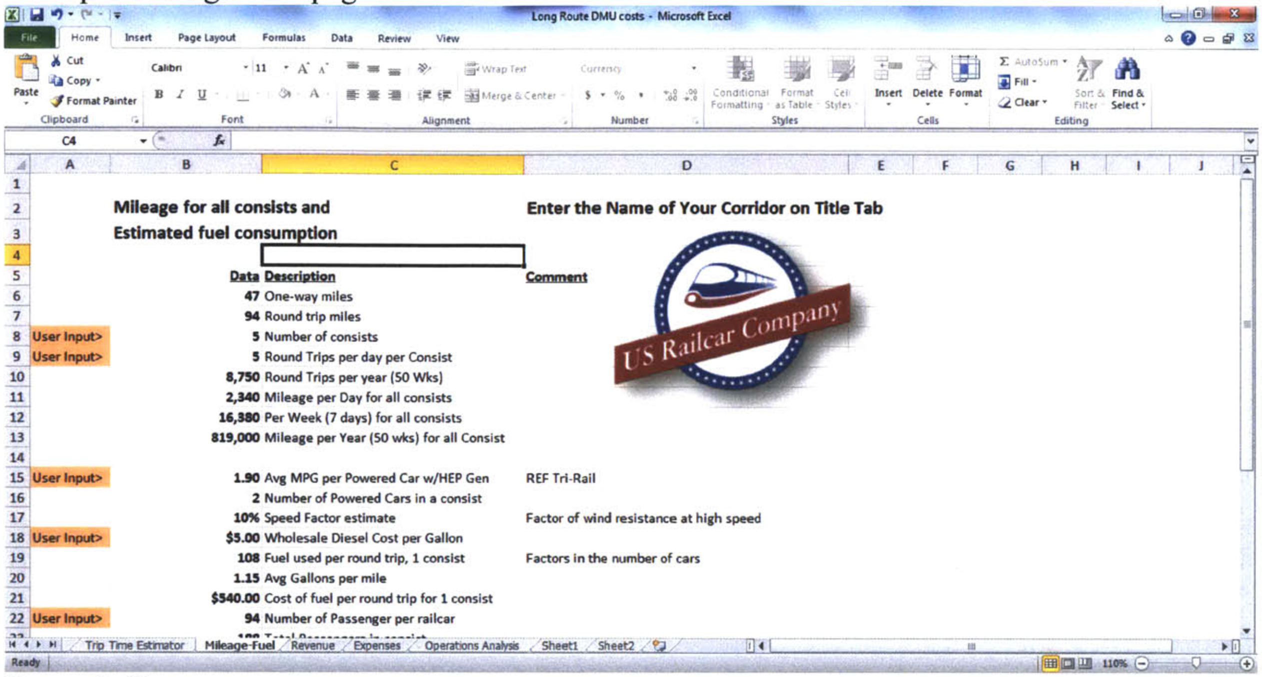




Cost Spreadsheet Tool

Example Mileage-Fuel page

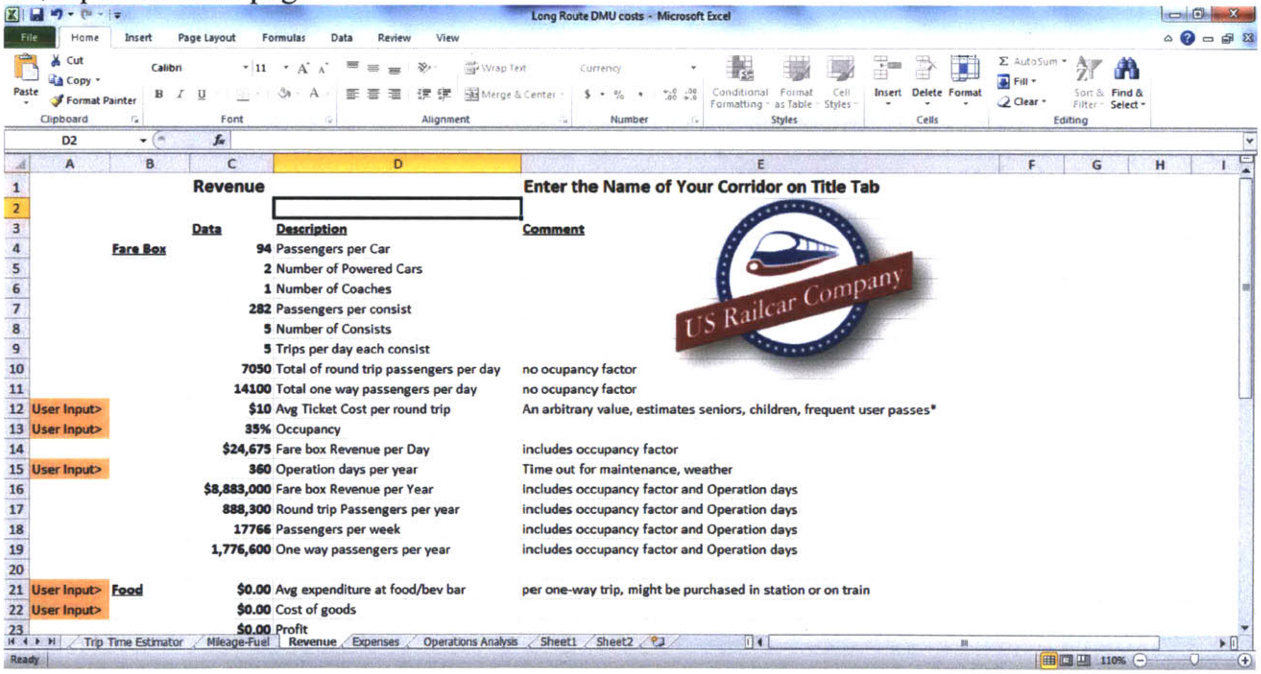


Mileage for all consists and Estimated fuel consumption

Enter the Name of Your Corridor on Title Tab

		Data	Description	Comment
6		47	One-way miles	
7		94	Round trip miles	
8	User Input>	5	Number of consists	
9	User Input>	5	Round Trips per day per Consist	
10		8,750	Round Trips per year (50 Wks)	
11		2,340	Mileage per Day for all consists	
12		16,380	Per Week (7 days) for all consists	
13		819,000	Mileage per Year (50 wks) for all Consist	
14				
15	User Input>	1.90	Avg MPG per Powered Car w/HEP Gen	REF Tri-Rail
16		2	Number of Powered Cars in a consist	
17		10%	Speed Factor estimate	Factor of wind resistance at high speed
18	User Input>	$5.00	Wholesale Diesel Cost per Gallon	
19		108	Fuel used per round trip, 1 consist	Factors in the number of cars
20		1.15	Avg Gallons per mile	
21		$540.00	Cost of fuel per round trip for 1 consist	
22	User Input>	94	Number of Passenger per railcar	

Example Revenue page

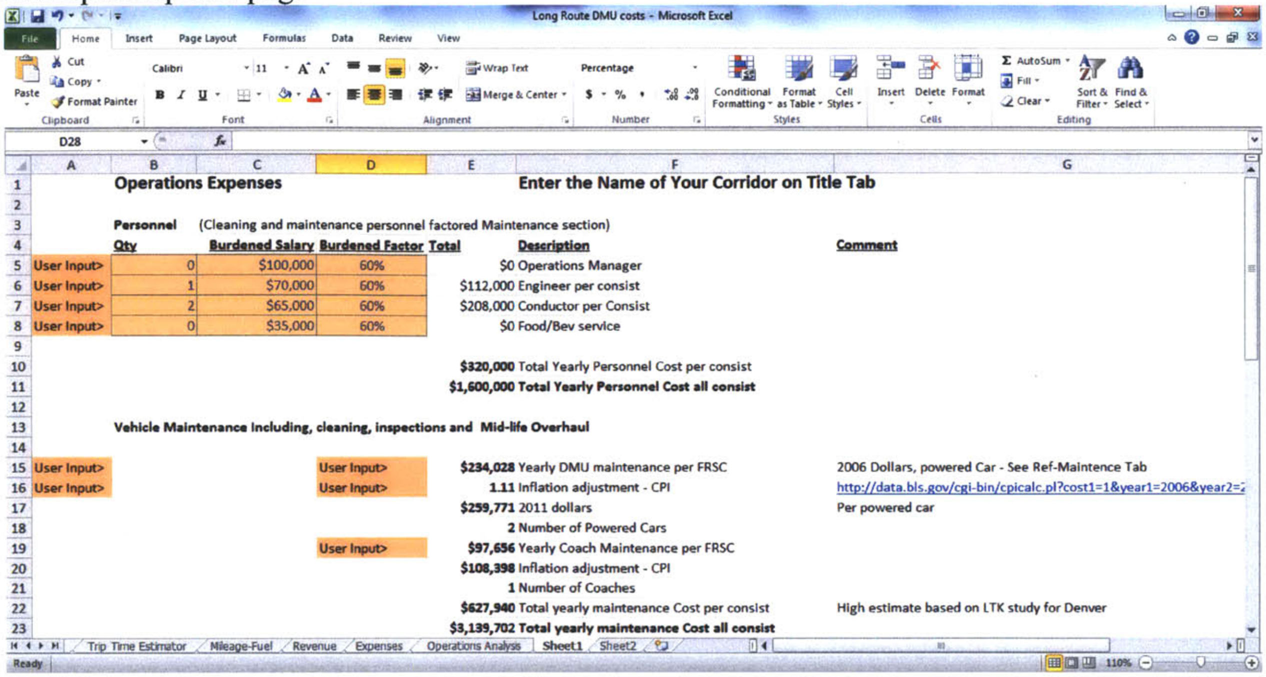


Revenue

Enter the Name of Your Corridor on Title Tab

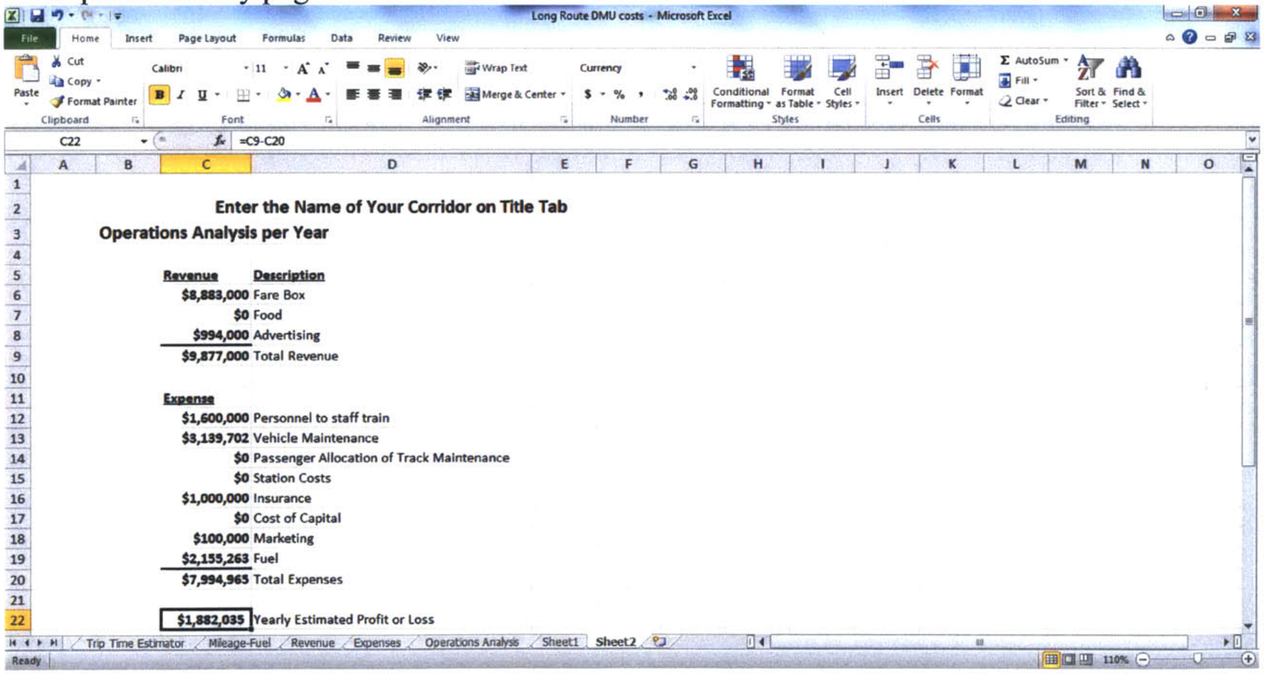
			Data	Description	Comment
4		Fare Box	94	Passengers per Car	
5			2	Number of Powered Cars	
6			1	Number of Coaches	
7			282	Passengers per consist	
8			5	Number of Consists	
9			5	Trips per day each consist	
10			7050	Total of round trip passengers per day	no ocupancy factor
11			14100	Total one way passengers per day	no ocupancy factor
12	User Input>		$10	Avg Ticket Cost per round trip	An arbitrary value, estimates seniors, children, frequent user passes*
13	User Input>		35%	Occupancy	
14			$24,675	Fare box Revenue per Day	includes occupancy factor
15	User Input>		360	Operation days per year	Time out for maintenance, weather
16			$8,883,000	Fare box Revenue per Year	Includes occupancy factor and Operation days
17			888,300	Round trip Passengers per year	includes occupancy factor and Operation days
18			17766	Passengers per week	includes occupancy factor and Operation days
19			1,776,600	One way passengers per year	includes occupancy factor and Operation days
20					
21	User Input>	Food	$0.00	Avg expenditure at food/bev bar	per one-way trip, might be purchased in station or on train
22	User Input>		$0.00	Cost of goods	
23			$0.00	Profit	

Example Expense page



	A	B	C	D	E	F	G
1		**Operations Expenses**				**Enter the Name of Your Corridor on Title Tab**	
2							
3		**Personnel**	(Cleaning and maintenance personnel factored Maintenance section)				
4		**Qty**	**Burdened Salary**	**Burdened Factor**	**Total**	**Description**	**Comment**
5	User Input>	0	$100,000	60%	$0	Operations Manager	
6	User Input>	1	$70,000	60%	$112,000	Engineer per consist	
7	User Input>	2	$65,000	60%	$208,000	Conductor per Consist	
8	User Input>	0	$35,000	60%	$0	Food/Bev service	
9							
10					**$320,000**	Total Yearly Personnel Cost per consist	
11					**$1,600,000**	**Total Yearly Personnel Cost all consist**	
12							
13		**Vehicle Maintenance Including, cleaning, inspections and Mid-life Overhaul**					
14							
15	User Input>			User Input>	**$234,028**	Yearly DMU maintenance per FRSC	2006 Dollars, powered Car - See Ref-Maintence Tab
16	User Input>			User Input>	**1.11**	Inflation adjustment - CPI	http://data.bls.gov/cgi-bin/cpicalc.pl?cost1=1&year1=2006&year2=
17					**$259,771**	2011 dollars	Per powered car
18					**2**	Number of Powered Cars	
19				User Input>	**$97,656**	Yearly Coach Maintenance per FRSC	
20					**$108,398**	Inflation adjustment - CPI	
21					**1**	Number of Coaches	
22					**$627,940**	Total yearly maintenance Cost per consist	High estimate based on LTK study for Denver
23					**$3,139,702**	**Total yearly maintenance Cost all consist**	

Example Summary page



C22 =C9-C20

	B	C	D
1			
2			**Enter the Name of Your Corridor on Title Tab**
3	**Operations Analysis per Year**		
4			
5		**Revenue**	**Description**
6		**$8,883,000**	Fare Box
7		**$0**	Food
8		**$994,000**	Advertising
9		**$9,877,000**	Total Revenue
10			
11		**Expense**	
12		**$1,600,000**	Personnel to staff train
13		**$3,139,702**	Vehicle Maintenance
14		**$0**	Passenger Allocation of Track Maintenance
15		**$0**	Station Costs
16		**$1,000,000**	Insurance
17		**$0**	Cost of Capital
18		**$100,000**	Marketing
19		**$2,155,263**	Fuel
20		**$7,994,965**	Total Expenses
21			
22		**$1,882,035**	Yearly Estimated Profit or Loss