Strategies for Meeting Future Capacity Needs on the Light Rail MBTA Green Line

by

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Abstract

The MBTA Green Line in the Boston metropolitan area is the busiest light rail system in the United States. Aging infrastructure and vehicles, a soon-to-be-constructed line extension, and the potential for 40% ridership growth by midcentury will tax already inconsistent service. But in this challenge lies opportunity: a potential full-fleet replacement and accompanying infrastructure upgrades would remove constraints which have long affected operations and vehicle selection.

Service evaluation and operations planning including frequency assignment, scheduled setting, and vehicle allocation are relatively well-understood problems for simple public transit lines. However, complex systems like the Green Line - those with multiple overlapping service patterns or branches sharing a trunkline - often present a transit planner with multiple tradeoffs and difficult decisions. Similarly, selection of appropriate rolling stock to help meet increasing capacity requirements is more difficult on a legacy system with physical constraints. Detailed analysis of various automated data collection sources can be used to assist medium-term and long-term planning decisions for these complex systems.

This thesis offers a sequential approach to improving the Green Line in that context. Analysis before and after schedule changes in spring 2016 (including the removal of three-car trains) shows that overall capacity increased and passenger waiting times decreased. However, this is largely the partial reversal of service deterioration since 2010, rather than significant long-term improvement. The development of a linear optimization model for determining service frequency and vehicle allocation provides a method to incorporate observational data into evaluation of alternate service scenarios. Analysis of potential rolling stock models based on capacity and physical characteristics indicates that current light rail product lines from four manufacturers can be viable for future Green Line use, although some modifications and infrastructure upgrades will be necessary to meet long-term capacity needs. Although the specific details of this case study are particular to the Green Line, the process should be broadly applicable to other complex branched transit systems.

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Chapter 1

Introduction

The problems of public transportation frequency assignment, vehicle allocation, and service evaluation are relatively well-understood for simple lines. However, complex systems — those with multiple routes sharing a trunk line, but with multiple branches or turnback points - present substantially more difficulty. Automated data collection presents an opportunity to improve medium-term and long-term planning decisions for these complex systems.

This thesis will focus on the Green Line light rail system, operated by the Massachusetts Bay Transportation Authority (MBTA) through Boston and three of its inner suburbs. The Green Line is a legacy system, with four surface routes feeding into a downtown subway built in the late 19th and early 20th centuries. Rising passenger volumes combined with aging equipment and infrastructure necessitate proactive scheduling to ensure that acceptable crowding levels and minimum policy frequencies are maintained on the system. The pending addition of two additional branches, now scheduled for 2021, will put additional strain on much of the system. However, new technologies and data sources, plus the planned replacement of the full fleet, present a chance to meet these challenges and improve the Green Line.

1.1 Background and motivation

New data sources provide new opportunities for modifying transit service to increase efficiency and improve the passenger experience. The MBTA can use these opportunities to maintain and even improve the system, even in the face of stagnant finances and rising demand. The MBTA's first-generation automated fare collection (AFC) system, the CharlieCard, was implemented in 2005. A second-generation system, expected to begin service in 2019, will add a range of upgrades, including provision for all-door boarding on surface vehicles. In 2014, the MBTA activated GPS tracking on most Green Line trains; cleaning code written by Fabian has greatly improved the reliability of this automated vehicle location (AVL) data.(Fabian, 2017a) The MIT-developed ODX (origin-destination-interchange) model uses these two sources to infer passenger paths and estimate passenger flows. An update to this by Sánchez-Martínez corrects for farebox noninteraction at surface stops, further improving accuracy.(Sánchez-Martínez, 2017a)

Malikova (2012) demonstrated how running times, headway distributions, and throughput can be determined with AVL and used to evaluate the performance of the Green Line and to weigh the merits of potential operating changes. The newly cleaned Green Line GPS and wayside AVL data is a chance to update this with a larger sample size, and to demonstrate multiyear performance trends. Recent trends of increased derailments and slow orders resulting from them may have significant effects on system performance; this offers a chance to quantify the changes.

When work on this thesis was begun, the first phase of the Green Line Extension was expected to open in 2017. This research was thus to inform immediate scheduling and operations strategies for the expanded Green Line system. With delay of the extension until at least 2021, the intention has shifted to forging methods for a more general medium-and-long-term approach to improvements, albeit with some specific recommendations for the Green Line Extension. The MBTA Service Delivery Policy specifies minimum service frequencies and maximum crowding levels on the Green Line. Combined with constraints from infrastructure and fleet size, this creates the problem of how to optimize vehicle allocation to minimize overall crowding.

The MBTA Fiscal Management and Control Board was formed in 2015 to provide financial oversight of the MBTA, with a focus on controlling costs. However, the Board has demonstrated willingness to invest in quality and capacity enhancements on current corridors, including full-fleet replacement for the Red Line. During the two-year span of this thesis, the possibility of a full-fleet replacement for the Green Line has emerged as a desirable funding priority. This creates an opportunity for an early outside analysis of procurement considerations like capacity needs and off-the-shelf vehicle designs to compare with and inform the MBTA's internal research. A full-fleet replacement provides a rare chance to erase many system constraints that have been incrementally added over the years because each small additional has had to be compatible with the existing system.

Over the last several decades, there has been a large increase in the number of LRT and BRT systems in the United States. New complex interlined systems have been built in a diverse set of cities and operating characteristics. These systems will require continual monitoring and service planning to ensure quality service as they mature, and many will require fleet replacement in coming years. All of the methodology in this thesis is intended to be adaptable to other systems to fit the system geometry and the data that is available.

1.2 The MBTA Green Line

The MBTA operates public transit in eastern Massachusetts and the Boston metropolitan region. The agency runs five color-coded rapid transit lines: the heavy rail Red, Orange, and Blue lines (including the Ashmont-Mattapan High-Speed Line, a short light rail feeder to the Red Line), the bus rapid transit Silver Line, and the light rail Green Line.

The Green Line consists of the Central Subway (Kenmore to North Station, plus the elevated section from North Station to Lechmere) plus the four surface branches, lettered B through E. (The A Branch was discontinued in 1969 and replaced with the route 57 bus; several proposals and lawsuits to restore it yielded no results.) The B and C branches run in dedicated median lanes with frequent grade crossings. The D Branch, a converted commuter rail line, runs on a longer grade-separated right of way with only pedestrian crossings. The E Branch runs in a tunnel section close to the Central Subway, dedicated median lanes further from the city center, and in mixed traffic near its outer end. (A further mixed-traffic section, the Arborway Line, was closed in 1985.) Under the Green Line Extension project, two grade-separated surface branches will be extended from Lechmere to the north and west.

The Green Line is the second-oldest continuously operating light rail system in the country, after the St. Charles Street line in New Orleans (Federal Transit Administration, 1997); some segments of what is now the E Branch were operated as a horsecar line starting in 1857, and what is now the C Branch was electrified in 1889. The Tremont Street Subway, the first section of the Central Subway, was completed in 1897; it was the first rapid transit subway in the country. Extensions were added in 1898, 1912, 1914, 1932, and 1941.(Clarke and Cummings, 1997) The initial subway segments were designed to remove streetcars from busy surface streets, rather than to act as a true rapid transit system. They were built to accommodate the 20-foot and 25-foot streetcars then in use by the Boston Elevated Railway – which could navigate curves of small radius then prevalent on Boston streets – rather than the longer cars built later in the 20th century.(Cummings and Cox, 1963) After the East Boston Boston (now the Blue Line) was converted from streetcar use to heavy rail in 1924, plans were made to similarly convert the Tremont Street Subway, but this was not done for financial and practical reasons.(Clarke and Cummings, 1997)

The Green Line has 13 subway stations (including Lechmere and Science Park), five of which offer transfers to the other rapid transit lines. Lechmere, Haymarket, Copley, Hynes Convention Center, and Kenmore are also major bus transfer hubs. All subway stations are handicapped accessible except Hynes Convention Center (renovations planned for 2019), Symphony (renovations proposed), and Boylston. The line has 53 surface stations, of which 22 - largely busy stations and those with bus transfers - are accessible.(MBTA staff, 2014) Four non-accessible stops on the B Branch are planned to be consolidated into two accessible stops around 2020.

The Green Line uses two fleets: 120 Kinki Sharyo Type 7 cars delivered in 1987 and 1997, and 95 AnsaldoBreda Type 8 cars delivered in 1999-2008. Due to accidents, long-term reliability issues, and an overhaul program, approximately 75 vehicles of each type are available for daily service. Type 7 cars have a high floor and can only be boarded by handicapped passengers at a small number of stations with ramps or portable lifts; Type 8 cars have a low-floor center section and can be boarded by handicapped passengers at all accessible stations. Twenty-four CAF Type 9 low-floor cars are on order and expected to arrive in 2018. All trains are expected to have at least one accessible car. Trains operate as two-car sets with one Type 7 and one Type 8 car on weekdays so that all trains have an accessible car; single Type 8 cars are operated during lower-demand periods on weekends.

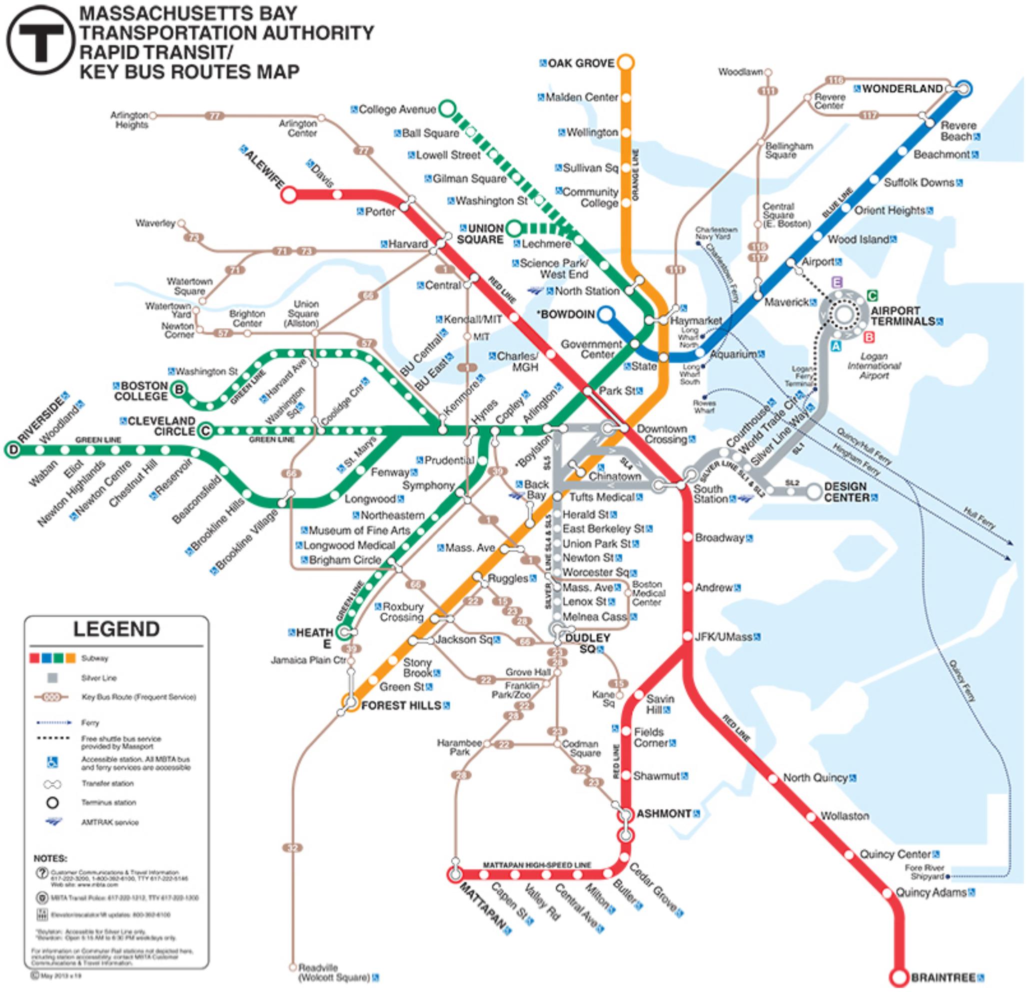

Figure 1-1: Schematic map of the MBTA rapid transit system, including key bus routes and the planned Green Line Extension.[2]

The MBTA's light rail operations - including the much smaller Ashmont-Mattapan High Speed Line - are the busiest light rail system in the country, with 226,500 daily boardings in the fourth quarter of 2016.(Dickens, 2017) The Green Line Extension is expected to add about 26,000 daily boardings by 2030;(Massachusetts Department of Transportation, 2011) the rapid transit system is expected to undergo an additional 20% to 40% ridership growth

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[2] Since this map was published, two GLX station names have changed: Washington Street to East Somerville, and Lowell Street to Magoun Square. A not-shown extension of the Silver Line to Chelsea, announced shortly after this map was published, will open in late 2017.

by 2050.(Massachusetts Bay Transportation Authority, 2015)

1.3 Objectives of research

The aim of providing a methodology with which to evaluate and improve complex systems divides into three overlapping parts. The first is broadly an update and extension of Malikova's work with the larger and more accurate datasets that are now available.(Malikova, 2012) This will determine how reliable existing service is, how schedule changes affect actual vehicle flows, and whether vehicles are able provide reasonably uniform schedules on each branch. From these results can come recommendations for medium-term changes to scheduling and dispatching.

The second is to create a method for solving the vehicle allocation problem, in order to meet service delivery standards within a given fleet size while minimizing overall crowding. While designed for the Green Line, the method is intended to be adaptable to any rail or bus system where several routes share a trunk. From this can come recommendations for service patterns and vehicle allocations using scenarios such as short turn overlays.

The third is to use those results to inform the preliminary phase of fleet planning as the MBTA looks to the long term and the potential of a full fleet replacement. This includes determining optimal vehicle size and fleet size to meet capacity needs, analyzing the possibility of buying an off-the-shelf vehicle rather than a custom model, and compiling infrastructure needs that must be packaged with the vehicle order.

1.4 Research approach

The service measurement chapter retains many of Malikova's methods, including her use of reference time and of Boylston eastbound as a standard reference point. Running times are calculated using cleaned data (which includes AVI, track circuit, and GPS data), and cycle times using proxy time for turnarounds. Graphical examination and disaggregate analysis is used to set more sophisticated cutoffs of erroneous running times. Like Malikova, throughput is determined by counting the number of trains and cars passing the reference point. All of these values are compared with current schedules to determine opportunities for improved schedules.

The replacement vehicle evaluation chapter uses a three-step process to evaluate off-the-shelf light rail vehicles. The first step evaluates vehicles on physical characteristics; this includes a compilation of infrastructure changes necessary for the vehicles to be optimally used. The second step determines the capacity of available vehicle lengths and what train sizes are needed to handle projected demand; this includes a method to estimate flows on the new GLX segment under construction using existing bus ridership as a basis for projected demand patterns. The third step evaluates fleet sizes and approximate costs of various vehicle types.

The vehicle allocation work, presented as Appendix A, uses the results of the service measurement as inputs. A demonstration of a linear optimization model using vehicle count as the objective function is developed. The model divides the Green Line into bidirectional segments and assigns service levels on the four branches that provide sufficient capacity to meet estimated flows. A nonlinear model with passenger-centric crowding as the objective function is outlined as a potential improvement on the linear model.

1.5 Organization of thesis

Chapter 2 provides a more detailed overview of pertinent characteristics of the Green Line and its history. Chapter 3 outlines current issues with the Green Line and a review of previous work on this subject. Chapter 4 details a methodology for evaluation of complex systems on several criteria, with recent results and comparison with previous results presented for the Green Line. Chapter 5 details evaluation of future Green Line fleet needs, using the results of Chapters 4 and analysis of available technologies. Finally, Chapter 6 presents a summary of results and pertinent recommendations to the MBTA, and suggests opportunities for future research.

Chapter 2

The Green Line and its operations

The MBTA rapid transit system consists of three heavy rail lines (the Blue Line, the two-branched Red Line, and the Orange Line), one electric BRT tunnel (serving two of the four branches of the Silver Line), and the four-branched light rail Green Line. The Green Line serves several overlapping purposes in the transportation network. The four western surface branches serve as radial commuter lines, bringing passengers from residential areas to commercial and employment centers, as well as local service in those suburbs. The Central Subway serves as an east-west distributor, allowing passengers from the heavy rail lines, northside commuter rail lines, and several groups of bus lines[1] to reach destinations like the Back Bay and Longwood Medical Area. It also serves some demand patterns outside the traditional peaks, including the sports and entertainment venues of Fenway Park and TD Garden, and the student populations of Boston University, Northeastern University, and several smaller institutions. The combination of these demand patterns causes the Green Line to have heavy bidirectional ridership through the Central Subway and portions of the branch lines, and significant usage during midday and at night.

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[1] A large number of bus lines intersect the Green Line, with three groups of routes serving as primary feeders: western and crosstown routes (8, 19, 57, 60, and 65) at Kenmore; North Shore and Charlestown routes (92, 93, 111, 325, 326, 424, 426, 428, 434, and 450) at Haymarket; and Cambridge and Somerville routes (69, 80, 87, and 88) at Lechmere.

2.1 Geography and physical characteristics

The Green Line is primarily oriented east-west, and the convention of eastbound/westbound is used throughout this thesis.[2] A map of right-of-way types of the Green Line is shown in Figure 2-1. The Central Subway includes the east-west Boylston Street Subway, the north-south Tremont Street Subway, the northwest-southeast Lechmere Viaduct, and the southwest-northeast Huntington Avenue Subway. It is fully grade separated (save for a pedestrian crossing between eastbound platforms at Park Street station), allowing trains to avoid the congestion of downtown city streets. Stations have a mix of side and island platforms. A typical side platform subway station is shown in Figure 2-2; representative surface stations are shown in Figures 2-3 through 2-6.

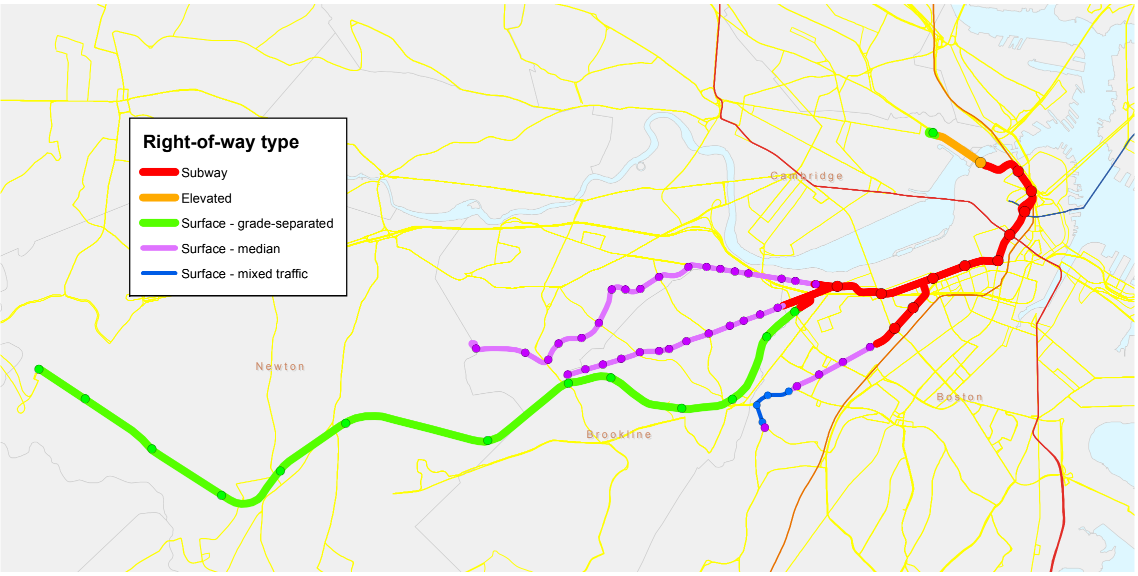

Figure 2-1: Green Line right-of-way and station characteristics. Map by the author, available on Wikipedia Commons.

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[2] In this thesis, "eastbound" indicates any train headed towards Lechmere, and "westbound" indicates any train headed away from Lechmere. "Inbound" and "outbound" are often used in other publications; however, they cause confusion in the segment between Park Street and Lechmere. Park Street is the traditional divisor between inbound and outbound; thus, a train from Lechmere to Heath Street would go inbound then outbound without switching directions.

Figure 2-2: Prudential, a typical Green Line subway station. Photo by the author, available on Wikimedia Commons.

The B Branch (Boston College Line / Commonwealth Avenue Line), the northernmost of the four western surface branches, runs entirely in the median of Commonwealth Avenue except for a short tunnel segment at its eastern end (where it connects to the Boylston Street Subway at Kenmore). It has 18 surface stops and 26 grade crossings (plus 4 pedestrian-only crossings not at stops) along its 4.1-mile length. All but one stop have a grade crossing at one or both ends. Platforms are typically narrow side platforms and directly adjacent to travel lanes, with minimal shelter for passengers. The Boston College loop is on the side of the road on MBTA land.

The C Branch (Cleveland Circle Line / Beacon Street Line) runs in the median of Beacon Street (except for a short tunnel near Kenmore). Unlike the B Branch, it shares a wide median with parking spots and landscaping. It has 13 surface stops and 18 grade crossings (plus two pedestrian crossings not adjacent to stops) along its 2.8-mile length. Eight stops have a grade crossing at one or both ends. Most platforms are side narrow platforms, although not all are adjacent to travel lanes; several stops have small passenger shelters.

Figure 2-3: Chestnut Hill Avenue, a B Branch station with narrow platforms and no passenger facilities. Photo by the author, available on Wikimedia Commons.

Figure 2-4: Englewood Avenue, a typical C Branch station. Photo by the author, available on Wikimedia Commons.

The D Branch (Riverside Line / Highland Branch) runs on the surface on a former commuter rail right-of-way, with a short tunnel connecting it to the C Branch west of Kenmore. It has 13 surface stops along its 9.4-mile length. There are no grade crossings except for a pedestrian crossing at "Chicken Farm" west of Chestnut Hill, though pedestrians must cross the tracks at all stations. The D Branch is capable of higher speed operation than the other branches, with up to 50 mph possible on several straightaways. Platforms are wider than other stations, and all stops have at a heated shelter with fare machines. All stops have side platforms except for Riverside, which has one side platform and one island platform.

Figure 2-5: Brookline Village, a typical D Branch station, with accessible platforms. Photo by the author, available on Wikimedia Commons.

The E Branch (Heath Street Line / Huntington Avenue Line) runs in the Huntington Avenue Subway east of Northeastern, in the median of Huntington Avenue between Northeastern and Brigham Circle, and in lanes shared with auto traffic west of Brigham Circle. It is the only remaining portion of mixed-traffic streetcar operations in the metro area. The line has 11 stops: two subway stations, four median stops, four mixed-traffic stops, and the Heath Street loop on private land. The subway stations are similar to the others in the Central Subway, and the median stops are similar to the B Branch. The stops in mixed traffic have no platforms; they share bus shelters with several bus routes. Passengers wait on the sidewalks and cross one auto lane to reach trains. There are five grade crossings on the median section (plus one only used by emergency vehicles); there are six signalized intersections, four unsignalized intersections, and numerous driveways along the mixed traffic section.

Figure 2-6: Two Green Line trains and a bus at Mission Park, a typical E Branch station in mixed traffic. Photo by the author, available on Wikimedia Commons.

2.1.1 Tracks and terminals

The vast majority of the Green Line is double-tracked, with limited passing opportunities. A short section of the Central Subway is four-tracked; it is possible for trains to pass westbound but not eastbound at Park Street station. There is a pocket track near Blandford Street on the B Branch, and a siding near Northeastern University on the E Branch.

Four locations typically serve as eastbound terminals: Park Street loop, Government Center loop, pocket tracks at North Station, and Lechmere loop. Kenmore loop is occasionally used to reverse short-turn trains. The typical westbound terminals are the ends of the branches: Boston College loop (B), a tail track at Cleveland Circle (C), crossovers at

Riverside (D), and Heath Street loop (E). The yard leads at Reservoir (D) and the crossover at Brigham Circle (E) are commonly used for short turns; the Blandford Street pocket track and the crossovers at Coolidge Corner (C) and Washington Street (B) are occasionally used for short turns.

The surface branches and Central Subway have a relatively small number of other crossovers; the D Branch has a pair of crossovers approximately every two stations. Except at the eight normal terminals and the two triple-track segments, there are only a small number of places that a disabled train can be temporarily stored, including stage tracks (normally occupied with maintenance equipment) near Boylston and Arlington, and Kenmore Loop. A track map of the Green Line is shown in Figure 2-7.

Park Street loop and Government Center loop have no storage available; a train sitting in either loop prevents any other train from going through the loop. Boston College and Lechmere are similar, though trains can be pulled into the yards if necessary. Heath Street loop has two tracks, allowing one train to lay over, and North Station has two pocket tracks. Trains can easily loop in the yards at Cleveland Circle and Riverside; only there are layover times truly unbounded.

The Green Line has four major yards. The largest are at Riverside (95 vehicles capacity) and Reservoir (79 vehicles capacity), both of which have large maintenance facilities. The Boston College yard is smaller (24 vehicles) and has a light maintenance facility. The Lechmere yard is for storage only (about 20 vehicles) and has no maintenance operations.

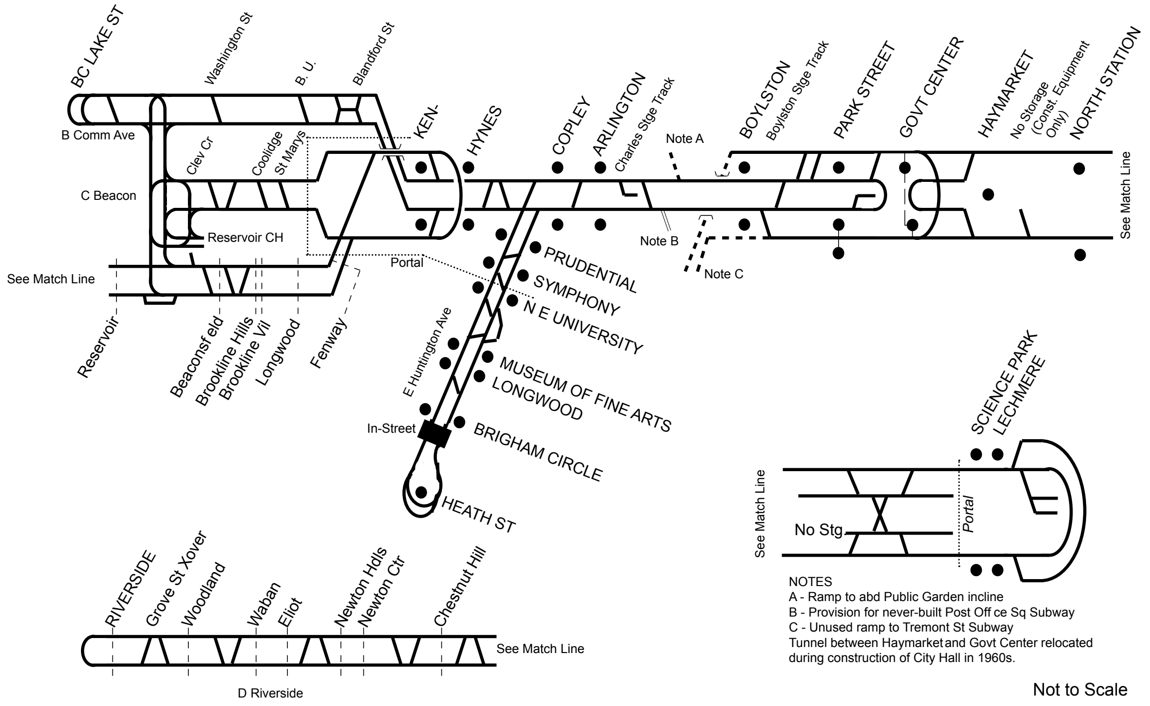

Figure 2-7: Track map of the Green Line, published by the MBTA.

2.1.2 Control systems

Unlike heavy rail lines and some modern light rail lines, the Green Line does not have any active (automatically enforced) control systems. In the Central Subway and on the D Branch, a fixed block wayside signal system is used. The system gives red (stop) signals at the entrance to the first two blocks behind a train, and yellow (proceed with caution) at the entrance to the third block behind. This gives the following train sufficient stopping distance in case of an emergency.

Signals are not used inside stations. Instead, line-of-sight operations are used, allowing trains to move within feet of each other at low speed. Line-of-sight operations are also used on the surface sections of the B, C, and E Branches, and inside yard limits. Those three branches also have three-phase (proceed-caution-stop) indicators at signalized grade crossings. These indicators are linked to the traffic light system and allow trains to proceed only when there is not conflicting cross traffic or left-turn traffic. West of Brigham Circle, E Branch trains follow regular traffic rules and traffic lights. At unsignalized street and pedestrian crossings, trains are required to slow down or come to a complete stop before proceeding.

The signal system is passive; it does not enforce a stop if a train passes a red signal. (However, such a violation will be noticed by the dispatchers.) Thus, there is nothing to prevent an operator from mistakenly passing red signals and causing a collision. A Positive Train Control (PTC) system that would enforce signals as well as speed limits was evaluated in 2012, but found to be excessively expensive and have severe throughput limitations. Instead, the MBTA is planning an Automatic Train Control (ATC) system which will enforce red signals and protect stopping distances during line-of-sight operation, but will not regulate speeds.

Most switches used in revenue service are controlled by Automatic Vehicle Identification (AVI) units on each vehicle, which are read by trackside sensors. Operators set a route code which automatically lines switches to the correct direction. Most other switches are power switches that can be controlled by trackside panels; a small number (mostly those in streets) require manual operation with a metal lever. Only one crossover used in regular service cannot be controlled with AVIs: the manual crossover at Cleveland Circle.

The Operations Control Center (OCC) is responsible for most control and dispatching except at terminals. OCC staff have access to all location data as well as live headway information. Most real-time control actions are initiated by the two Green Line dispatchers at the OCC. Inspectors are located at most terminals and are responsible for dispatching trains from those locations into service. Inspectors at major stations like Reservoir and Kenmore also make some control actions, particularly holding.

2.1.3 Operations and capacity

The Central Subway has always operated with some services running through the whole subway and others turning back partway through. The MBTA and its predecessors have frequently changed the downtown terminals of each service in response to demand and operational considerations. Since March 2016, the B Branch has turned at Park Street, the C Branch at North Station, the D Branch and Government Center, and the E Branch at Lechmere. Dispatchers can decide to short turn or extend a trip to a different terminal if needed to fill a gap. All trips are scheduled to run the full length of each route, except for a small number of D Branch trains that originate or terminate at Reservoir. Short turns at Brigham Circle are frequent when heavy traffic affects service on the outer section of the E Branch.

Weekday service consists entirely of two-car trains, most of which are composed of one high-floor Type 7 vehicle and one low-floor Type 8 vehicle. A two-car train has a seated capacity of 90 passengers and a policy capacity of 202 passengers (though a packed train may have over 300 passengers). Typical branch headways are 5 to 7 minutes at peak periods, for a total of about 44 TPH (8,900 passengers per hour) in each direction through the Central Subway. Off-peak headways are typically 6 to 11 minutes. Weekend service operates on headways of 9 to 12 minutes (with slightly higher frequency on Saturday peak periods) using two-car trains during the day and single-car trains at the margins of service.

2.1.4 Green Line Extension project

The MBTA is planning to restart construction in late 2017 on the Green Line Extension — the agency's first rail rapid transit extension since 1985[3] — with completion now planned for 2021. The Extension will begin at Lechmere, which will be relocated on an elevated structure east of Route 28. The elevated structure will parallel Route 28 as far as the Fitchburg mainline, where it will split into two on the complex Red Bridge. One branch will follow the north side of the Fitchburg mainline to a new station at Union Square in Somerville. The other will parallel the Lowell Line with new stations at East Somerville[4], Gilman Square, Magoun Square[5], and Ball Square in Somerville, and at College Avenue in Medford.

The Green Line Extension will be built to modern light rail standards, with 50 mph top speeds and full grade separation except for pedestrian crossings at some stations. An extension of the Somerville Community Path (which currently ends near the site of Magoun Square station) will parallel part of the Extension and serve as emergency egress from some

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[3] The last major rail rapid transit project was the 1979-1987 Southwest Corridor project, which relocated and modernized the southern section of the Orange Line, but did not extend service. The Red Line Northwest Extension, completed in 1985, was the last project to add route mileage.

[4] Known as Washington Street and Brickbottom during early planning; Cobble Hill was also suggested. East Somerville traditionally referred to an area further east near Sullivan Square.

[5] The station will be located on Lowell Street about 0.4 miles from Magoun Square proper.

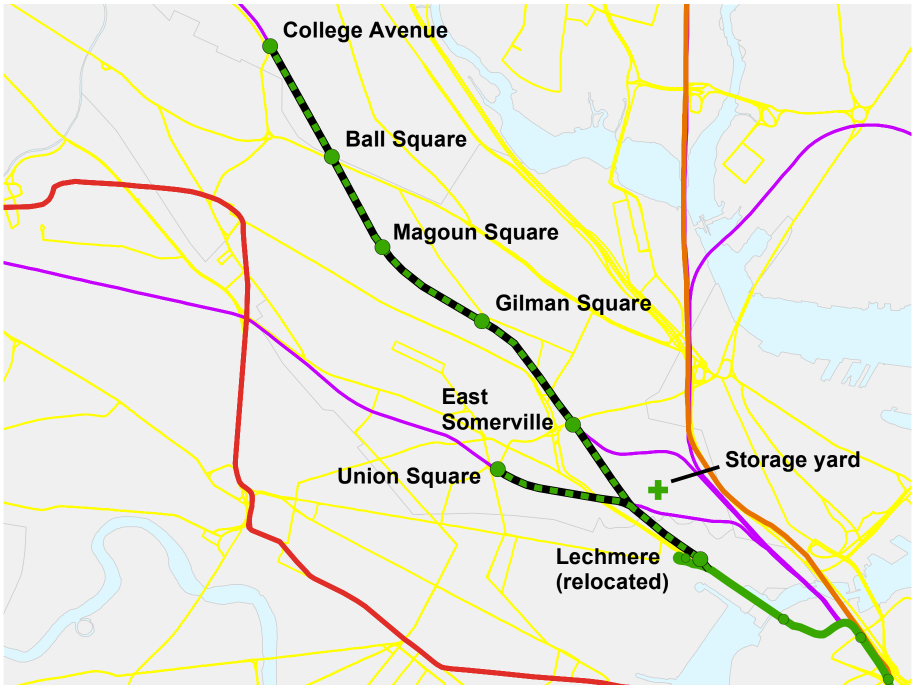

Figure 2-8: Map of the Green Line Extension showing its relation to existing rapid transit, bus, and commuter rail lines. Map by the author, available on Wikipedia Commons.

stations. A small storage yard will be constructed, with tail tracks connecting to the new branches near Red Bridge, and space is available for eventual addition of a maintenance facility. A map of the project is shown in 2-8.

2.2 Historical background

The current Green Line is necessarily the product of its past, and its history must be understood in order to properly plan its future. Many of the modern operating patterns, vehicle designs, and physical constraints have their origins many decades ago. The first recognizable ancestor of the Green Line opened in 1857; the first tunnel segments, still in use, opened in 1897. Since then, nine distinct generation of vehicle types have been produced, with the design of each constraining and influencing the next. Several proposals that would have fundamentally altered the Green Line were never implemented, but after many years of proposals, the Green Line Extension is under way.

2.2.1 History of the Green Line

Details in this section are from Clarke and Cummings (1997) except where noted.

Local public transportation in Boston began with a Boston-Cambridge stagecoach line in 1793, followed by horse-drawn omnibuses in 1826. Mainline rail service began on what is now the Worcester Line in 1834, but rails were not used for street transit until a Bowdoin-Central horsecar line opened on March 26, 1856. In 1857, the West Roxbury Railroad opened a horsecar line from Jamaica Plain to Roxbury Crossing, which included tracks on South and Centre Streets. It was almost immediately leased to the Metropolitan Railroad to extend its downtown-Roxbury Crossing line. In 1859, the Metropolitan opened a branch from Roxbury Crossing to near Brookline Village via Tremont Street (part of which is now Huntington Avenue). In 1881 and 1883, the Metropolitan extended tracks from Copley Square to West Chester Park (Massachusetts Avenue), then to Brigham Circle.

By the mid-1880s, the extensive horsecar system was controlled by seven companies and saw some 100 million annual riders. Competition for tracks, slow speeds, inconsistent fares, and downtown congestion made service poor for riders, and the 8,000 horses required vast quantities of feed and produced manure which lined the streets. In 1887, Henry Whitney consolidated all but the Lynn & Boston into his West End Street Railway conglomerate. The West End evaluated several new propulsion technologies; storage batteries, cable cars, and steam engines were all found to be insufficient.

On June 1, 1888, the West End opened a new horsecar line along Beacon Street as far as Coolidge Corner, part of a highly successful land development scheme which produced many of the residential buildings that still line the boulevard. Unlike previous horsecar lines in Boston, these tracks ran on a dedicated median, separated from traffic except at cross streets. Six weeks later, Whitney contracted with Frank J. Sprague to electrify the line, following Sprague's successful installation in Richmond. Electric trolley service began on the line on January 3, 1889, using overhead lines through Brookline and a third-rail-like conduit in the Back Bay. Public reaction to the fast and clean service was highly favorable, and the West End moved quickly to electrify its existing lines and construct new lines on developing corridors. Much of the development of Boston between 1860 and 1910 was based around these "streetcar suburbs", with dense mixed-use and residential development surrounding radial streetcar lines.(Warner, 1978)

The Huntington Avenue trackage east of Brigham Circle was electrified on a dedicated median in 1893. The West End opened a new electric line from Governor (now Kenmore) Square to Cottage Farm (now the Boston University Bridge) along the median of the new Commonwealth Avenue in 1894, and extended it to Brighton Avenue (Packard's Corner) the next year.(Engineering and Maintenance Department, 1981) On August 15, 1896, the Beacon Street Line was extended on Chestnut Hill Avenue and Commonwealth Avenue to the Newton border at Lake Street, where it met the Commonwealth Avenue Street Railway's line through Newton to Norumbega Park.

Elevated transit lines in Boston had been proposed as early as 1879, and the West End made a serious proposal for a downtown tunnel to reduce congestion in 1887. After several competing acts of legislation, a Board of Subway Commissioners was created in 1893. A citywide referendum in 1894 barely supported the financing and construction of the subway, and construction began under the control of the Boston Transit Commission in 1895. Despite a gas explosion in March 1897, the subway was quickly completed. The Tremont Street Subway opened from the Public Garden Portal (off Boylston Street west of Charles Street) to Park Street station via Boylston station on September 1, 1897. Beacon Street and some Huntington Avenue service were immediately rerouted into the new tunnel; most Commonwealth Avenue service soon followed.

A southern branch from Boylston station to the Pleasant Street Incline opened on September 30, 1897. The tunnel was extended from Park Street to the Canal Street Incline via Scollay Square, northbound-only Adams Square, and Haymarket stations on September 3, 1898. By this time, the entire streetcar system and the new tunnels were controlled by the Boston Elevated Railway (BERy), which had leased the West End in 1897 to operate in concert with its under-construction elevated line.

On May 26, 1900, tracks on Commonwealth Avenue were opened from Chestnut Hill Avenue to Brighton Avenue, allowing through service on Commonwealth from Lake Street to downtown Boston. Tracks were added on South Street from Jamaica Plain carhouse to Forest Hills / Arborway on May 17, 1902, and on South Huntington Avenue from Riverway to Centre Street on July 11, 1903. This completed trackage from downtown to Forest Hills, although through service on the Arborway Line was not initiated until 1915.

From 1901 to 1908, the Main Line Elevated (now the Orange Line) used the outer tracks of the Tremont Street Subway for heavy rail rapid transit service; streetcars used the inner tracks and looped at Park Street, Scollay Square, and Adams Square. By 1903, peak periods saw more than 250 streetcars per hour loop at Park Street — an effective headway of 14 seconds. The East Boston Tunnel (today's Blue Line) reached Court Street station (attached to Scollay Square station) in 1904; it was extended through Scollay Square Under to Bowdoin in 1916. The Cambridge Tunnel (today's Red Line) reached Park Street Under in 1912; Park Street station was heavily modified in 1915 to accommodate transferring passengers.

By this time, the success of the Tremont Street Subway had led to extensions. The Causeway Street Elevated and Lechmere Viaduct opened on June 1, 1912, allowing faster service from East Cambridge directly into the subway. After abandoned plans for a Riverbank Subway (under today's Storrow Drive), construction began on the Boylston Street Subway in 1912, with the intention of continuing it past Tremont Street to Post Office Square. It was built instead with a connection to the existing subway next to the Public Garden, with that portal replaced with the Boylston Street Portal. The Boylston Street subway opened to just east of Governor Square on October 3, 1914, with intermediate stations at Copley Square and Massachusetts (Avenue). An infill station at Arlington, delayed by World War I, opened in 1921.

The BERy prided itself on smooth transfers between surface routes and rapid transit lines; transfer facilities were added at Massachusetts in 1919 and Lechmere in 1922 — the latter to serve as a terminal for longer trains running through the subway to the Beacon Street and Commonwealth Avenue trunk lines. A detail from a 1925 system map, showing how the Tremont Street Subway was the centerpiece of a dense network of surface streetcar lines, is shown in Figure 2-9. Turnbacks were added to support short turn overlays on the busiest lines: Francis Street (Brigham Circle) crossover in 1926, Washington Street siding in 1926, Blandford Street pocket track in 1934, and Heath Street loop in 1945. A new loop terminal was added at Lake Street in 1930, replacing the original center-median station.

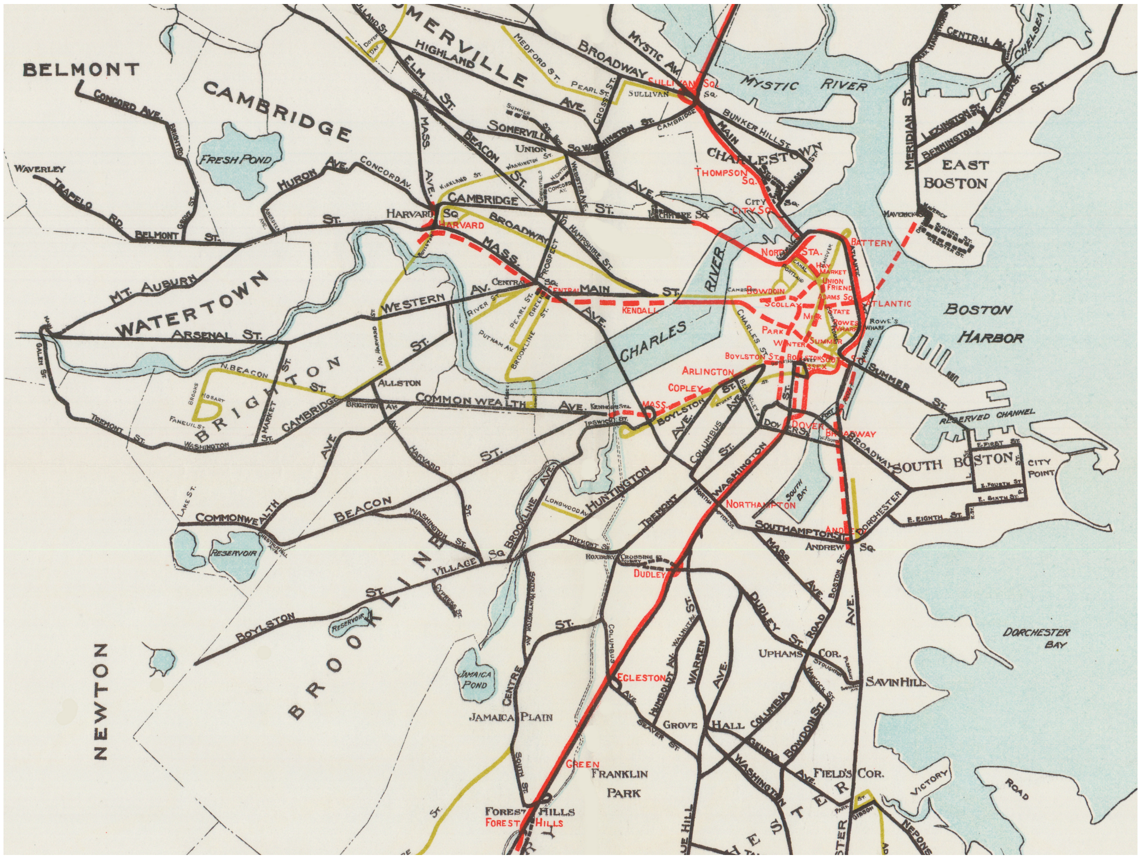

Figure 2-9: Detail of a 1925 BERy system map, showing the Tremont Street Subway and its extensions as the centerpiece of a dense network of streetcar lines. Public domain image via Wikimedia Commons.

On October 23, 1932, the Boylston Street Subway was extended to reduce congestion in Kenmore Square, following a never-pursued plan for an overpass.(Electric Railway Journal, 1926) A new four-track subway station was built at Kenmore, with tunnel branches to new portals at St. Mary's Street and Blandford Street. Kenmore station was intended to support a never-pursued conversion of the line to heavy rail; the Commonwealth Avenue tracks could be easily lowered, and a loop was constructed to allow Beacon Street trains to terminate at Kenmore with a cross-platform transfer to the center tracks. On February 16, 1941, the Huntington Avenue Subway opened from Copley station to a portal near Opera Place,[6] with

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[6] The incline was placed on a temporary wooden trestle, with the subway shell extended some additional

new stations at Mechanics (later Prudential) and Symphony. This removed surface cars from Boylston Street and Copley Square and was the last major tunnel extension of the streetcar system.

In 1947, the nominally private BERy was replaced by the publicly-controlled Metropolitan Transit Authority (MTA). The MTA was forced to bustitute many of the remaining streetcar lines in response to auto competition, but still made some investments in the core system. The Charlestown lines (now the 92 and 93 buses) — the last surface lines feeding in from the north through the Canal Street Incline — were bustituted in 1948 and 1949. The Lenox Street line became the route 43 bus in 1961, though a shuttle service continued using the southern branch of the original subway to the Pleasant Street Incline until 1962. The MTA opened an infill station at Science Park in 1955.

As the Massachusetts Turnpike neared completion in the 1950s, the Boston and Albany Railroad attempted to shed its failing commuter rail services. The Worcester mainline was spared and is now a thriving commuter rail line, but the Highland Branch was closed in 1958 for conversion to a modern streetcar line. The grade-separated line opened on July 4, 1959, branching off from the Beacon Street line just west of Kenmore. A large yard and maintenance facility were opened at the line's Riverside Terminal over the next two years. Although built for mid-century streetcars, the short section of new tunnel contains a severe height restriction.(Cummings and Cox, 1963)

The original subway through the Scollay Square area was rebuilt in 1963 as part of the Government Center project. Little-used Adams Square was eliminated, and the northbound track was rerouted to the west. Scollay Square station was reconstructed as Government Center station, with Government Center loop added just to the north. This made the outer loop at Park Street redundant, and it was removed the next year.

In 1964, the MTA was expanded into the Massachusetts Bay Transportation Authority (MBTA), intended to subsidize suburban rapid transit extensions to replace commuter rail

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length with the expectation of a future extension. The trestle was filled later in the century to accommodate heavier trains.

services. The newly formed MBTA, seeking to shed the MTA's poor public image, immediately engaged in an aggressive modernization program. The rapid transit lines were given color designations, with the Tremont Street subway becoming the Green Line. The five branches were lettered in 1967 as A Watertown, B Boston College, C Cleveland Circle, D Riverside, and E Arborway, though the A Branch lasted just two years before it became the route 57 bus. A series of station modifications, with new color-coded signage and maps designed by Cambridge Seven Associates, began with Arlington station in 1967.(Lukach, 1967) Haymarket station was rebuilt in 1971 as a single island platform south of the original two-island station.

Commonwealth Avenue was rebuilt in segments to prioritize automobiles; the transit median was moved between Packards Corner and Warren Street around 1960, and between Chestnut Hill Avenue and Boston College in 1970. The entire D Branch was rebuilt in segments from 1973 to 1976. Most of the B Branch was rebuilt in 1980; stations were modernized with 230-foot asphalt platforms and several closely-spaced stations were consolidated.[7] The C Branch was similarly rebuilt in 1982.[8] The E Branch median was heavily rebuilt in 1982-83.[9] In 1983, the B Branch was rebuilt between Packards Corner and Warren Street. Several changes were made with the coming of the USLRVs in the 1970s, including new maintenance facilities at Riverside in 1976 and Boston College in 1979, and horsecar-era-vintage Reservoir Carhouse being completely rebuilt in 1982. The Arborway Line was cut back to Heath Street during street reconstruction in 1985; it was "temporarily suspended" until officially abandoned in 2011.

Most Green Line changes in recent years have been modification of stations with raised platforms for handicapped accessibility. Key surface stations and some subway stations were accessible by 2003, followed by high-profile renovations of Arlington, Copley, Kenmore, and Government Center. As part of the 1993 deal to build the new TD Garden, a shell was built for a new Green Line tunnel under the arena.(General Court of Massachusetts, 1993)

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[7] Leamington Road and Colburne Road were consolidated into Sutherland Road. Several years before, University Road had been outright closed and Alcorn Street moved to Babcock Street.

[8] Strathmore Road, Winthrop Street, and Carlton Street stops were eliminated; Winchester Street and Summit Avenue were combined.

[9] Stops at Parker Street, Vancouver Street, and Wigglesworth Street were eliminated. Street-running stops south of Brigham Circle were modified at various times during the MBTA era; north of Heath Street, there has only been the elimination of Frawley Street and the addition of Back of the Hill.

The Causeway Street Elevated was torn down in 2004; the Green Line was rerouted under the new arena, including a "superstation" with a southbound cross-platform connection to the Orange Line. A pair of underground pocket tracks replaced the Canal Street surface terminal, which had been closed in 1997. Four surface stations on the B Branch were closed in 2004 to reduce travel times.[10] A map of the original construction dates of Green Line segments is shown in Figure 2-10.

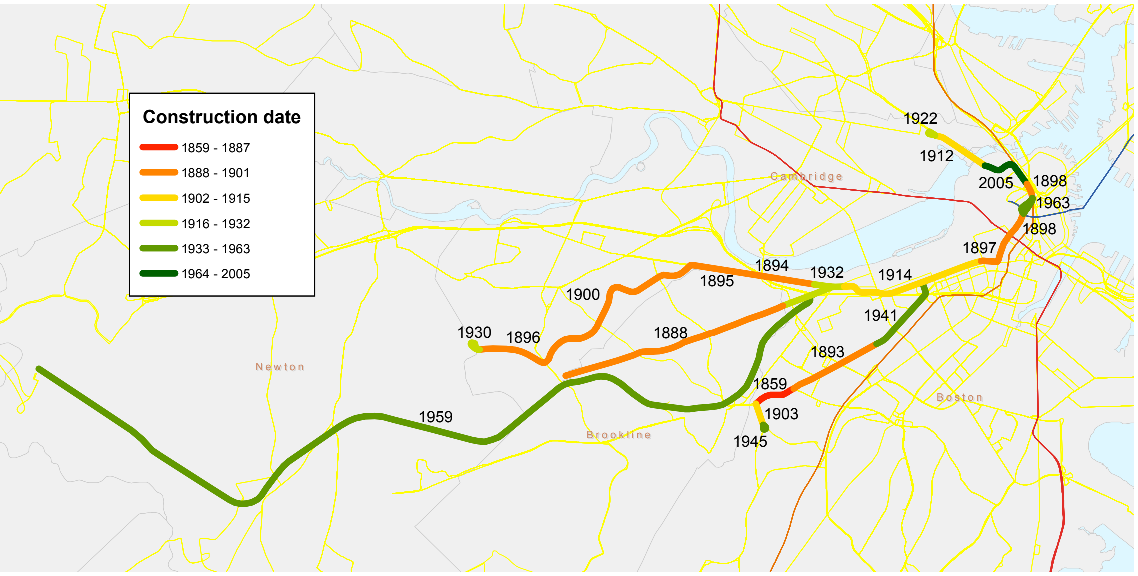

Figure 2-10: Original construction dates of current Green Line segments — i.e., the date when clearances and other physical constraints were fixed on that segment. A number of segments were substantially relocated from earlier surface trackage. Periodic track and catenary replacement, which are not likely to affect physical constraints, are not shown. Map by the author, available on Wikipedia Commons.

2.2.2 Development of the Green Line Extension project

Extension of what is now the Green Line north into Somerville was first seriously proposed in 1926 as a line along the Boston and Maine Railroad (B&M) New Hampshire Main Line to Woburn Center, with a potential branch on the Fitchburg Cutoff through Davis Square to Belmont or Bedford. The 1945 Coolidge Commission report recommended only the route to Woburn and estimated some 12 million yearly riders on the extension.(Somerville Transportation Equity Partnership, 2006) The 1962 North Terminal Area Study actually

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[10] Fordham Road, Summit Avenue, Mount Hood Road, and Greycliff Road were closed; Chiswick Road was spared due to a nearby retirement community.

recommended that the line be abandoned north of North Station, claiming that the recent Highland Branch conversion had shown that PCC Streetcars were not ideal for suburban rapid transit extensions. Instead, the Main Line (now Orange Line) was to have a branch follow the B&M to Woburn, with a possible third branch following the Fitchburg Cutoff to Alewife and Arlington.(Barton-Aschman Associates, 1962)

As planning progressed on the Orange Line extension to Malden, and protests decreased the palatability of highway extensions, a Green Line Extension returned to the table. The 1966 Program for Mass Transportation and the 1972 Boston Transportation Planning Review both recommended a Green Line extension along the New Hampshire Main Line in addition to — rather than in competition with — a Red Line extension to Arlington.(Massachusetts Executive Office of Transportation and Construction, 1973) Although Red Line and Orange Line projects received priority, planning slowly progressed for the Green Line with the 1981 Green Line Northwest Project Study.

In the late 1980s, the MBTA designed the initial section of an extension: a relocation of Lechmere station on the east side of Route 28, with commuter parking and a new Green Line yard. However, the project was never implemented due to lack of funding.(Vanasse Hangen Brustlin et al, 2005, Chapter 1, pages 1-2) Soon after, however, the Conservation Law Foundation's legal challenge to the Big Dig project led the state to commit to a number of transportation projects as environmental impact mitigation — including a $600 million Green Line Extension to Medford Hillside and an extension of the Blue Line to Charles/MGH station.[11] A 2000 Administrative Consent Order, which updated the original 1991 settlement, required the Extension to be complete by the end of 2011.(Vanasse Hangen Brustlin et al, 2005, Chapter 1, pages 1-2)

This resulted in the 2005 publication of the Beyond Lechmere Northwest Corridor Study, a Major Investment Study / Alternatives Analysis which initiated the formal planning and design process. This study introduced a new possibility not previously considered: a branch onto the Fitchburg Line to Union Square. (A Fitchburg Cutoff branch was not considered

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[11] Medford Hillside is the area of Somerville and Medford centered along Boston Avenue between College Avenue and the Mystic River. The B&M's Medford Hillside station, closed in May 1958, was located at Winthrop Street.

because the 1985 Red Line extension included a stop at Davis Square). The Beyond Lechmere report analyzed a West Medford Branch with and without a Union Square Branch, a Union Square Branch plus BRT to West Medford, and commuter rail shuttles to West Medford or Anderson RTC with new infill stops. The LRT and BRT alternatives were judged to be substantially superior on the grounds of user and environmental benefits.(Vanasse Hangen Brustlin et al, 2005, Chapter 5)

Despite that study, however, the state did not actively pursue the extension. In 2006, another lawsuit forced the state to agree to move forward with environmental impact analysis, with a December 2014 completion of the project.(Cummings, 2007) In 2008, the EPA approved the state's State Implementation Plan (SIP), which specified a Medford Hillside terminus.(Environmental Protection Agency, 2008) The 2009 Draft Environmental Report Statement analyzed six alternatives, including both Medford Hillside and Route 16 termini, as well as the possibility of running the Union Square branch along Somerville Avenue. West Medford was removed from consideration due to the cost of Mystic River bridges and modifying grade crossings in West Medford, and the Winthrop Street station was cut.(Federal Transit Administration and Massachusetts Executive Office of Transportation and Public Works, 2009, Chapter 3) The preferred alternative had branches to Union Square and College Avenue via the commuter rail rights-of-way, with a future extension to Route 16.(Federal Transit Administration and Massachusetts Executive Office of Transportation and Public Works, 2009, Executive Summary) The cutback to College Avenue drew local criticism, but the state believes that College Avenue is in compliance with previous agreements.(Fichter, 2012)

The Final Environmental Impact Report was released in June 2010, with the Extension expected to open in 2015. However, in 2011 the completion date slipped to 2019 due to delays in land acquisition and environmental approval.(Byrne, 2011) MassDOT agreed to interim measures like increasing bus frequency or adding temporary commuter rail stations to make up for the delay.(Peterson, 2012) The project entered Preliminary Engineering for the FTA's New Starts program in June 2012.(Mello, 2012) In August 2012, the city of Somerville reached an agreement with the MBTA to open the Union Square Branch in 2017.(Byrne, 2012) By this time, the project was expected to cost about $2.2 billion, with half of that paid by the FTA. However, in 2015 it became clear that the project would cost $3 billion, putting its future in doubt. The increase was largely due to an unproven contracting method that did not prevent the contractor from arbitrarily increasing costs, plus changes to the project scope.

A project review ordered by the state governor resulted in a revised plan with bare-bones stations, cuts to the maintenance facility and Somerville Community Path extension, and other changes.(Interim Project Management Team, 2016) The FTA approved the $2.3 billion revised project in April 2017; it is now expected to be complete by the end of 2021.(Dungca, 2017a)

2.2.3 Evolution of Green Line vehicles

Details in this section are from Cummings and Cox (1963) except where noted.

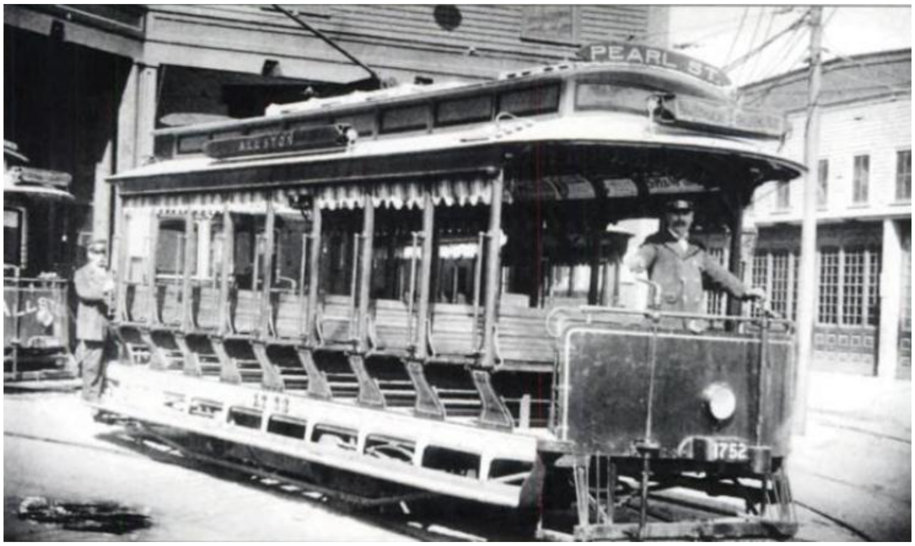

Figure 2-11: The first car into the Tremont Street Subway - a typical single-truck streetcar open to the elements - pictured on the day of its fateful run. Public domain photo via Wikimedia Commons.

Prior to 1903, the BERy and its predecessors primarily used converted horsecars and derived designs. Cars ranged in length from 16 to 25 feet (plus open vestibules), with one or two trucks. They tended to be slow and inadequately sized; the initial subway segments were designed for these cars, which did not exceed 35 feet in total length. A typical such car is shown in Figure 2-11. In the 1910s, the BERy converted a small number of older cars to longer articulated vehicles with a new mid-body section. Although the articulated design expanded capacity, the converted cars were underpowered and were scrapped within the decade.

The BERy bought slightly longer "26 1/2 foot" cars, the first with air brakes, in 1903. A new line of double-truck semi-convertibles,[12] known as Type 1 through Type 3 depending on the manufacturer, arrived between 1905 and 1908 and remained in service until 1931. These cars were larger — up to 45 feet — and faster — up to 28 mph — than their predecessors. Several remained in service as snowplows until the 1990s.

The Type 4 semi-convertibles arrived beginning in 1911. Forty-eight feet long, they were rated for 52 seated passengers and an incredible 107 standees. They introduced pre-payment, where riders paid their fares in the front vestibule — an early method of controlling fare evasion. A total of 275 were built; they were converted for one-man operation in the 1920s and served until 1951.

Starting in 1916, the BERy acquired 405 center-entrance cars, starting with trailers and later adding motorized versions. Known as "crowd-swallowers", they used a low-floor section in the center of the car to board passengers through wide doors. Well-suited for the high passenger loads on the subway routes, they remained in use until 1953. A train of center-entrance cars on Commonwealth Avenue is shown in Figure 2-12.

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[12] Semi-convertibles could have some side panels removed for summer operation, as air conditioned streetcars did not come to Boston until the USLRVs.

Figure 2-12: Two center-entrance cars on Commonwealth Avenue (at what is now Griggs Street / Long Avenue stop) in 1927. Public domain photo from the City of Boston Archives.

The BERy purchased 471 of its Type 5 cars between 1922 and 1927. Essentially upgraded Type 4 cars, they were used mostly on surface routes, though they were used heavily on the subway-feeding Charlestown routes and later on the inner Arborway Line. The last Type 5 cars were retired in 1959.

In the mid-1930s, the President's Conference Committee designed a standardized streetcar that could be used on subway and surface routes across the country. The resulting PCC Streetcar was among the most successful rolling stock ever produced. The first PCC arrived in Boston in 1937, but a larger fleet was not acquired until 1941-1951.[13] A typical PCC car in MBTA service is shown in Figure 2-13. Their reliable all-electric operation, two sets of doors per side, and ability to run in trains as long as three cars made them highly useful in the subway. They were the only vehicles used on the Green Line between 1959 and 1976 — the only time that the Green Line has had a uniform fleet.

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[13] 25 additional PCC cars, built in 1945, were acquired from Dallas in 1958-59 to bolster the fleet for the Riverside Line's opening

Figure 2-13: PCC Streetcars at Riverside Terminal in 1967. Photo by David Wilson, licensed Creative Commons Attribution 2.0, available via Wikimedia Commons.

Although the PCCs served well on the Green Line, they did not always age well, and they lacked some modern conveniences like air conditioning. In 1971, the MBTA ordered a pair of custom prototype vehicles from the experienced German company DuWag, funded two-thirds by an Urban Mass Transit Administration (UMTA) grant.(Oglesby, 1980) However, the Nixon administration sought to return light rail manufacturing to the United States, and the UMTA grant was canceled to coerce Boston into a common vehicle order with San Francisco.[14] The result was the US Standard Light Rail Vehicle (USLRV), a three-truck, 71-foot articulated vehicle produced by Boeing Vertol — a helicopter company with no transit experience. A USLRV on the D Branch is shown in Figure 2-14.

The USLRV provided a substantial per-vehicle capacity increase over the PCCs; introduced new technologies like pantographs, fluorescent lighting, PA systems, and air conditioning; and served as an example design for emerging light rail systems.(New England Electric Railway Historical Society, 2007) However, it failed to live up to the high expectations set by the federal government, and was a disaster for the Green Line. The MBTA was forced to be the guinea pig for the unproven vehicles, and they were rushed into service in late 1976

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[14] Philadelphia was originally part of the procurement process, but due to funding issues chose to drop out in favor of ordering custom vehicles from Kawasaki several years later.

Figure 2-14: A USLRV at Eliot station in 1984. Photograph via Wikimedia Commons, believed to be in the public domain.

after a severe snowstorm. Derailments were soon common, as were problems with the doors, articulation joints, and electrical systems.(W. H. She1ley, 1980) The MBTA terminated the contract with Boeing after 135 of the planned 175 vehicles were delivered, and eventually received a $40 million settlement from the company.(Oglesby, 1980) A number of PCC cars remained in service, mostly on the Arborway Line, until the mid-1980s.[15]

With the USLRV fleet of dubious value and the PCCs on their last legs, the MBTA ordered 100 custom Type 7 vehicles from Japanese manufacturer Kinki-Sharyo in the 1980s. Based on the LRV's form factor but with numerous design improvements for optimal use in Boston, the Type 7s proved reliable and popular; an additional 20 vehicles were ordered a decade later as a stopgap measure. A Type 7 in MBTA service is shown in Figure 2-15.

In 1995, the MBTA awarded a contract for 100 custom Type 8 vehicles to Italian company AnsaldoBreda, one of which is shown in Figure 2-16. The Type 8s were to update the

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[15] Ten cars were retained for the Ashmont-Mattapan High Speed Line, where they will remain in service into the 2020s.

Figure 2-15: A Type 7 vehicle on the Causeway Street Elevated in the 1990s. Photograph by Kinki-Sharyo, available under Creative Commons Attribution 2.0 license via Wikimedia Commons.

MBTA for compliance with the 1990 Americans with Disabilities Act (ADA), with low-floor sections for wheelchair boarding and new automated announcements. The first Type 8 cars entered service in 1999, but were quickly withdrawn due to braking problems. After being reintroduced, they were again pulled after a series of derailments. A 2001 independent report indicated that the center trucks of the Type 8s were the main cause of derailments. They use stub axles (to accommodate the low floor) rather than solid axles. The report recommended that the MBTA improve track maintenance standards, limit the speed of the cars especially on reverse curves, and make other changes.(DeNucci, 2007)

After further issues, the MBTA ended the contract with Breda in 2004 with just 47 vehicles produced. In 2005, the MBTA reached an agreement for Breda to make modifications to the vehicles and ultimately deliver 85 vehicles. This was increased to 95 vehicles in 2007, with the remaining 5 incomplete shells stored for parts. The last USLRVS were retired in 2007, and the Type 8s have been operating on all lines since 2008 (usually in consists with one Type 7 and one Type 8). However, reliability and derailment issues have persisted. Under a 2012 contract, Alstom is overhauling 86 of the original Type 7s and 17 of the later set, with the intention of extending the fleet's life into the mid-2020s.

Figure 2-16: A Type 8 vehicle at Tappan Street on the C Branch. Photo by the author, available on Wikimedia Commons.

In 2014, the MBTA approved a contract with Spanish company CAF to produce 24 custom Type 9 vehicles for fleet expansion for the Green Line Extension. The Type 9 is roughly based on the Type 8 design, but with improved truck design and crash energy management. The whole fleet is expected to be in service by the end of 2018.(Massachusetts Bay Transportation Authority, 2017a)

2.2.4 Train length

Early streetcars were not equipped for multiple unit operation. A small number of 26 1/2 foot cars were converted for motor-trailer operation in 1906. Type 1 through Type 3 cars were equipped with trainline controls, but were not often used in trains except in the East Boston Tunnel. The Center-entrance trailers were the first cars designed for regular use in trains, and the Center-entrance motors allowed multiple powered cars in a single train. PCC

Streetcars were designed for multiple unit operation from the outset, and regularly ran in trains of two and three cars on Central Subway routes.

Substantially longer than the PCCs, the USLRVs were usually operated as singles or doubles. Three-car trains of USLRVs were run from 1987 to 1990, and triples of Type 7s were run on a small number of trips beginning in 1994. Triples of Type 7s and Type 8s were run on the D Branch occasionally beginning in 2000, and on the B Branch in 2003 when trips were combined due to equipment shortages. The B Branch was scheduled to use only triples at peak for the summer of 2005, but reverted to doubles in the fall. In 2007, the last single-car trips on weekdays were changed to doubles.(Belcher, 2017a)

A small number of three-car trains were added to the D Branch schedule on October 25, 2010, and to the B Branch a week later. More trips were added on March 21, 2011, and several 3-car Brigham Circle short turns were added to the E Branch. However, these three-car trips did not represent a net increase in passenger capacity; longer headways were scheduled before them, resulting in negligible change in actual cars per hour. An experimental four-car train was operated as proof-of-concept from Blandford Street to Park Street after a Red Sox game in April 2011. The E Branch (Brigham Circle) short-turns were later removed. Three-car trains proved problematic; the different electrical systems caused frequent issues with the Type 8 car between two Type 7 cars, and the third car was often lightly used. On March 21, 2016, the B and D Branches were returned to doubles on consistent headways at peak hours.(Belcher, 2017a)

2.2.5 Plans and canceled projects

There have been numerous attempts to expand and modify the Green Line over the years, many of which have been unsuccessful. The first of these was from the 1926 Report on Improved Transportation Facilities in the Boston Metropolitan District, which proposed to turn the existing streetcar tunnels into a pair of high-floor rapid transit lines. The East Boston Tunnel would have been connected to the inner tracks of the Tremont Street Subway at Park Street; that line would have followed the existing tunnel to Kenmore, continued along or under Commonwealth Avenue, and terminated at a streetcar transfer station at

Warren Street east of Brighton Center.[16] A subsidiary proposal would have extended the east end of the line to a new transfer station with the Boston, Revere Beach and Lynn Railroad, a narrow-gauge commuter rail line, near Day Square. The second line would have run from the 1922-built Lechmere transfer station, through the existing tunnel and on the outer tracks, and used the existing southern branch as far as the Pleasant Street Portal. From there it would have paralleled the Boston & Albany Railroad to Back Bay station, the New Haven Railroad's Providence Division to Massachusetts Avenue, then curved onto Huntington Avenue to a transfer station at Brigham Circle.(Central Transportation Planning Staff, 1993) A map of the proposal is shown in Figure 2-17.

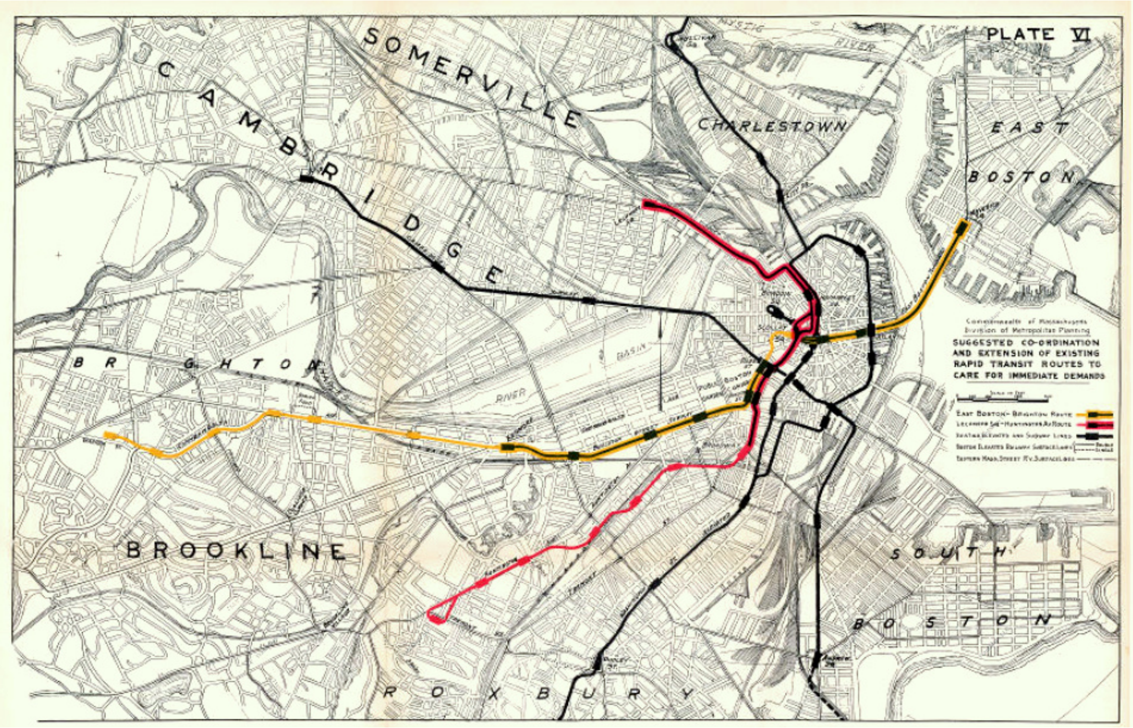

Figure 2-17: Map of the 1926 proposal to convert the Tremont Street Subway into two rapid transit lines. Image from the report, believed to be public domain, obtained via scan at Ward Maps website.

Although this proposal was not directly enacted, several of the lower-priority proposals in the report were eventually built or strongly considered.[17] The proposal also influenced

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[16] An earlier and less aggressive plan had called for a surface-level prepayment station at Linden Street near Allston Village, which was shot down by the neighborhood.

[17] The proposals eventually enacted were the Revere Extension (1952-54), Highland Branch conversion

several Green Line projects, notably the 1932 Kenmore Extension and 1941 Huntington Avenue Subway. Along with the construction that same year of the Francis Street crossover, it established the division of the Huntington Avenue line into the inner rapid-transit-like section and the outer mixed-traffic section. Along with then-under-construction Dorchester Rapid Transit project, it set in motion the long-term notion of converting existing railroad rights-of-way to rapid transit rather than attempting to construct wholly new lines under city streets.

The next major regional transit plan, the 1945-47 Coolidge Commission report, reached similar conclusions to the 1926 report for many corridors. Like the earlier report, it recommended an extension from Lechmere to Woburn, and conversion of the Highland Branch — albeit via Kenmore rather than via Brigham Circle, and with an additional branch to Needham. The southern tunnel branch, instead of Huntington Avenue, was to follow the Boston & Albany to Riverside or beyond. Only the Riverside extension has actually been built, but the continuation of the Green Line as a multi-branched streetcar service and the possible Needham flank were significant conclusions. Most major expansion plans during the MBTA era have focused on the northern extension of the Green Line, with relatively limited changes to the central and western segments. Typical among these is the 1971 Central Area Systems Study. Its primary conclusion was the need for new PCC-replacement vehicles for the Green Line, along with upgrades to the power supply, bridges, passenger shelters, and other existing infrastructure. Only the long-term recommendations in the report called for substantial change — in this case the conversion of the Riverside Line to a Blue Line extension.

Proposals to revive the Watertown Line lasted until the line's abandonment in 1994.[18] Restoration of the Arborway Line was an official MBTA project for many years, mandated as Big Dig mitigation. However, the agency and the city were not always in support of the restoration, and the MBTA was relieved of it in 2011. A Green Line branch using the aban-

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(1959), Red Line branch to Braintree (1971-80), Orange Line north relocation (1975-77), and Southwest Corridor rapid transit conversion (1987). A Green Line extension to Woburn (now being planned as far as Medford) and a circumferential line (the currently-shelved Urban Ring) were also proposed, along with a number of other extensions.

[18] The Watertown Carhouse was used for heavy repairs to Green Line vehicles until the end of the PCC era. Several LRVs were equipped with trolley poles for use as tow cars, as the catenary was never upgraded for pantographs.

doned southern tunnel was originally a possibility for Washington Street service after the Elevated was removed in 1987,[19] but trolleybuses (and later diesel buses) were eventually chosen.

Several cancelled projects from recent years would have potentially relieved the load on the Green Line's most congested segments; the failure of these proposals places additional importance on a systemic improvement of the Green Line. The Urban Ring project would have created a circumferential transit line — first BRT, later rail — to relieve downtown transfer loads. The line would have connected to the Green Line at Lechmere, BU Central, Yawkey/Kenmore, and Fenway; by providing a direct connection between the Red Line and the Longwood Medical Area, it would have reduced demand on the D and E Branches. Phase III of the Silver Line would have connected the Washington Street and Waterfront branches with a new tunnel, including a Green Line connection at Boylston. By providing a direct connection to South Station and the Seaport, transfer crowds at Park Street would be reduced. Both projects were suspended in the late 2000s due to changing administrations with new priorities.

The Worcester Line parallels the Green Line in some segments; expanded service to inner stations could provide an express alternative to the Green Line. The North-South Rail Link project would have connected North Station and South Station with a new tunnel, allowing through-running electric commuter rail service at higher frequency. Originally proposed as part of the Big Dig, it was cancelled due to cost and political reasons, though advocacy for it has recently re-emerged. A later proposal would have run high-frequency diesel multiple unit (DMU) service on several commuter rail lines (including the Worcester Line as far as Riverside with a spur to North Station over the Grand Junction Branch), creating the rapid-transit-like Indigo Line. The DMU plan was canceled in 2015; the renovation of Yawkey station, 2017 opening of Boston Landing station, and the planned West station will provide some alternatives to the Green Line, though only with traditional commuter rail frequency.

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[19] Some early proposals called for using Green Line cars on the Elevated structure, as it was judged to have several decades of serviceable life remaining.

2.3 Data sources

Much of the impetus of updating and expanding portions of Malikova's prior operations performance research is the increased availability of data sources. Her work reached the limits of what could be done with only 17 AVI locations (6 of them not bidirectional) — all that was available in 2010-12. Since then, the MBTA has compiled several large datasets:

2.3.1 Fare collection

Current Green Line vehicles do not have Automatic Passenger Counting (APC) systems, although these are planned for the next-generation vehicles. Fare transaction data is available from faregates (all heavy rail stations, several Silver Line stations, and all underground Green Line stations plus Lechmere, Science Park, and Riverside) and fareboxes (surface Green Line trains and buses). Faregates tend to count about 95% of boardings, with minor loss due to children, fare evaders, and occasional stuck gates. Farebox data is not as accurate; the MBTA allows riders with monthly passes to board through the rear doors of Green Line trains during peak periods. Additional causes of farebox noninteraction include intentional fare evaders, non-passholders boarding through the rear doors on severely crowded trains, children, passengers with mobility devices who cannot access the farebox, and passengers who show a pass to the driver while boarding the front door. However, manual counts can be used to approximate the noninteraction rate to allow scaling the raw farebox data.

All stations with faregates also have fare vending machines, so all faregate interactions are via electronic fare media (plastic CharlieCard and paper CharlieTicket). The electronic fare media have unique identifiers, so they can be used to understand a rider's movement through time and space. There are not fare vending machines available at most Green Line surface stops or bus stops, so fareboxes also allow cash transactions, which cannot uniquely identify a rider.

The MBTA rapid transit and bus systems are tap-on only; there is not a tap-out required.

2.3.2 Vehicle location

The Green Line uses three separate technologies to determine vehicle location. The oldest of these is the Automatic Vehicle Identification (AVI) system, installed in the 1980s to automate switch movements at junctions. Each vehicle carries a transponder unit with a hard-coded vehicle ID and a manually entered route ID, which are read by sensors located before switches and at other locations. The route ID indicates the vehicle's origin and destination, which the system uses to determine which way to move switches.[20] The system was originally limited in scope: when Malikova wrote her thesis in 2012, she had just 28 AVI sensors at 17 locations to work with. Additional AVI sensors before and after most underground stations were installed around 2015 to enable more granular tracking.

Although well-proven, the AVI system has several issues. Some older sensors (some of which have since been replaced) are unreliable and frequently miss or double-count a vehicle, or read a two-car train as two separate trains. Car numbers are sometimes misread, or read as default values of '3000' or '9999'. The hard-coded vehicle number is occasionally incorrect; during debugging in 2016, a number of AVI transponders belonging to the former USLRVs were found to be in use with their former vehicle number. Drivers will sometimes input an incorrect route ID, or change destinations en route.

Two sections of line — Hynes Convention Center station to the western portals, and Haymarket through Lechmere — also have track circuits installed in the 1990s and 2000s. These can provide more granular locations near the portals than the AVI system, but suffer from similar data reliability issues.

On the western surface branches, GPS units installed in 2014 provide tracking. This system was based on the highly successful deployment of GPS across the bus fleet several years before. GPS accuracy is nominally extremely high, but this is affected by buildings and hills near the right-of-way. Data is geofenced to designated points on the right-of-way as an early processing step. Ping frequency is nominally every 6 seconds. Unlike AVI and track circuits, GPS pings also give speed data. GPS units were originally installed only in Type 8 vehicles, though they have been added to some Type 7 vehicles as part of the overhaul program. Trains without a Type 8 car, or where the GPS unit is malfunctioning, will have their surface locations noted only when they encounter an AVI sensor.

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[20] A pair of unique route IDs can be temporarily entered to force a switch to one direction without affecting the previous destination information. This is used primarily at Park Street westbound — where trains occasionally use the opposite track from their designated berth — and to cross over at Riverside.

Accurate records of train location and consist are essential for evaluating service quality and passenger experience, inferring passenger behavior, and testing operational improvements. Fabian (2017a) developed a method of cleaning the raw data to improve accuracy. This cleaning includes removing bad consist and location data, inferring missing consist and location data, and inferring arrival and departure times at all stops. This represents a vast improvement over the quality of data Malikova had to work with; the location of all trains are now known to an accuracy of one station or less. Except when noted, the methods in this thesis use cleaned data.

2.3.3 Passenger behavior

Because the MBTA system is tap-in only, the location of passenger alightings is not explicitly known, nor is vehicle assignment at faregated stations. For tap-ins at fareboxes, only the vehicle ID and time are known. The ODX (origin-destination-transfer) model, originally developed at MIT for use in Chicago and London, can infer many of these missing data points with high accuracy.(Sánchez-Martínez, 2017b)

Tap-ins at fareboxes have their origins inferred by cross-referencing AFC and AVL data to determine the most likely stop that the passenger boarded from. Except for occasional errors near terminals, this method has high precision. Destination is inferred using the passenger's other boardings to detect recurring trips. Route choice — including transfers, out-of-system segments, and vehicle choice when not explicitly known — is inferred by assuming the passenger took the most desirable route (with in-vehicle time preferred to waiting time) with full future knowledge. While this is not perfect — a passenger will of course board a train without knowing it will suffer a long delay en route — it is still a useful approximation for a relatively simple rapid transit system like the MBTA, where alternate routes are limited.

Chapter 3

Green Line issues and previous work

3.1 Current Green Line problems

As the Tremont Street Subway approaches its 120th anniversary, the Green Line faces a host of problems stemming from growing ridership, aging infrastructure, and decades of underinvestment in the urban core transit system. As of April 2017, overall Green Line service reliability (the proportion of passengers waiting less than one scheduled headway) hovers around 80% - well below the 90% goal that the three heavy rail lines usually achieve.(Massachusetts Bay Transportation Authority, 2017b) Poor reliability is itself a symptom of other issues, including less-than-optimal scheduling, irregular dispatching, variable dwell times, vehicle availability and mechanical issues, and delays from automobile traffic. Portions of several issues — scheduling, crowding, accessibility, dwell times, derailments, and travel time — are within the scope of this thesis. Most other issues have solutions in active development or implementation; some have not entered the formal study phase.

3.1.1 Issues potentially addressed in this thesis

- Scheduling: Until 2016, the running times and cycle times used for scheduling the Green Line were not empirically determined, but largely based on feedback from operators about how often they were able to make schedule. This resulted in many running and cycle times being substantially shorter than were necessary for reliable operation. In 2016, the MBTA began using data-based running times and cycle times. The work in this thesis builds off that initial work by incorporating outlier filtering and other improvements.

- Crowding: Many passengers experience high levels of crowding on the Green Line, and crowding is a major cause of fare evasion.(Prokosh, 2016) Crowding can be reduced by improving service reliability, or by adding frequency of vehicles when needed. The work in this thesis focuses on reducing crowding by the potential reallocation of vehicles, and by the purchase of new vehicles capable of handling larger numbers of riders.

- Ridership growth: The Green Line Extension will increase current ridership by almost one-sixth. Many areas with active or planned development in the metropolitan area — including North Station, Longwood Medical Area, Brookline Village, South Huntington Avenue, Massachusetts Turnpike air rights, Union Square, Fenway/Kenmore, and Cleveland Circle — are well-served by the Green Line. New fleets on the Red and Orange Lines are expected to increase capacity and improve service on those lines — and thus may increase transfer loads on the Green Line. A 2015 MBTA study indicated that ridership on the rapid transit lines will likely increase 14% to 28% by 2040 — and by as much as 40% by 2050.(Massachusetts Bay Transportation Authority, 2015) The combination of scheduling improvements, vehicle allocation strategy, and fleet replacement evaluated in this thesis will be necessary to handle such a substantial increase.

- Accessibility: Currently, only 21 of 53 surface stations and 10 of 13 underground and elevated stations are handicapped accessible with raised platforms. Current plans call for several additional station modifications, but still only 43 of 72 stations (60%) will be accessible by 2025. Most peak trains consist of one accessible low-floor car and one non-accessible high-floor car; even low-floor cars require a movable ramp to be extended for a passenger using a mobility device to board. The work in this thesis analyzes new fully-accessible vehicles and the potential for more complete accessibility.

- Dwell times: Long and irregular dwell times degrade service reliability and increase travel times. In 2016, ten surface stations had average dwell times over 1 minute. (Massachusetts Bay Transportation Authority, 2016) These problematic dwell times are caused by crowding, the need to step up onto the vehicle, and a limited number of open doors — all of which are affected by the vehicle and access improvements discussed in this thesis.

- Derailments: The current Type 8 fleet is highly susceptible to derailments due to design errors. Rail grinding and speed restrictions have mitigated this to some extent, but a rash of derailments occurred in 2016.(Dungca, 2017b) Ultimately, a new fleet with superior truck design is needed.

- Travel time: Due to speed restrictions, dwell time increases, and subway congestion, travel times have slowly increased over the decades.[1] Aside from dwell times, the vehicle selection in this thesis also considers the desirability of increased speeds.

3.1.2 Other Green Line problems and projects

- Safety: Several low-speed collisions, a 2008 collision in Newton that killed an operator, and the recent derailments have led to discussion of safety improvements on the Green Line. After a 2012 study indicated high costs and capacity decreases for full Positive Train Control (PTC), the MBTA has decided to pursue a more limited train protection system that should protect against the types of collisions experienced in recent years.(Massachusetts Bay Transportation Authority, 2016) If that system proves insufficient, full PTC or Automatic Train Operation (ATO) may be necessary in the Central Subway to maintain sufficiently frequent service while maintaining safety.

- Dispatching: The Green Line is currently dispatched based on schedules rather than actual headways, and both dispatching and real-time control is performed manually. Research by Fabian (2017b) has evaluated several semi-automated real-time control strategies with simulation models and tested headway-based dispatching on the D Branch. The MBTA has expressed interest into continuing testing to more fully implement these strategies.

- Traffic interference: Unlike most modern light rail systems, Transit Signal Priority (TSP) has not been implemented on the Green Line, despite hardware installed on the E Branch as early as 2002. Traffic signals frequently cause delays on the B, C, and

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[1] For many years, signs at Blandford Street and St. Mary's Street advertised "9 minutes to Park Street"; the same trips are now scheduled for 15 minutes at rush hour. The first Riverside Line timetable in 1959 claimed 35 minutes to Park Street — a distance now scheduled for 42 to 47 minutes.

E branches. The MBTA is currently testing TSP at several intersections to determine the viability and effectiveness for implementing it across the system.

- Fare payment: The current fare payment system requires interaction with a large and expensive farebox. Paper tickets and especially cash payments require additional time, causing long and irregular dwell times at surface stops. The AFC 2.0 system, planned to be introduced in 2019, will have tap targets at all doors, allowing consistent all-electronic fare payment.

- Stop spacing: A number of Green Line stations are spaced below the 1200'-1400' distance recommended for light rail networks. This is particularly prominent on the B Branch, on which the three worst offenders — between the four stops on Boston University's West Campus — will be reduced to two stops in the next several years.(Massachusetts Bay Transportation Authority, 2016)

- Train tracking: The Type 7 vehicles are receiving GPS units as part of the overhaul program, which will reduce the number of trains that run without surface tracking. After this is complete, any remaining tracking issues should largely be resolvable by data cleaning rather than additional hardware.

- Power: The current traction power system is barely sufficient for current needs, with some substations needing replacement in the near future. The MBTA is forced to be conservative with vehicle usage — especially with three-car trains — because the exact limits of the current system are not known.(Malikova, 2012) The MBTA is planning a full evaluation of current and future power needs.

- Signal system: The current signal system uses outdated technology, with many components built in the 1910s. Repair of these components is increasingly infeasible; it will soon be necessary to fully replace much of the signal system.(Massachusetts Bay Transportation Authority, 2016) The signal power system is particularly problematic; power failures can cause cascading delays as the affected segment incurs 15-20 minute holds.(Malikova, 2012)

3.2 Previous work

Most academic research work on the Green Line has focused on real-time control strategies. Macchi (1989) determined that expressing, in combination with the then-new AVI system, could provide operational benefits. Fellows (1990) explored enhancements to the AVI system to provide real-time headway data and even forecasting. Deckoff (1990) determined how to use the AVI system to make better decisions whether to short-turn a train. Soeldner (1993) compared available control options and determined that short-turning inbound trains is usually better than expressing them on their outbound return trip. Wile (2003) showed the promise of automated data collection for service analysis and real-time control. Fabian (2017b) builds on these works with a simulation model and testing of new control strategies in revenue service.

Most analysis of medium-term and long-term needs for the Green Line have been conducted by the MBTA or consultants for internal use. They tend to focus on single system needs like additional capacity or fare evasion rather than holistic issues, and sometimes are prompted by changes in political administration and management as well as operational needs. These analyses serve their roles, but longer-timescale considerations are also needed.

Malikova (2012) analyzed the impacts of the 2010 introduction of a limited number of three-car trains on the B, D, and E branches. These trials used a small number of three-car trains which were scheduled on longer headways than two-car trains on the same lines. The trials and research were motivated by the then-planned PTC system, which would have reduced Central Subway frequencies and required longer headways on the branch lines. Her research covered the theoretical and actual changes to a wide range of service characteristics, including passenger waiting time, throughput, running times, and terminal dispatching. Her work was focused on the B, C, and D Branches, as location data was not available for the surface section of the E Branch. Much of the work in the first third of this thesis involves expanding Malikova's work with additional data.

Malikova used a 'reference time' — the time when a given train reached Boylston eastbound — as the binning method for her statistics. Her throughput measurements were made by counting vehicles detected by AVI sensors at Boylston. Her running times were determined by taking the time between AVI detections at the western and eastern terminals. In some cases, proxy times were added when AVI units were not at terminals (like the B Branch AVIs located at Chestnut Hill Avenue, 0.7 miles from the terminal). She included turnaround time some terminals in her running times. She compared the 50th percentile running time (as running time) and 90th percentile (as approximate cycle time) to the schedules. Malikova calculated headways using the time between successive AVI records at each sensor. All trains had headways calculated, but only trains that had valid reference times were used for compiling statistics. Malikova also observed terminal and yard operations at Riverside and Lechmere to analyze their effect on performance.

Malikova determined that the 3-car train trials had a mix of positive and negative results. D Branch service was slower during peak periods, as was C Branch service (which did not have any three-car trains) in the Central Subway, though B Branch service was slightly faster on the surface. Headway variability increased on the B and D Branches. Her observations of terminal operations showed the importance of minimizing small headway variability induced at terminals: "Practicing more precise terminal departure management may well be the single most effective change the MBTA can make to improve service quality and increase capacity on the Green Line." She also emphasized the need for further trials and for more granular location data.

Malikova presented evidence that mixing doubles and triples on a branch increases dwell times, which degraded service quality. She identified several scenarios to isolate three-car trains on branches. The first used three-car trains at reduced frequency (equal vehicle throughput) on the D Branch; the second added additional vehicles to increase throughput. Her other two scenarios separated the E Branch into a three-car-train Brigham Circle-Lechmere service and a one-car-train Heath Street-Northeastern shuttle; one scenario used the current number of vehicles, while the other added additional vehicles. The scenarios that used additional vehicles provided substantial increases in capacity, but those that did not increase vehicle counts provided relatively little benefit other than consistent headways and train sizes.

Malikova suggested several priorities for future research, some of which are included in this thesis. They included an analysis of medium-to-long-term needs, operations simulation, analysis of splitting and combining trains at junctions, evaluation of the E Branch using new data, evaluation of any future operational changes, and analysis of new vehicles.

Chapter 4

Review of current service

4.1 Background

When examining the operational performance of a light rail service, three primary measures of service provided can be analyzed:

- Distribution of **running times**, the amount of time spent in service from terminal to terminal
- Distribution of **headways**, the amount of time between successive arrivals or departures at a given location
- **Throughput**, the number of trains or individual vehicles passing a given point in a period of time

A number of more useful characteristics can be derived from these. A typical running time — usually the 50th or 55th percentile — is chosen as the **book time**, the running time used for setting schedules. The **cycle time**, the scheduled time between two successive trips of the same train, includes recovery time and time to loop or reverse at each terminal. A common method of determining cycle times is to take the 90th or 95th percentile running times plus appropriate terminal turnaround time; this will allow 90 to 95 percent of trips to start on time. Cycle times and desired headways can be used to determine vehicle requirements. Running times between shorter segments of the line can be used to set the scheduled arrival and departure times at each station, which are then provided for public use.

If passengers are assumed to arrive randomly at a stop, which is a reasonable assumption for high-frequency transit like the Green Line, then more passengers will be waiting for a late train than an early train. Thus, **expected waiting time** — the average time that a passenger waits for a train — is higher than the average headway and is influenced by the variability of headways.

Multiplying vehicle throughput by vehicle capacity yields the **passenger throughput capacity**: how many passengers can travel through a single point in the system in a given time period.

Malikova (2012) used AVI (automated vehicle identification) data from 2010-2011 to perform an analysis of running times. While she produced good running time results with the data then available, her input dataset had several flaws which this thesis attempts to correct. She only had AVI data available; this work uses a combination of the AVI, GPS, and track circuit data which have been interpolated to infer station arrival and departure times. This allows for choosing any line segments independent of AVI location; whereas, for example, she had to add a representative running time on the outer section of the B Branch because of a limited number of working AVIs on the branch. There were no operable AVI units on the surface section of the E Branch at the time, so it is not included in her analysis. AVI units are unreliable, so she had to use manual counts for headways, while the newly available interpolated location data allows for this to be automated. Additionally, she only had 1-3 weeks of data from each time period, whereas this work allocates 5-12 weeks for each.

4.2 Methods

4.2.1 Running and cycle times

Raw running times are determined as the departure time at the start terminal to the arrival time at the end terminal; terminal dwell times are considered separately. Ideal time points for these lines were the eastbound departure from the western terminal, eastbound departure from the last eastbound surface stop, eastbound arrival at the eastern terminal, westbound departure from the eastern terminal, westbound arrival at the first westbound surface stop, and westbound arrival at the western terminal.

Park Street eastbound was used as the reference timepoint for the B, C, and D branches for running and cycle times (i.e., any train that arrives at Park Street eastbound between 7:00:00 and 7:59:59 is binned into the 7:00 reference hour). Malikova (2012) used Boylston because Park Street data was not as reliable as it is now. Because the E Branch is based out of Lechmere rather than Heath Street, it required several points to be reversed. The reference timepoint for E Branch trains is their arrival at Heath Street; only trains continuing past Brigham Circle to Heath Street are considered here, although Brigham Circle short turns can be analyzed with the same methods.

Although the interpolated data is more reliable, there were still several issues to deal with. For a variety of reasons (including operator failing to set the destination), terminal arrivals and departures were unreliable in several cases, so the next stop inbound was used. Although initially needed on all branches, further improvements to the cleaning code meant only 1 minute from Heath Street to Back of the Hill (eastbound only) and 2 minutes from Lechmere to Science Park (westbound only) were ultimately needed. Westbound D Branch departures at Park Street were inconsistent because trains sometimes used incorrect AVI codes to switch to the opposite track to allow passing. (This was partially rectified in early 2016 with new AVI codes that set switches but do not change destination settings, but not all operators have begun to use them consistently.) Thus, an additional running time of 1 minute from Park Street to Boylston was added and Boylston used as a time point.

The closure of Government Center station from March 2014 to March 2016 presented additional difficulties. The B Branch was cut back to Park Street for the closure, and it was kept as such following the reopening of the station. The D Branch was extended to North Station on weekends and off-peak times, and cut to Park Street (but still usually looping at Government Center) at other times, but returned to Government Center after the reopening. To provide a standard measurement of this, 2 minutes in each direction was added between Park and Government Center for D Branch trains, even after D Branch service was restored to Government Center. The North Station terminus, used by some D and all C trains during the analysis period, is difficult to analyze — because there are two tail tracks, one train can be held on one track while another turns, so it is the only eastbound turnaround location where layover time can be larger than the headway using the turnaround.

To mitigate those situations, proxy turnaround times were used for several segments to generate minimum cycle times (actual eastbound running time + eastern proxy turnaround time + actual westbound running time + proxy western turnaround time) as the effective minimum running time that could have been achieved. Although actual partial cycle times were higher than this in most cases — and some additional turnaround time is desired to permit real-time control and to allow operator breaks — these minimum times act as a baseline for which to base schedules on. The 50th (or 55th) percentile partial cycle time should be used to set running times and minimum turnaround time; the 90th or 95th percentile partial cycle time should be used to set total cycle time. (Allocation of recovery time between the eastern and western termini can be determined separately based on operator and dispatch constraints, and/or set to allow a certain percentage of eastbound trains to arrive in time to depart on time westbound.)

Malikova (2012) stated that turnaround times averaged about 4 minutes at Government Center (including the B which was then turned there) and North Station (although she did not include this in her running times because some trains are held on the North Station sidings for longer periods). This analysis assumes 4 minutes for proxy turnaround times at all four eastern termini; all except North Station may be able to be slightly reduced later, although this would require changing operator schedules to permit consistent use of drop-back at Lechmere.

Malikova (2012) did not include turnaround times at the western termini for her running or estimated cycle times; however, this appears to be necessary at least three of the termini. At Boston College, trains must go around a 900-foot-long loop. At Cleveland Circle they pull past the platform to use a trailing point crossover, and at Riverside, trains usually cross over using a universal crossover east of the station (before or after the station stop); both require changing ends. For these three an additional four minutes of proxy time is assumed. Heath Street has a single platform on a balloon loop; one minute of proxy time has been assumed to allow for dwell time.

For determining current schedule times, the full cycle time (including recovery at both terminals) from GTFS was used, because this is what the observed 90th or 95th percentile would be used for.

MBTA schedulers used an early version of this method to make significant changes to running and cycle times for the Spring 2016 schedule, and to make minor changes since. Thus, one of the intended purposes of this analysis — to make recommendations for changed cycle times — is less significant than planned earlier. However, the method still demonstrates where current schedules do not accurately reflect real operations.

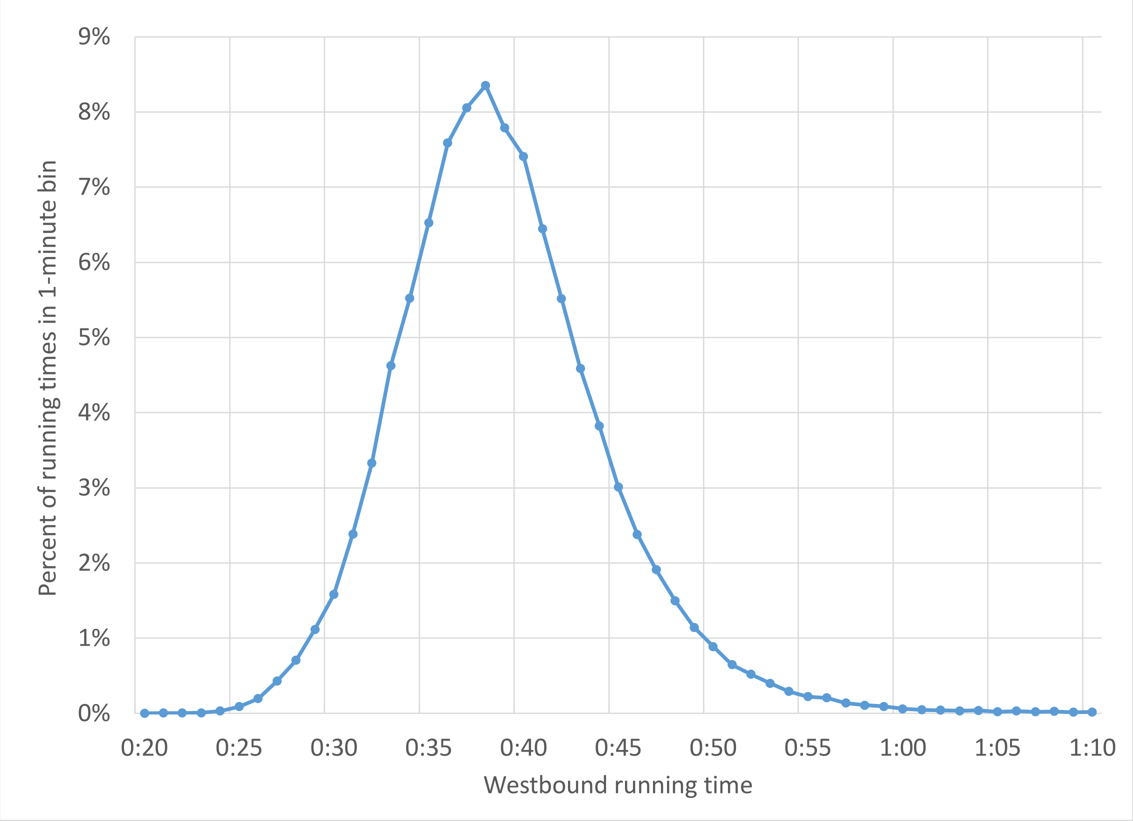

Figure 4-1: Distributions of westbound running times on the C Branch, 2016-2017, showing the long tail.

As shown in Figure 4-1, running times largely follow a normal distribution, but with a long tail corresponding to extremely slow trains. It is necessary to differentiate between slow trains (which should be included in the analysis) and service disruptions and bad data (which should not). A detailed discussion of outlier exclusions is given in Appendix B.

4.2.2 Vehicle requirements

Setting running and cycle times is a balancing act between reliability and required fleet size. The scheduled running time (book time) should reflect what percentage of trips will run earlier than scheduled. The Green Line is a high-frequency service; current headways do not exceed 11 minutes on weekdays and are 7 minutes or less at rush hour. Most passengers will then simply arrive at their stop without checking data, or will use live data at the last minute before leaving their origin, rather than checking predetermined schedules. Thus, the 50^{th} percentile should be used for the book time, as an early train is at worst a minor inconvenience to passengers.

The scheduled cycle time should reflect what percentage of trips will arrive back at their terminals with sufficient time to prepare for their next inbound trip. Setting this too low can cause cascading delays on a service like the Green Line that has high utilization — one trip that starts late or is missed can cause that train or the following train to be extremely crowded and slow, inducing bunching and likely causing that trip to fail to return in time as well. While some of this can be mitigated with real-time control, the threshold should still be high enough to cause very few late trips. However, if it is set too high, then more vehicles and operator will be scheduled than actually required, costing the transit agency money.

TCRP 113 recommends using the 95^{th} percentile running time as the cycle time for high-frequency services like the Green Line. This analysis follows that recommendation, except during some peak periods where it deviates closer to the 90^{th} percentile to decrease vehicle requirements. This section of the analysis looks at vehicle requirements with current headways; these cycle time periods were chosen to match existing headway periods where possible.

During a presentation of some of this material in May 2016, it was suggested that instead of taking the 50^{th} and 95^{th} percentile running times for each hour separately, to instead use the 50^{th} percentile day and the 95th percentile day. That would account for patterns across days — a Red Sox game might cause higher running times over much of the afternoon and evening, for example. However, there is no obvious way to condense each day down to a single value to do this. Additionally, doing so might underestimate the 95th percentile, as many days will have a better AM peak paired with a worse PM peak or vice versa.

For various reasons, current headways are irregular at times, particularly when the D Branch is feeding the other branches at the beginning of peak periods. Additionally, scheduled arrival times (and thus headways) are rounded to the nearest minute by the scheduling software — for example, a 5:20 headway would be produced as a repeating pattern of 5-5-6 minute headways. For this analysis, the scheduled headways were smoothed in half-hour increments to produce a less irregular average headway to determine car counts. An example is shown in Figure 4-2.

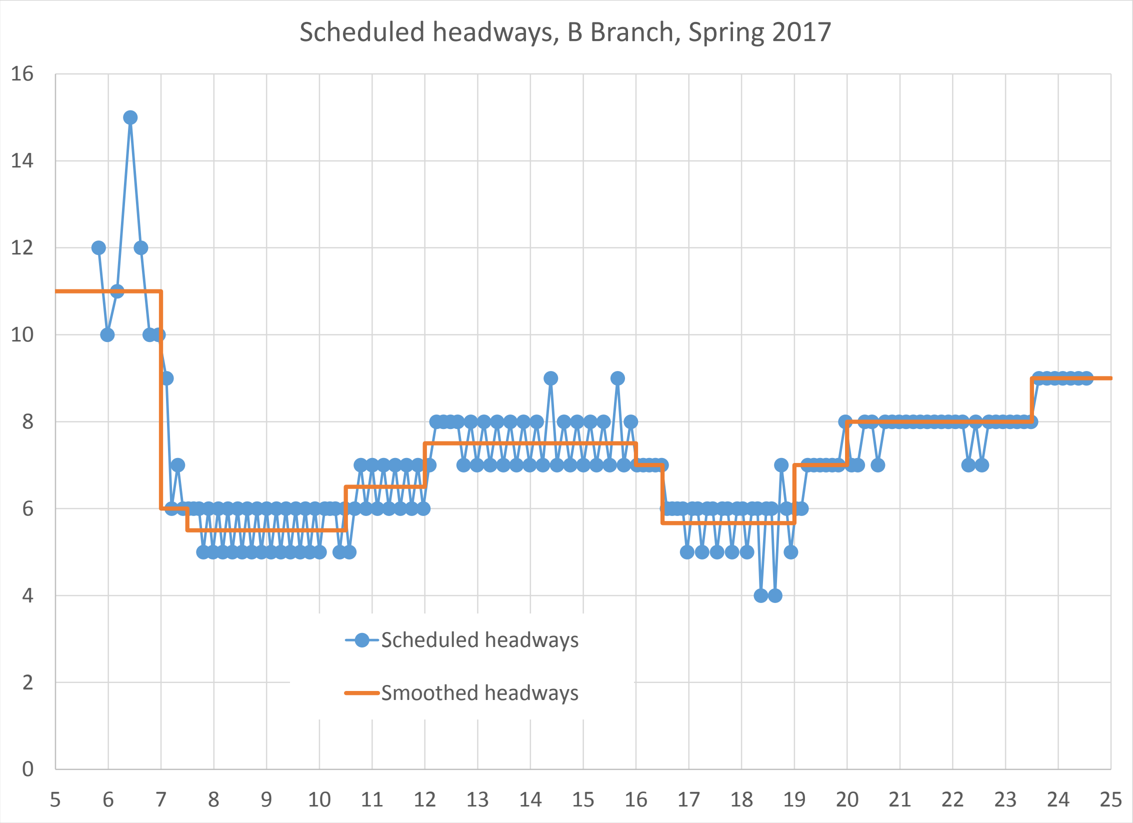

Figure 4-2: Scheduled headways on the B Branch, Spring 2017

Similarly, cycle time periods were smoothed to partial-minute averages, with an attempt to match cycle time periods to headway periods where possible. This resulted in 10 to 13 headway/cycle periods for each line. An example is shown in Figure 4-3.

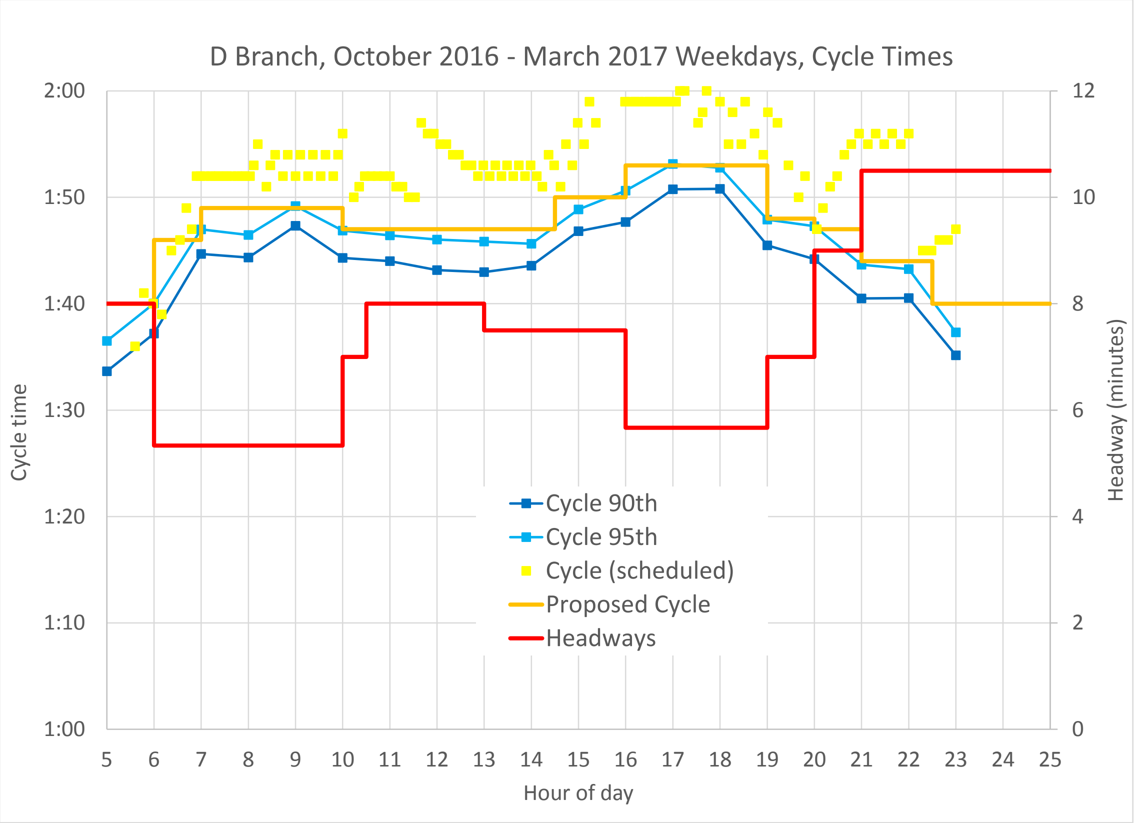

Figure 4-3: 90^{th} and 95^{th} percentile running times, smoothed cycle times, and scheduled cycle times and headways on the B Branch, 2017-2017.

From this, trainset requirements can be estimated by integer dividing cycle time by headway. Vehicle requirements can then be determined from train length; the analysis in this chapter assumes two-car trains at all hours on weekdays, as is currently done. This is only an approximation: at the beginning of peaks, vehicle requirements will be overestimated, as trains that passed Park Street previously with longer headways are still operating. The reverse occurs at the end of peaks, with longer headways having begun at the terminals but not yet reached Park Street. However, off-peak periods near peaks may be underestimated, as peak-headway trains are running at some location but not counted. The maximum car utilization will be correct if the period of peak utilization is longer than the cycle time, as is the case for all four lines at both peaks in this analysis. A comparison of the simple estimation method (in blue), and a more accurate manually blocked schedule (in red), is shown in Figure 4-4. The comparison shows how trainsets are gradually phased in and out of service at the shoulders of peaks, which is not as well captured by the simple estimation.

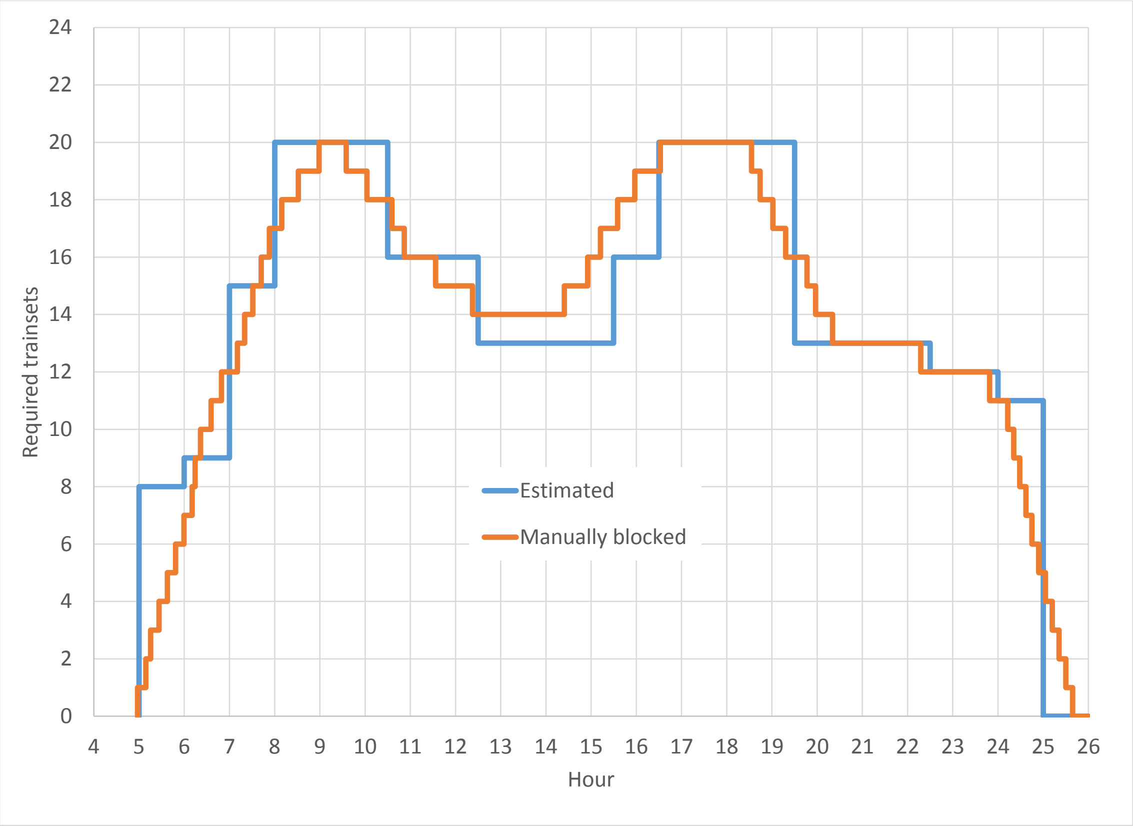

Figure 4-4: Trainsets required to run B Branch service in Spring 2016, estimated using cycle times and determined with manual blocking.

To determine actual vehicles used in service, the number of distinct valid car numbers seen in the cleaned data between 5:00 and 11:00, and between 15:00 and 21:00, were counted on each weekday with normal service. The same exclusions as the cycle times were used — on holidays and days with service disruptions less cars may be in service, while some holidays (notably Patriot's Day) have all working vehicles pressed into service to handle crowds. These counts may overestimate if a car is only operated as a deadhead or test train on a given day; however, it is unlikely for this to be more than one or two cars on a day.

4.2.3 Throughput

Throughput is determined by counting the number of trains per hour running eastbound through the AVI east of Boylston station, using the interpolated data. (This is the closest possible singular AVI to Park Street, as trains can be on two separate tracks at Park Street). The cleaned data should have all trains interpolated; however, in case there were either missing data points or trains that were removed in the cleaning process, two check methods were used. The first was adding two additional locations (Copley and Arlington stations) with the cleaned data; the second was to use four AVI points and the uncleaned data. All three methods produced identical results.

4.2.4 Headways

Headways are determined by taking the difference in successive arrival times at a stop, using the cleaned data. As with Malikova's work, headways were calculated at the terminal and the easternmost surface stop for the branches. For this thesis, the first eastbound stop after the terminal was used for the eastbound terminal headways. For visually demonstrating the predicted increase in variation over the course of each branch, major stations near the midpoints — Harvard Avenue, Coolidge Corner, Reservoir, and Brigham Circle — were also analyzed.

Expected waiting time can be determined from the average and standard deviation of headways as:

$$E[W] \quad = \quad \frac{\bar{h}}{2} \cdot \left(1 + \frac{\bar{h}^2}{\sigma^2}\right)$$

4.2.5 Analysis periods

MBTA ratings (changes in work shifts) and schedules change around the 21st of March, June, September, and December; the spring (March) and fall (September) changes are usually the most significant. Each analysis period used in this thesis thus starts shortly after a rating begins to account for operator and schedule changes. The spring period last 5 weeks, ending before college graduations affect demand (spring 2015 begins slightly later after service resumed from an unusually harsh winter). The summer period lasts 8 weeks, ending before students begin moving back into colleges. The fall period lasts 9 weeks, ending before the Thanksgiving holiday. The winter period lasts 11 weeks, beginning after New Year's.

For cycle time determination, a 24-week period of early October to mid-March was used as a sample of normal representative operations during the school year. This includes the fall period — minus September where there are many new operators — and the winter period.

Period	**Dates used**	**Length of period**
Spring 2015	March 29, 2015 — May 2, 2015	5 weeks
Summer 2015	June 21, 2015 — August 15, 2015	8 weeks
Fall 2015	September 20, 2015 — November 21, 2016	9 weeks
Winter 2016	January 3, 2016 — March 19, 2016	11 weeks
Spring 2016	March 27, 2016 — April 30, 2016	5 weeks
Summer 2016	June 19, 2016 — August 13, 2016	8 weeks
Fall 2016	September 18, 2016 — November 19, 2016	9 weeks
Winter 2017	January 1, 2017 — March 18, 2017	11 weeks
Spring 2017	March 19, 2017 — April 22, 2017	5 weeks
2015-2016 (main)	October 4, 2015 — March 19, 2016	24 weeks
2016-2017 (main)	October 2, 2016 — March 18, 2016	24 weeks

Table 4.1: Date ranges used for analysis

Table 4.1 shows the date ranges used for this analysis. Unless mentioned otherwise, all results hereafter are for weekdays only. Weekends, when vehicle availability is not a limited factor, do not have as critical needs for exact cycle times.

Because this analysis should represent the range of normal service, an attempt was made to exclude days where service (as operated) or demand were substantially different from normal days. Some of these are predictable events with different service or demand, including holidays, major travel days (Tuesday through Sunday of Thanksgiving week, and December 23rd through 26th), playoff games at Fenway Park, and the Free Fare Day offered in April 2015. Others are days where service was interrupted on one or more branches due to planned construction events, derailments, downed wires, power issues, vehicles on tracks, and other issues. Many of these only affected one or two branches and are only excluded from their data sets. There are several cases where separate events occurred that prompted exclusions: two days where the Orange Line was suspended between Back Bay and North Station (and thus demand on the Green Line was vastly increased), and one day where commuter rail trains could not reach South Station due to an interlocking failure (and thus travel patterns were markedly changed systemwide).

Regularly occurring and frequent events like in-season Red Sox games, and minor disruptions that do not involve a segment of line being closed, are considered to be within the realm of normal operations. The E Branch is frequently closed past Brigham Circle due to traffic conditions; because of how commonly this occurs, it was treated as a minor disruption rather than an issue justifying exclusion. Lists of holiday exclusion days, and of exclusions due to track work and unplanned service disruptions, are presented in Appendix C.

Due to an error in the cleaning code, no data for late-night operations after midnight was available at this time.

4.3 Results

4.3.1 Running and cycle times

Three important overall trends are apparent in the running time data. First, there is a marked variation between each consecutive season. The most severe example of this is during the June-August 2016 period. In March and May 2016, a host of speed restrictions were added to the Green Line after high-profile derailments and the discovery of rail wear and track gauge inconsistency. The Department of Public Utilities also began more strict enforcement of 10 mph speed limits over grade crossings. The combined effect of these resulted in the summer period having running times 3-5 minutes longer at all hours than previous periods on the B, C, and E branches, and 5-8 minutes longer on the D Branch. The spring data shows some of these increases, though not all restrictions were in place during the analysis period. These changes were intentionally left out of the fall 2016 schedule, as the increased cycle times would have reduced many operators from five daily trips to four. An aggressive maintenance program of rail grinding and wheel truing permitted the relaxation of most of the speed restrictions; fall 2016 running times are similar to those from the spring, and winter 2017 running times are similar to winter 2016. A comparison of winter and summer 2016 running times on the D Branch are shown in Figures 4-5 and 4-6.

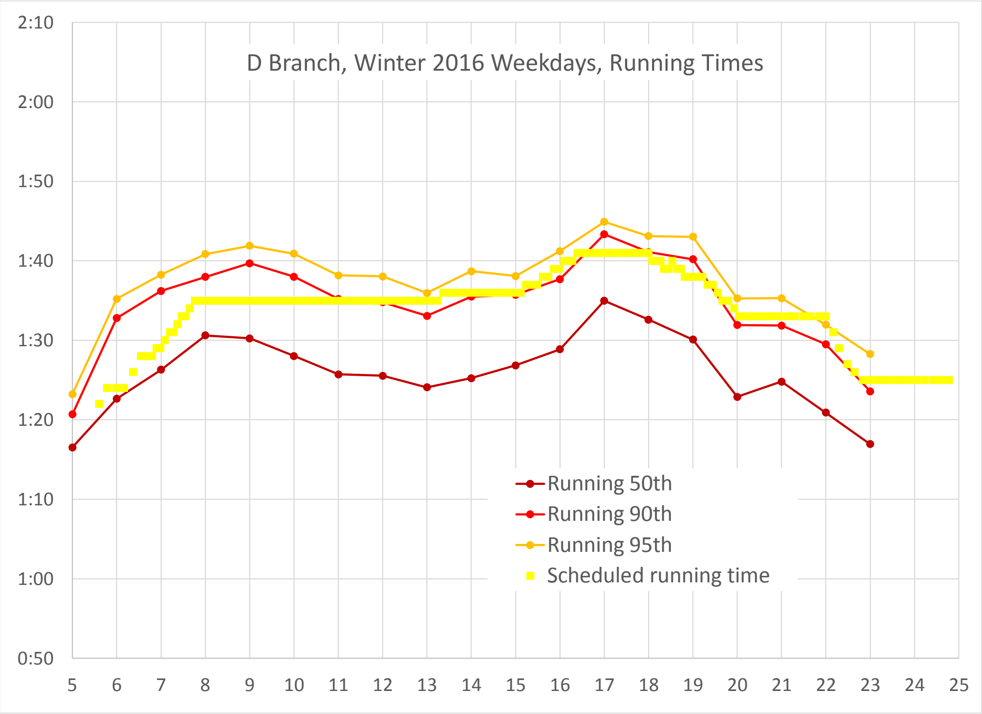

Figure 4-5: Winter 2016 running times and current scheduled running times on the D Branch.

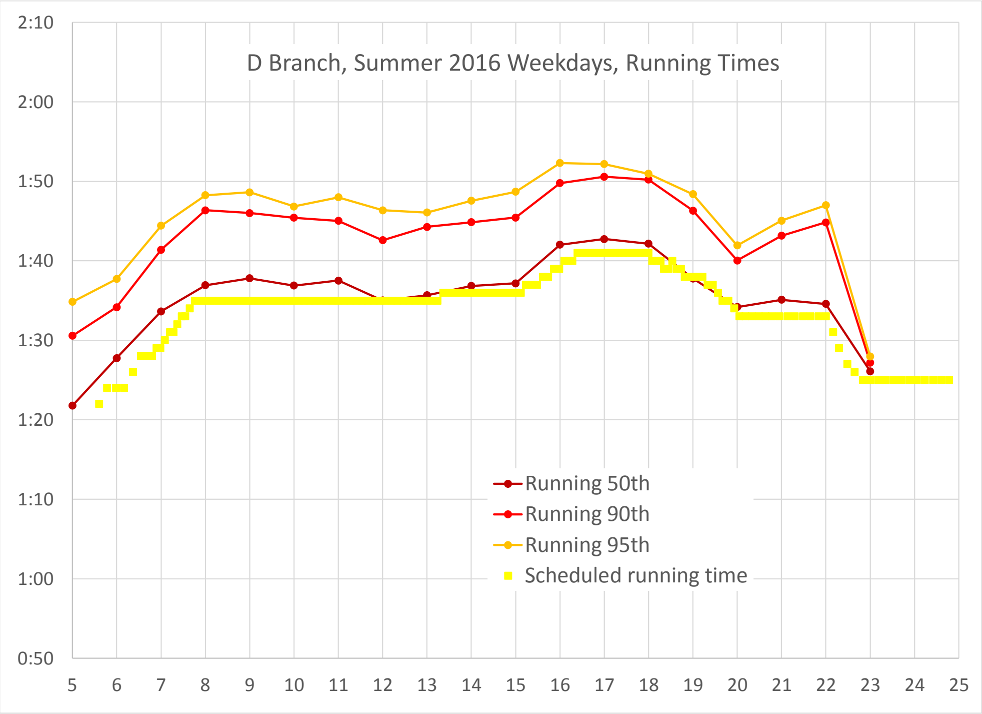

Figure 4-6: Summer 2016 running times and current scheduled running times on the D Branch, showing the effect of speed restrictions and enforcement, as well as longer running times around 10pm due to Red Sox games.

A smaller annual variation can also be observed, with spring and especially fall having slightly longer running times than summer and winter. Several factors play into this. New Green Line operators usually begin work at the spring and fall ratings; their inexperience often prompts them to operate more slowly than seasoned operators. A large portion of the region's student population — which represents a significant fraction of the population served by MBTA subway lines — is also not present during the summer. This is most likely to affect the B Branch (which serves Boston University and Boston College) and the E Branch (which serves Northeastern University). Fall, winter, and spring can likely be served with the same scheduled running and cycle times; however, summer schedules with shortened running times (except in the 10pm hour, when departing Red Sox game crowds cause slow service) may be advisable.

Second, despite the vast improvements in matching schedules to real-world running times, there are several situations where further changes should be made. In some cases, running times — especially on the surface sections — are insufficient even when the full cycle times are theoretically adequate. While incorrect running times do not cause overall frequency to be incorrect as incorrect cycle times do (and are thus a lower priority to fix), they do have operational and customer issues. Incorrect running times indicate to riders that their trip will be faster than it will actually, and that bus connections can be made that will be missed in real life. A rider leaving work in the Longwood Medical Area would far rather know they have to catch a train five minutes earlier than miss their once-an-hour bus at Lechmere. The following assessments are based on fall and winter weekday data (October 2016 — March 2017) with both excluded days and outlier trips removed. The B Branch has accurate scheduled eastbound running times, but the westbound schedules should actually be sped up by several minutes to match real running times. AM peak and midday eastbound surface running times, and early AM westbound surface running times, should be lengthened slightly in the schedule (with subway running times correspondingly shortened). The B Branch has adequate scheduled cycle times at all hours except for several short cycle times around 10am; if more than a small percentage of trains are not completing their cycles in time, it is due to poor terminal dispatching rather than an improper schedule.

Scheduled and calculated (running times plus proxy turnaround times) cycle times for the B Branch, showing that current schedules offer sufficient cycle time for reliable operations

On the C Branch, scheduled running times in both directions can be shortened by several minutes except during the AM peak. However, scheduled eastbound surface running times actually need to be lengthened by several minutes. Except for short periods in the early AM and mid-afternoon, cycle times are more than adequate; it may be possible to shorten scheduled cycle times by an amount of time equal to one headway (and thus use one less train) without impacting reliability.

On the D Branch, scheduled eastbound running times are mostly accurate, but westbound schedules can be shortened by about 5 minutes at most times. Cycle times are, again, more than adequate and could be reduced slightly.

Current E Branch schedules have running times near the 50th percentile and cycle times near the 95th percentile — exactly as they should be. However, eastbound trains take several minutes longer on the surface than scheduled, and several minutes less in the subway.

When previously measured (when after-midnight data was available), last-hour scheduled cycle times were significant underestimates because of MBTA policy that the final trains hold at the downtown transfer stations to guarantee connections. This is not an issue for equipment as all trains are simply headed to yards, but it does need to be considered for crew schedules.

These assessments are based solely on the data and assumptions outlined here, and do not always reflect the actual operational reality of the Green Line. Downtown terminal times are frequently longer than needed for turnaround time; even late trains are often held if the following train is also late. Because Lechmere is the primary crew base for the E Branch, layovers may also be extended there. The western terminals can be similarly inefficient.

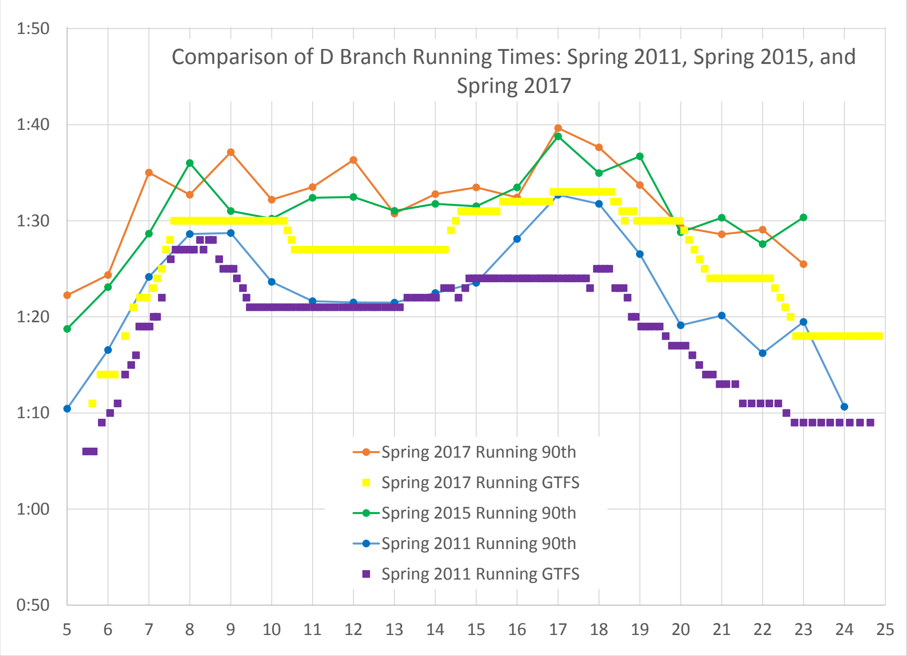

Figure 4-7: Comparison of D Branch running times between 2011, 2015, and 2017. Scheduled running times from 2011 and 2017 are shown.

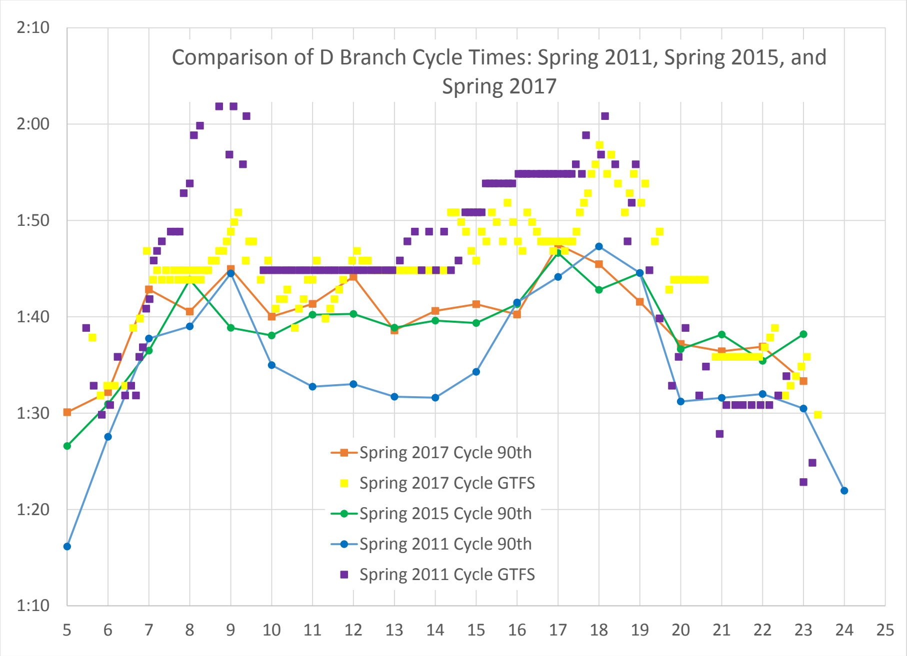

Figure 4-8: Comparison of D Branch cycle times between 2011, 2015, and 2017. Scheduled cycle times from 2011 and 2017 are shown.

Third, running and cycle times appear to have deteriorated since Malikova's research. A comparison of spring 2011, 2015, and 2017 running and cycle times shows an increase of 6-10 minutes between 2011 and 2015 (and no further increase between 2015 and 2017) principally during off-peak hours. Ridership on the Green Line did not increase substantially during this time, so this is unlikely to be due to delays at prepayment stations, and the time-of-day-dependent nature of the change indicates it is not a result of speed restrictions. Conversations with MBTA staff indicates it is likely due to the April 2012 implementation of front-door-only boarding and alighting during off-peak times. This would correspond to an average additional delay of around 15-25 seconds per surface stop. Graphs of compared running and cycle times are shown in Figures 4-7 and 4-8. A full set of running time, cycle time, eastbound and westbound running time, and eastbound and westbound surface running time charts are presented in Appendix D.

4.3.2 Vehicle requirements

The MBTA has a nominal Green Line fleet of 205 vehicles: 111 Type 7s and 94 Type 8s. As of May 18, 2017, 160 of these (77 Type 7s and 83 Type 8s) are in the active fleet, while the remaining 43 are out of service. After the completion of the Type 7 overhaul program, repairs to several other cars, and the arrival of the Type 9s, the fleet may number as high as 212 (103 Type 7s, 85 Type 8s, 24 Type 9s). However, an absolute maximum of 194 could be used in service at one time, as each train requires a low-floor car and Type 9s cannot electronically couple with Type 7s.

Until March 2016, the schedule required 143 cars (68 trainsets — 61 doubles and 7 triples) for the AM peak and 146 cars (69 trainsets — 61 doubles and 8 triples) for the PM peak. Since then, schedules have required 146 cars (73 doubles) for both peaks: 19 trains for the B Branch, 16 for the C branch, 21 for the D Branch, and 17 for the E Branch. Although this change eliminated triples, it requires more trains due to the increased scheduled running times. This also puts more constraints on the types of cars available, because each train needs at least one Type 8 car. Thus, even with the same PM car requirements, the recent schedules require four more Type 8s to be available. With an active fleet of 160 cars, a 146-car schedule represents an effective spares ratio of 10%. In 1995, the MBTA had a much higher 31% spares ratio (37 of 180 cars), with other systems ranging from 12% to

28%.(Pierce, 1995)

The cycle times calculated in this work result in estimated requirements of 148 cars in the AM peak and 146 in the PM peak — essentially equivalent to the current schedule, as shown in Figure 4-9.

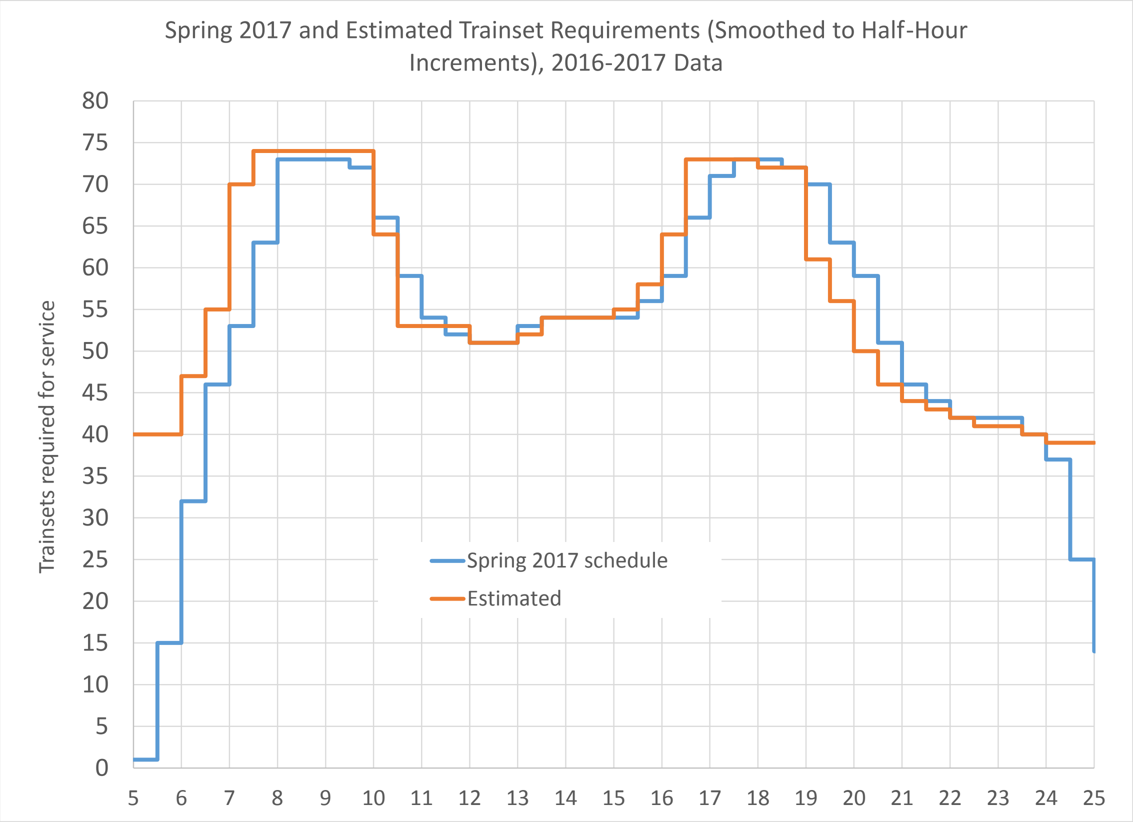

Figure 4-9: Trainset requirements for the Spring 2017 schedule, and estimated requirements using calculated cycle times.

However, all of this rests on the assumption that the scheduled number of vehicles will actually be available for service — which does not appear to be the case. From October 2015 to April 2017, the number of vehicles observed in service at each peak period has generally hovered between 135 and 145 — 1 to 4 trainsets short of scheduled service. Before March 2016, this often resulted in scheduled triples being run as doubles; of the scheduled 7-8 triples in each peak, on average less than one ran per weekday from October 2016 to March 2017. Since then, shortages have presumably caused dropped trips and lengthened headways. Vehicle availability increased for much of 2016, but has since fallen close to 2015 levels. Figure 4-10 shows car counts from 2015 to 2017.

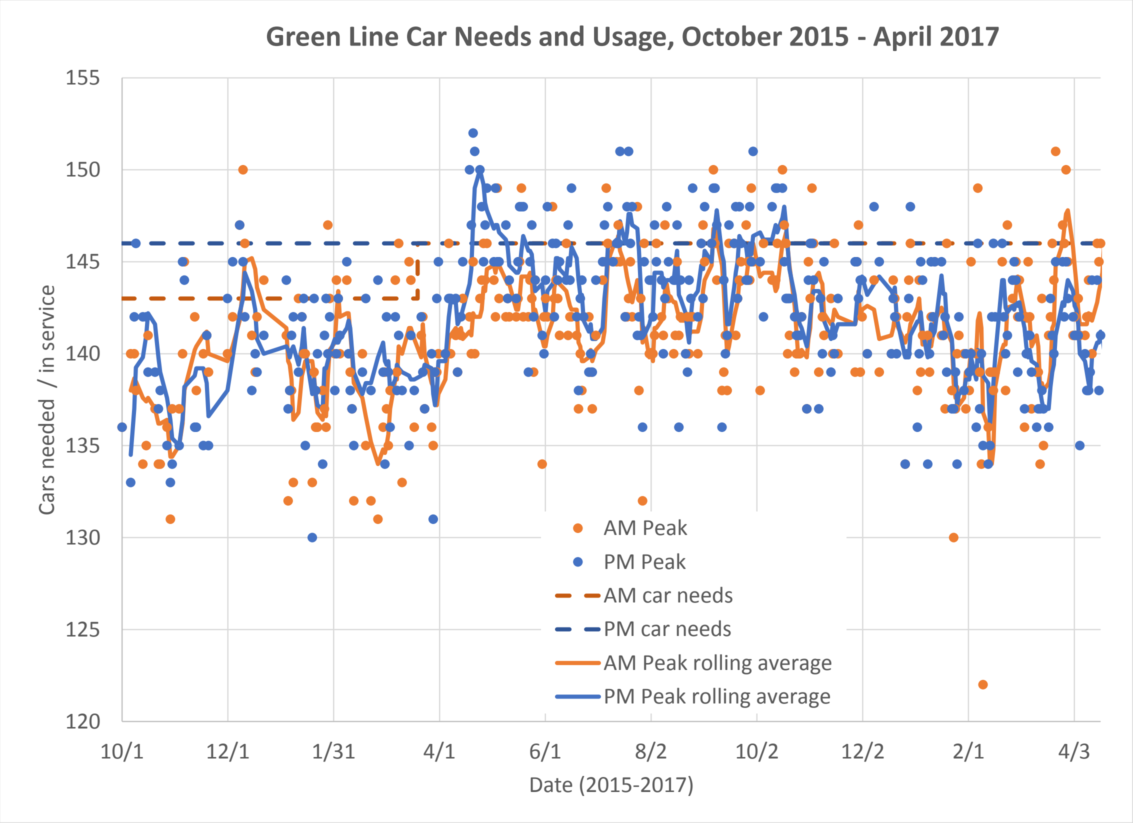

Figure 4-10: Peak vehicle needs, actual usage, and 5-day rolling usage average for October 2015 to April 2017. All dates with service disruptions are excluded.

Charts of suggested cycle times and approximate vehicle usage are presented in Appendix E.

4.3.3 Throughput

In order to prevent the lengthened scheduled cycle times from significantly increasing operator hours, the spring 2016 schedule cut midday service (by about 1 TPH on each branch) while maintaining peak service levels. Subsequent schedules have modified this slightly, including reducing frequency at the beginning of the PM peak.

In fall 2015, Green Line service was significantly less frequent than scheduled. There were 82 trains scheduled to arrive in the AM peak (7:00-9:00 am) and 126 in the PM peak

CARS	**Scheduled CPH**		**Actual CPH**		**Percent operated**	
	AM Peak	PM Peak	AM Peak	PM Peak	AM Peak	PM Peak
Fall 2010	85	78	80	79	94%	101%
Spring 2011	83	81	82	78	99%	96%
Fall 2011	85	84	81	74	95%	89%
Fall 2015	86	88	70	67	81%	77%
Spring 2016	81	84	76	74	94%	88%
Fall 2016	81	84	77	77	95%	91%
Spring 2017	80	79	75	73	94%	93%

TRAINS	**Scheduled TPH**		**Actual TPH**		**Percent operated**	
	AM Peak	PM Peak	AM Peak	PM Peak	AM Peak	PM Peak
Fall 2010	43	39	Data not available		Data not available	
Spring 2011	37	38				
Fall 2011	38	40				
Fall 2015	41	42	35	34	85%	80%
Spring 2016	41	42	38	37	94%	88%
Fall 2016	41	42	39	38	95%	91%
Spring 2017	40	39	38	37	94%	93%

Table 4.2: Scheduled and observed throughput during peak periods, 2010-201 and 2015-2017

(4:00-7:00 pm). However, only 72 (88%) and 105 (83%) of these were actually operated. Because many scheduled triples were run as doubles, this corresponds to just 84% and 80% of scheduled cars per hour. This is a decline from Malikova's measurements, which indicated that 95% of PM peak car throughput and 89% of AM peak car throughput was observed in fall 2011.

The combination of improved schedules and higher vehicle availability in spring 2016 resulted in improvements to throughput. Peak throughput jumped back to 2011 levels; off-peak frequency fell slightly to neatly match scheduled frequency. This improved service has continued; in spring 2017, peak throughout was at 94% (AM) and 93% (PM) of scheduled throughput. Table 4.2 summarizes throughput results; Figure 4-11 shows throughput change from 2015 to 2016.

Despite the recent improvements, throughput is still lower than scheduled. Known shortages of cars or operators at the beginning of rush hours may result in intentional decisions to drop some trips and stretch headways to avoid large gaps in service later caused by insufficient cars being in service. As shown above, actual car usage rarely meets scheduled usage, indicating that insufficient cars are in service to meet scheduled throughput even if

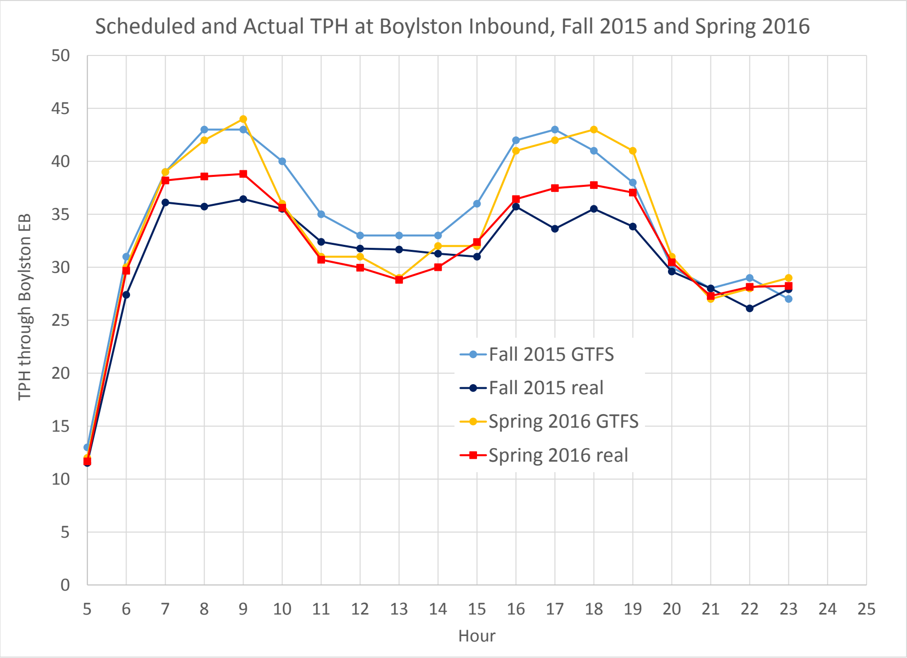

Figure 4-11: Scheduled and observed throughput in Fall 2015 and Spring 2016

all else goes well. Cycle times longer than scheduled — compounded by crowding caused by lower service levels — may cause trains to unintentionally miss their next trips. Inattentive terminal dispatching may also exacerbate these issues if returning trains are not turned quickly, inbound trains are not dispatched on their proper headways, or available trains are not pulled from the yard when needed to operate on time. It was suggested at a meeting with the MBTA in May 2016 that trips might be being pushed towards the ending shoulders of the peak rather than being dropped; however, there is no evidence that this is occurring.

4.3.4 Headways

The major schedule changes of spring 2016, and minor changes since, appear to have improved the consistency of Green Line headways. However, this is largely a reversal of deterioration that had occurred since 2010, rather than true long-term improvement.

In the AM peak, median headway decreased by an average of 16 seconds (across the four terminals and portals in both direction) from fall 2015 to spring 2016; standard deviation decreased by an average 37 seconds and expected waiting time by an average of 31 seconds. Between fall 2015 and spring 2017, these improvements were respectively 24 seconds, 46 seconds, and 40 seconds. The improvements were equally strong when measured only for the peak directions (eastbound on the B, C, and D branches, and both directions on the E Branch). However, there was no significant decrease in bunching (the number of trains with headways under three minutes) during this period. Additionally, the spring 2017 metrics are similar to the fall 2010 metrics, indicating that these improvements are merely a reversal of deterioration that occurred between 2010 and 2015, rather than long-term changes in service quality.

In the PM peak, median headway decreased by 37 seconds across the measured sites; standard deviation decreased by 15 seconds, and expected waiting time by 20 seconds. Between fall 2015 and spring 2017, the improvements were respectively 27 seconds, 38 seconds, and 35 seconds — and again equally strong for the peak direction only. However, like the AM peak, bunching did not improve, and the improvements do not represent a substantially difference from the 2010 metrics.

The theoretical distribution of headways at a given point will be a bell curve, with a small variance near the start terminal that increases further down the line. The curve is expected to be slightly skewed — physical operating characteristics prevent headways from going below about 30 seconds in most cases, and the tendency of late trains to become later will cause a long tail. Because westbound trains have traveled 5 to 8 stops in the subway before reaching the surface — and thus have interacted with and been impacted by the other branches — they will have higher variance on the surface than eastbound trains. All following results, unless noted, note headway adherence — here, the percentage of headways between 4 and 8 minutes at a given stop.

The following results are for Spring 2017 during the AM peak:

The eastbound B Branch shows the increase in variance as trains progress from the western terminal: 64% at Boston College to 44% at Blandford Street. The eastbound C Branch has identical distributions at Cleveland Circle and Coolidge Corner (75%), and only a slight increase in variance at St. Mary's Street (63%). This indicates that terminal headway reliability determines reliability on the whole line. The eastbound D Branch shows a high increase in variance from Riverside to Reservoir (80% to 56%, despite relatively good terminal headway control), and some increase from Reservoir to Fenway (47%); this indicates that dwell time or running time variability on the outer portion of the line is causing reliability issues. The eastbound E Branch has identical (at 42%, rather unreliable) distributions at Heath Street and Brigham Circle, but some improvement (53%) by Northeastern — the result of headway control at Brigham Circle.

The westbound B, C, and D branches largely show the expected changes, with some bimodal tendencies evident due to frequent bunching. The B Branch decays from 50% at Blandford Street to 26% at Boston College; the C Branch decreases from 41% to 29%. More than a quarter of trains arriving at Riverside have headways less than two minutes, and nearly another quarter have headways longer than ten minutes. Half of westbound trains at Riverside have headways between 4 and 8 minutes, but just 26% do at Riverside. The westbound E Branch has poor reliability, but shows little increase in variance across the line (40% to 34%).

The following results are for Spring 2017 during the PM peak:

The eastbound B, C, and D branches show the expected variation. The B Branch decreases from 63% to 44% along its length, the C Branch from 71% to 50%, and the D Branch from 80% to 50%. The E Branch increases from 35% at Heath Street to 49% at Northeastern due to headway control at Brigham Circle.

Westbound, Harvard Avenue and Boston College on the B Branch are skewed towards short headways with a long tail; 48% adhere to headway at Blandford Street, but just 30% by the terminal. The C Branch shows similar but less pronounced behavior (43% to 33%), while the D Branch has a similar skew similar to the B Branch (47% to 33%). The westbound E Branch shows increasing variability (44% to 35%) as trains deal with mixed traffic west of Brigham Circle.

Several of the indicated patterns are shown in Figures 4-12 through 4-15. Charts of headway distributions in both directions at both peaks are presented in Appendix F.

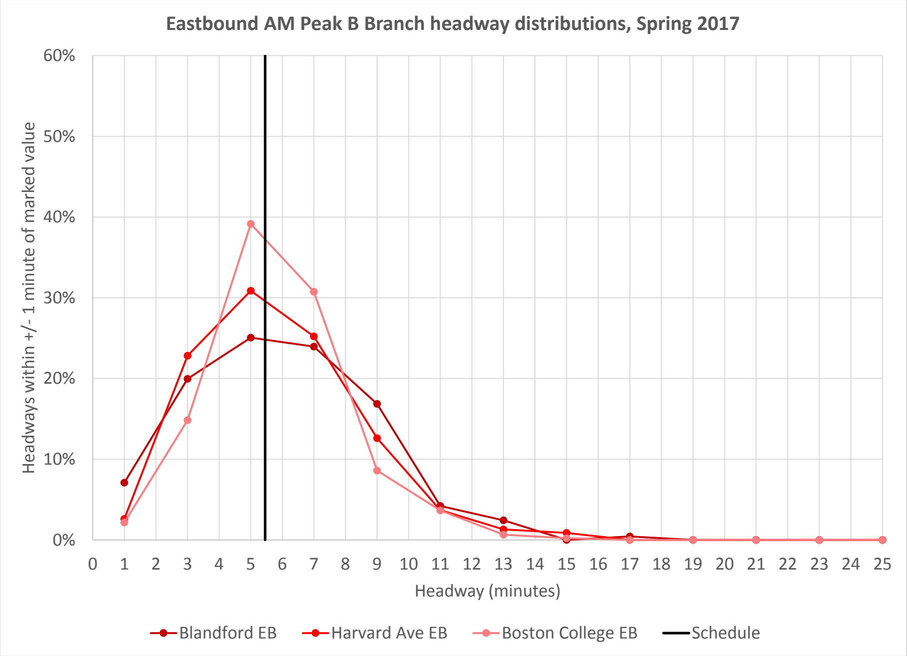

Figure 4-12: Headway distributions of AM peak eastbound B Branch trains, Spring 2017, showing mediocre terminal headway reliability and an increase in variance as trains proceed along the line.

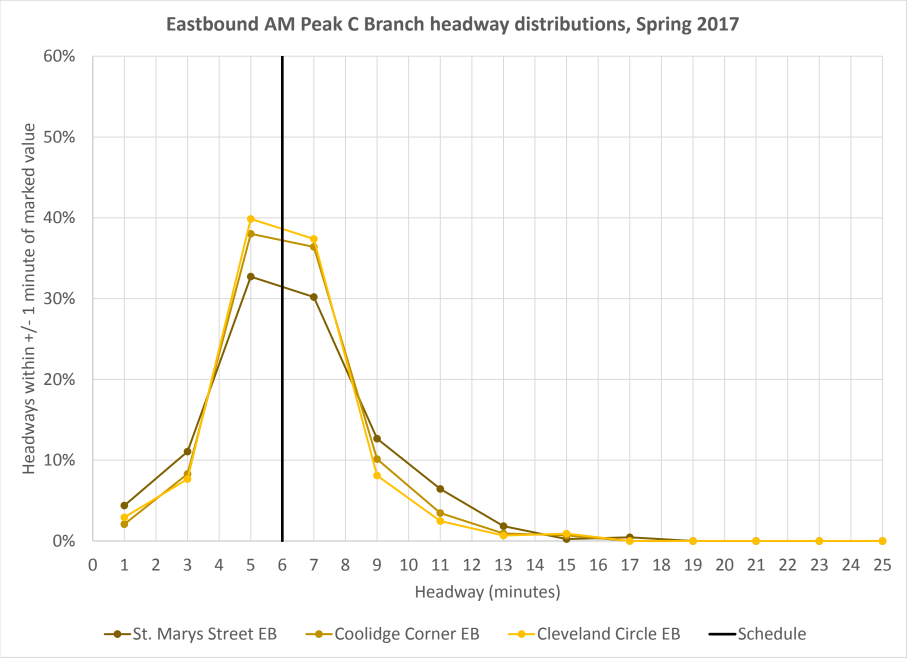

Figure 4-13: Headway distributions of AM peak eastbound C Branch trains, Spring 2017, showing mediocre terminal dispatching and little increase in variability as trains proceed along the line.

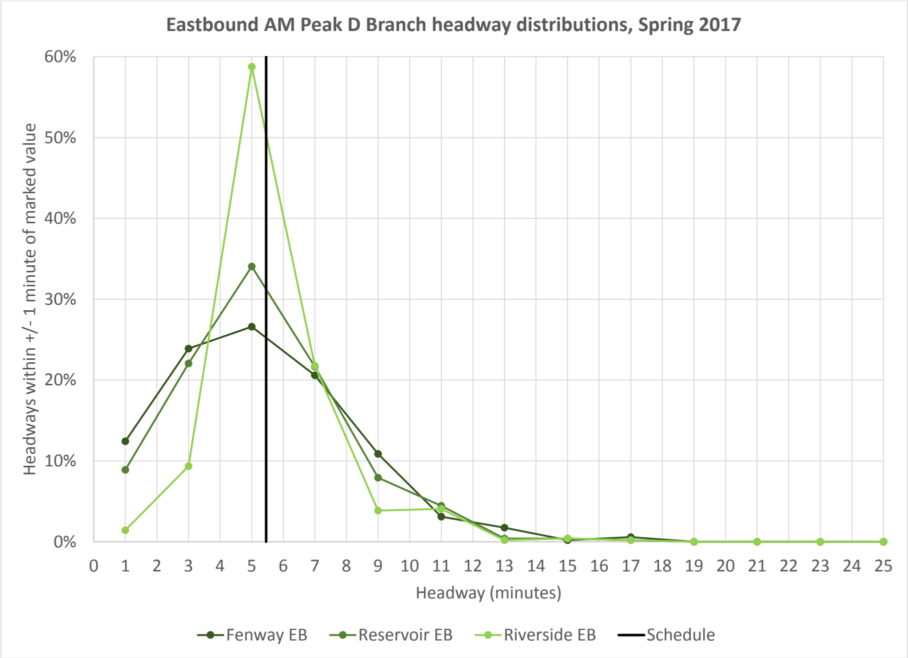

Figure 4-14: Headway distributions of AM peak eastbound D Branch trains, Spring 2017, showing decent though imperfect terminal dispatching and high increase in variability as trains proceed along the line.

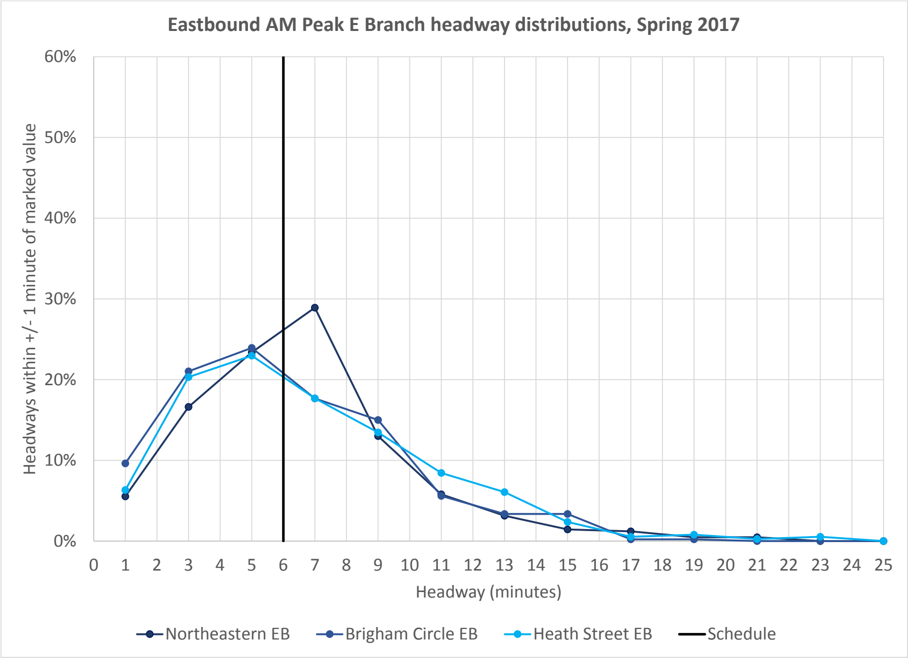

Figure 4-15: Headway distributions of AM peak eastbound E Branch trains, Spring 2017, showing poor reliability in the mixed-traffic section and slight improvement at Northeastern due to headway control at Brigham Circle.

4.4 Conclusions

The overall trend is that schedule changes in 2016 and 2017 have improved service quality — yet this is mostly a reversal of deterioration from 2010 to 2015, rather than true long-term improvement. Continued use of large-scale cleaned AVL data to analyze and tweak schedules is absolutely necessary to maintain this level of service, while additional methods — several of which are currently in development or testing — are likely needed to further improve service.

The schedule changes have largely made scheduled running and cycle times appropriately reflect real operations, although several improvements — particularly to scheduled surface running times, and to scheduled cycle times at some times of day — should be made. These improved schedules should not require any additional vehicles, though there appears to be an overall vehicle availability issue. A continued focus on eliminating speed restrictions, and on preventive maintenance to avoid future episodes, is needed. Off-peak running times have vastly increased since 2011, likely due to the front-door-only boarding policy; the planned implementation of all-door boarding in 2019 should correct this.

Headway and throughput results show an improvement since 2015, though the improved service is no better than it was in 2010 before reliable train tracking was possible. There still appears to be a number of dropped trips at rush hour.

Headway analysis largely shows the expected patterns of increased headway variability as trains proceed further from points at which headway is controlled. Bunching is common, particularly in the westbound direction as variable dwell times, running times, and grade crossing delays degrade service. This demonstrates a need for decreasing random variations as much as possible with methods like transit signal priority, all-door boarding, true level boarding, and reducing speed restrictions to allow for more consistent operation. However, these alone cannot produce reliable service if trains do not enter service on consistent headways. Just 60% to 80% of trains leave Boston College, Cleveland Circle, and Riverside close to their scheduled headways. The use of automated headway control tools, combined with inspector and dispatcher training and attentiveness, is necessary to produce the extremely reliable terminal dispatching that is crucial to regular headways across the system.

Along with these short-term and medium-term projects to improve service speed and reliability, it is necessary to ensure that service is being run where it is needed to meet current capacity constraints and to minimize crowding throughout the Green Line. Appendix A presents preliminary work on several methods of improving service allocation to reduce crowding — which in turn will support more reliable operations.

Chapter 5

Vehicle selection

Six extant light rail systems in the United States — what are now the MBTA Green Line in Boston, the SEPTA Subway-Surface Lines in Philadelphia, the RTA Rapid Transit lines in Cleveland, the Newark City Subway half of the NJ Transit Newark Light Rail, and the Muni Metro system in San Francisco — are legacy systems, with parts of their current tunnels opened between 1897 and 1935. Constructed in an era of small, lightweight streetcars, these systems often have physical characteristics which do not meet the standards expected of modern lines, which are typically constructed with a larger loading gauge for futureproofing.

Rolling stock for legacy systems is thus often chosen — and custom-ordered — to fit the perceived individual needs and physical characteristics of the system. All six legacy systems once used the PCC streetcar, which was extremely reliable and useful for many applications, but their designs diverged as capacity needs required longer vehicles which had to be customized to fit tunnels built to different standards. The last significant attempt to create a common style of rolling stock suitable for legacy systems, the Boeing-Vertol USLRV, was undertaken in the late 1970s in an attempt to popularize new light rail systems in the United States. The cars were a compromise design that was ill-suited for any system and plagued by poor reliability — the opposite of the PCC design whose success it intended to replicate. However, with the introductions of dozens of light rail and streetcar lines in the United States since 1980, many of the newer systems have begun to use similar or identical rolling stock. It is hypothesized that it may present benefits for legacy systems to invest in physical plant improvements during fleet replacement to allow use of existing vehicle designs; the expectation is that the cost of the infrastructure will be balanced by lower up-front costs for rolling stock and long-term improvements in reliability by using proven designs.

The intention of this chapter is to outline a basic framework for the evaluation of multiple rolling stock types for a light rail system, including comparing recent custom orders to existing common rolling stock, and to present an expanded example of the analysis for the MBTA Green Line. This analysis is intended as an introductory phase to the MBTA's Type 10 procurement process, in order to more fully inform the traditional procurement process and analyze the possibility of modifying infrastructure to allow use of existing vehicle designs.

5.1 Why full fleet replacement?

With all three MBTA heavy rail lines upgraded to uniform modern fleets by 2024, the Green Line will be the only of the agency's subway lines with non-uniform and pre-2005 rolling stock. The agency is considering a full replacement of all Green Line vehicles in the 2025 time frame, a possibility first publicly announced in March 2017. This represents a grand opportunity — the first since the 1970s — to make a commitment to a fully modern, uniform fleet for the Green Line, with improvements to reliability, capacity, and accessibility.

A common fleet would allow Green Line maintenance to be standardized on a single vehicle type — which the MBTA has not been able to do since the late 1970s — rather than the three types that will be in service by 2018. All vehicles would have common parts, which reduces training and warehousing costs, and common electronics would largely eliminate the trainlining consist issues encountered with the current fleet. Although there would be a difficult transition period where some new and some old cars are in service, a common fleet would also allow use of the best rail and wheel profiles — a frequent issue with the Type 7 and Type 8 vehicles.(DeNucci, 2007) A bulk order would amortize design and tooling costs over a large number of units, reducing the cost per vehicle, and make it more attractive for a manufacturer to build an in-state facility. Buying a full fleet would also prevent operational issues from a mixed fleet, where some vehicles have different safe operating speeds or dwell times and thus tend to bunch.

Moreover, a full fleet replacement would represent a great leap towards making the Green Line a fully 21st century light rail line, capable of reliably transporting a growing population. Purging the Type 8 cars, which are hamstrung by 19th century construction and poor 20th century procurement, would allow faster and safer service across the entire system. This also represents a once-in-a-generation chance to enact systemic changes, including conversion to true level boarding.

There are substantial operational and financial risks if the procurement is not carefully considered and designed. The difficulties with the Type 8s (unproven technology with an otherwise reliable vendor) and the LRVs (unproven technology with an inexperienced vendor) are cautionary tales. However, these failures should been seen not as reasons to avoid fleet replacement, but as motivation to use new data sources and careful research to procure the best fleet possible. A 2007 state audit of the Type 8 procurement process noted a number of problematic elements, some of which can be mitigated with an off-the-shelf design. There is inherent technical risk in using an unproven vehicle design, particularly on complex legacy systems like the MBTA. The audit concluded that errors that created the need for track modification, wheel profile changes, and higher track maintenance standards cost the MBTA some $101 million — thus increasing the procurement cost by nearly 50%. These design errors were magnified by the testing process, which was compressed by 40% from original plans and took place primarily at night when track characteristics are different.(DeNucci, 2007) Using an off-the-shelf vehicle would reduce risk by using a proven design and allowing vehicles from other systems to be borrowed for preliminary testing. Minimizing risk via standardization would make the cost of a new fleet — and accompanying physical plant modifications — more palatable in the current fiscally constrained environment. It may be possible to have the vendor participate in the infrastructure modifications to provide a single point of accountability.

5.2 Methods

This proposed evaluation framework weighs several off-the-shelf lines of rolling stock (each of which may contain several models of different lengths or other characteristics) against a baseline on different criteria. A model of rolling stock with well-known characteristics should be chosen as the baseline. This model should be low-risk, but not necessarily the optimal choice for the future of the system. This could be recently acquired rolling stock of which the agency could acquire additional units, existing rolling stock for which a rebuild program is being considered, or a model that a similar system has successfully used. Several other rolling stock lines should be chosen on preliminary characteristics like responses to a request for information. These may represent choices like novel propulsion technologies or different vehicle sizes than currently operated that offer higher risk but also higher possible return, or rolling stock used on other systems that has not been previously considered.

The evaluation is divided into three stages. In the first, the baseline model is evaluated against the standardized vehicle lines on physical criteria. This is expected to contain two types of criteria: fixed and desired. Fixed criteria may include a minimum speed, loading gauge or other physical characteristics that would be prohibitively expensive to change, and ability to operate in the full range of weather conditions encountered on the system. All fixed criteria must be fully met for a type of rolling stock to be considered. Desired criteria may be a sliding scale, or binary characteristics that are preferred but not strictly necessary. These may include the proof of reliability from use on other systems, any modifications required to existing stations and maintenance facilities, and whether the manufacturer is willing to build a production facility nearby. The comparison with the baseline model should be presented as a differential rather than a total value; this method attempts to rank and compare possible rolling stock choices, rather than to provide an absolute estimate of total value.

In the second phase, the various vehicle types are evaluated on their ability to meet future capacity needs. This is accomplished using ODX data to estimate flows on various segments of the Green Line (using an algorithm developed by Gabriel Sánchez-Martínez of MIT) and using projected service characteristics to approximate the ridership growth that can be accommodated by vehicles of various sizes. This analysis includes a method of approximating additional flows on the Green Line Extension, which will both increase systemwide flows and alter the location of the largest flows.

In the third phase, the same flows plus previously produced running time data can approximate the number of vehicles that are needed to run service. Unit costs of vehicles are necessarily a very rough approximation; they will vary greatly based on design costs, fleet size, economic variables like materials and labor costs, and strategies of the competitive bidding process. However, the unit costs of recent orders by other systems can provide some indication of what costs can be expected to be, and whether they will differ greatly between models.

5.3 Vehicles to evaluate

5.3.1 Baseline

The baseline model is the Type 9 Green Line vehicle, currently under production by CAF in Elmira, New York. It retains some of the physical characteristics of the Type 8 vehicles, including the seating plan and high-floor sections near the ends, but with significant changes. They include a Crash Energy Management (CEM) design with "crumble zones" to better protect operators during collisions, improved trucks intended to address derailment and braking issues with the Type 8 vehicles, and improved auxiliary power systems. They have a superior bridge plate design, and the plug doors do not preclude future operation with 12" platforms. Interior layout changes including wider articulations increase theoretical capacity by 10%.(Massachusetts Bay Transportation Authority, 2017a)

The first Type 9 will enter revenue service in Spring 2018, with all 24 units planned to be in service by the end of 2018. Thus, the MBTA will likely have operational experience with the Type 9 — and with their post-delivery working relationship with CAF — by the time a full fleet order will be made. While not the ideal model for long-term use — the 74-foot length limits capacity, and the MBTA has committed to 100% low floor for the Type 10s — the Type 9 represents a functional possibility for fleet replacement.

5.3.2 Standard models

A number of manufacturers — Alstom, AnsaldoBreda, Bombardier, CAF, Kinki-Sharyo, Siemens, Stadler, and others — build light rail vehicles which may be considered for Green Line use. Stadler has had success with diesel light rail (hybrid rail) vehicles in the United States and electric light rail elsewhere, but has not made electric light rail vehicles for the North American market. AnsaldoBreda and the MBTA have a contentious history over the Type 8 vehicles, and the company has largely retreated from North America after a similarly troublesome order by SFMTA. While the MBTA has had a more favorable relationship with Kinki-Sharyo — and they will likely bid on a Type 10 order — the company tends to produce custom models rather than a standard line as analyzed here.

Alstom's Citadis line has been in production for 15 years, with over 2,300 vehicles produced.(Alstom, 2017) The line is widely used in Europe, South America, and Australia. The first North American units — a five-section, 100%-low-floor variant called the Citadis Spirit — will begin use on the Confederation Line in Ottawa in 2018. An additional 61 units for use on Metrolinx lines in Ontario are on order for 2019.(Progressive Railroading, 2017) The most likely standard model for MBTA use would be the Citadis X05, an export model currently on order for several systems. The Citadis Line is designed for additional modular articulated units to be added to vehicles later in their life.

Bombardier's Flexity Line has over 1,700 vehicles currently in service, with total orders exceeding 3,500.(Bombardier, 2017) The Flexity Swift model is in use on the Blue and Green Lines in Minneapolis-St. Paul, and a modified Flexity Outlook is in use on TTC streetcar lines in Toronto. The Flexity Outlook and Flexity Freedom lines are most likely to be useful in Boston; the Freedom has a higher top speed but larger minimum radius.

Siemens' S70 line has become the most widely used light rail vehicle in North America, with several hundred vehicles in use or on order for nine systems.[1] The older Siemens U2 and SD lines are in use on three of those systems and six others in North America.[2] Siemens also is producing the high-floor S200 line for Muni Metro, a system very similar to the Green Line.

CAF is a relatively new player in the North American market; the first units in operation were small orders for the KC Streetcar (Kansas City) and the Cincinnati Bell Connector, both of which entered service in 2016. Both were the 3-segment (75-foot) version of the Urbos 3 line. The Purple Line in Maryland, if built, will use the 7-segment (136-foot) version

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[1] In use on METROrail (Houston), San Diego Trolley, Lynx Blue Line (Charlotte), MAX (Portland), The Tide (Norfolk), UTA Trax (Salt Lake City), Metro (Twin Cities), and Atlanta Streetcar; on order for Link Light Rail (Seattle) plus additional units for Charlotte and the Twin Cities.

[2] In use on San Diego Trolley, RTD Light Rail (Sacramento), Edmonton Light Rail Transit, C-Train (Calgary), UTA Trax, TheRide (Denver), Pittsburgh Light Rail, MetroLink (St. Louis), and MAX.

of the Urbos 3.[3] While a vehicle of this length — or even the 9-segment (184-foot) version — would be a more significant departure for the MBTA than the other lines, it raises the possibility of only needing a single operator for most or all revenue operations.

All of the latter four manufacturers offer variations in length; longer multiple-articulated models create the possibility of using fewer but longer vehicles — and thus fewer operators. Other technical innovations available have some attractive benefits, but present higher cost or risk. Most models of the Citadis line can be ordered in off-wire (ground power or battery) versions, and Charlotte has purchased six S70 vehicles allowing off-wire operations on some segments for the Lynx Gold Line. However, the cost of these vehicles is typically higher than conventional catenary-powered vehicles. Off-wire operation could potentially reduce the cost of maintaining the Green Line's catenary, which is frequently damaged by wind-downed trees on the D Line and is also vulnerable to high winds and ice. While off-wire operation might be desired for future light rail expansion in the Boston area — especially as the visual impacts of catenary have previously deterred trackless trolley expansion — the high costs make it unpalatable for or the current Green Line. Siemens also offers an Ultra-Low Floor line, with level boarding just 7 inches above the top of rail. This would allow true level accessible boarding with minimal modifications to current platforms, but the ULF line is primarily intended for low-speed streetcar use and would not be compatible with the higher-speed segments of the Green Line, nor some vertical curves.

5.4 Evaluation on physical criteria

5.4.1 Evaluation criteria

Fixed criteria for the Green Line in this analysis are:

- Minimum speed: The grade-separated surface sections of the Green Line — the D Branch and the future northside branches — are capable of higher speeds than many

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[3] The Purple Line was originally planned to use the 3-segment model; cost-cutting ordered by the Maryland governor in 2015 resulted in the decision to use the longer units with the intention to reduce labor costs. However, the 2015 changes plus falling ridership on the connecting (but jurisdictionally separate) WMATA heavy rail system resulted in a 2016 lawsuit forcing parts of the environmental documentation to be redone. Although the lawsuit was clearly filed under false pretenses, it nonetheless significantly increases the chance that the Purple Line will not be built.(Alpert, 2016) As of this writing, a Federal Appeals Court has issued to ruling for the judge to reach a final decision in the case.

streetcar lines and demand rolling stock capable of minimizing travel time on these branches. Type 7 cars are capable of safe operation at 55 mph.(Kinkisharyo International, 2015) However, Green Line structures are designed to support only 50 mph;(Vanasse Hangen Brustlin, 2009) any new vehicles should be capable of safe revenue operation at this speed in order to maintain existing run times, but there is no likely future benefit to providing faster speeds.

- Unfixable physical constraints: Much of the Central Subway is built under narrow streets near historic buildings on filled land — a trifecta of inopportune conditions for underground construction. As illustrated by the damage to Old South Church in 2008 during ADA renovations to Copley station, construction work in these areas can be hazardous or prohibitively costly. This is particularly true for expansions of stations, which occupy a much larger area than tunnels. New vehicles must be capable of navigating any permanent physical constraints in the old tunnels and stations, although reasonable changes to other constraints must be considered to allow a wider range of vehicles to be considered.

  The existing westbound wall track at Park Street station is sandwiched between the centuries-old Park Street Church, historic headhouses, elevator shafts, stairs to the Red Line level, and the injection point from the subway under narrow Tremont Street. Expanding the current 68-foot-radius curve to the international standard 82 feet (25 meters) is highly infeasible; any vehicle that cannot be built with a minimum radius of 68 feet or smaller simply cannot be used on the Green Line.

  The B Branch has several hills between 7% and 8% slope near Washington Street, with a similar grade on the south approach to the Lechmere Viaduct. It is essential that vehicles be able to climb these grades with full passenger loads in any weather condition.

- Local conditions: Vehicles must be capable of operating in the sometimes extreme weather conditions of Boston, including cold temperatures, aggressive snowfall, and "slippery rail" conditions where tracks are slick from crushed wet leaves or ice. Typical yearly temperatures in Boston range from about 0° F to 95° F; however, during the lifetime of the vehicles, climate change is likely to cause an increase in severe weather events. A more conservative operable temperature range would be the historic extremes of −18° F to 104° F.(Rosen, 2015) Vehicles must also be capable of safe operation in snowfalls of several inches per hour, likely including small truck-mounted plows.

- Accessibility: Vehicles must meet all ADA accessibility standards as well as certain stricter standards that the MBTA has agreed to in negotiations with advocacy groups. Accessibility must be maintained at all currently accessible stations during the transition to a new fleet, with minimal disruption to operations or additional personnel required. Boston has standardized on low-floor vehicles, as full-length high platforms would not fit street-level stations on the B, C, and E branches, and mini-high platforms were judged to be insufficient for the high ridership of the Green Line. The MBTA has committed for new cars to be 100% low floor, with at least 3 low-floor doors on each side.

Desired criteria for the Green Line in this analysis are:

- Fixable physical constraints: Some physical constraints like minimum radius, loading gauge / kinematic envelope, and train length on the surface may be fixable as an appropriate cost to enable a superior fleet and improved related performance. However, the cost and difficulty of these modifications should be considered to avoid disruption and minimize the total outlay as described above. The projected cost of such modifications must be weighed against the benefits of the vehicle type — and any procurement cost savings.

  A 49-foot minimum radius would be extremely inexpensive and easy to achieve by 2025. Any vehicle that could achieve this would involve minimal infrastructure costs, and a borrowed test unit could run everywhere except Lechmere and Lake Street loops on the current system. A 60-foot minimum radius would require one major station modification at Park Street, elimination or modification of Brattle Loop and Kenmore Loop, and changes to non-revenue trackage. A 66-foot minimum radius would additionally require major modifications to Government Center.

The current dynamic envelope[4] extends a maximum of 56.75" from the rail centerline at 61 inches above top of rail, with more limited dimensions at other heights. Actual clearances must be maintained at least three and usually six inches beyond this. Since 102 inches is a standard width for most light rail vehicle lines, this should not cause significant issues for overall dimensions, with the possible exception of the narrowing near the top of the vehicle. However, the many tight curves on the system cause the ends of vehicles to push the limits of the dynamic envelope; all Green Line vehicles since the USLRV have had tapered ends to reduce overhang.(Vigrass, 1975) This tapering prevents doors at the extreme ends of the cars from properly interfacing with raised platforms.(United States Urban Mass Transportation Administration, 1979) Smoothing the tightest curves will reduce the number of locations where overhang is a major issues. It may also be possible to scrape walls and move columns in some locations to increase clearances. The MBTA could have vehicle manufacturers include the costs of such clearance work in their bids, but should have an independent cost estimate before selecting a manufacturer. These modifications could be bundled in with later GLX construction to speed construction.

- Boarding speed: Dwell time is a significant cause of delays on the Green Line. All-door boarding (planned to be implemented with AFC 2.0 in 2019) will reduce this at surface stations, but vehicles that can reduce dwell time at busy stations and minimize disruptions from events like wheelchair boardings are preferred.

  Current Green Line cars have three doors per side; the first door on Type 8 cars and all doors on Type 7 vehicles require using stairs, which slows boarding.(Tirachini, 2013) The first door on all vehicles is adjacent to the driver and only convenient for a limited number of passengers. Type 9 vehicles will have a similar layout to Type 8 vehicles.

  With planned all-door boarding, it may not be necessary to have a door adjacent to the driver for farebox supervision. A more even distribution of doors along the length of the vehicle would allow faster loading and unloading, especially at stops like Park Street where a significant fraction of passengers board or alight. No fewer than the

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[4] The dynamic envelope is for a loaded car with 1.625 inches of truck yaw and 3.23° of roll on tangent track with no superelevation; consideration must be given to actual roll on superelevated curves.

current three doors per side should be used; an additional door would be desirable or even necessary on longer vehicles.

Currently, the floor of even low-floor cars is 12 inches above the top of the rail; this is 4 inches above accessible platforms and about 12 inches above non-accessible platforms. Passengers on wheeled mobility devices must have the driver extend a ramp using a manual switch, a process that takes several minutes and can cause delays and bunching. It would be preferred to have vehicles that could board such passengers directly from platforms without need of a ramp, which would speed boarding and also eliminate a potential mechanical failure point.

- Proven technology: The MBTA has had poor experiences with unproven equipment designs, including the USLRVS and the more recent Type 8s. The 2007 state audit of the Type 8 procurement process strongly suggested that the MBTA buy technologies with a proven track record in order to minimize such issues in the future. As maintenance standards and weather conditions in the United States are often different from European countries, designs that have served well in this country are preferred.

- Ability to use existing infrastructure: In order to minimize total costs and ease transition, as much infrastructure — existing station platforms, maintenance facilities, and yard space — should be able to be used by new vehicles without extensive modification. Currently, most platforms in the Central Subway are between 250 and 350 feet long, and most on the surface between 200 and 250 feet. Retrofitting most platforms to 220 feet of accessible space with 250 feet between pedestrian or street crossings that cannot be blocked by a stopped train is relatively easy to achieve. Basic trains should thus ideally have no more than 220 feet between the outer edges of the first and last doors, with no more than 250 feet over the couplers at each end. However, the ability to add an additional vehicle for up to 290 feet of accessible platform is highly desirable.

Most off-the-shelf lines are built for true level boarding (12-14 inches) without bridge plates. The MBTA is understandably concerned about the cost of retrofitting stations to provide this — especially at stations with elevators currently built to the 8-inch height. However, given the myriad benefits of true level boarding, this should be considered a fixable physical constraint, and almost all off-the-shelf models are designed for true level boarding. At many stations, it would likely be possible to have a gently sloping ramp (ADA allows a 1:12 slope) connect the elevator to the full-height platform, rather than having to modify the elevator. Additionally, many of the surface stations modified around 2002 have substantial concrete deterioration and will need to be rebuilt in the near future regardless of rolling stock. The MBTA would not be the first system to undergo such a conversion: San Diego successfully converted their lines around 2010 by raising platforms and undercutting tracks.(Terry, 2010)

Current yard and maintenance facilities are set up to maintain a 220-vehicle fleet of 74-foot length. The storage tracks and carhouses at Reservoir and Riverside are significantly longer than a single car; although lifts and other equipment will have to be modified for longer cars, it is likely that space can still be used efficiently. However, several tracks at Lake Street and the proposed Inner Belt yard — and both carhouses — are designed around 74-foot vehicles.(Massachusetts Department of Transportation, 2010) It may only be possible to fit a single longer vehicle in some locations that fit a current deuce. This may be mitigated by changes at Lake Street, and at Inner Belt with an expanded carhouse as a bidding option; additionally, capacity expansion will likely dictate expansion of existing yards and/or additional storage facilities.

There are additional infrastructure elements that are out of scope of this analysis but may be impacted by vehicle choice. These include the need to upgrade the power system, and to reinforce or replace certain bridges (Lechmere Viaduct, crossings of the Blue and Red lines, Kenmore Loop, numerous bridges and culverts on the D Branch).

- Local production: Policy makers desire to increase the political palatability of expensive equipment orders by mandating that some production be done in Massachusetts, often in areas of the state that support the MBTA by sales tax but do not receive MBTA service. Some manufacturers are willing to engage in this practice; others insist on using existing plants and their already-highly-trained workforce.

5.5 Evaluation

5.5.1 Baseline model (Type 9)

Fixed criteria:

- Maximum speed: Type 9 vehicles are designed for a maximum safe speed of at least 50 mph, meeting the requirements. The improved center truck design is intended to allow Type 9 cars to safely operate at their design speed. While this will not bring about any speed increases while Type 8 cars are still in revenue service, an all-Type-9 fleet would be able to run schedules several minutes faster on some lines (particularly the D Branch) than today.

- Unfixable physical constraints: Type 9 vehicles are designed to fit all current physical constraints on the Green Line.

- Local conditions: Type 9 vehicles are designed to operate in Boston weather conditions.

- Accessibility: Type 9 vehicles are 70% low-floor and have two low-floor doors on each side. They meet all ADA requirements; however, they do not meet the MBTA's commitment to 100% low-floor purchases in the future.

Desired criteria:

- Fixable physical constraints: Type 9 vehicles are designed to fit all current physical constraints with no infrastructure modifications.

- Boarding speed: Since Type 9 vehicles have similar layouts to Type 8 vehicles, they share the same limitations on boarding speeds. They will have some improvement over Type 7 cars because of having some doors which do not require climbing steps. The sliding doors on the Type 9 vehicles is designed not to preclude future level boarding.

- Proven technology: Type 9 cars are a custom design not in use elsewhere. CAF USA has some experience building light rail vehicles for the US market — Pittsburgh Light Rail and Sacramento RTD cars in 2003, and several models from its Urbos line for streetcars in Cincinnati and Kansas City and Houston METRORail. The trucks, which are intended to prevent the derailment issues of the Type 8s, are custom-made but have been extensively modeled. Type 9 vehicles will begin testing in 2017 and service in 2018; by the time a fleet replacement order would be made, the MBTA will likely have some operating experience with the Type 9 vehicles to sufficiently evaluate them by.

- Ability to use existing infrastructure: Identical in size to the existing fleet, Type 9 cars can use the same maintenance facilities and yard space. However, expansion of the fleet size to allow three-car trains at peak hours would likely require additional yard and maintenance facility space.

  Up to a three-car train of Type 9 vehicles can use most existing platforms without modification. Four-car trains would be able to use 290-foot platforms.

- Local production: The 24 cars of this order are being produced in CAF's existing Elmira, New York facility. CAF may be amenable to building a local production facility for a larger order. CAF used the Elmira plant to build 28 new cars and rebuild 55 others for Pittsburgh, but opened a new facility for the 55-vehicle Sacramento order.(Larson, 2002)

5.5.2 Evaluation of possible models

Alstom Citadis line

The Citadis X05 export line has three models: the 3-segment 205, the 5-segment 305, and the 7-segment 405. At over 140 feet in length, the 405 is too long for serious consideration in Boston, as it would require substantial modifications to infrastructure. The following considers both the 78-foot 205 and 110-foot 305 models.

Fixed criteria:

- Maximum speed: The 205 has a maximum speed of 43 mph, which would not be desirable for the Green Line. The 305 has a suitable maximum speed of 50 mph. Some Citadis models like the Spirit have higher maximum speeds.

- Unfixable physical constraints: Both models can operate around curves of 66' in non-revenue operation; it is possible that revenue operation could be approved at this radius as well. The 305 is available in both 95" and 104" widths, indicating that Alstom is able to modify the body shell.

- Local conditions: The Citadis Spirit is capable of operations in temperatures as low as $-36°$ F.(Progressive Railroading, 2017)

- Accessibility: Both models are 100% low-floor.

Desired criteria:

- Fixable physical constraints: The 66' non-revenue radius of the Citadis is the most aggressive modification for the current Green Line. However, that makes it more likely to meet dynamic envelope requirements for the system after modification. Most versions of the Citadis have a door near the cab, which may not be able to platform because of tapering.

- Boarding speed: Both models allow for true level boarding. The 205 model has 4 doors per side; the 305 is available with four or six doors.

- Proven technology: The Citadis line is widely used in Europe. No Citadis vehicles are currently used in the United States, though they will begin operation in Ottawa in 2018.

- Ability to use existing infrastructure: Similar in size to the existing fleet, the 205 model could likely use the same maintenance facilities and yard space. However, expansion of the fleet size to allow three-car trains at peak hours would likely require additional yard and maintenance facility space. The 305 model would require modification of facilities.

  The 205 model is currently only available in 95" width, which would cause platforms to have to be extended towards the tracks. The 205 model could fit 3 vehicles on 220-foot platforms, or 4 on 290-foot platforms. The 305 could fit 2 and 3, respectively. However, Alstom only claims the vehicles to be capable of 2-car MU operation; it may be necessary to extend the vehicles rather than add additional cars to trains.

- Local production: Alstom has shown some willingness to have partial local production to comply with Buy America provisions. The vehicles for Ottawa are being built in the Hornell, New York plant, with final assembly in Ottawa.

Bombardier Flexity line

The most likely models from Bombardier's Flexity line are the 101-foot Freedom and Toronto's modified 99-foot Outlook. Toronto's vehicles are built for Toronto's nonstandard gauge and are unidirectional, but provide a useful example of the Outlook model being modified for a legacy system.

Fixed criteria:

- Maximum speed: The TTC Outlook has a maximum speed of 43 mph, which would not be desirable for the Green Line. The Freedom has a suitable maximum speed of 50 mph.
- Unfixable physical constraints: The Freedom is currently only available with the standard 82-foot minimum radius. The TTC Outlook is built for curves down to 36-foot radius, which would allow it to run in Boston with no curve modifications. It may be possible to substitute turning for speed to obtain a model with 50 mph speed and slightly higher radius.
- Local conditions: Flexity models are operated in Toronto and Minneapolis-St. Paul, both of which have similar winters to Boston.
- Accessibility: Both models are 100% low-floor.

Desired criteria:

- Fixable physical constraints: Both Flexity models have cab-adjacent doors, which may be an issue with tapered ends.
- Boarding speed: Both models allow for true level boarding. The Freedom has four to six doors per side; the TTC Outlook has four doors.
- Proven technology: The Flexity Swift has been operated in the Twin Cities since 2003. The first TTC Outlook vehicles started service in 2014; deliveries have been extremely slow, leading to other Canadian agencies threatening to cancel their Freedom orders.
- Ability to use existing infrastructure: Both models would require yard and maintenance facility space to be modified for their longer size. Both models would fit 2 on a

220-foot platform and 3 on a 290-foot platform. The Freedom can MU in trains up to four vehicles; the Outlook is generally not designed for MU operation.

- Local production: Bombardier is a Canadian-based corporation and generally constructs vehicles in their Thunder Bay, Ontario plant. However, they do comply with Buy America regulations; lacking a dedicated American plant, they would likely be willing to complete final assembly in Massachusetts.

Siemens S70 line

Siemens builds two model ranges for the US market: "streetcar" and "ultra short" models 79-81 feet long, and "standard" models 91-96 feet long. This analysis is largely based on the 81-foot "ultra short" Salt Lake City and 96-foot Houston versions. A 120-foot version is in tram-train service in France, but has not been built for the North American market.
Fixed criteria:

- Maximum speed: The Salt Lake City model has a maximum speed of 55 mph; the Houston model can reach 65 mph.
- Unfixable physical constraints: Both models are limited to the standard 82-foot radius. The "streetcar" variant has an option for a 59-foot radius, but at the expense of speed.
- Local conditions: S70 models are operated in the United States in a wide variety of climates, from the Twin Cities to Texas.
- Accessibility: Both models are 100% low-floor.

Desired criteria:

- Fixable physical constraints: Since the "standard" model is a 3-segment vehicle (most its size are 5 segments), it is likely to have a wider swing on curves, which may involve a need for more aggressive tapering, tunnel modifications, or even more aggressive changes to the vehicle design. The S70 does not have cab-adjacent doors.
- Boarding speed: Both models allow for true level boarding with four doors per side.
- Proven technology: The S70 is in use or on order for nine US cities, some with over a decade of operation.

- Ability to use existing infrastructure: The "standard" models would require yard and maintenance facility space to be modified for their longer size; the shorter models may not. The shorter model could fit 3 vehicles on 220-foot platforms, or 4 on 290-foot platforms. The "standard" could fit 2 and 3, respectively. All are capable of MU operation up to 4-car trains.

- Local production: Siemens generally does heavy construction at their existing plants but will complete final assembly locally.

CAF Urbos 3 line

CAF will build a 5-segment version of its Urbos 3 line for Maryland's Purple Line. At 136 feet, it is almost as long as a current double. While cars of this length have not been previously considered for the MBTA, they present the possibility of reduced operator costs.

Fixed criteria:

- Maximum speed: Most Urbos 3 models have a maximum speed of 43 mph; however, variants have been produced with a maximum speed of 56 mph.

- Unfixable physical constraints: The Purple Line is a new-build system with the standard 82-foot minimum radius; however, the Urbos 3 is available with a 59-foot radius.

- Local conditions: The Urbos line is used in three cities in the United States; however, none have winters as severe as Boston.

- Accessibility: The 100 series of the Urbos 3 line is 100% low-floor (although the Purple Line is using an 80%-low-floor version).

Desired criteria:

- Fixable physical constraints: The Purple Line cars have lengthy end segments — around 40 feet long — which would have wide swing on curves. However, most Urbos vehicles of this size have 7 segments, with shorter end segments. The Purple Line vehicles do not have cab-adjacent doors.

- Boarding speed: The Purple Line cars allows for true level boarding with six doors per side.

- Proven technology: The Urbos 3 is recently in use in small quantities in two cities, plus the similar model in Houston.
- Ability to use existing infrastructure: The vehicles models would require substantial changes to yard and maintenance facility space. Only one car could fit on 220-foot platforms, or two on 290-foot platforms. The Purple Line cars are not designed for MU operation, though Houston's cars are.
- Local production: As noted with the Type 9 evaluation, CAF would likely be amenable to opening a local plant for a large order.

5.5.3 Results

As expected, no off-the-shelf model fully meets the complex criteria of the Green Line. Most models designed for true light rail use, rather than purely as streetcars, have either standard 82-foot radii or questionably make the 66-foot cutoff. All have possible issues with swing on tight curves, and with tapered ends not meeting platforms. None are claimed to handle grades above 7%, and only the S70 has substantial usage in the US. The Citadis models may not be able to operate in trains longer than two cars. Because of this, the MBTA should negotiate with manufacturers and closely analyze their offerings before choosing a model.

However, this analysis does indicate that multiple manufacturers have existing lines with desirable characteristics like level boarding, more doors, and increased capacity that could allow the Green Line to handle future ridership increases. Physical constraints like radius, speed, gradient, and MU operability are common issues for manufacturers to confront; very few legacy systems use completely off-the-shelf vehicles. There are frequent design tradeoffs, notably speed versus minimum radius; by relaxing some constraints where possible, it will likely be possible to customize an existing standard line for the Green Line rather than buying a truly custom vehicle.

The S70 Standard, the Citadis 305, and the Flexity Freedom models are the most likely candidates to be modified for the Green Line. All three are part of well-proven lines, and all three are specifically designed for the North American market rather than on European systems. When planning the Type 10 order and accompanying physical plant upgrades, the

MBTA should operate under the assumption that one of these manufacturers will be chosen.

5.6 Capacity

No matter how ideal a vehicle's physical and logistical characteristics may be, it is only ideal for the Green Line if it can actually handle the immense capacity demands of the system. The Green Line is already the busiest light rail system in the country, with some 227,000 weekday boardings. The Green Line Extension will open in 2021; it is projected to add 36,000 weekday boardings by 2030, which will result in the Green Line challenging the heavy rail Red Line as the MBTA's busiest rail line.(MBTA staff, 2014) Even by 2025, the Green Line will likely exceed the daily ridership of most individual heavy rail trunk lines in the country outside of New York City.

Most previous Green Line fleets have lasted 30 to 40 years before replacement; the current fleet will range from 17 years to 38 years in 2025 (with almost half at the upper bound), although the Type 9s will be just 7 years old.[5] Any Type 10 vehicle purchase should provide, at minimum, enough capacity to handle 25 years of the realistic upper bound growth. Any additional train capacity above minimum levels provides enhanced passenger comfort in the short term and futureproofs against higher-than-expected ridership growth and additional extensions in the long term. This is especially important with the pending Green Line Extension, which will not open (and thus have definite ridership numbers) until after the MBTA will have committed to a Type 10 purchase.

A 2015 MBTA study using MAPC population estimates and CTPS demand estimates gave bounds of 14% to 28% ridership growth on rapid transit and bus by 2040. Extrapolated linearly to 2050, this equals 20% to 40% growth.(Massachusetts Bay Transportation Authority, 2015) This analysis will use the higher value of 40% for a conservative estimate of capacity needs, in light of the state Global Warming Solutions Act which set a goal of tripling non-motorized mode share.(Massachusetts Executive Office of Energy and Environmental Affairs, 2014) Additionally, baseline GLX ridership will be assumed to be 20% higher

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[5] The PCC streetcars on the Mattapan are "Wartime" cars, built in 1945-46 and rebuilt twice since; they will be 80 years old in 2025. If the 20 1997-built Type 7 cars are assigned to the Mattapan Line or elsewhere on the MBTA system, it is likely they will see their 40th birthday and more.

than projections. This represents just a 4% increase in total boardings, but protects against the possibility of faster-than-expected growth due to additional development in the GLX corridor planned since the GLX environmental documents were prepared.

5.6.1 Capacity determination

Passenger capacity through congested segments is essentially the product of train length and frequency, with minor influences from interior layout and other factors. Frequency is governed by dwell times, power availability, signal systems, and merging and headway regularity — the latter three of which are largely dependent on factors exterior to this analysis. For reasons discussed below, this analysis assumes overall frequency to be fixed at the current 40 TPH, with capacity a function of train length.

Most manufacturers advertise capacity at 4 or 6 passengers / m^2; for 2.65 m (104 inch) wide vehicles like those the Green line currently uses, this translates to 3.2 to 4.8 passengers per linear foot of passenger cabin, or 200 to 300 passengers for a typical current Green Line vehicle. However, even the lower numbers represent crush loads that should be avoided, and average loads for planning purposes are substantially lower. The MBTA's 2010 Service Delivery Policy allowed up to 2.25 total passengers per seat (104 passengers per vehicle).(Massachusetts Bay Transportation Authority, 2010) The 2017 Service Delivery Policy punted on establishing a new standard because APC data was not available.(Massachusetts Bay Transportation Authority, 2017c) However, a previous presentation to the board floated $3.75ft^2$ of aisle space per standee (2.9 standees / m^2), which would result in the same policy capacity.(Office of Performance Management and Innovation, 2016) Because interior space allocation, including the total number of seats, will vary between vehicle models, neither of these methods are sufficient for comparing distinct lines. Instead, a simple value of 1.7 passengers per linear foot of cabin (2.1 passengers / m^2) will be used; this matches the previous MBTA standards for comfort.

The MBTA desires lower crowding at off-peak times. The 2010 Service Delivery Policy allowed 1.4 total passengers per seat (64 passengers per vehicle) in the Central Subway and 1.0 per seat (46 per vehicle) on the surface. The 2016 proposal called for 10 ft^2 of aisle space per standing passenger at all locations, equal to the higher value. Combined with lower off-peak frequency, this can actually indicate a need for larger vehicles at certain off-peak times than are required at peak. This is an allocation and policy issue — off-peak frequencies are determined by spending priorities and not infrastructure — and this analysis uses the higher peak ridership to determine capacity needs.

5.6.2 Throughput challenges

This challenge is compounded by the planned implementation of a train protection system intended to prevent accidents like the 2008 collision that killed an operator on the D Branch. The MBTA currently schedules up to 44 TPH per direction through the Central Subway, with 38 to 42 TPH actually run on a typical day.[6] A 2012 study indicated that PTC would decrease this to just 34 to 36 TPH; 3-car operation and speed increases were required just to maintain current throughput.(HNTB, 2012) The MBTA is currently planning a less aggressive train protection system for the Central Subway and D Branch that may have less severe impacts on throughput. That system, for which bids were received in February 2017, will enforce red signals and thus attempt to prevent collisions, but will not directly enforce speed limits as a full PTC system does.(Belcher, 2017b)

However, the long-term solution may be to remove the variable element of human drivers entirely. San Francisco's Muni Metro — the Green Line's nearest US peer — uses a Thalys ATCS system in their subway tunnels and conventional manual operation on the surface. Their system achieves 38 TPH at peak. Although Muni has advantages of high platforms and stations long enough for multiple trains, their limiting headway is based on their ability to turn trains at Embarcadero station — the system itself can safely handle 60 TPH.[7] ATO systems also have other potential benefits, including more consistent running times and a smoother ride for passengers, but they are largely out of scope of this analysis.

Assuming the MBTA makes responsible choices with train protection (and possibly even-

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[6] From September 10, 1988 to April 9, 1994, the D Branch had regularly scheduled Reservoir short turns (AM peak only after December 28, 1991) resulting in a combined 20 TPH on the inner half of the line. By 1992, the Green Line topped out at 49 TPH during the AM peak.(Soeldner, 1993, Belcher, 2017a) The only light rail system that exceeds the Green Line in frequency is SEPTA's Subway-Surface Lines, which briefly reaches almost 60 TPH during the peak. That system uses single-car trains, of which two or even three can fit on many platforms, which would not be possible with the MBTA's trains.

[7] Muni runs LRVs of similar size to the Green Line, but with the same high floor of the Boeing LRVs and the Type 7s. The tapered front door cannot be used at many subway stations. Level boarding, more doors, and avoid severe crowding can potentially reduce dwell time, which is currently the governing factor for MBTA headways.

tually automatic operation) systems, throughput should be able to be maintained at or near the current level. This analysis assumes a steady-state capacity of 40 TPH during the peaks, which would allow an average of 6-minute headways on the four current branches.

5.6.3 Methods

This analysis is based on the MBTA's 2010 Service Delivery Policy, which set limits on crowding experienced at the maximum load point, averaged over half-hour periods. The 2017 policy switched to a more passenger-centric measure of crowding for buses by instead limiting what proportion of passenger hours can exceed that load. The newer methodology is a superior way of evaluating overall service quality; however, it allows average loads to regularly exceed comfortable levels at the maximum load point if the rest of the route is less crowded. The older, more conservative measure provides a safer margin for capacity planning; this is especially true on rail, where it is not possible to simply add vehicles to an overcrowded route.

The key part of this method is the creation of a flow matrix detailing the average maximum flow through each segment during each half-hour interval. For current ridership on the current system, this was previously done as a SQL query by Gabriel Sánchez-Martínez of MIT using existing ODX data. Changes for this method was limited to averaging the existing 15-minute intervals into 30-minute intervals, and other trivial post-processing.

However, flow data had to be estimated for GLX — including the additional flows it induces as an overlay on the existing system. This was done in two parts. New flows on the existing system were created by scaling the origin/destination patterns of current ridership to and from Lechmere to match projected GLX ridership. Ridership currently originating at Lechmere was scaled to the projected ridership from the rebuilt Lechmere station, and ridership currently originating on buses to Lechmere was scaled to projected ridership from the new stations. Outbound ridership was scaled in the same manners. Flows within GLX were created by taking the temporal distribution of current Lechmere-terminating bus ridership and scaling that to projected corridor ridership. The assumption that these scaling processes were a valid approximation was tested by comparing destination groupings for riders originating at Lechmere, at Sullivan station, and on the north end of the Orange

Line. A more detailed report on the methodology for creating the new flows is presented in Appendix I.

These two flow tables were summed to create an approximate flow table for the whole Green Line after the GLX opens. (Similar methods could be used to add any future extensions, or account for major developments or connecting services along existing routes). This table was condensed by choosing the maximum flows on each segment for four periods: AM peak, midday, PM peak, and evening. For each period, a percentage of throughput and a vehicles-per-train value was assigned to each service, and each segment assigned to one or more routes. This allows train length, allocation, and even terminals to be changed between periods. This gives a service quantity — vehicles per hour divided by arbitrary throughput — for each segment during each period.

$$Service\ quantity \left[\frac{vehicles\ per\ hour}{total\ TPH}\right] = \sum_{services} allocation \left[\frac{TPH\ on\ service}{total\ TPH}\right] \cdot \frac{vehicles}{train}$$

Combining the maximum flow with service quantity, scaling factor, and total throughput provides the number of passengers that each vehicle must comfortably carry:

$$\frac{passengers}{vehicle} = \frac{Maximum\ flow[\frac{passengers}{hour}] \cdot (1 + scaling\ factor[\%])}{Service\ quantity[\frac{vehicles\ per\ hour}{total\ TPH}] \cdot total\ TPH}$$

This is presented with a matrix of scaling factors and total throughput to demonstrate how those factors affect the results. From this, a similar matrix of vehicle lengths can be created:

$$Length = cab\ length + \frac{\left(\frac{passengers}{vehicle}\right)}{\left(\frac{1.7\ passengers}{foot}\right)}$$

Separately, the same spreadsheet was used to estimate fleet size. Throughput multiplied by allocation determines the frequency for each service; multiplying this by cycle time (including estimates for the GLX) gives the minimum fleet size. A spares ratio of 15% was then added.

There are four important caveats to this method. First, the corridor trips which are scaled include only those with properly inferred destination. If these trips are not a representative sample of all trips in the corridor, or if ridership patterns change more substantially after the GLX opens, these results may be less accurate than desired.

Second, the method is only as good as the data. The existing flow assignment algorithm uses a fixed factor of around 35% to estimate farebox noninteraction at surface stops. However, this is known to not be completely accurate — noninteraction varies by branch, time of day, and location on the branch. The inner D and E branches frequently have higher noninteraction rates, meaning that this method may underestimate their capacity needs. An MBTA study determined that noninteraction was largely caused by uneven crowding rather than attempted fare evasion — and thus the introduction of AFC 2.0 with all-door boarding is likely to improve the accuracy of this method.(Prokosh, 2016)

Third, uneven crowding caused by bunching also effectively reduces the capacity of the Green Line. This is particularly true when using passenger-centric measures, as a higher proportion of passengers than trains experience high crowding. This method predicts, for example, that current two-car trains can handle all passengers with capacity to spare — yet many passengers experience overcrowding on a daily basis. This method essentially represents the capacity possible with perfect service on even headways, and thus will tend to predict fewer and smaller vehicles than are actually needed. Ongoing headway management projects may help real service to reach closer to this theoretical point.

Finally, in a number of these test cases — particularly those with scaling factors over 200% — the actual maximum increase that a vehicle type can handle may be higher than computed here. This is due to the scaling process used to estimate GLX flows. The flow algorithm incorrectly assigns some very small flows — on the order of 3-10 passengers per hour — to the western Green Line branches at most or all hours. Normally these spurious flows would be lost in the noise; however, due to the high scaling factor used to translate small bus ridership into large rail ridership and the additional scaling factor of ridership growth, they can become significant enough to affect the results. Ideally, it would be possible to identify and fix the source of these spurious flows to separate them from smaller but real flows. However, since they only affect results in ridership growth regimes far beyond those currently projected, this was not a priority under the time constraints of this research. This issue also occurs around the same scaling factor as when 220-foot trains are not sufficient for the inner E Branch, so it is not clear whether Brigham Circle short turns with longer consists would substantially increase capacity.

5.6.4 Results

All of the analyzed vehicle types are fully capable of handling the highest projected ridership from 2050 and beyond. The short (72-81 foot) and medium (96-110 foot) length vehicles can do so with the shorter 220-foot platforms; the long (136 foot) vehicles would need longer platforms on one branch to handle the upper end of the projected growth range. If the MBTA commits to maintaining a sufficiently large fleet, and to making the assorted infrastructure upgrades to allow their full use, the Green Line can provide comfortable service even in the most optimistic growth scenarios.

For the mid-length vehicles, there is a likely decision between extending a second western branch north to the end of the Medford Branch and using triples on the D Branch. The vehicle count results generally favor extending the C Branch — where a substantial portion of the extended route serves the maximum loads — versus adding a third car over the entire D Branch route. Since these vehicles provide around 50% per-vehicle capacity increase over existing stock already, using triples is only necessary in the event of ridership increases exceeding those currently projected. Similarly, quadruples of shorter vehicles are not necessary for projected 2040 volumes. Thus, platform extensions beyond the current standard length are not likely to be soon needed, although they absolutely must not be precluded on the B, D, and inner E branches. However, the MBTA must be prepared to extend the C Branch to College Avenue should actual ridership demand it. This is accommodated in the fleet sizes in this analysis, but would still require aggressive headway management and terminal dispatching to handle the resulting 3-minute headways on the branch.

With some mid-length vehicles, the minimum-vehicle-count scenario actually handles 40% growth slightly below 40 TPH. However, maintaining 40 TPH is highly desirable to maintain high-frequency service on the branches — especially if additional branches or short turn services ultimately reduce frequency at some stops. A plot of vehicle length versus minimum and recommended fleet sizes is shown in Figure 5-1. The relationship is inverse, as expected; the product of length and fleet size is approximately the same regardless of vehicle length.

Figure 5-1: Vehicle length versus the minimum fleet size (with 15% spares ratio) that can handle the maximum projected 2050 ridership, and recommended fleet size to optimally use 40 TPH throughput

Cost It is desired to minimize the expected cost of the fleet order. The MBTA operates in an extremely fiscally constrained environment; even if the funds are available for a full fleet replacement, it is important that costs be controlled. However, cost should not come at the expense of capacity or vehicle quality; in the long term, a good procurement will cost less than a poor procurement.

The 24 Type 9 vehicles cost $118 million, for an average cost of $4.92 million each; with a recommended fleet of 260 vehicles (234 new), a full procurement would cost $1.15 billion. (However, without new design costs, the cost per vehicle might be lower for a larger order).

Cost data is available for all North American S70 orders except those in San Diego. Cost varies from as low as $3.3 million for Charlotte's order delivered in 2006, to $4.5 million for Seattle's on-order vehicles. Adjusted for inflation, this range increases to $4-5 million.

Bombardier and Alstom's contracts in Canada and elsewhere often include maintenance schemes or other bundling, which makes it difficult to determine the actual cost of the vehicles alone. For example, Ottawa's Citadis order averages $11.6 million per vehicle — but includes 30 years of vehicles and track maintenance. The Metrolinx order averages $6.4 million per vehicle. The CAF vehicles for the Purple Line are substantially more expensive than shorter models, at some $8.25 million apiece. A comparison of inflation-adjusted vehicle costs is shown in Figure 5-2.

Based on the available data, the most likely scenario is that Siemens, Alstom, CAF, and Bombardier would all put in competitive bids in the $4-5 million range for a Type 10 order. This leads to a total vehicle cost on the order of $1.1 billion for the Citadis 205 or S70 Streetcar, or $0.9 billion for the Citadis 305, S70 Standard, or either Flexity model. At Maryland's cost, the longer Urbos 3 model would cost about $1.0 billion in total.

Although the capital costs of vehicles and infrastructure modifications is the primary fiscal concern, the effects on operating costs should not be discounted. Using short vehicles (with three-car sets) requires about 60 more vehicles to run peak service than using medium-length vehicles. The cost of additional operator hours to run the third vehicles would be on the order of magnitude of $5 million per year — well over $50 million over the lifetime of the vehicles (adjusted for inflation). Using the long vehicles would provide a similar though somewhat smaller savings over the medium-length vehicles. However, short and medium-length vehicles can be run in shorter consists during off-peak hours, requiring less energy and allowing vehicles to receive daytime maintenance, which may offset that savings.

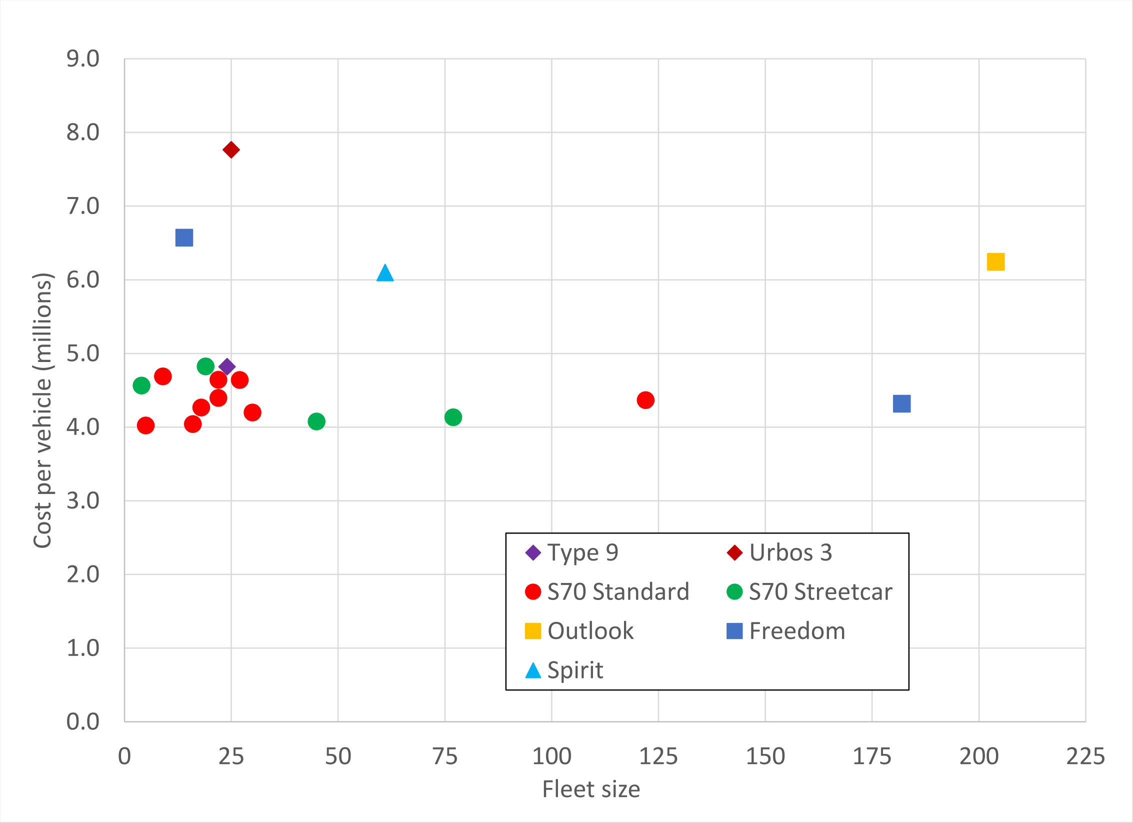

Figure 5-2: Costs per vehicle from recent North American vehicle purchases from which cost data is available, in 2017 dollars, assuming 2% annual inflation

5.7 Conclusions

No current light rail vehicle line could be used in Green Line service in off-the-shelf condition. Any such vehicle would require modification of minimum radius, overhang on curves, maximum grade, and/or MU operation in order to work on the Green Line. However, Alstom, Bombardier, CAF, and Siemens all produce light rail vehicle lines that are viable for modification to serve the Green Line, while retaining much of their proven technology to reduce risk and cost.

Vehicles of any size from current 3-segment, 72-foot cars to 7-segment cars exceeding 130 feet could viably handle expected capacity needs for the foreseeable future. However, the "sweet spot" is clearly 95 to 110 feet long. Such vehicles could handle substantial ridership increases with two-car trains, while requiring relatively few platforms to be lengthened. Because they cost little more than shorter vehicles, they likely present the most cost-effective fleet, with both capital and operational savings in the hundreds of millions of dollars versus maintaining current vehicle lengths. A comparison of technical, capacity, and cost information is shown in Table 5.1.

A Type 10 procurement will likely provide all service on the Green Line until midcentury, and the decisions made during this procurement process will resonate on an even longer timescale. The next vehicle procurement may not be a full fleet replacement — the last full fleet replacement was 80 years before this one — so the physical constraints of the Type 10 order may last through several additional generations of vehicles. Those elements must be considered in their long-term context, and fiscal concerns must not be allowed to cause the MBTA to buy inferior vehicles, or to fail to purchase enough to adequately handle future capacity needs. This is especially true in regards to platform height, where the upfront cost of station modification is unpalatable. However, this cost must be considered an investment in long-term benefits — improved and universal accessibility for an aging population, faster boarding for all users, more consistent dwell times, and no need for problem-rife movable ramp systems — that are necessary for a truly 21st-century light rail system.

In addition, no part of the Type 10 design should preclude any of the following expansions which may be constructed by midcentury:

- Extension of Medford Branch to Route 16
- Spur of the D Branch to Needham
- Conversion of the Silver Line Waterfront to light rail
- Conversion of the Silver Line on Washington Street to light rail
- Second east-west trunk line (Stuart Street Subway)
- D-E Connector

The Type 10 procurement will require particularly close collaboration between a number of entities at the MBTA. Vehicle Engineering cannot commit to a fully modern vehicle design without a commitment to physical constraint modification, platform raisings, power supply improvements, maintenance facility improvements, and to signal and safety systems that protect throughput — but those commitments cannot be made without a commitment to a modern vehicle design to make use of them. The combined package of vehicle procurement and infrastructure upgrades must be planned and executed as a single modernization project.

Manufacturer	CAF USA	Alstom		Bombardier		Siemens		CAF USA
Line	Type 9	Citadis X05		Flexity		S70		Urbos 3
Model		205	305	Freedom	Outlook	Streetcar	Standard	100
Segments	3	3	5	5	5	3	3	7
Max. speed (mph)	50+	43	50	50	43	55	65	43
Minimum radius (ft)	42	66	66	82	36	59	82	59
Length (ft)	72	78	110	101	99	81	96	136
Width (in)	104	95	104	104	100	104	104	104
Maximum grade	8%	~6%	~ 6%	6%	6%	7%	7%	6%
Empty weight (lb)	~80k	~80k	~ 125k	~ 110k	106k	97k	97k	~ 150k
Use in US?	(MBTA)	No	No	No	(TTC)	Yes	Yes	(Maryland)
Doors per side	3	4	4-6	4-6	4*	4	4	6
Low-floor fraction	70%	100%	100%	100%	100%	100%	100%	100%
Threshold height	1̃2"	11"	11"	12"	12"	14"	14"	14"
True level boarding	Possible	Yes	Yes	Yes	Yes	Yes	Yes	Yes
MU operation	4	2	2	4	No	4	4	No
Maximum cars on 220-foot platform	3	3	2	2	2	3	2	1
Maximum cars on 290-foot platform	4	4	3	3	3	4	3	2
Manufacturer claimed capacity	110	142	233	186	200	225	241	306
Calculated capacity	105	116	170	155	151	121	146	214
Maximum ridership increase (220-foot)	190%	205%	202%	184%	180%	215%	173%	136%
Maximum ridership increase (290-foot)	215%	233%	235%	214%	209%	245%	202%	253%
Vehicles needed for 40% increase	225	207	128	148	148	207	148	105
Minimum fleet size	259	239	148	171	171	239	171	121
Recommended minimum fleet size	234	240	195	195	195	240	195	125
Projected unit cost ($ M)	4.9	4.5	4.5	4.5	4.5	4.5	4.5	8.0
Projected total cost ($ M)	1151	1080	878	878	878	1080	878	1000

Table 5.1: Technical specifications, capacity, and cost of the evaluated models

Chapter 6

Conclusions and recommendations

The MBTA Green Line is a complex legacy light rail system with both common and unique challenges. Aging infrastructure and vehicles, an soon-to-be-constructed extension, and the potential for 40% ridership growth by 2050 will tax already inconsistent service. But in these challenges lies opportunity: new data sources and the potential of full-fleet replacement offer a rare change to turn the Green Line into a truly modern light rail system.

This thesis offers a sequential approach to improving the Green Line in this context. The first stage analyzes current service quality, the second evaluates potential service changes, and the third examines full-fleet replacement and accompanying infrastructure upgrades. Although the specific details of each stage are particular to the Green Line, the process should be broadly applicable to complex branched transit systems.

6.1 Research summary

The goal of this thesis was to evaluate current service on the MBTA Green Line and determine strategies for improvements to meet the capacity needs of the next several decades.

Methodology adapted from Malikova (2012) was presented for using previously cleaned AVI and GPS location data to determine running and cycle times and to compare these to scheduled times. The data was also used to calculate vehicle throughput in the Center Subway (which determines the overall capacity of the system), plus headway distributions and expected waiting times at various locations on the surface branches. These service quality measures were analyzed from spring 2015 to spring 2017. This allowed determination of how spring 2016 schedule changes, which removed three-car trains from the schedule and lengthened many cycle times, affected service quality.

A preliminary approach to design a linear optimization model was developed to better determine ideal frequencies and vehicle allocation between the various branches. Physical and policy constraints like maximum crowding and minimum frequency were implemented as linear inequalities. The objective function was set to minimize vehicle usage as a proxy for minimizing crowding. However, despite initial results that show the promise of optimization models, it was concluded that a more refined nonlinear optimization model was required to fully address the objective of equalizing and minimizing overall crowding on the four branch services.

Four currently available models of light rail vehicles in three length categories were examined for their ability to meet the future capacity needs of the Green Line. Current physical characteristics of the Green Line infrastructure, and the feasibility of modifying them to allow use of off-the-shelf vehicles, were considered. This was conducted to help inform the procurement process for new vehicles, which the MBTA is currently beginning.

6.2 Results

6.2.1 Analysis of current service

The service analysis procedures developed in this thesis can be reliably used to evaluate running and cycle times, train throughput, and headway reliability using current data sources. This represents a substantial improvement over Malikova's 2012 thesis, at which time location data were much more limited that today and E Branch location data were wholly unavailable.

Generally, schedule changes in 2016 and 2017 have improved service quality — yet this is mostly a reversal of service deterioration from 2010 to 2015, rather than significant long-term improvement. The schedule changes have largely made scheduled running and cycle times more appropriately reflect real operations. However, this analysis suggests that some scheduled cycle times could be reduced slightly for more efficient operations. Additionally, a number of surface and tunnel sectional running times should be modified in order to provide more accurate travel time estimates and arrival times to passengers. These improved schedules should not require any more vehicles than in current schedules, although there appears to be a multi-year-long issue of insufficient vehicles being available for daily service. Peak running times are similar to those from 2011, but off-peak running times have significantly increased since 2011. This is likely due to the off-peak front-door-only boarding policy; the planned implementation of all-door boarding in 2019 should permit reduced dwell times and reduce running times.

Headway and throughput results show an improvement since 2015, though again this is merely a return to circa-2010 quality rather than long-term improvement. There still appears to be a number of dropped trips during the rush hour. Headway analyses largely show the expected patterns of increased headway variability as trains proceed further from points at which headway is controlled. Bunching is common, particularly in the westbound direction as lack of recovery time and space and the downtown terminals, variable dwell times, running times, and grade crossing delays degrade service. In additional, at most times, a significant portion of trains do not leave Boston College, Cleveland Circle, and Riverside close to their scheduled headways, which causes service to be unreliable at all points.

6.2.2 Vehicle allocation

After several attempts to develop a fully validated allocation model, it was concluded that a nonlinear optimization model can be formulated to more optimally reallocate service on complex branched systems. Both policy goals and physical constraints can be converted to matrix form for use in such models. Existing optimization tools in languages like MATLAB and Python can aid in the development of models, but a substantial amount of development and debugging is still required for reliable use.

The demonstration linear optimization model indicates that some reallocation may be useful to more equitably serve current ridership — primarily by reallocating trains from the C Branch to the B Branch. However, these results are limited in scope and are affected by current limitations in the model, including incomplete boarding data and inability to optimize directly on crowding.

6.2.3 Vehicle selection

Evaluation of vehicles in 70-80, 95-110, and 136-foot lengths indicated that vehicles in any of the three size ranges can handle the largest likely ridership increase (40% growth above the GLX-included baseline envisioned by the 2050 planning horizon). Data on vehicle cost is limited, but the mid-size vehicles may have a slightly smaller total fleet cost than the smaller or larger vehicles. A fleet size of about 200 mid-length vehicles will most likely be capable of supporting the Green Line system through 2050.

Alstom, Bombardier, CAF, and Siemens all offer attractive and well-proven light rail vehicle lines. No off-the-shelf models are capable of operation on the Green Line due to tight curves, limited clearances, and steep grades. However, many physical constraints can be reduced through a reasonable amount of renovation work, and it is likely that any of the four manufacturers could slightly customize their existing lines for Green Line service.

6.3 Recommendations to the MBTA

The research presented in this thesis has revealed a number of opportunities for the MBTA to improve Green Line service and create a true 21st-century light rail system. These recommendations are divided into two groups: those that involve service analysis and planning and can be implemented in the short term, and those that involve infrastructure or new vehicles and will have medium-to-long-term effects. The following recommendations apply to service analysis and planning:

- The service analysis methods developed in this thesis should be maintained and automated by the MBTA to allow periodic service analysis (possibly as part of the existing dashboard UI). This analysis should be used to identify opportunities to improve schedules as well as resolve issues that cause poor service. A real-time version could allow dispatchers to quickly identify and correct service disruptions before they cause cascading delays.

- Right-of-way maintenance efforts should continue to focus on continuously preventing and eliminating track conditions that result in speed restrictions or potential danger like those encountered in mid-2016. Vehicle maintenance should focus on having enough vehicles in service to operate full peak hour schedules.

- Aggressive headway management should be pursued by further development of the recently-tested tablet-based system. The keystone of improving service quality is reliable terminal dispatching so that all trains enter service on consistent headways to prevent large gaps. This will require further development of enterprise field systems and tools, and cooperation and dedication from dispatchers, inspectors, yard managers, and operators. The headway distribution analysis methods of this thesis can be used to show where to concentrate efforts.

- The existing trial of transit signal priority on several surface branches should be evaluated not just by average running time, but by the reduction in running time variability (which will allow reducing scheduled cycle times). TSP buildout should be prioritized at locations that cause the most delays and the most service variability — particularly in the eastbound direction on the B and C branches and the westbound direction on the E Branch.

- The MBTA should continue development of a stable, reliable, and easy-to-use service optimization model for Green Line and bus service planning. Such a model should incorporate passenger-centric considerations like using a nonlinear optimization on weighted-average crowding.

- An optimization model should be used periodically in concert with more reliable boarding data inferred from field counts or the new fare collection system in order to evaluate service scenarios, both in the near term and after the GLX opens. GLX service should be optimized based on passenger experience, including the possible need to run two existing services on the Medford Branch. A variety of possible services, including short turn overlays, should be considered. The model should be used to design service for days with unusual demand patterns, or even for handling the crowds around Red Sox games.

The following recommendations apply to infrastructure and vehicles:

- Purchase approximately 200 new light rail vehicles of 90-110 foot length to fully replace the Type 7, Type 8, and Type 9 vehicles. (The Type 9s could then be used on the Mattapan Line or to add light rail service to the Silver Line tunnel). The new vehicles should be a proven model from an established manufacturer, with as few modifications as necessary to run on the Green Line. Green Line maintenance staff and operators should be frequently consulted during the design process. The vehicles should be heavily tested under a variety of conditions before entering service.

- Parallel to the introduction of the new vehicles, platforms should be raised to approximately 12 inches to provide true level boarding and eliminate the need for movable ramps on the vehicles. Stations should be made fully handicapped accessible with these modifications, along with improvements like additional access points, full-length platforms, and electronic signage where feasible.

- The new vehicles should be part of a package of holistic improvements to the Green Line. Such work should include the station modifications, power system upgrades, yard expansion, modifications to improve minimum radius and other physical constraints, bridge weight limit improvements, and track upgrades to allow 50 mph operations on the D Branch. By improving all of these elements in parallel, no single element will cause artificial limitations on other improvements of the Green Line.

- The MBTA should claim all available space for Green Line yards, and resist the temptation to sell viable yard space for development. The recommended fleet of 200 cars will require about one-third more yard space than the current and on-order fleet — an increase of about a mile of yard tracks above and beyond the planned GLX yard. The most likely spot for this expansion is Riverside, where current TOD plans would occupy half the parking lot. The MBTA cannot lose the most feasible and least expensive location for yard expansion; the TOD plans should be modified to include a larger yard with TOD on a deck. The MBTA should also modify Lake Street Yard for better space usage (and absolutely must prevent the parcel from being taken for Boston College's aggressive expansion plans), build the a full-size GLX yard / maintenance facility, and investigate opportunities for additional yard space near Heath Street or Hyde Square and East Somerville to have small yards at all terminals.

- The MBTA should continue plans for a train protection system, but should not allow the protection system to reduce train throughput capacity. It would be inadvisable to make service worse for hundreds of thousands of daily riders when the Green Line has experienced few collisions. The MBTA should strongly consider full ATO, which is more likely to ensure sustained or increased throughput as well as providing a high level of safety.

6.4 Future research

Just as this thesis built on Malikova's thesis, future research should build upon this research. Pending and proposed changes to the Green Line will substantially change operations, and the increased ridership from the GLX and other sources will place additional stress on the Green Line. Recommendations for future research are:

- As discussed in the MBTA recommendations, the service analysis could be continued and used to evaluate the effects of TSP, real-time control, and all-door boarding. Further in the future, it can be used to compare projected and actual changes to service after the opening of the GLX and the arrival of new vehicles. These methods could also be extended to other systems with different service characteristics and challenges.

- The vehicle allocation optimization model proposed here could be developed to be adaptable to other light rail, heavy rail, and bus systems with complex route combinations. Optimization of vehicle allocation based on passenger crowding is a focus area without substantial research, yet with potential benefits for a broad range of transit systems.

- Live measurements of service quality using the techniques of this thesis could be combined with work by Fabian (2017b) on real-time control to support the development of passenger-centric real-time control measures that incorporate travel times and throughput. For example, a tool might consider not just headways on one branch, but the combined Central Subway throughput of all branches, when deciding whether to introduce an RAD train.

Appendix A

Vehicle allocation on the Green Line

A.1 Introduction

The MBTA Green Line is a complex branched legacy light rail system with unique challenges. Continued ridership growth, aging infrastructure and vehicles, and the pending construction of a two-branched northern extension result in the need for the most efficient service patterns and allocation of vehicles between the various services provided. Several competing factors must be considered to determine a more optimal allocation. The primary desires are to minimize overall crowding (which can be determined by a weighted average of the crowding experienced by each passenger), and to maintain policy frequencies on the surface branches. The MBTA Service Delivery Policy specifies maximum average passenger loads on vehicles, which vary by time of day and location on the system,[1] as well as minimum frequencies. Additional constraints come from the limited working fleet size, as well as infrastructure considerations that limit frequencies at certain locations.

This methodology converts these constraints into a linear optimization problem, which can then be solved computationally (here, using MATLAB). The model takes as input a spreadsheet of parameters, including passenger flow data developed using MIT's origin-destination-transfer (ODX) inference model. A linear optimization function attempts to minimize vehicle usage, subject to approximately equalizing crowding on the surface branches, as a proxy for the nonlinear weighted-average crowding measure.

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[1] A draft update in 2016 indicated that future standards may use the same crowding standards at all locations. The 2017 Service Delivery Policy did not include crowding standards, stating that better APC data was needed.

The basic use of the model was to determine a more optimal vehicle allocation between the four routes, and what headways should be run using those vehicles to meet the Service Delivery Policy. More advanced use could include analyzing vehicle and frequency needs for scenarios like the future extension or Red Sox game-day service, and analyze different operating scenarios (such as adding short turn services) to determine whether they improve overall passenger experience. For further development, use of a nonlinear optimization function is suggested to allow the model to directly minimize both branch and trunkline crowding.

A.2 Preliminary work: downtown terminals

The MBTA and its predecessors have changed the eastern terminals of surface branches on numerous occasions. For decades, the B and C branches were run through to Lechmere as the primary trunk routes. In recent years, the E Branch has been matched to Lechmere so that the branch can be served partially from Lechmere Yard. With new data available, passenger flows as well as operational considerations should be used to match branches to terminals.

ODX data can be used to estimate the number of passengers forced to transfer between branches — a key consideration. An origin-destination matrix (with the Green Line simplified into segments that share the same services) was created using October 2016 data, and a spreadsheet lookup table was used to count all OD pairs that would require transfers in a given scenario. Because not all destinations are inferred, the aggregated inferred trips of each segment were scaled up to match MBTA boarding counts. A second version was made to estimate transfers required after the GLX is in operation, with Lechmere data scaled to approximate additional origins and destinations on the two branches.

The current pairing (B — Park Street, C — North Station, D — Government Center, and E — Lechmere) is fairly efficient, with 10,023 of 209,369 passengers estimated to have to change Green Line trains. (Of those, 2,635 travel between points west of Kenmore, or between the E Branch and points west of Copley, and would have to transfer under any service pattern.) While keeping one branch per terminal, the least-transfer pairing (B — Park Street, C — Government Center, D — North Station, and E — Lechmere) would require 9,840 transfers, just 183 fewer transfers than the existing configuration.

Extending an additional branch to Lechmere has been proposed as legally-required mitigation for delays with the GLX. As well as providing more frequent service to Lechmere, this would reduce the number of passengers that need to transfer. Extending the B Branch to Lechmere would halve the number of transfers to 5,302.

Although the GLX will increase daily Green Line boardings by about one-sixth, it will involve multiple through-running routes and thus could actually decrease the number of transfers required (as well as substantially reducing bus-rail transfers at Lechmere). The current planned service (B — Park Street, C — North Station, D — College Avenue, and E — Union Square) would reduce transfers slightly to 9,813. Switching the B and C terminals plus switching the D and E terminals would reduce this further to 9,066. It may be necessary to add a second service to the Medford Branch during rush hours to handle crowding. If the C Branch was extended to College Avenue at all hours, transfers would fall to 4,131.

A.3 Methods

A.3.1 Overview and purpose

The purpose of this methodology was to have a semi-automated method of assigning frequencies and vehicle allocation which can accept a variety of input parameters and various service scenarios. Past methods used by the MBTA (mostly done before full Green Line tracking and ODX data were available) have generally done this at the period level, with headways kept constant for periods of several hours or longer. Skilled schedulers have made this work relatively well, but it still suffers from the coarseness of the periods and the limited data used. The maximum flows (passengers per hour in one direction that travel through the maximum load point) on the four surface branches plus the Huntington Avenue Subway are presented in Figure A-1, showing the variation within periods that makes this coarse method imperfect.

The disadvantages of using long headway periods is that ridership does not remain con-

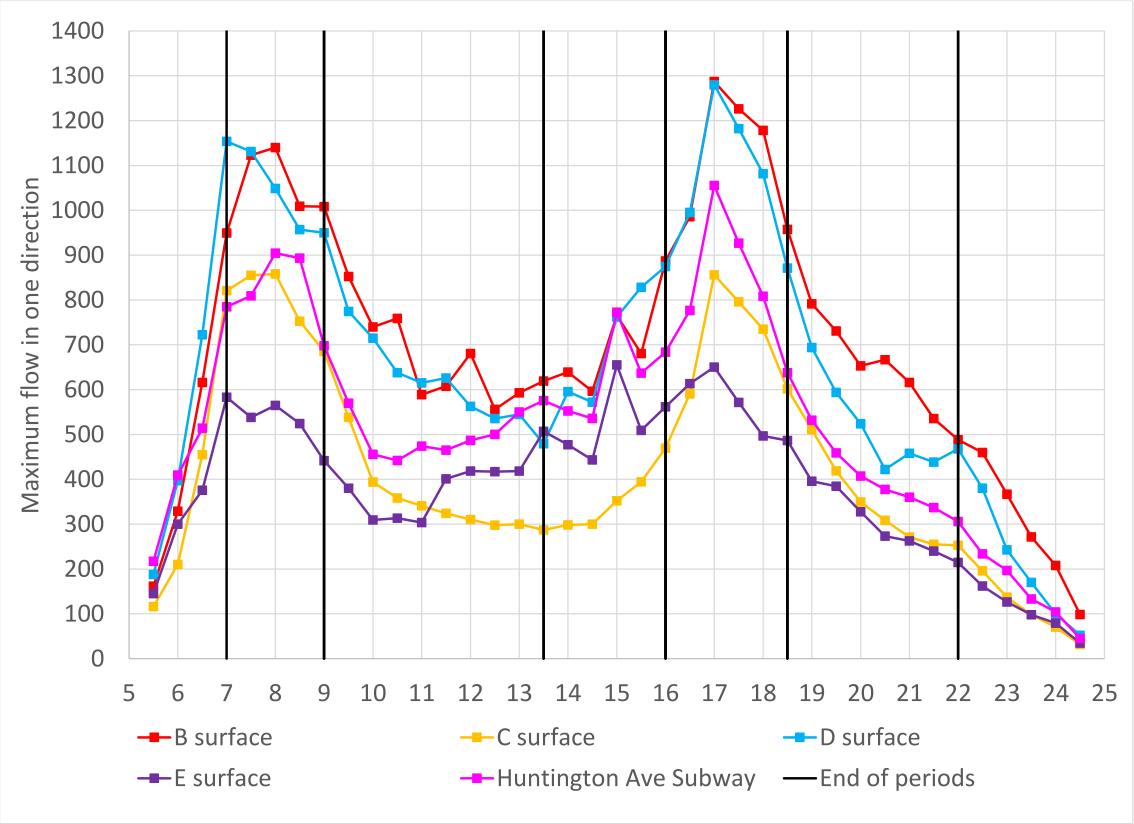

Figure A-1: Maximum load (in either direction) for the four surface branches and the Huntington Avenue (E Branch) Subway for each half-hour time band

stant across periods, nor are maximum flows always during the traditional peaks. The MBTA Service Delivery Policy sets maximum per-train loads not to be exceeded during half-hour intervals during high-demand periods and hour intervals at other times. Thus, setting headways at the period level requires using the highest flows within that period — which may be inefficient as more service than is needed is sometimes operated. Setting headways at the period level would, for example, base the midway headways on the surface C Branch and the E Branch tunnel on the 700 passengers per hour maximum flows at 9:00-9:30 am — but by the end of that period, the tunnel flow has decreased to a maximum 560 passengers per hour, and the C Branch has just half of that. If headways were constant across that period, trains would run far under capacity near the end of the period, especially on the C Branch.

This method converts a variety of constraints to a linear optimization (simplex) problem. However, this requires that smoothing be performed separately at the end, making some results slightly inaccurate. For the purposes of this method, the system is divided into non-overlapping sections (each composed of two segments in the two directions), with their borders at turnback points, junctions, and other locations where services terminate or diverge. Each segment is assigned a minimum frequency at each half-hour period based on recorded ridership and MBTA crowding policy. Linear inequalities are set up to enforce that service on that segment and that time (composed of one or more operating routes) meets that minimum frequency, while not exceeding the maximum that the infrastructure supports. A second set of linear inequalities allow for maximum loads to be set roughly equal across lines, thus ensuring approximately equal accommodations for all riders. The optimization function is a weighted average of the half-hour vehicle requirements implied by the chosen frequencies.

A.3.2 Modeling system geometry

For this model, the system is divided into sections of line, each of which consists of a pair of one-way segments. Boundaries between sections should be at turnback points, junctions, portals, and other locations where either service patterns or service delivery requirements change. The line is divided up into segments, each of which is served by one or more service patterns. For this initial work, twenty segments (ten bidirectional sections), shown in Figure A-2, were used:

- Surface sections of the B, C, D, and E branches
- Symphony - Copley
- Kenmore - Copley
- Copley - Park Street
- Park Street - Government Center
- Government Center - North Station
- North Station - Lechmere

The segment load only considers the loads after trains have left the first station of the segment but before they arrive at the last station. For example, the Park Street - Government Center loads are those leaving Park Street / arriving Government Center eastbound, and those leaving Government Center / arriving Park Street westbound. Loads on trains arriving at Park Street eastbound or Government Center westbound, and those departing Park Street westbound and Government Center eastbound, are part of other segments.

The section of a line between the last surface station and the first underground station is considered to be a surface section for the purpose of this analysis; this eliminates the need for additional segments near Kenmore where the B, C, and D branches have short underground segments. A more granular model would move the E Branch section boundary to Northeastern, and add a Blandford Street-Kenmore segment on the B Branch, to better consider short turns at those locations.

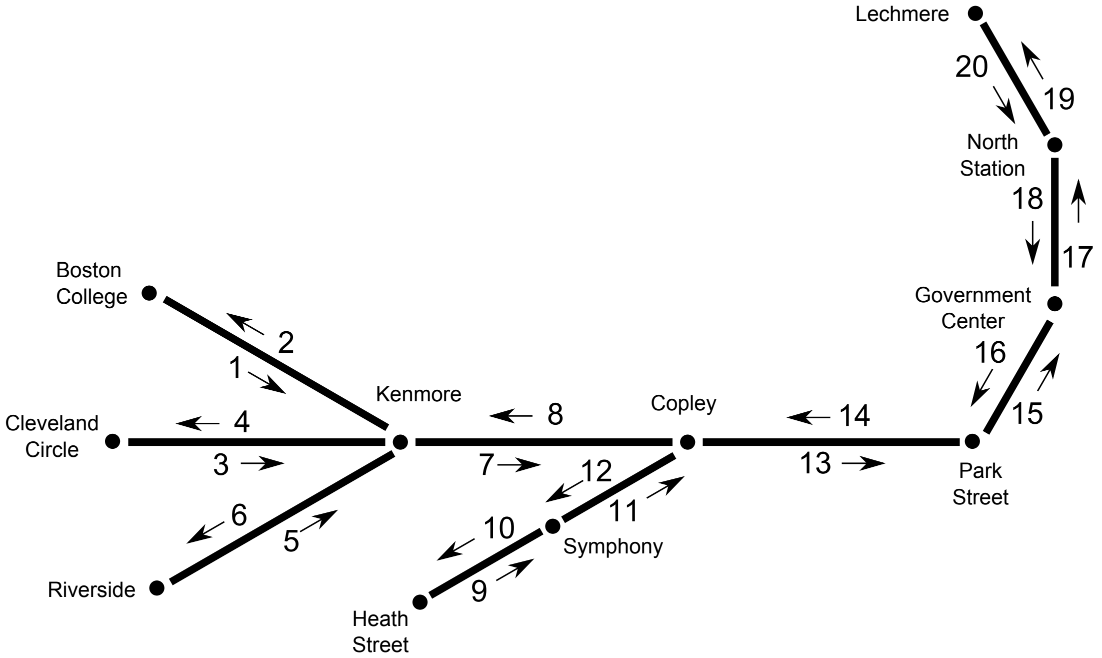

Figure A-2: Diagram of the 20 segments used for this analysis

Each segment is served by one or more services at each time. Each service is a closed loop following one or more sections of line; both ends of the service should be at viable turnback points. Five services, shown in Figure A-3, are used for this demonstration: the current four letter services (B Boston College - Park Street, C Cleveland Circle - North Station, D Riverside - Government Center, and E Heath Street - Lechmere) plus an optional Run As Directed (RAD) service to provide extra service in the subway between Kenmore and Park Street. As with the previous chapter, eastbound/westbound notation is used for all segments.

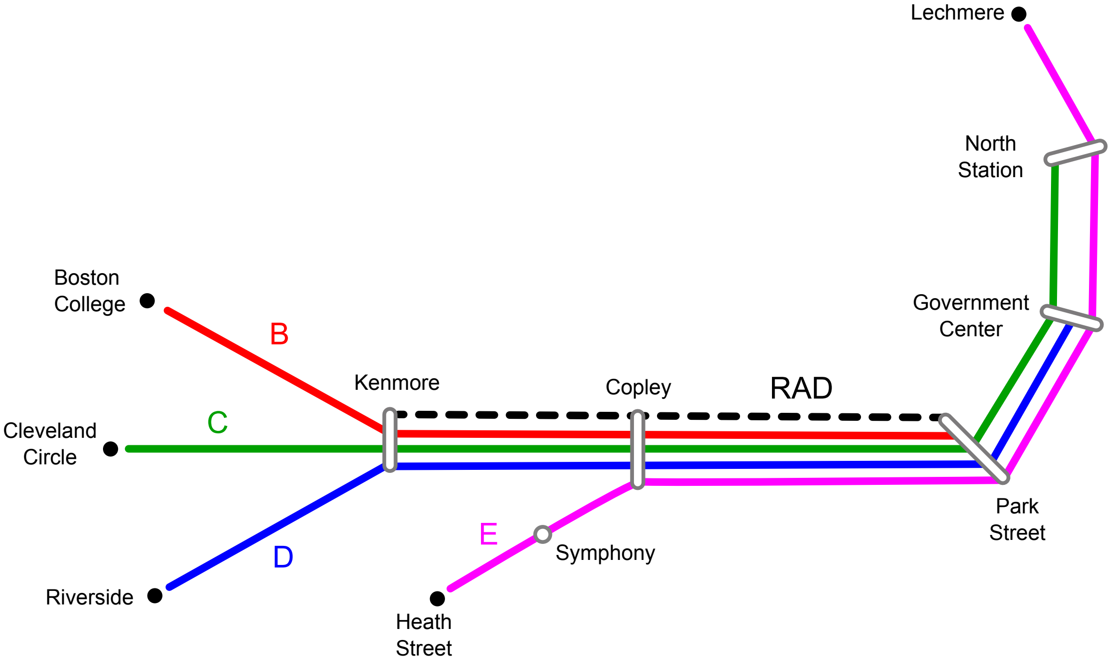

Figure A-3: Diagram of the 5 services used in this analysis

A.3.3 Crowding and frequency constraints

The 2017 MBTA Service Delivery Policy does not set crowding standards for light rail, claiming a lack of accurate crowding data. This analysis uses constraints from the 2010 Service Delivery Policy, which sets periods (lengths of time between half an hour and several hours) for defining service standards, as shown in Table A.1.

Time Period	Definition
Early AM	6:00 AM — 6:59 AM
AM Peak	7:00 AM — 8:59 AM
Midday Base	9:00 AM — 1:29 PM
Midday School	1:30 PM — 3:59 PM
PM Peak	4:00 PM — 6:29 PM
Evening	6:30 PM — 9:59 PM
Late Evening	10:00 PM — 11:59 PM

Table A.1: Periods used to define service standards

This analysis uses the same periods for setting minimum frequencies, with the additions of extending the Early AM period to 5:30 AM and the Late Evening period to 12:59 AM to account for existing Green Line usage at these hours.

The 2010 Service Delivery Policy sets two policy standards for light rail: vehicle load and minimum frequency. The Vehicle Load Standard allows average passenger load up to 225% of the number of seats during AM and PM Peak, Early AM, and Midday School periods. During other times, this changes to 140% of seats in core areas (Lechmere-Copley-Kenmore)[2] and 100% of seats on the surface branch lines. For a two car train with 44 seats per car, this translates to 198, 123, or 88 passengers. (The model assumes that all trains have two cars, though longer or shorter trains could be simulated by changing these inputs). Figure A-4 represents a typical peak load as allowed by policy.

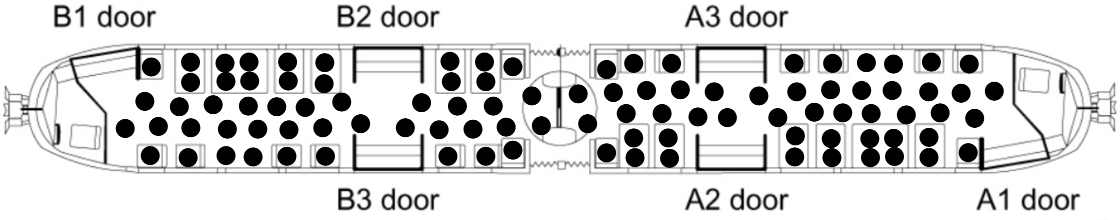

Figure A-4: Diagram of a Type 7 vehicle with 99 passengers — the maximum allowed by current policy

The Service Delivery Policy requires that these thresholds not be exceeded, on average, during each half-hour **time band** during most periods of the day. Hour time bands are allowed at some times; however, flow data is available in half-hour increments and thus half-hour time bands will be used for this analysis. To generate minimum frequencies on each segment at each time band, the scaled maximum flow is divided by the allowable average crowding, thus generating a frequency with units of trains per hour (TPH).

The fundamental demand-based scheduling inequality holds that for each segment, at each time band, the service provided is equal to or greater than the demand. For example, on the westbound segment between Park Street and Copley during the 5:00 pm bin, the

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[2] The Service Delivery Policy allows 140% of seats of the Huntington Avenue Subway as well. However, this testing used the lower 100% value to reflect that only one branch serves that subway section.

frequencies of the four base services plus any RAD service operating over that segment must sum to at least the minimum frequency calculated from the flows. On segments where not all services operate, the sum of only the operated services must be sufficient.

It is tempting to imagine that all segments can be solved simultaneously for a given half-hour time band, and then that calculation repeated for every such time band. Unfortunately, the problem is not that simple. Trains operate as round trips; one-way trips are generally not possible, as four terminals (Park Street, Government Center, North Station, and Heath Street) have storage space for no more than two trains. A westbound E train picking up inbound riders at Lechmere in the 6:00 am time band will also arrive at Longwood Medical Area westbound in the 6:30 am band, and at Park Street eastbound in the 7:00 am band. Thus, frequency in each period is linked to the periods before and after it.

This can effectively be ignored when doing period-level analysis, as the periods are longer than most cycles times, but cannot when using a half-hour time band. Instead, it is necessary to solve demand for all periods simultaneously. There are two ways to do this. One is to divide decision variables by segment, time band, and service, then to set up a series of equalities linking which decision variables represent the same trips and thus must be equal. However, this requires an extremely large number of decision variables — some 3,900 for this demonstration model alone. Instead this model reduces each segment-service-time band triplet to a service-time band pair, where the time band is the band in which such trains arrive at Park Street eastbound, using a lookup table provided as part of the input dataset. With decision variables then divided only by service knd time band, 195 decision variables are needed for this demonstration model.

The lookup table also functions as an accounting of what services run on what segments at what time; a null value indicates that the service does not serve that segment at that time. This allows for routes to change at different times of day, such as extending more services to North Station or Lechmere at off-peak hours to maintain frequent service on those sections. Optimized frequencies should also be subject to the physical limits of the system, including minimum headways, interlockings and junctions, and storage space. These include:

- Flat junctions at Copley Junction, Beacon Junction, and Reservoir, where trains moving in opposite directions must be coordinated;

- Other junctions at Kenmore, Park Street, Government Center, Haymarket (Brattle Loop), and North Station, where only moves in the same direction must be coordinated;
- Crossovers at North Station, Blandford Street, Cleveland Circle, and Riverside, which may limit how quickly trains can reverse directions;
- Limited storage space available for schedule recovery at Park Street, Northeastern, Cleveland Circle, Government Center, Park Street, and Lechmere;
- Manual operation, current signaling, and rules prohibiting two trains occupying a platform track simultaneously (except at Park Street) limit the maximum frequency over grade-separated two-track lines. A limit of 40 TPH is used here for reasons discussed in detail in the next chapter.
- The B, C, and E Branches have numerous at-grade street crossings with no signal priority. While TSP implementation and planned real-time control will mitigate this to a degree, too-frequent service on these branches is difficult to maintain without severe bunching and long gaps.

Most of these restrictions affect junctions of segments, making them difficult to implement without code that is specific to each instance. They are also heavily dependent on changeable factors — for example, real-time control that provides more consistent running times will reduce required recovery time at turnarounds, allowing more frequent service without changes to the track geometry. Some junction-based restrictions could be implemented in the future, but this version only incorporates by-segment restrictions.

These infrastructure-based restrictions have the same parameters as the crowding-based minimums and are implemented identically. This does create the possibility of conflicts which will render a given input unsolvable, if existing demand requires more service than can be physically provided while maintaining allowable crowding. If this occurs, then may be a need to manage the demand by other means, like running three-car trains or directing passengers to alternative services.

The Minimum Frequency of Service Standard from the Service Delivery Policy calls for maximum 10-minute headways (minimum 6 TPH) on light rail routes at AM and PM peak, and 15-minute headways (minimum 4 TPH) at other times. (This restriction only applies to the basic routes; overlay services like RAD trains that duplicate parts of other routes can be operated at any frequency.) No limits on maximum frequency are set by policy; maximum frequency is governed by infrastructure and vehicle constraints instead. This demonstration, based on input from MBTA managers, maintains a 6 TPH minimum on all base services until 8:00 pm.

This minimum is enforced by service, rather than by segment. This is somewhat of an arbitrary choice, but it has three advantages. One, the MATLAB linear solver allows for upper and lower bounds to be input as vectors rather than as individual equations, which simplifies implementation.

Second, this allows for minimum direct frequencies between OD pairs to be maintained. For example, after a Red Sox game, some service on the Riverside Branch may be operated as Kenmore-Riverside shuttles to handle the crowds. However, it is still desirable to have a certain number of regular Government Center-Riverside trips so that passengers do not have to change trains at Kenmore.

Third, it more closely aligns with the policy for bus routes, where even when several routes share a trunk, their frequencies are considered independently for the purposes of the policy.

A.3.4 Load balancing constraints

A system like the Green Line with unequal ridership on different branches must balance two opposing goals: equal passenger experience of waiting time (equity of distribution), and equal passenger experience of crowding (equity of outcome). An ideal method would have some way to balance out the two factors; this demonstration uses an optional method of enforcing approximately equal crowding on the four surface sections of the lines, with the assumption that the minimum frequency standards will provide sufficiently similar waiting times.

The intent is that during each time band, the maximum load experienced on each of the four surface branch lines will be approximately identical. It is not possible to make them exactly equal for two reasons. Because each time band is linked to the others as discussed above, forcing exact equality would result in unsolvable equations. For example, if the higher demand direction is inbound on the B Branch until noon and outbound thereafter, both the 11:30 inbound and 12:30 outbound loads will be based on the frequency of 12:00 (adjusted) arrivals at Park Street. However, the 11:30 will be compared with the 11:30 maximum load on the C Branch, and the 12:30 will be compared with the 12:30 maximum load on the C Branch, which may well be different. This will then generate two contradictory frequencies for the 12:00 B Branch adjusted period. Secondly, it may not be always desirable to have exactly matched loads. If one branch has very low ridership during some time bands, the minimum policy headways will create very low crowding, requiring high frequencies to be run on busier branches to match.

Instead, the load balancing equations use a variable p to determine the maximum ratio between two loads that should ideally be equal. The program starts with p=0 (all branches having equal loads), then p is iteratively increased by 0.01 until a solution is found.

A.3.5 Fleet usage constraint

It is of course necessary that the vehicle requirement does not exceed the number of vehicles available (with an acceptable spares ratio, of course). Exact vehicle counts are difficult to determine without performing the actual blocking, but multiplying the frequency of each route by the 95^{th} percentile running time (a common determination of scheduled cycle times) for each period is a useful approximation. Only at rush hours is the full complement to be operated — off-peak service is expected to use fewer vehicles to reduce operating costs. Thus, the method accepts as input a vector of the maximum vehicle counts by time band. Currently, this is set to approximately equal the theoretical vehicle usage of the current schedule.

A.3.6 Optimization

As implemented, the optimization function attempts to minimize utilization of resources by estimating vehicle count at each time band, and minimizing the sum of those counts (subject to the iteration over p as discussed above). This will produce a useful relative allocation, but may produce vehicle usage different than currently operated at some off-peak times. It may still be desired to use approximately the current count by scaling some off-peak headways on all services simultaneously.

The optimization function includes the ability to weight by segment and time band. This was intended to be used to focus the optimization on the rush hour periods when the highest crowding is experienced. However, testing showed that this weighting does not in fact have any real effect, and it can be safely ignored.

A.4 Implementation

A.4.1 Data preparation

The flow data used as input is taken from the MIT-developed origin-destination-transfer (ODX) model, with approximately 30% scaling to account for estimated farebox noninteraction (passengers who do not pay at the farebox — either because they have already purchased a monthly pass, or to avoid paying a fare — and are thus not recorded in AFC data). MBTA surveys taken in 2016 indicated that this 30% factor might be too low during peak periods, which would skew results; the E Branch with its bidirectional peak demand may be particularly affected by this.

The flow data is initially given as the average flow (passengers per hour) leaving each station in each half-hour interval. To prepare this data for the model, the maximum flow experienced after any station on each segment (the maximum load point for that time band) is taken as the flow, in order to ensure that maximum crowding will not be exceeded at any point.

Although the flow data has already been scaled for noninteraction, the model provides for an input matrix to allow for additional scaling by segment and time band. This can be used to fine-tune flows by various parameters:

- Increasing tunnel flows to account for "ghost gates" (faregates not properly accounted for in AFC data)
- Accounting for new demand on a segment due to a new housing development, connecting bus line, etc.
- Scaling overall flows to represent year-over-year ridership growth

A.4.2 Creation of constraint matrices

The creation of the constraint matrices requires the use of numerous variables. The following common indices are used for these variables:

- u: time band without adjustment
- n: segment $n$umber
- k: service
- h: time band adjusted to reflect a train's time through Park Street eastbound, generally obtained as a function $u + G_{u,n,k}$

A number of matrix variables can then be designated. Some are inputs:

- $L_{u,n}$: maximum average flow (passengers per hour) on segment n during unadjusted period u
- $S_{u,n}$: factor by which to scale $L_{u,n}$
- $F_{u,n}$: maximum passengers per two-car train on segment n during period u
- $Q_{u,n}$: maximum TPH on segment n during period u (infrastructure constraint)
- $G_{u,n,k}$: time-shift necessary to represent real train speeds by period h on segment n with service k
- $M_{h,k}$: minimum headway-based policy TPH on service k during period h
- $Y_{h,k}$: required cycle time in minutes on service k during period h
- J_h: maximum car count allowed during period h
- $W_{h,k}$: importance weighting factor for service k during period h

Others are created during the program:

- $O_{u,n}$: scaled flow on segment n during period u
- $T_{u,n}$: minimum demand-based policy TPH on segment n during period u

- $X_{h,k}$: scheduled TPH on service k during period h
- $V_{h,k}$: vehicles in two-car trains required to run service k during period h

The basic demand inequality is that for each segment at each time band, the service provided is greater than or equal to the estimated demand:

$$\sum_k X_{k,n,u} \geq T_{u,n} \ \forall \ u, n$$

MATLAB's linear solver only accepts the standard form $A \cdot x \leq b$; therefore, the signs must be reversed:

$$-\sum_k X_{k,n,u} \leq T_{u,n} \ \forall \ u, n$$

A lookup table (an implementation of function G) is used to correlate unadjusted periods on each segment (by route and period) with adjusted hour by route. This allows the inequality to be expressed in terms of the data available:

$$-\sum_k X_{k,h(u,k,m)} \leq T_{u,n} \ \forall \ u, n$$
$$where \ h(u,k,n) = u + G_{u,k,n}$$

For example, when applied to the westbound Central Subway between Park and Copley in the 5:00 pm to 5:30 pm period:

$$-X_{B,14,u=17} - X_{C,14,u=17} - X_{D,14,u=17} - X_{E,14,u=17} - X_{R,14,u=17} \leq -T_{14,u=17}$$

Becomes:

$$-X_{B,H=17} - X_{C,H=16.5} - X_{D,H=16.5} - X_{E,H=18} - X_{R,H=17} \leq -T_{14,u=17}$$

This procedure is used identically (except for signs) to implement the infrastructure-based maximum frequencies.

The ideal load balancing equation is:

$$max\left(\frac{X_{B\ EB,u}}{T_{B\ EB,u}},\frac{X_{B\ WB,u}}{T_{B\ WB,u}}\right)=max\left(\frac{X_{C\ EB,u}}{T_{C\ EB,u}},\frac{X_{C\ WB,u}}{T_{C\ WB,u}}\right)$$
$$=max\left(\frac{X_{D\ EB,u}}{T_{D\ EB,u}},\frac{X_{D\ WB,u}}{T_{D\ WB,u}}\right)=max\left(\frac{X_{E\ EB,u}}{T_{E\ EB,u}},\frac{X_{E\ WB,u}}{T_{E\ WB,u}}\right)\ \forall\ u$$

With the addition of p (the the maximum ratio between two loads that should ideally be equal), this single equation is split into twelve equations that can be implemented as inequalities:

$$max\left(\frac{X_{B\ EB,u}}{T_{B\ EB,u}},\frac{X_{B\ WB,u}}{T_{B\ WB,u}}\right)-max\left(\frac{X_{C\ EB,u}}{T_{C\ EB,u}},\frac{X_{C\ WB,u}}{T_{C\ WB,u}}\right)\cdot(1+p)\leq 0$$
$$-max\left(\frac{X_{B\ EB,u}}{T_{B\ EB,u}},\frac{X_{B\ WB,u}}{T_{B\ WB,u}}\right)\cdot(1+p)+max\left(\frac{X_{C\ EB,u}}{T_{C\ EB,u}},\frac{X_{C\ WB,u}}{T_{C\ WB,u}}\right)\leq 0$$

These are then repeated for the other line pairings (B/D, B/E, C/D, C/E, D/E). Similar to the demand inequalities, these are then adjusted for travel times, using h(u,n,k) instead of u. For this implementation, only loads from 7:30 am to 9:00 pm were compared, as early morning and late evening ridership is so low that exact matching would be unnecessary.

The vehicle constraint is implemented as:

$$\sum_k X_{h,k}\cdot Y_{h,k}\cdot\frac{1\ hour}{60\ minutes}\leq J_h\ \forall\ h$$

The optimization function is:

$$f=\sum_k\sum_h X_{h,k}\cdot Y_{h,k}\cdot W_h\cdot\frac{1\ hour}{60\ minutes}\leq J_h\ \forall\ h$$

Unlike with the vehicle constraint, the constant can be dropped without affecting the results of the optimization.

A.4.3 Implementation in code

MATLAB was chosen as the language for the initial implementation for its ease of use, matrix-based workflow, and built-in linear solver. (Future versions may be ported to Python or another freely available language to avoid being tied to the MATLAB environment.) The value of these languages is in their adaptability and transparency. All equations which determine frequencies are generated by the code, which should mitigate the potential for nearly invisible errors in spreadsheet calculations. Using matrices to store and modify data and parameters allows scaling factors to be implemented with single lines of code, and even conversion to different geometries or service patterns can be done by modifying or adding subroutines, without changing the fundamental logic used. This allows more complex scenarios like short turn overlays or the addition of the GLX to be more easily simulated.

All input data is added to a preformatted Excel spreadsheet, which the program imports. The data consists of matrices for $L_{u,n}$, $S_{u,n}$, $F_{u,n}$, $G_{h,n,k}$, $M_{h,k}$, $Q_{u,n}$, $Y_{h,k}$, J_h, and $W_{h,k}$ as defined in the previous section, plus a binary indication of whether smoothing should be performed, and a list of the starts of smoothing periods.

The program loops through each segment and time band pair to generate most of the constraint matrices discussed above. The car count constraint matrices are generated directly from diagonal matrices.

The linprog routine, available as part of the Optimization Toolbox in MATLAB, is used to perform the optimization. If the routine cannot optimize, p is increased by 0.01 and optimization attempted again. If p reaches a value of 2, it is assumed that optimization is impossible for any value of p, and the program terminates.

A.4.4 Smoothing

Although passenger demand changes rapidly, constantly fluctuating headways are neither practical to operate nor easy to communicate to passengers. It is then necessary to smooth headways into periods of one to several hours. Here, this is done with manually determined periods largely between 1:30 and 2:30 in length, as several of the MBTA-defined periods have significant changes in demand across the period. For each defined period, the maximum frequency on each service during that period is used for the whole period. This could be ignored for RAD-type services which may only be needed for brief intervals. The smoothed frequencies are then converted to raw headways, which are then rounded down to the nearest half-minute for scheduling purposes. (Rounding up should be avoided, as it could cause higher crowding than allowed.) The rounded headways are then converted back to frequencies.

While this smoothing process generates continued half-integer headways that are practical to schedule, it does slightly increase the number of vehicles used by about 3-5% during peak periods. Future versions may incorporate smoothing into the optimization function; however, with this version of the model it is usually necessary to reduce the vehicle usage maximum inputs by around 4% to result in currently-sized outputs.

A.4.5 Evaluation

In order to compare the effectiveness of scenarios, we must have an appropriate evaluation measure. A weighted sum of crowding, with the weighting based on the flow through each segment at each time band, can approximate the crowding experienced by the average passenger, rather than the average train. This is an important distinction when loads can vary greatly between trains. For example: if two consecutive trains have 10 and 90 passengers on board, the average train has $\frac{(90+10)}{2} = 50$ passengers, but the average passenger experiences significantly higher crowding of $\frac{(90 \cdot 90+10 \cdot 10)}{(90+10)} = 82$ passengers.

The output spreadsheet calculates weighted sum of crowding experienced for each time band, each segment, and overall (the latter to provide a single easy-to-compare metric) for each scenario.

A.5 Results

A.5.1 Sensitivity analysis

Most of the model parameters are basic characteristics of the physical system and ridership demand; exploring their effects on service was the intention of the model. However, two parameters — the vehicle count weighting in the optimization function, and the value p that sets the maximum allowed relative difference between branch line loads — are peculiar to this model, so it is important to understand how they affect results.

The algorithm was run using April 2016 load data. Minimum headways and maximum load factors were taken from the Service Delivery Policy as discussed above. Maximum frequencies were set at 15TPH for the surface branches and 45 TPH for the Central Subway. Cycle times were obtained by the methods discussed in Chapter 4. No RAD trains were used.

A variety of weighting matrices were tested, ranging from rush hour weights equal to off-peak weights, to rush hour weights larger by a factor of 5. In all cases, the vehicle counts were exactly the same. Thus, weighting does not produce any additional optimization of rush hour services, and it does not need to be included in the model.

Changing p (by disabling the secondary optimization and hard-coding p) produces significant differences. For this example dataset, values of p below 0.10 failed to reach a solution. Maximum vehicle usage was 146 with $p = 0.10$, dropping to 130 at $p = 0.35$ and remaining largely constant with higher values of p. The average vehicle usage over the day declined from 116 with $p = 0.10$ to 96 with $p = 1$, again remaining largely constant at higher values. Average (weighted-sum) crowding varies from 75 at $p = 0.10$ to 88 at $p = 1$. This is shown in Figure A-5.

The conclusion to be drawn from this is that the model is extremely sensitive to changes in low values of p — an arbitrary parameter that passengers do not experience directly (as opposed to crowding or frequency itself). With the model in its current state, increasing p has almost no effect on the actual allocation — from $p = 0.25$ to $p = 1$ there is almost no change in how many vehicles are used per line. Instead, it is simply reducing vehicle usage and increasing crowding, which is not the intention of the model. This suggests more sophisticated ways of measuring and optimizing on crowding may be useful, as the current use of p adds little value.

A.5.2 Reallocation for regular service

The first test of the model was under assumptions of current service, with no regular RAD service, scaling of 1.2 times on the E Branch to compensate for farebox noninteraction, and a minimum of 6 TPH until 8:00 pm, to see how the model would reallocate service. However, the results showed one of the flaws in the model. Because of the need to balance crowding in the midday period without exceeding the allowed vehicle count, midday vehicle usage is almost as high as peak usage — with 134 cars for midday service and 146 at peak. This

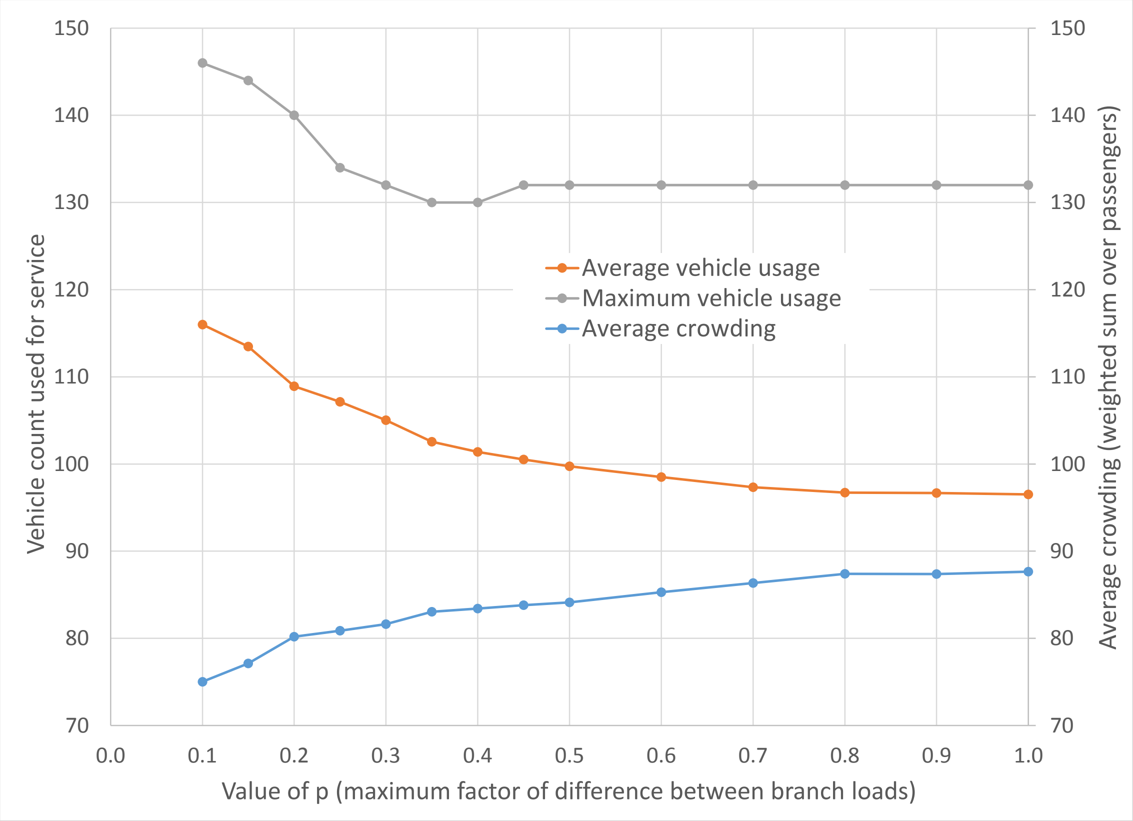


Figure A-5: Average and maximum daily vehicle usage, and average daily crowding, as a function of maximum crowding level ratio

appears to be a fundamental problem with using a single value of p for the whole day — it results in too-high car usage off-peak and often too-low usage during peak.

Without significant improvements to the model — either to allow different values of p for different time intervals or to make more radical changes — the next-best way to get useful preliminary results is to relax the minimum frequency off-peak to the 4 TPH allowed by the Service Delivery Policy. With this change, the otherwise same inputs produce a maximum of 144 vehicles used at peak, and as low as 100 at midday.

The (first order approximation) vehicle usage with this input, shown in Figure A-6, closely parallels the current schedule. The model indicates an evening peak earlier than the current schedule, likely driven by the Longwood Medical Area and other employment centers with earlier demand. The model output drops to 4 TPH on all lines after 11 pm; if increased to a minimum of 6 TPH at this time, it would closely approximate current service.

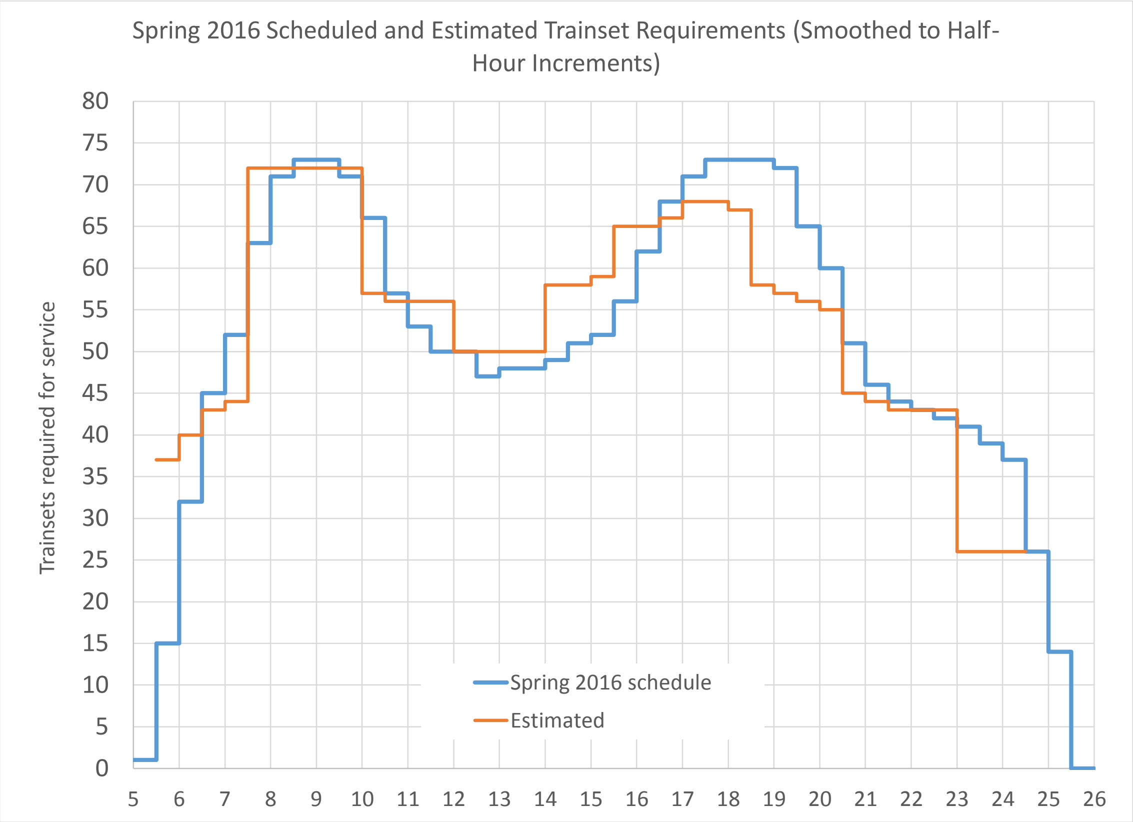


Figure A-6: Spring 2017 scheduled vehicle usage and approximate vehicle usage from model output

However, the branch frequencies are rather different from those of current service. Table A.2 shows the reallocation of trainsets suggested by this test output at 8:00 am, 1:00 pm, 3:00 pm, 5:30 pm, and 10:00 pm. The C Branch loses vehicles for much of the day — thus dropping to 9 TPH at the peaks and 4 TPH at midday — and the B Branch gains vehicles. The D Branch loses vehicles at the peaks, but gains at midday (as compensation for increased cycle times rather than frequency gain). The E Branch gains vehicles at midday and the school peak to handle increasing demand from the Longwood Medical Area.

Comparison of current scheduled frequencies and frequencies suggested by the test model are shown in Figures A-7 through A-10.

	B	**C**	**D**	**E**
AM Peak	3	-3	-1	0
Midday	1	-3	2	2
School Peak	3	-3	-1	4
PM Peak	1	-3	-2	-1
Evening	2	0	0	-1

Table A.2: Changes in the number of trainsets used per branch between the spring 2017 schedule and the estimated usage

This also demonstrates several issues with these results. First, they rely exclusively on ODX data, which uses estimated farebox noninteraction rates for surface stations. If noninteraction is more common than assumed — as appears to be the case on the E Branch — then the loads will be underreported and the model will assign fewer trains than are actually necessary. In this test, an additional scaling factor of 1.2 was necessary to have the model outputs approximately match the levels of service known to be needed. More detailed study of noninteraction rates, and especially the implementation of all-door-boarding in 2019, can improve this. Second, the model does not account for the headway variability seen in the previous chapter, which causes more crowding than predicted on some trains. Third, the model optimizes on vehicle usage rather than crowding, and thus will use fewer vehicles even if crowding is increased.

This output produces a weighted average of 77 passengers per train — about 3% higher than the 74.5 estimated for current service. However, this is likely to decrease when using a model that actually optimizes on crowding. Using 4 TPH minimum frequency used an average of 106 vehicles (53 2-car trains) across the service day.

It must be emphasized that these results are representative of typical results from the model, rather than being an actual recommended reallocation. Further refinement of data sources, optimization function, and stability are needed before this model can give recommended implementable results.

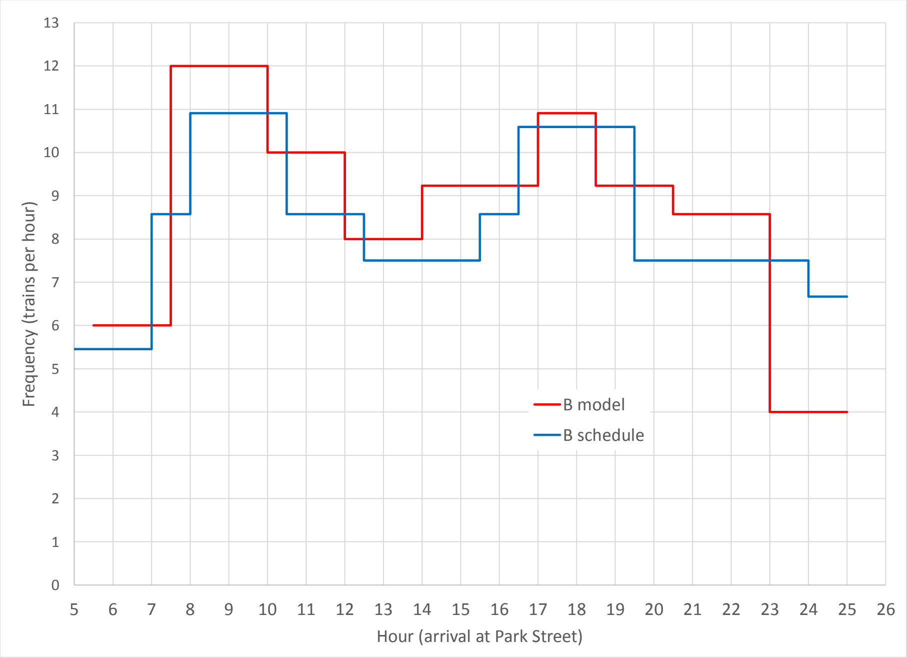


Figure A-7: Currently scheduled and model-proposed frequencies on the B Branch

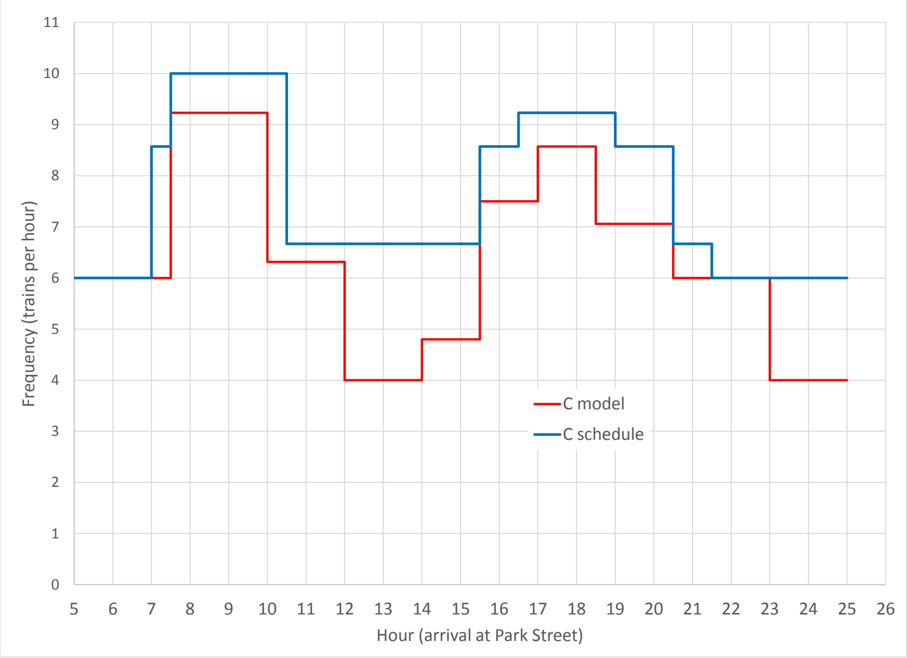


Figure A-8: Currently scheduled and model-proposed frequencies on the C Branch

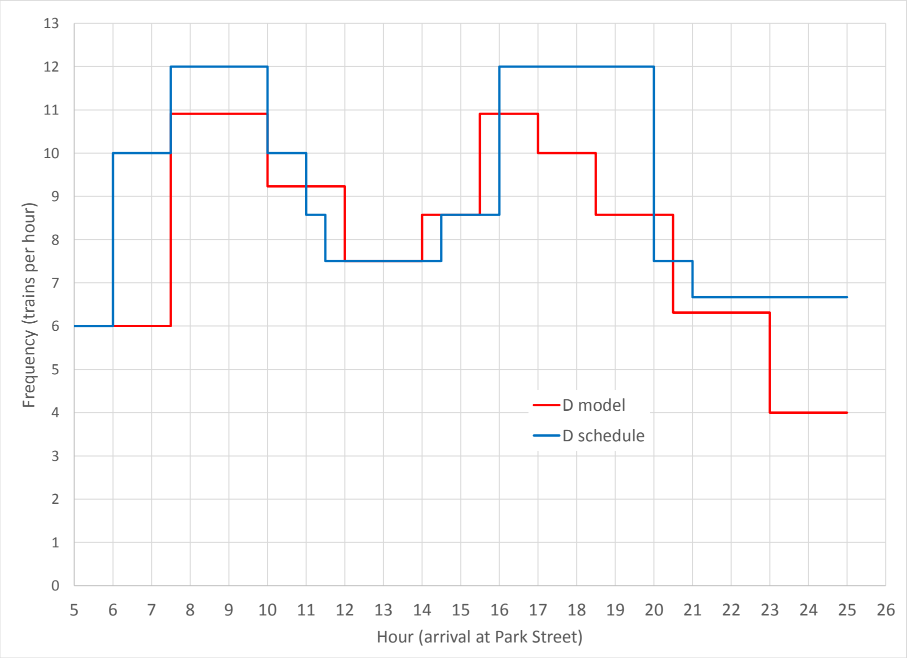


Figure A-9: Currently scheduled and model-proposed frequencies on the D Branch

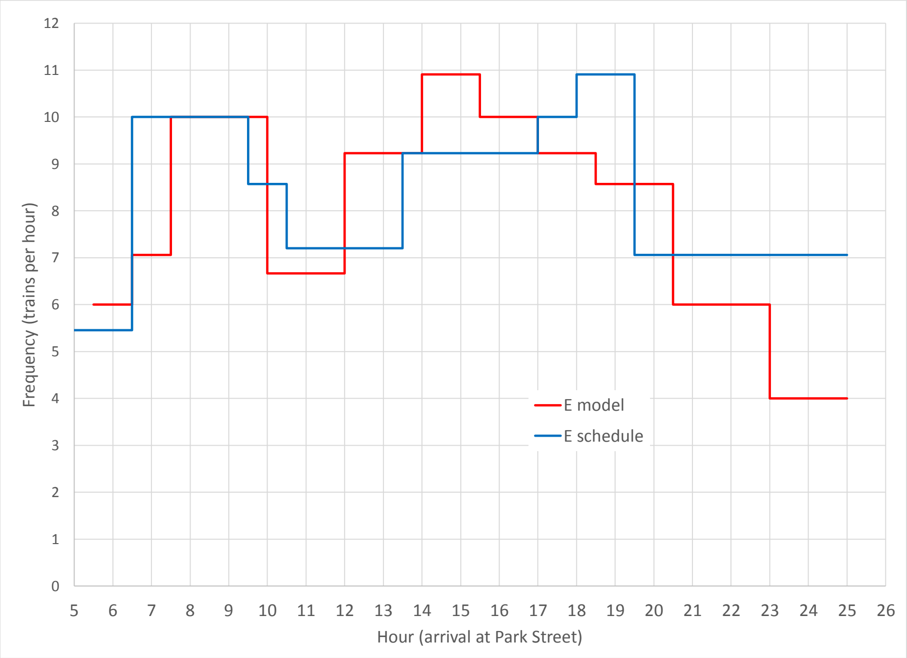


Figure A-10: Currently scheduled and model-proposed frequencies on the E Branch

A.6 Recommended improvements

This demonstration version shows the potential value of matrix-based optimization methods for evaluating service patterns. However, the limited time available for fully specifying and coding a nonlinear optimization model meant that many potential avenues for improvement were left untested.

A.6.1 Nonlinear model

The current version of the model has three significant flaws. First, optimizing on vehicle count rather than a crowding-based metric results in unused cars and higher-than-necessary crowding at some times. Second, attempting to equalize the loads between branches ignores loads elsewhere on the system. Third, the post-optimization smoothing procedure results in car counts different (and generally higher) from those used to optimize.

There is potential to use a nonlinear solver, such as the fmincon routine in MATLAB, to improve the results of the model. A nonlinear solver can take a complex function — in this case, a weighted-sum crowding metric — that is not necessarily a linear function of the decision variables. This nonlinear function can even have subroutines like the smoothing algorithm built in, so that the optimizer works on the same values that the final output will produce. Nonlinear optimization does have some downsides: specifying and debugging is more difficult, and neither global optimization nor even finding a local optimum are guaranteed as they are with linear optimization.

Such a nonlinear model, with sufficient development, would theoretically produce a more optimized vehicle allocation and allow accurate comparison of potential service patterns. This development should also include the development of a more intuitive interface to allow planners to easily use the model.

A.6.2 Scenario testing

Because the model can accept an arbitrary number of services and segments, it lends itself well to testing different service routings. Several additional types of scenarios would be useful to evaluate with a fully validated model.

Which services run to which downtown terminals has been frequently changed during the history of the Green Line. This has usually been based on operational reasons (like higher reliability on the surface branches that are through-routed to Lechmere) rather than understanding where passengers are headed. Using the transfer model presented earlier will fill this gap, while the model can then provide allocation and headway recommendations for the scenarios that are best for passengers.

The mixed-traffic section of the E Branch past Brigham Circle is extremely unreliable; the MBTA wishes to see whether scheduled short turns at Brigham Circle can provide improved service on the inner branch while not reducing Heath Street service below acceptable levels. Other short turns — Reservoir, Coolidge Corner, Washington Street, and the potential for a Harvard Avenue turnback added during upcoming street reconstruction can also be analyzed.

The pending Green Line Extension will add two northside branches from Lechmere, with the opportunity for northside trains to turn at Government Center, Blandford Street, or be through-routed to any of the four western branches. Using estimated demand, adding segments to the model allows for predicting service parameters after the GLX opens. A 36-segment possibility with short turns and the GLX is shown in Figure A-11.

The potential introduction of positive train control may reduce maximum frequency through the Central Subway, making it advantageous to turn some or all trains from either the C or D Branch at Kenmore. The model can cast light on the practicality of this.

Twenty-four new Type 9 cars will begin arriving in 2018, but the GLX for which they were intended will not come until 2021. Additionally, more Type 7 cars will be in service after the current overhaul program finishes. This raises the possibility of alternate service patterns with the larger fleet, including running single low-floor cars at higher frequency during off-peak periods on some lines.

Several additional scenarios involve extensions that have current serious proposals, but are not programmed to be built. These include an extension of the Medford Branch of the

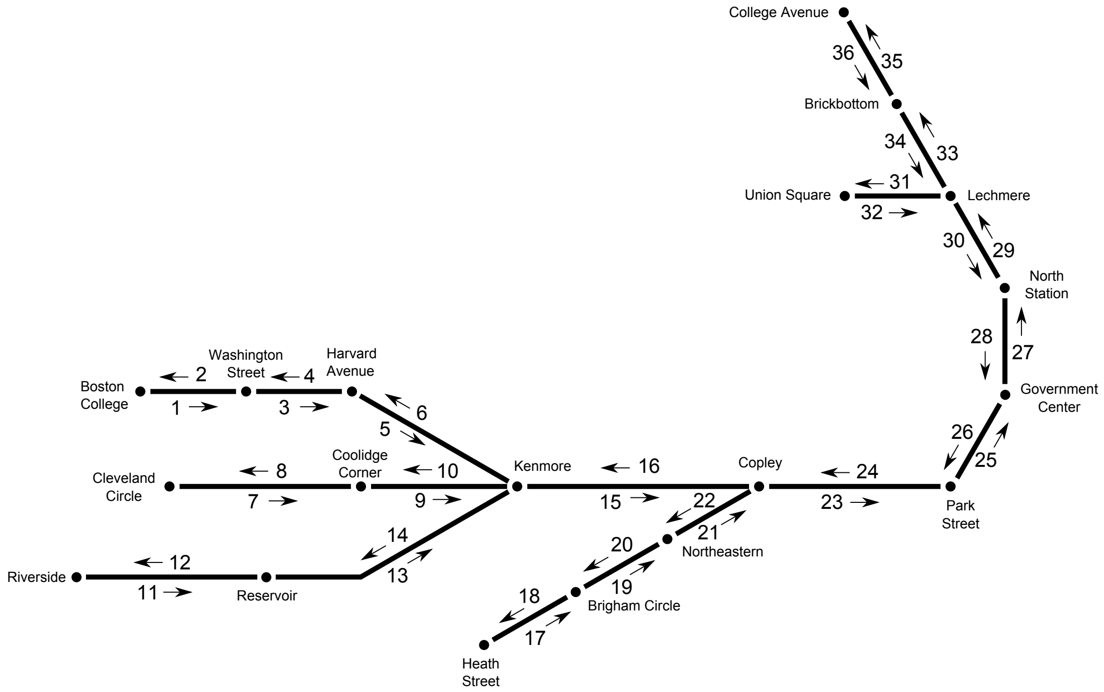


Figure A-11: Diagram of an expanded 36-segment model

GLX to Route 16, an extension of the E Branch to Hyde Square, and a new branch from Boylston to Dudley Street Terminal.

Appendix B

Excluding improper running times

The Green Line is a complex system which uses three different data sources; even with a highly developed cleaning algorithm, there are still errors which necessitate exclusion of data believed to be unreliable. The current interpolation code sets a limit of around 35 mph when interpolating more than 2.5 miles at a time; this limits inaccurate interpolations on the D Branch, but still allows some questionably short times on the other branches and in the Central Subway. Extremely long running times are more common; they are often due to service disruptions or equipment failure (rather than merely slow but operational trains) or missing data causing a train to be interpolated as traveling much more slowly than in reality. The raw running times for any given segment thus generally roughly follow a normal distribution with a long tail.

Malikova (2012) excluded running times longer than 1.5 times the average for each branch; and because she only used AVI data with no interpolated data, too-short running times were not an issue. This analysis uses numerically set exclusion limits for seven types of running times — the two directional surface segments, the two directional tunnel segments, the two directional running times, and the overall running time — for all four branches. The exclusions cascade up; for example, a train with a reasonable eastbound surface running time and total eastbound running time but a too-long eastbound tunnel time would have its eastbound surface time included, but total eastbound running time excluded. The valid data (including well-interpolated data) typically represents over 98% of the total segment running times generated, so this does not remove significant amounts of data; however, failing to remove the questionable data would have significantly skewed the 90^{th} and 95^{th} percentile times used for scheduling.

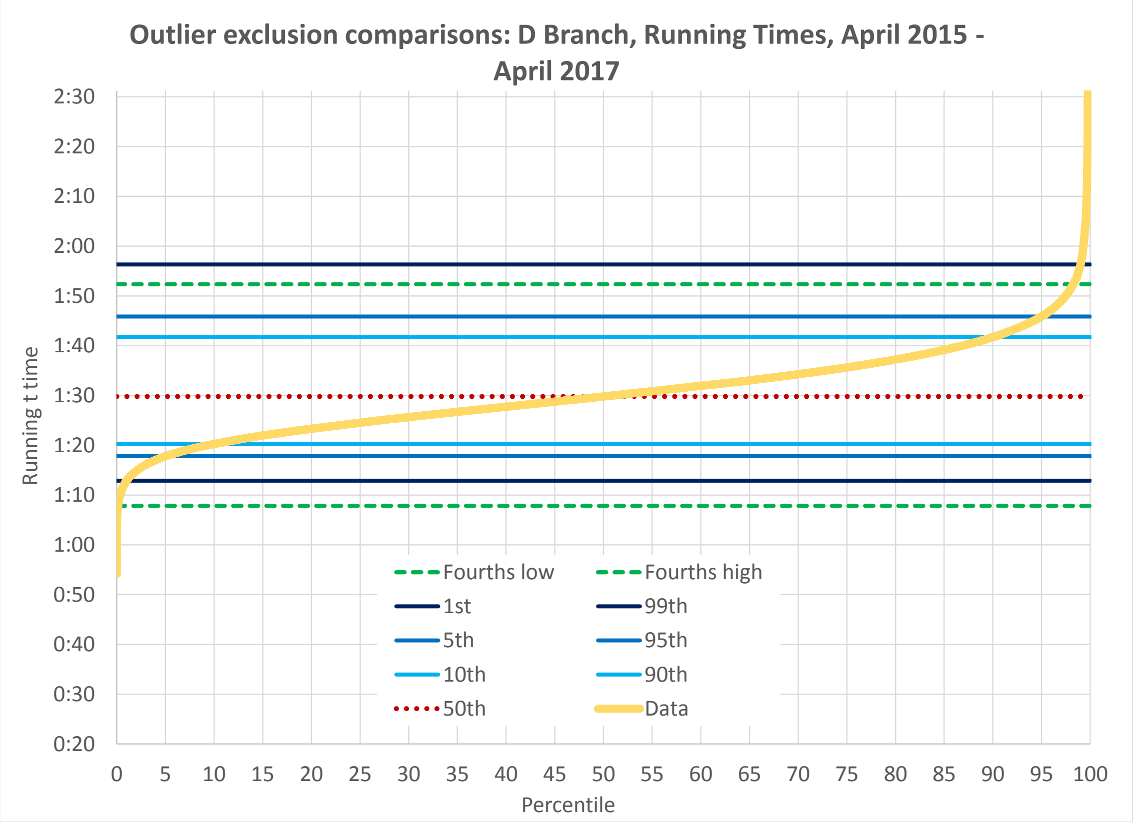


Figure B-1: Distribution of D Branch round trip running times (not including turnaround times), April 2015 — April 2017, with IQR and percentiles marked.

Statistical methods were used to attempt to eliminate outliers. The usual method for eliminating outliers is the fourths spread or interquartile range (IQR) method. The IQR is equal to the 75^{th} percentile minus the 25^{th} percentile. In this method, outliers are defined as those more than 1.5 times the IQR less than the 25^{th} percentile, or more than 1.5 times the IQR more than the 75^{th} percentile. This method performs well with the lower bound, where it eliminates less than one percent of data but excludes running times clearly resulting from false interpolation. However, on the upper bound, the long tail presents an issue. The IQR method often eliminates one to five percent of running times, including some long but real running times. For this upper bound, the 99^{th} percentile is used instead as the cutoff. While not as empirically based as the IQR method, it represents a more realistic boundary between service disruptions and mere delays. A typical example of running time distributions, showing percentile and IQR breaks, is shown in Figure B-1.

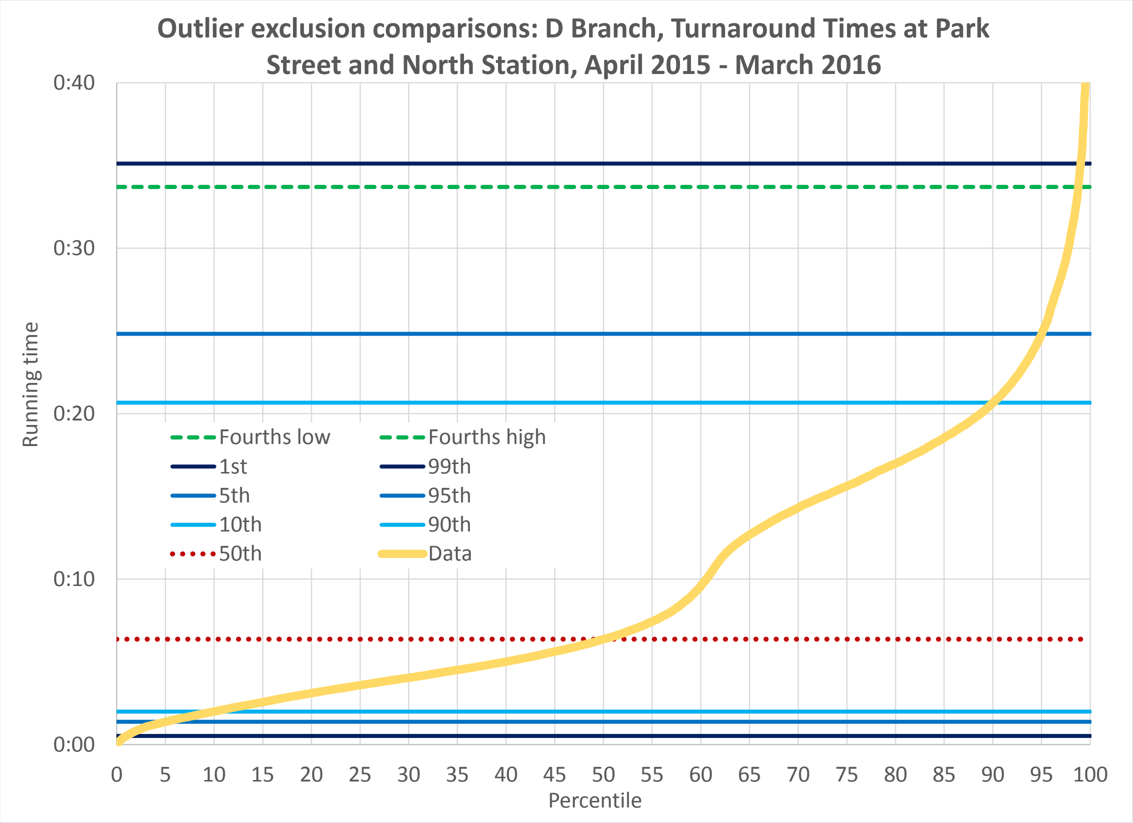


Figure B-2: Distribution of D Branch turnaround times, April 2015 — March 2016. The distribution is bimodal due to service patterns during this period: peak trains turned at the Park Street or Government Center, while off-peak trains turned at North Station.

Turnaround time presents an additional problem. Since proxy times are used instead of real turnaround times when computing cycle times, observed turnaround times different than normal will not affect the results of this analysis. Nor do extremely long turnaround times necessarily indicate bad data — trains can be held out of service at the North Station tail tracks or in Lechmere Yard without impeding operations, and an overly long turnaround time for a B or D train often means the train was extended to cover a gap in service to North Station or Lechmere. However, overly long turnaround times must be excluded due to the manner in which running times were calculated. For example, a 9:00 am eastbound arrival at Park Street might go out of service at North Station at 9:15, lay over for seven hours,

	B Branch		C Branch		D Branch		E Branch	
	min	max	min	max	min	max	min	max
Running	1:02	1:50	0:53	1:41	1:08	1:56	0:55	1:43
Eastbound surface	0:18	0:43	0:09	0:28	0:20	0:41	0:07	0:27
Eastbound tunnel	0:07	0:23	0:12	0:30	0:11	0:26	0:13	0:36
Eastbound	0:30	1:00	0:24	0:54	0:33	1:02	0:24	0:57
Westbound surface	0:18	0:41	0:09	0:26	0:19	0:42	0:08	0:23
Westbound tunnel	0:07	0:24	0:14	0:34	0:11	0:23	0:16	0:34
Westbound	0:28	0:55	0:25	0:55	0:32	1:00	0:27	0:53
Turnaround (2015-2016)	0:00	0:19	0:00	0:18	0:00	0:33	0:00	0:04
Turnaround (2016-2017)	0:00	0:17	0:00	0:17	0:00	0:14	0:00	0:07

Table B.1: Weekday exclusion points for all four branches used in this analysis

and not complete its westbound trip until 5:00 pm. The two directions could be considered separately; however, this would ignore a very real correlation between the two directions for many trains, and likely underestimate the higher percentiles. Instead, exclusions are necessary to prevent the westbound trip from being binned into the 9:00 to 10:00 period. The allowed range is set from 0 minutes to the upper IQR break. Because the D Branch terminal was changed in March 2016, a different exclusion was computed for March 2016 — April 2017. An example distribution of turnaround times is shown in Figure B-2.

The exclusion points used in this analysis are shown in Table B. They were hard-coded into the queries used in this running time analysis; however, it would be possible to dynamically generate them. The values given are for weekdays only (weekends generally have faster running times), with a number of days excluded as discussed later.

Appendix C

List of days excluded from service analysis

Table C.1: Holidays and other dates excluded from analysis, April 2015 — April 2017

DOY	DOW	Date	Branch(es)	Description
110	Mon	4/20/2015	All	Patriot's Day (Marathon Monday)
114	Fri	4/24/2015	All	Free Fare Day
145	Mon	5/25/2015	All	Memorial Day
184	Fri	7/3/2015	All	Independence Day (observed)
185	Sat	7/4/2015	All	Independence Day
250	Mon	9/7/2015	All	Labor Day
285	Mon	10/12/2015	All	Columbus Day
315	Wed	11/11/2015	All	Veteran's Day
328	Tue	11/24/2015	All	Travel day for Thanksgiving
329	Wed	11/25/2015	All	Travel day for Thanksgiving
330	Thu	11/26/2015	All	Thanksgiving
331	Fri	11/27/2015	All	Travel day for Thanksgiving
332	Sat	11/28/2015	All	Travel day for Thanksgiving
333	Sun	11/29/2015	All	Travel day for Thanksgiving

Table C.1 – continued from previous page

DOY	DOW	Date	Branch(es)	Description
357	Wed	12/23/2015	All	Travel day for Christmas
358	Thu	12/24/2015	All	Travel day for Christmas
359	Fri	12/25/2015	All	Christmas
360	Sat	12/26/2015	All	Travel day for Christmas
365	Thu	12/31/2015	All	New Year's Eve
1	Fri	1/1/2016	All	New Year's Day
18	Mon	1/18/2016	All	MLK Day
46	Mon	2/15/2016	All	Presidents Day
77	Thu	3/17/2016	All	St Patrick's Day
109	Mon	4/18/2016	All	Patriot's Day (Marathon Monday)
151	Mon	5/30/2016	All	Memorial Day
186	Mon	7/4/2016	All	Independence Day
249	Mon	9/5/2016	All	Labor Day
284	Mon	10/10/2016	All	Columbus Day; playoff game at Fenway Park
316	Fri	11/11/2016	All	Veteran's Day
327	Tue	11/22/2016	All	Travel day for Thanksgiving
328	Wed	11/23/2016	All	Travel day for Thanksgiving
329	Thu	11/24/2016	All	Thanksgiving
330	Fri	11/25/2016	All	Travel day for Thanksgiving
331	Sat	11/26/2016	All	Travel day for Thanksgiving
332	Sun	11/27/2016	All	Travel day for Thanksgiving
358	Fri	12/23/2016	All	Travel day for Christmas
359	Sat	12/24/2016	All	Travel day for Christmas
360	Sun	12/25/2016	All	Christmas
361	Mon	12/26/2016	All	Travel day for Christmas
366	Sat	12/31/2016	All	New Year's Eve
1	Sun	1/1/2017	All	New Year's Day
16	Mon	1/16/2017	All	MLK Day
51	Mon	2/20/2017	All	Presidents Day

Table C.1 – continued from previous page

DOY	DOW	Date	Branch(es)	Description
76	Fri	3/17/2017	All	St Patrick's Day
107	Mon	4/17/2017	All	Patriot's Day (Marathon Monday)

Table C.2: Other dates excluded due to track work, bustitution, or other changes in service or demand, April 2015 — April 2017

DOY	DOW	Date	Branch(es)	Description
89	Mon	3/30/2015	C	C Branch closed due to auto accident
91	Wed	4/1/2015	All	Track issue at Government Center
93	Fri	4/3/2015	D	D Branch closed due to burst pipe nearby
102	Sun	4/12/2015	B	B Branch closed due to auto accident
116	Sun	4/26/2015	D	D Branch closed for maintenance
125	Tue	5/5/2015	D	D Branch closed due to power issues
129	Sat	5/9/2015	D	D Branch closed for maintenance
130	Sun	5/10/2015	D	D Branch closed for maintenance
149	Fri	5/29/2015	D	D Branch closed due to tree on wires
159	Mon	6/8/2015	B	B Branch closed for unknown reason
166	Mon	6/15/2015	B	B Branch closed due to medical emergency
171	Sat	6/20/2015	All	North Station - Lechmere closed due to disabled train at Science Park; D Branch closed for maintenance
172	Sun	6/21/2015	D	D Branch closed for maintenance
177	Fri	6/26/2015	All	Orange Line closed between Back Bay and North Station
178	Sat	6/27/2015	D	D Branch closed for maintenance
179	Sun	6/28/2015	D	D Branch closed for maintenance
184	Fri	7/3/2015	D	D Branch closed due to power issues

Table C.2 – continued from previous page

DOY	DOW	Date	Branch(es)	Description
191	Fri	7/10/2015	B	B Branch closed due to debris falling from bridge over Mass Pike
193	Sun	7/12/2015	C, D	Derailment at Longwood; outer D Branch routed over C Branch
208	Mon	7/27/2015	All	Significant power issue
210	Wed	7/29/2015	E	Derailment at Lechmere
218	Thu	8/6/2015	D	D Branch closed due to power issue
222	Mon	8/10/2015	D	North Station-Lechmere closed due to disabled train
224	Wed	8/12/2015	D	D Branch closed due to power issue
229	Mon	8/17/2015	B	B Branch closed due to disabled train
275	Fri	10/2/2015	D	D Branch closed due to tree on wires
304	Sat	10/31/2015	All	Park Street - Haymarket closed for Government Center construction
305	Sun	11/1/2015	All	Park Street - Haymarket closed for Government Center construction
312	Sun	11/8/2015	All	Derailment at Copley
314	Tue	11/10/2015	E	E Branch closed due to police action
336	Wed	12/2/2015	B	B Branch closed due to car on tracks
337	Thu	12/3/2015	B	B Branch closed due to pedestrian strike
339	Sat	12/5/2015	E	North Station-Lechmere closed for track work
340	Sun	12/6/2015	E	North Station-Lechmere closed for track work
350	Wed	12/16/2015	E	E Branch closed due to manhole fire and power issues
358	Thu	12/24/2015	B	B Branch closed due to auto accident
363	Tue	12/29/2015	B, C	B Branch closed due to power issue; auto strike at Coolidge Corner
12	Tue	1/12/2016	All	Park Street - Haymarket closed for Government Center construction

Table C.2 – continued from previous page

DOY	DOW	Date	Branch(es)	Description
16	Sat	1/16/2016	B	B Branch closed due to car on tracks
30	Sat	1/30/2016	D	Derailment at Reservoir
36	Fri	2/5/2016	All	Multiple bustitutions
44	Sat	2/13/2016	All	Park Street - Haymarket closed for Government Center construction
45	Sun	2/14/2016	All	Multiple major issues across system
47	Tue	2/16/2016	All	Orange Line closed between Back Bay and North Station
49	Thu	2/18/2016	All	Commuter Rail terminated outside South Station due to interlocking failure
51	Sat	2/20/2016	All	Park Street - Haymarket closed for Government Center construction
52	Sun	2/21/2016	All	Park Street - Haymarket closed for Government Center construction
54	Tue	2/23/2016	All	Park Street - Haymarket closed for Government Center construction
55	Wed	2/24/2016	B	B Branch closed due to unknown issue
56	Thu	2/25/2016	All	Park Street - Haymarket closed for Government Center construction
65	Sat	3/5/2016	All	Park Street - Haymarket closed for Government Center construction
66	Sun	3/6/2016	All	Park Street - Haymarket closed for Government Center construction
70	Thu	3/10/2016	B	B Branch closed due to auto accident
74	Mon	3/14/2016	All	Train fire at Kenmore
79	Sat	3/19/2016	All	Derailment at Copley
81	Mon	3/21/2016	All	Delays associated with Government Center reopening

Table C.2 – continued from previous page

DOY	DOW	Date	Branch(es)	Description
85	Fri	3/25/2016	B, C	B Branch closed due to unrelated fire at Boston University; C Branch used to turn trains
94	Sun	4/3/2016	D	D Branch closed due to tree on wires
95	Mon	4/4/2016	C	C Branch closed due to auto accident
97	Wed	4/6/2016	All	Medical emergency at Government Center
104	Wed	4/13/2016	D	D Branch closed due to power issue
121	Sat	4/30/2016	All	Significant power issue
123	Mon	5/2/2016	All	Significant power issue
130	Mon	5/9/2016	B	B Branch closed due to auto accident
134	Fri	5/13/2016	All	Derailment at Park Street
164	Sun	6/12/2016	D	D Branch closed due to tree on wires
165	Mon	6/13/2016	D	D Branch closed for tree removal
182	Thu	6/30/2016	All	Significant power issue
194	Tue	7/12/2016	D	D Branch closed due to wire issue
205	Sat	7/23/2016	D	D Branch closed due to tree on wires
243	Tue	8/30/2016	B, C	Track issue at Boston College; wire issue at Cleveland Circle
277	Mon	10/3/2016	All	Derailment at Copley
281	Fri	10/7/2016	B	B Branch closed due to disabled train
286	Wed	10/12/2016	All	Service suspended due to police action at Park Street
304	Sun	10/30/2016	B	B Branch closed due to derailment
322	Thu	11/17/2016	B	B Branch closed due to track issue
326	Mon	11/21/2016	B	B Branch closed due to auto accident
341	Tue	12/6/2016	D	D Branch closed for tree removal
342	Wed	12/7/2016	D	D Branch closed for tree removal
343	Thu	12/8/2016	D	D Branch closed for tree removal
348	Tue	12/13/2016	D	D Branch closed for tree removal

Table C.2 – continued from previous page

DOY	DOW	Date	Branch(es)	Description
349	Wed	12/14/2016	D	D Branch closed for tree removal
350	Thu	12/15/2016	D	D Branch closed due to tree on wires
351	Fri	12/16/2016	B	B Branch closed due to power issue
352	Sat	12/17/2016	All	Bustitution for maintenance
353	Sun	12/18/2016	All	Bustitution for maintenance
3	Tue	1/3/2017	D	Power problem near Kenmore
21	Sat	1/21/2017	All	High demand due to Women's March
25	Wed	1/25/2015	B	B Branch closed due to power issue
29	Sun	1/29/2017	All	High demand due to protest; Copley closed
32	Wed	2/1/2017	D	D Branch closed for tree removal
33	Thu	2/2/2017	D	D Branch closed for tree removal
35	Sat	2/4/2017	D, E	Tree removal and maintenance work
36	Sun	2/5/2017	B, C, D	Kenmore bypassed during Super Bowl per BPD request
37	Mon	2/6/2017	C	C Branch closed due to auto accident
38	Tue	2/7/2017	All	High demand due to Patriots parade
46	Wed	2/15/2017	C, E	Terminated at Government Center due to police action
61	Thu	3/2/2017	D	D Branch closed due to tree on wires
63	Sat	3/4/2017	E	North Station-Lechmere closed for maintenance
91	Sat	4/1/2017	All	Service disruption between Government Center and Lechmere
97	Fri	4/7/2017	All	Disabled train at Boylston
112	Sat	4/22/2017	C, D	Bustitution between Kenmore and portals

Appendix D

Running and cycle time charts

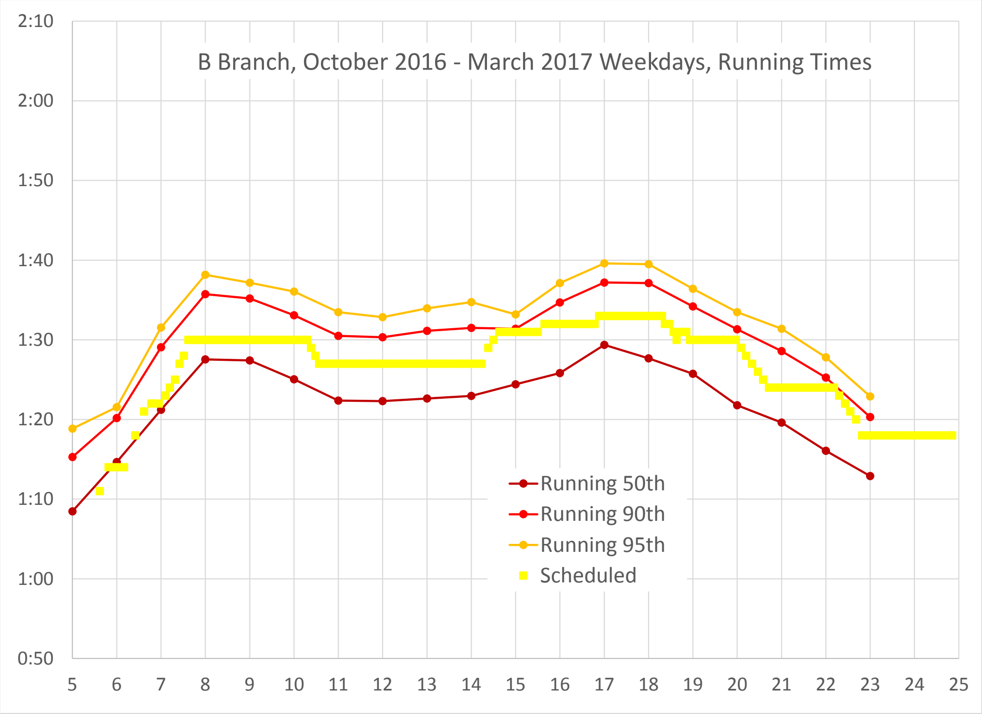


Figure D-1: Observed and scheduled running times for the B Branch

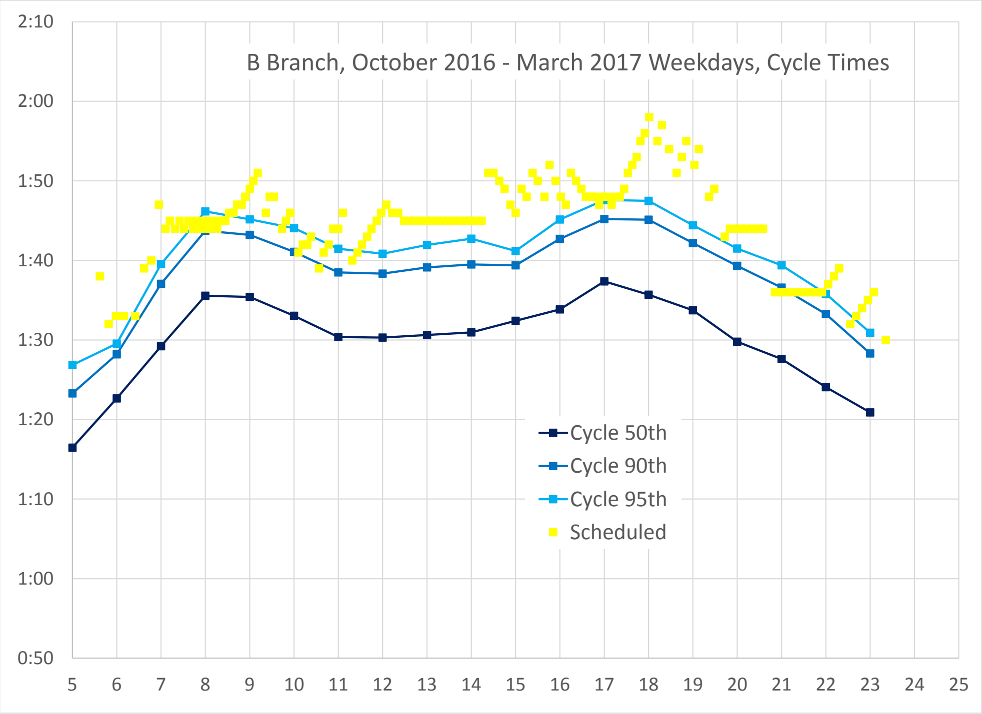


Figure D-2: Observed and scheduled cycle times for the B Branch

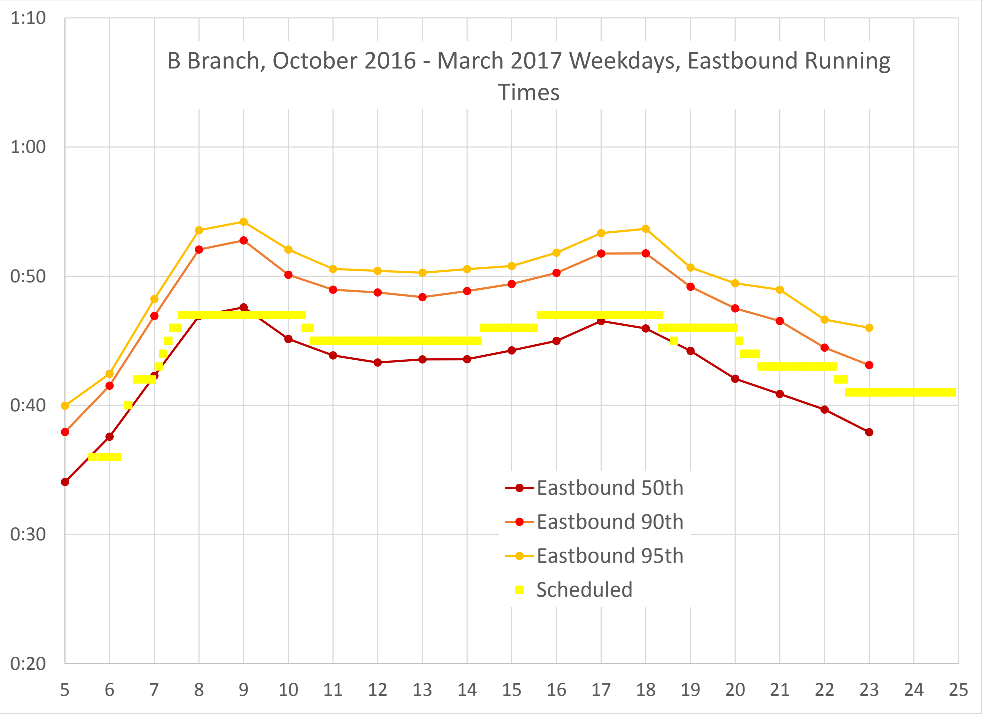


Figure D-3: Observed and scheduled eastbound times for the B Branch

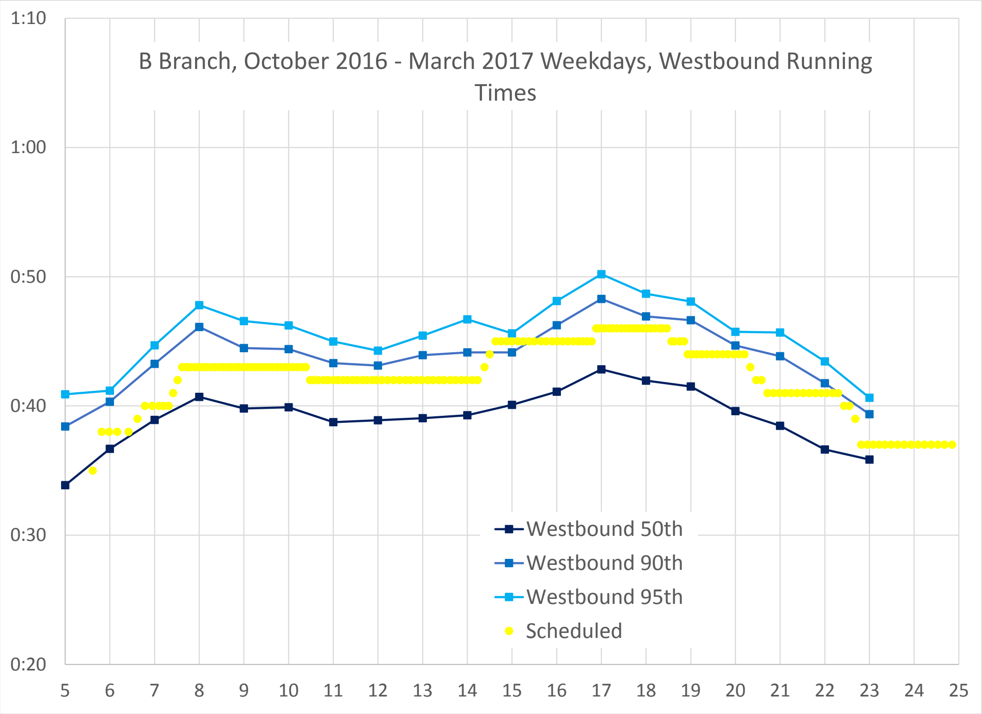


Figure D-4: Observed and scheduled westbound running times for the B Branch

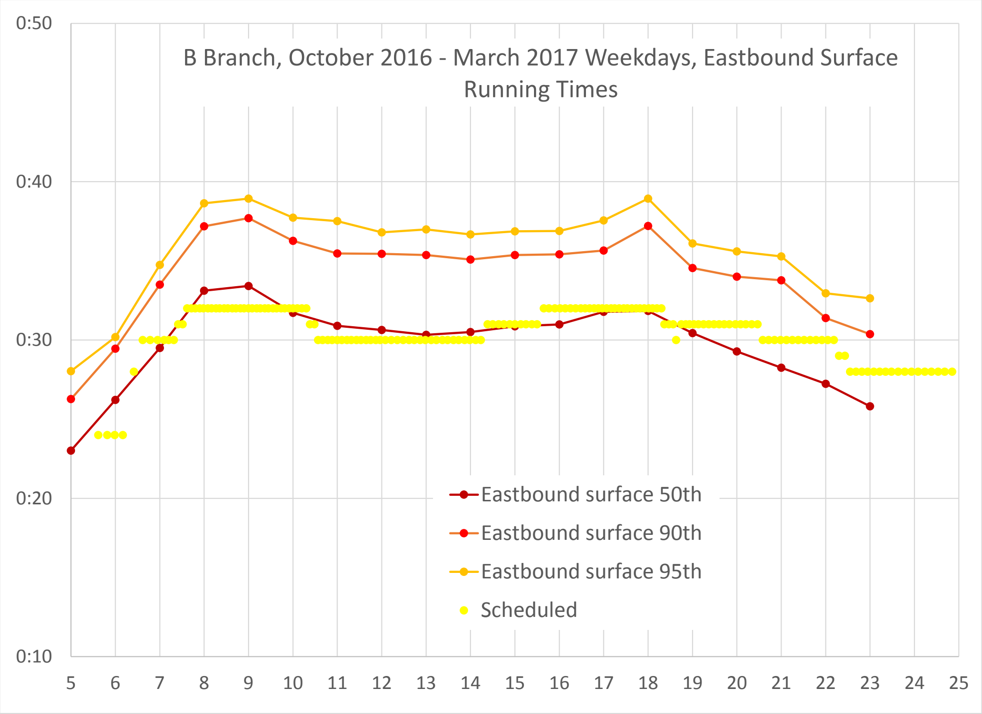


Figure D-5: Observed and scheduled eastbound surface times for the B Branch

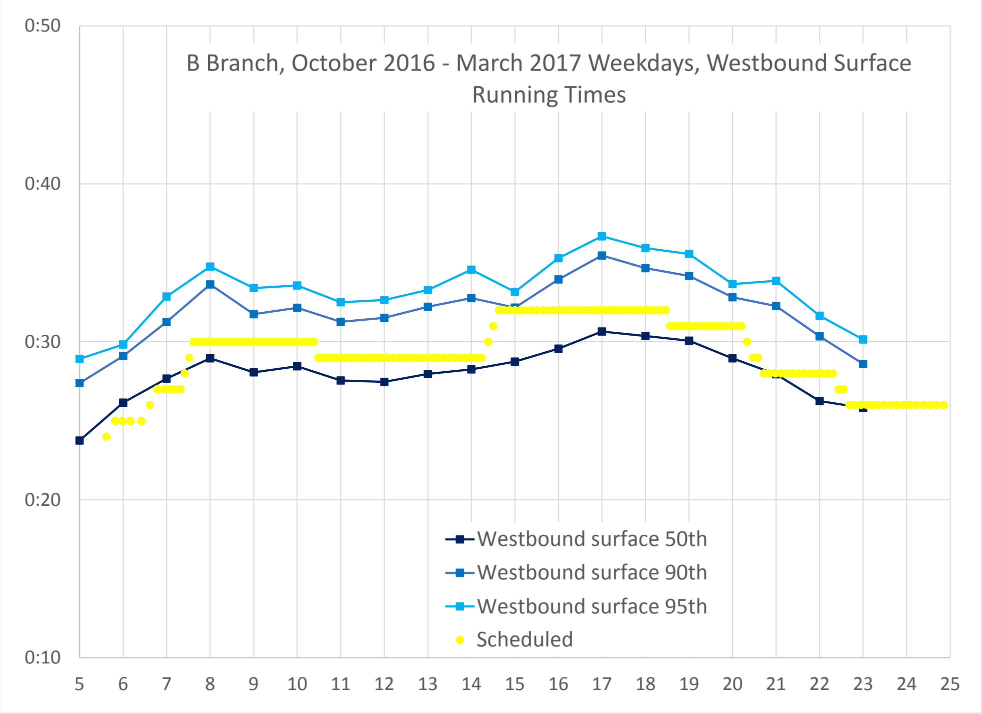


Figure D-6: Observed and scheduled westbound surface running times for the B Branch

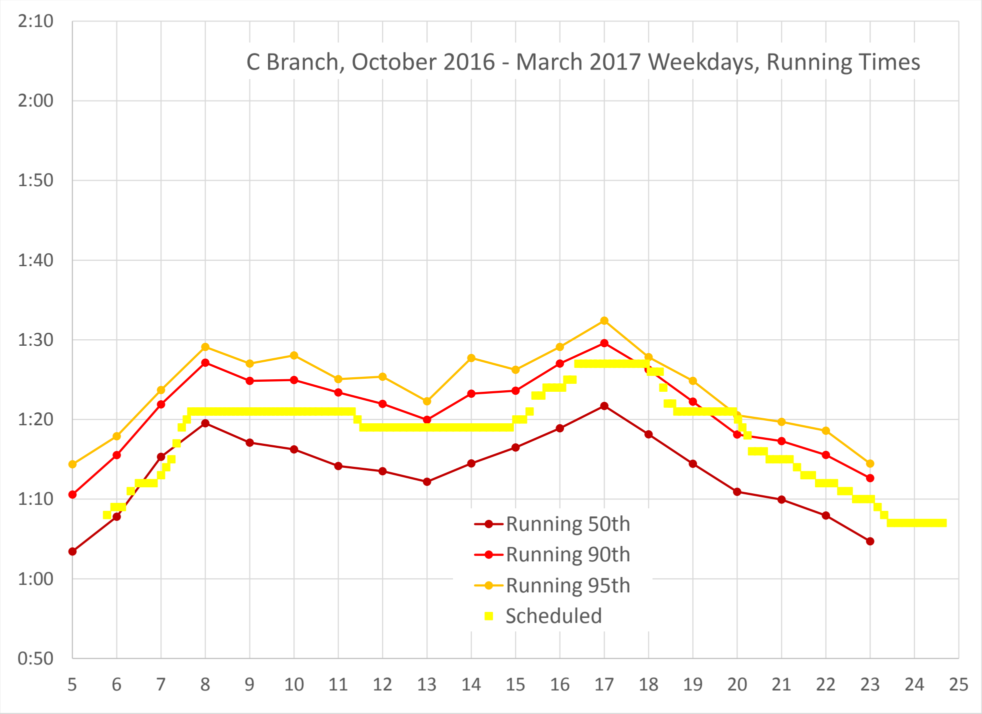


Figure D-7: Observed and scheduled running times for the C Branch

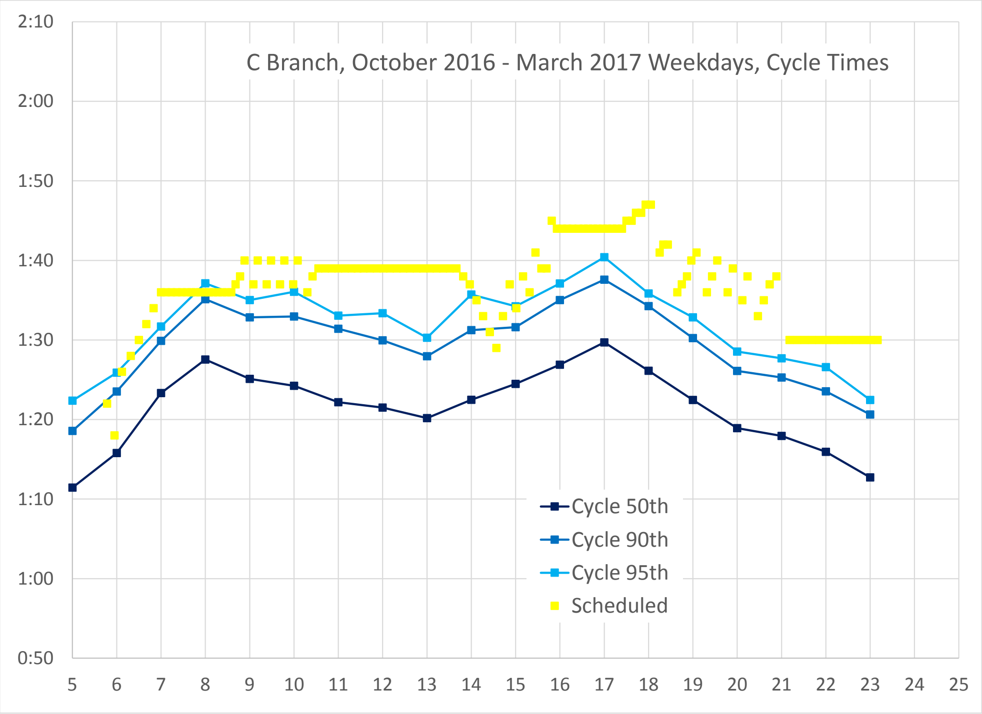


Figure D-8: Observed and scheduled cycle times for the C Branch

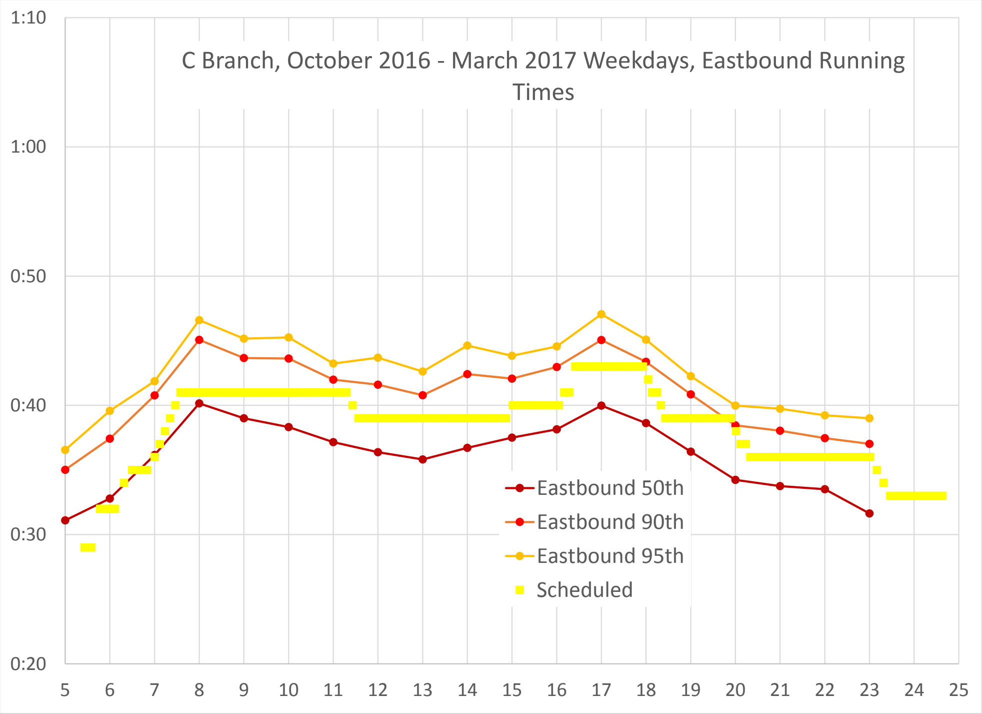


Figure D-9: Observed and scheduled eastbound times for the C Branch

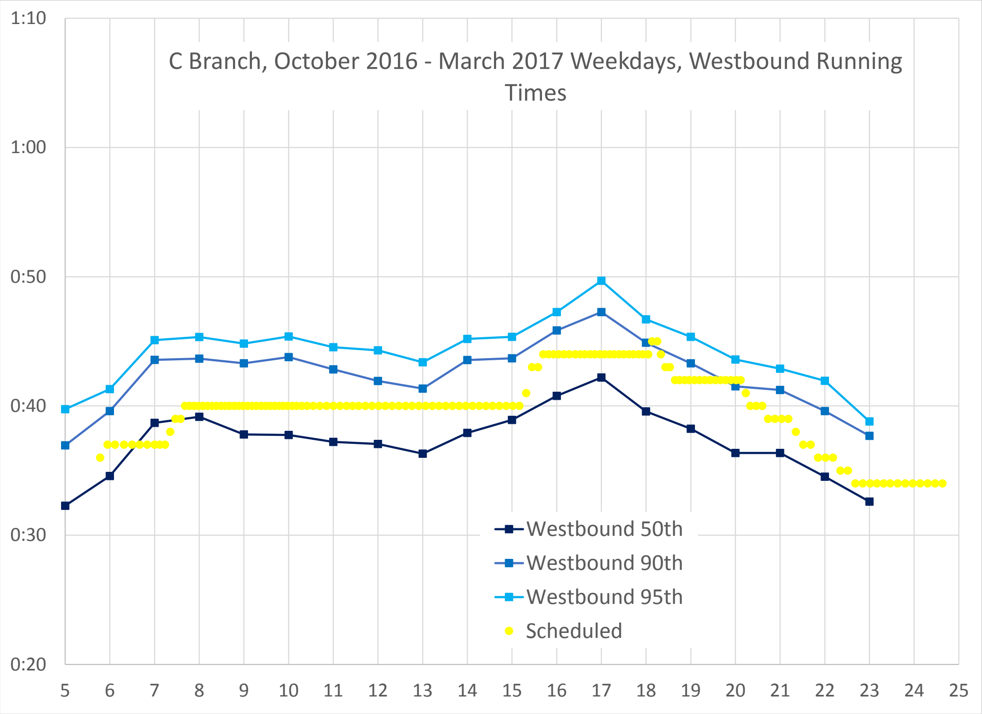
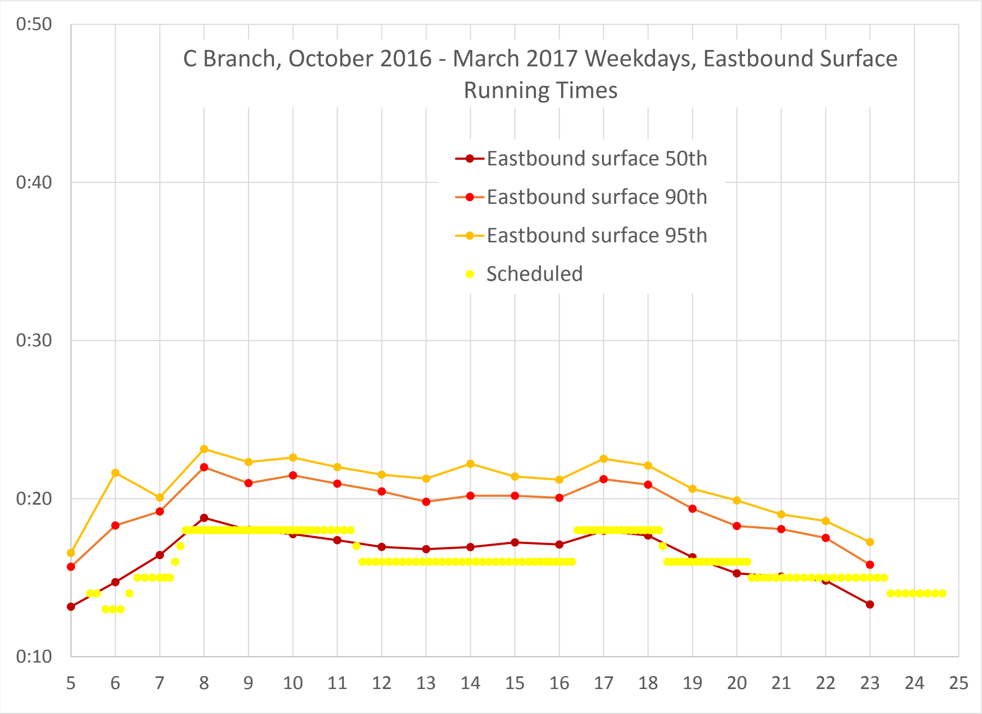


Figure D-10: Observed and scheduled westbound running times for the C Branch



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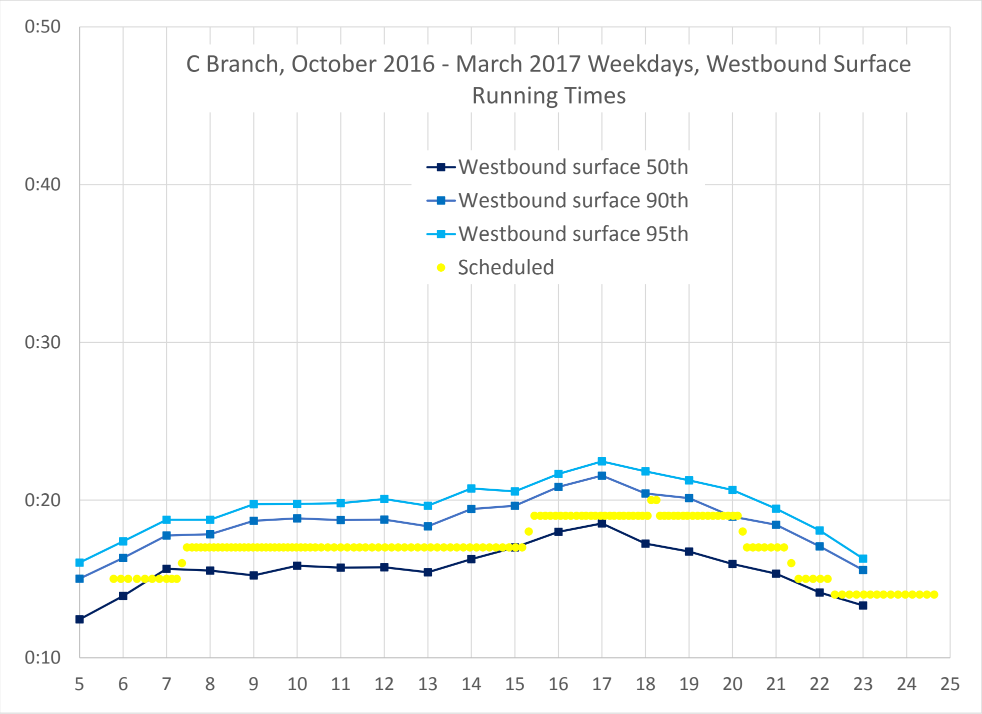

Figure D-12: Observed and scheduled westbound surface running times for the C Branch

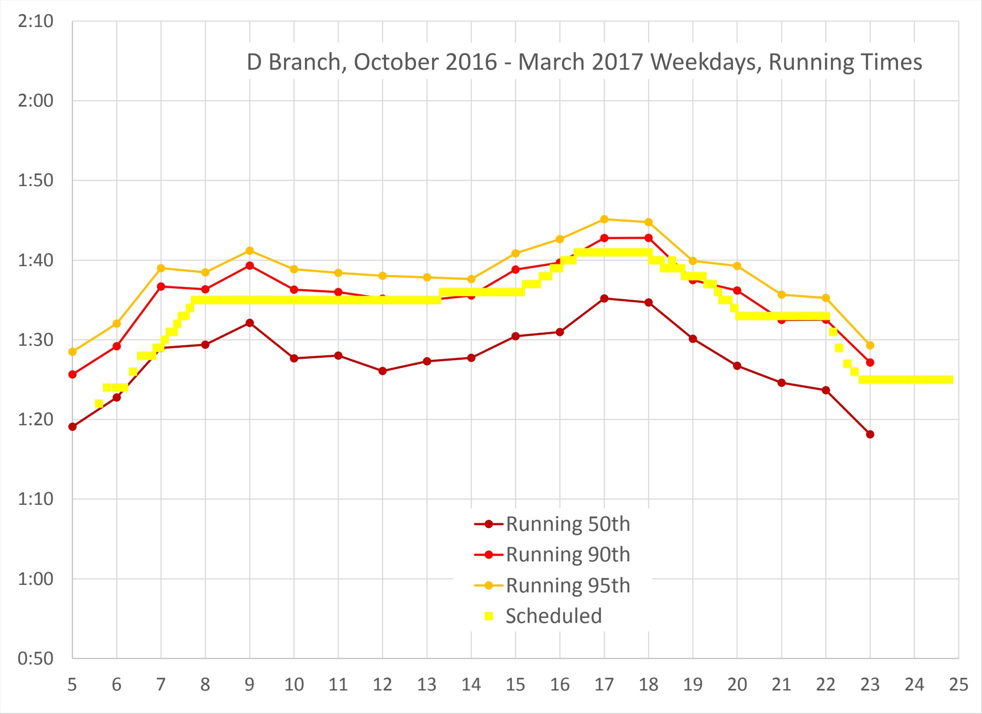

Figure D-13: Observed and scheduled running times for the D Branch

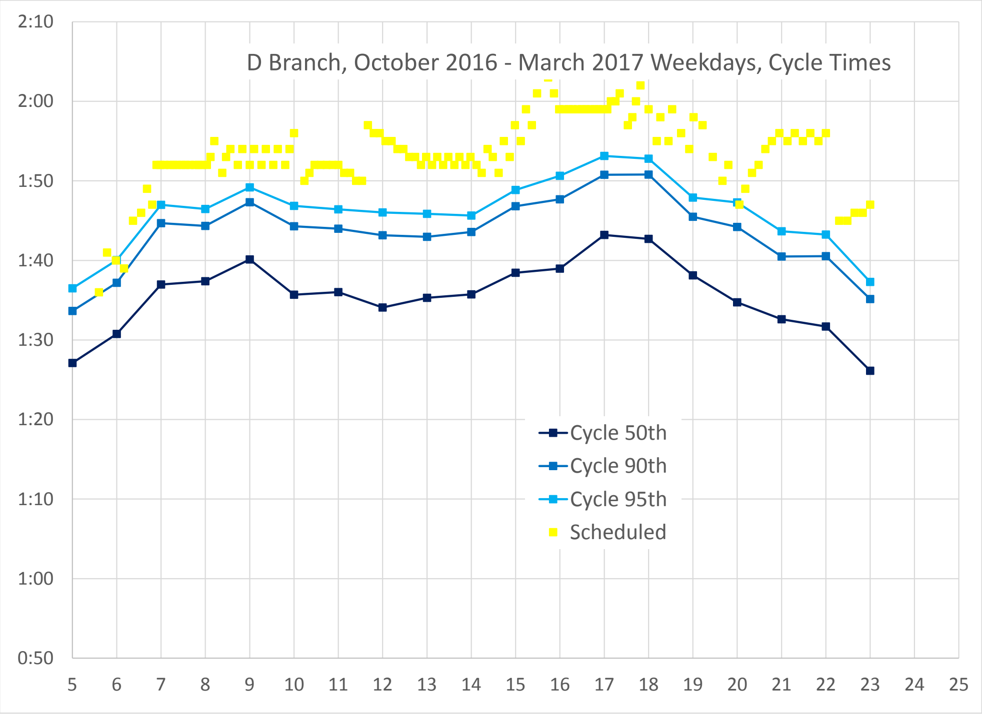

Figure D-14: Observed and scheduled cycle times for the D Branch

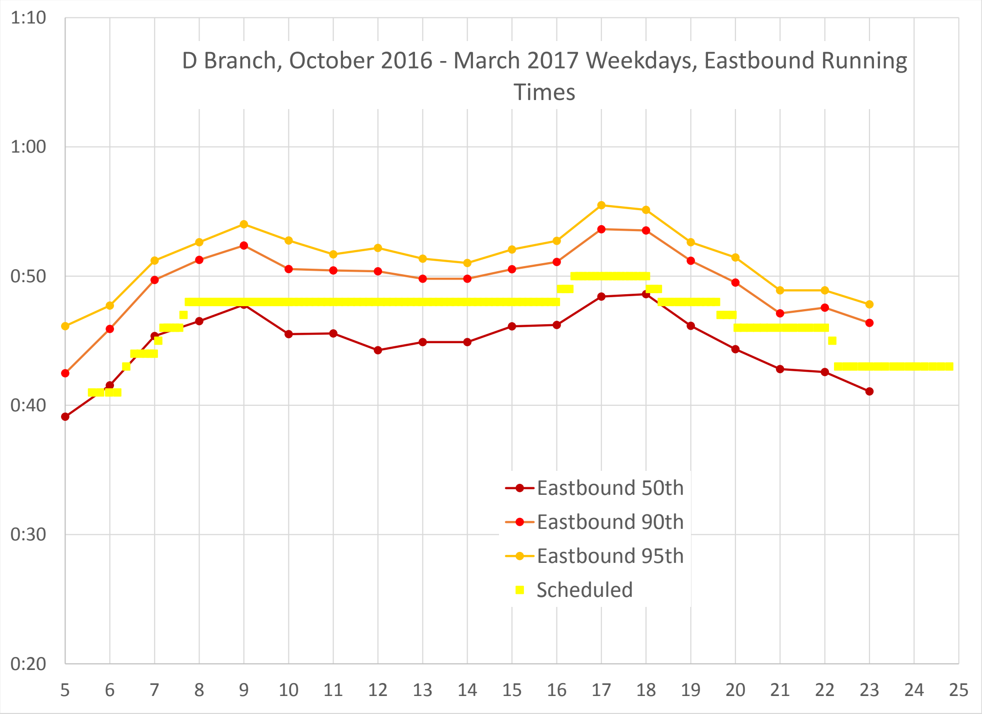

Figure D-15: Observed and scheduled eastbound times for the D Branch

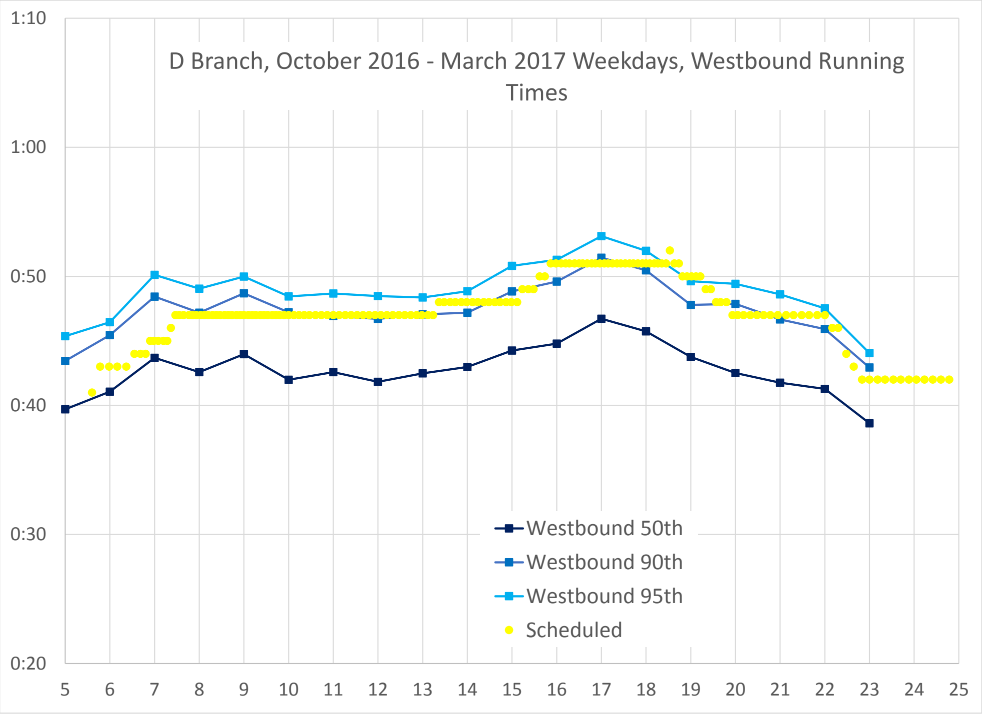

Figure D-16: Observed and scheduled westbound running times for the D Branch

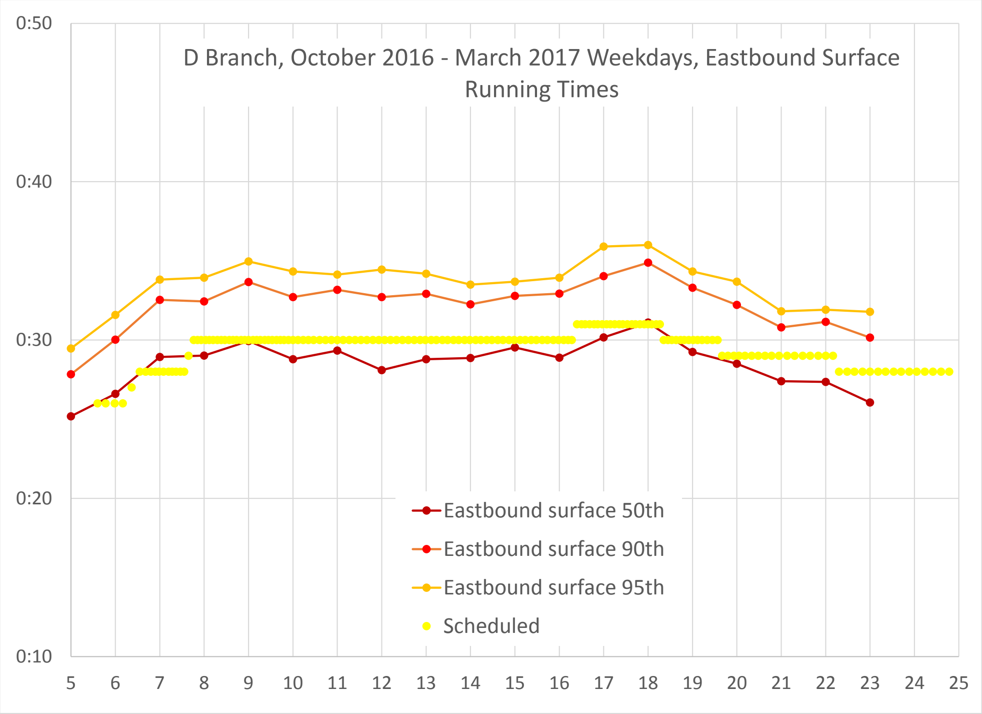

Figure D-17: Observed and scheduled eastbound surface times for the D Branch

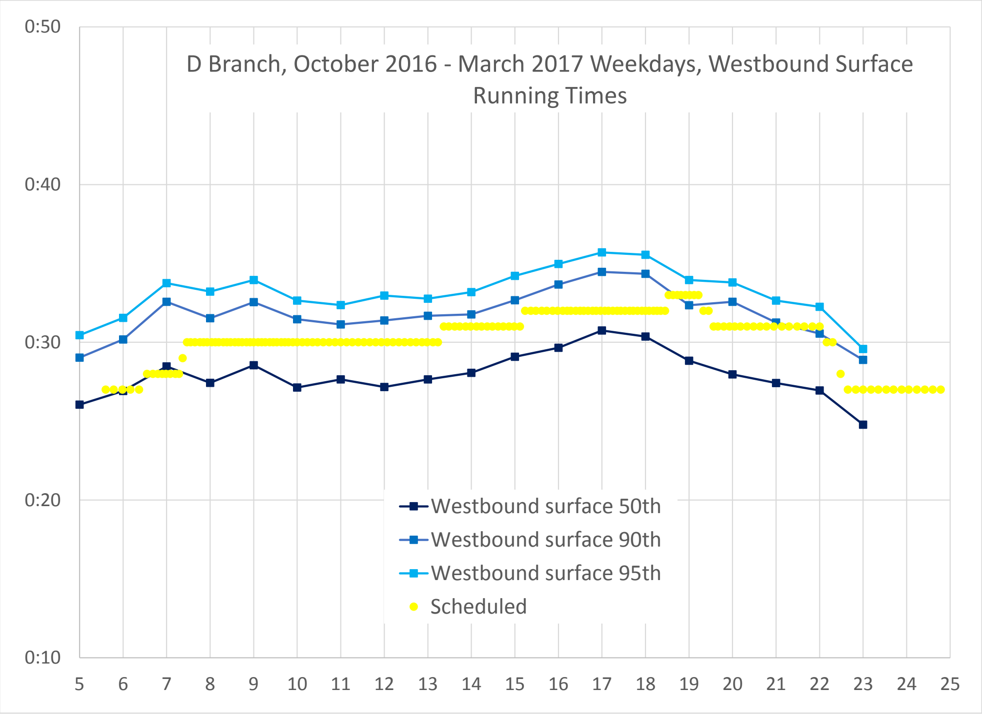

Figure D-18: Observed and scheduled westbound surface running times for the D Branch

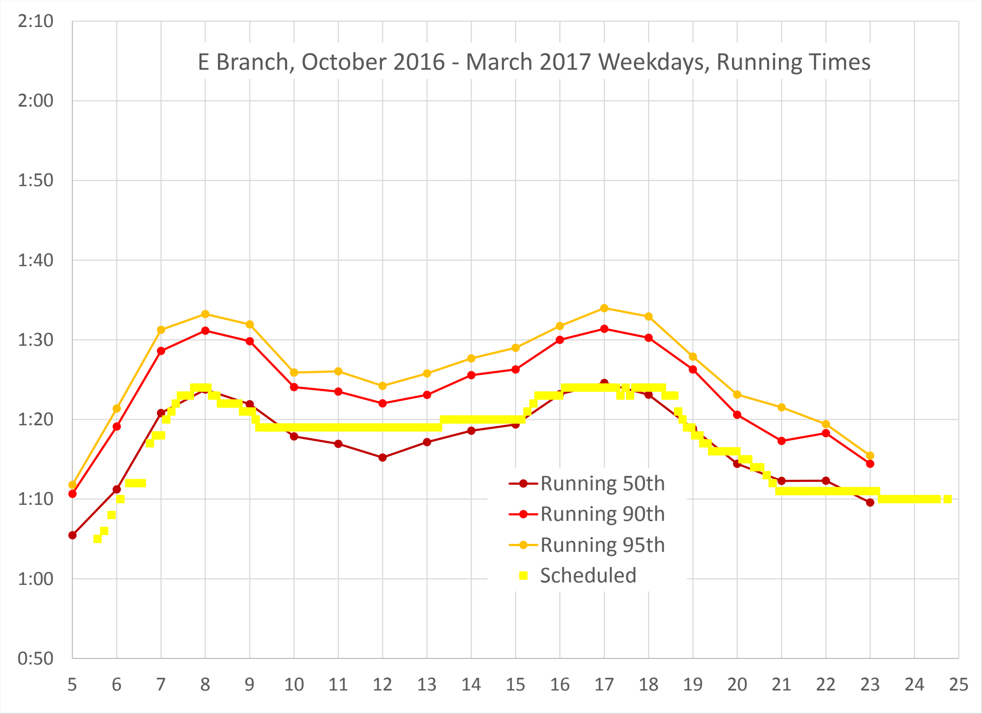

Figure D-19: Observed and scheduled running times for the E Branch

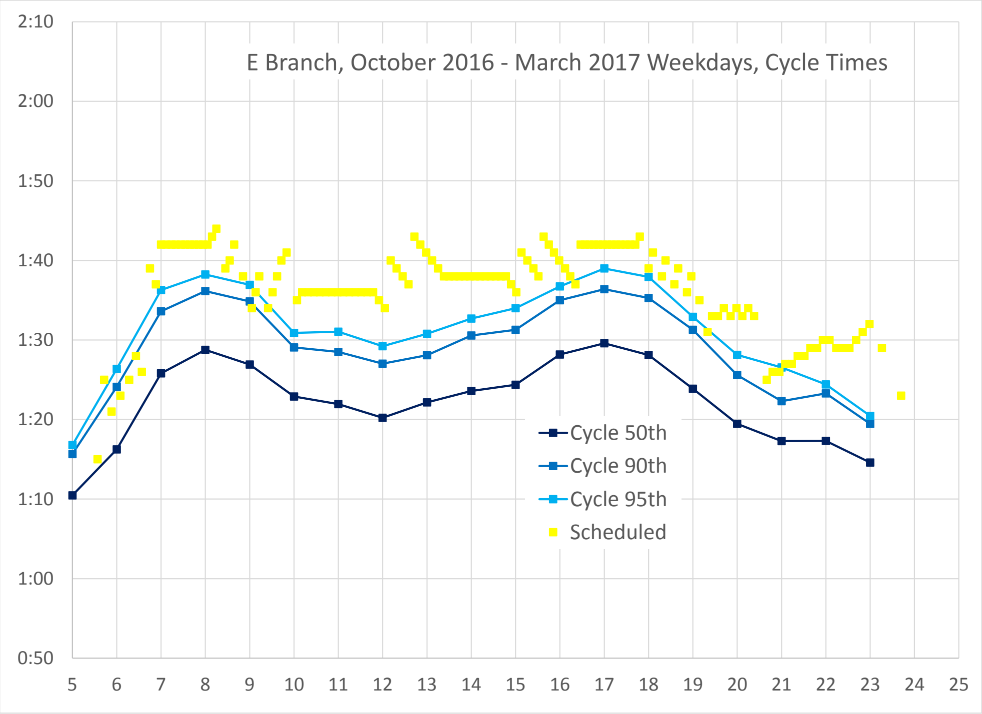

Figure D-20: Observed and scheduled cycle times for the E Branch

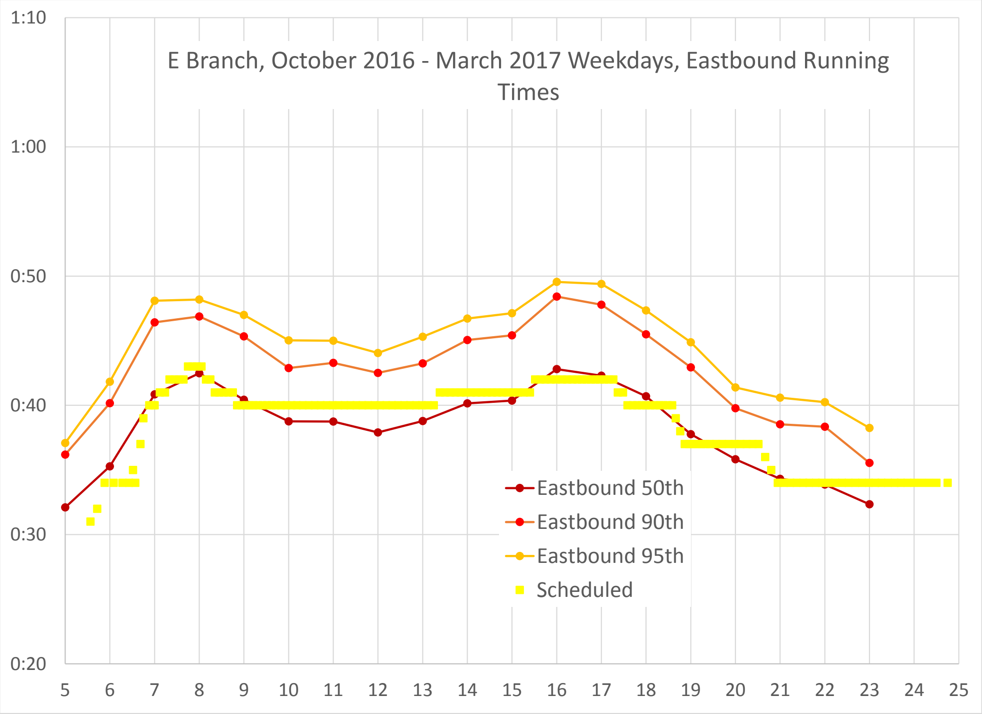

Figure D-21: Observed and scheduled eastbound times for the E Branch

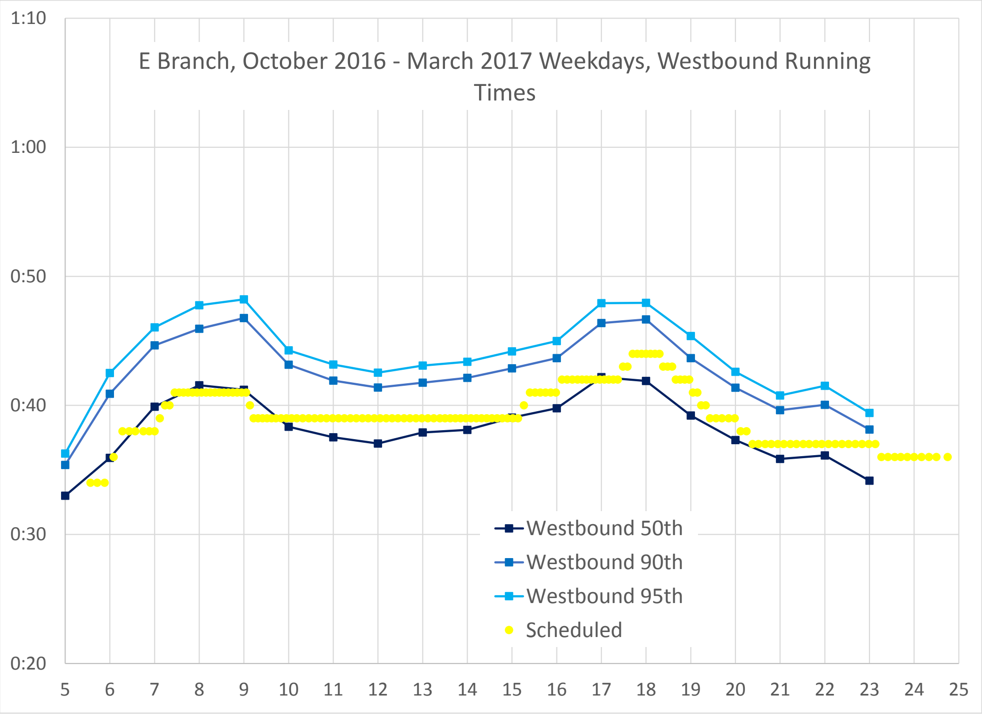

Figure D-22: Observed and scheduled westbound running times for the E Branch

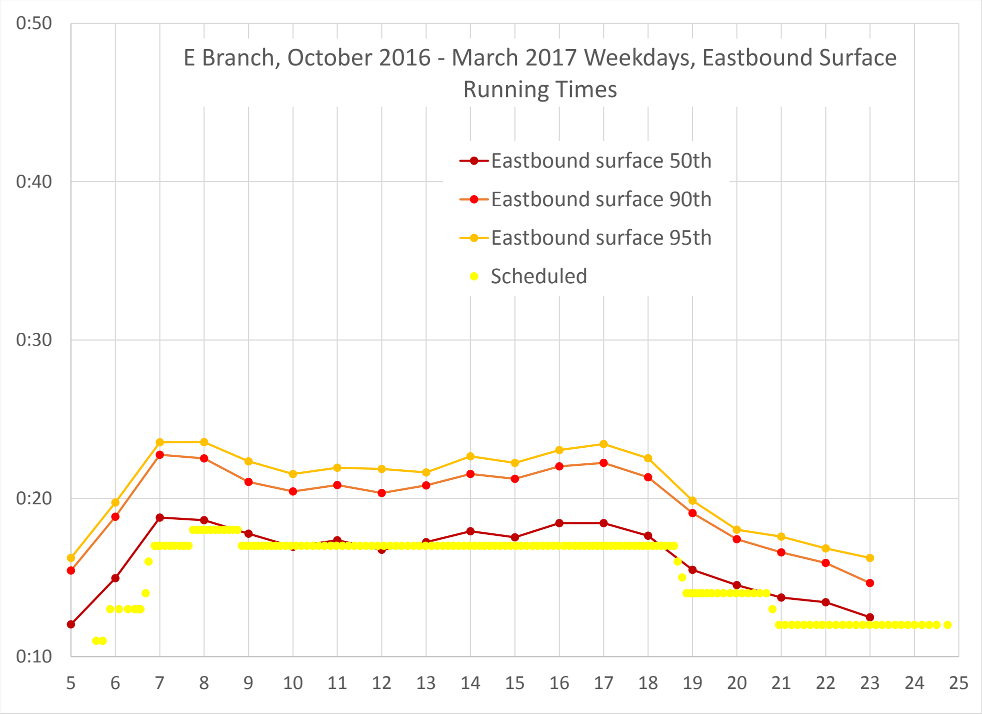

Figure D-23: Observed and scheduled eastbound surface times for the E Branch

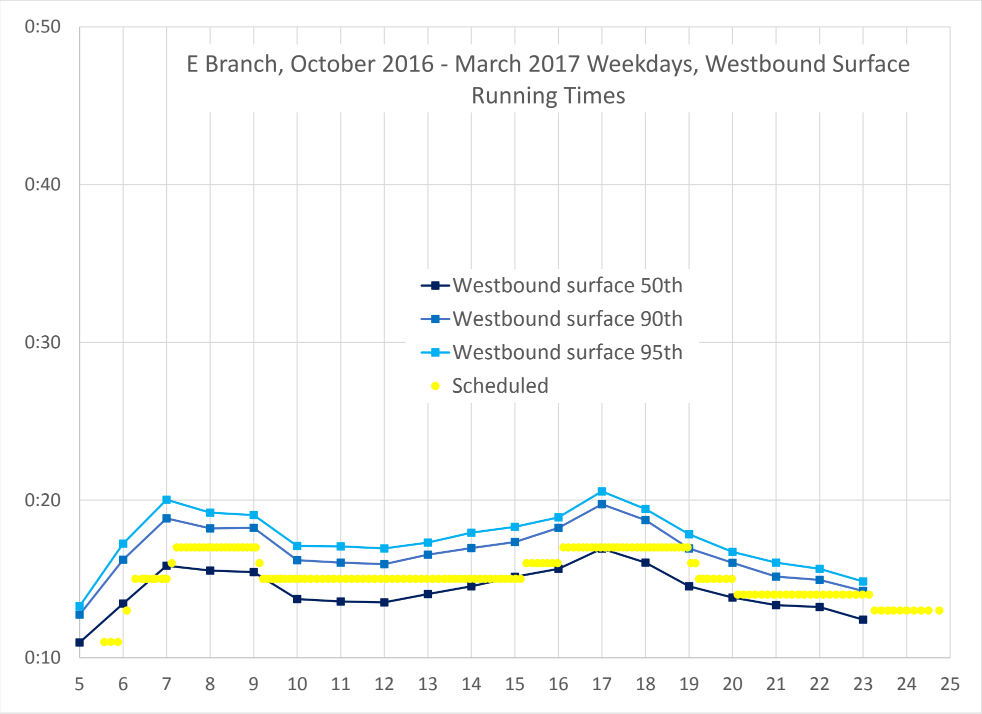

Figure D-24: Observed and scheduled westbound surface running times for the E Branch

Appendix E

Cycle period and trainset requirement charts

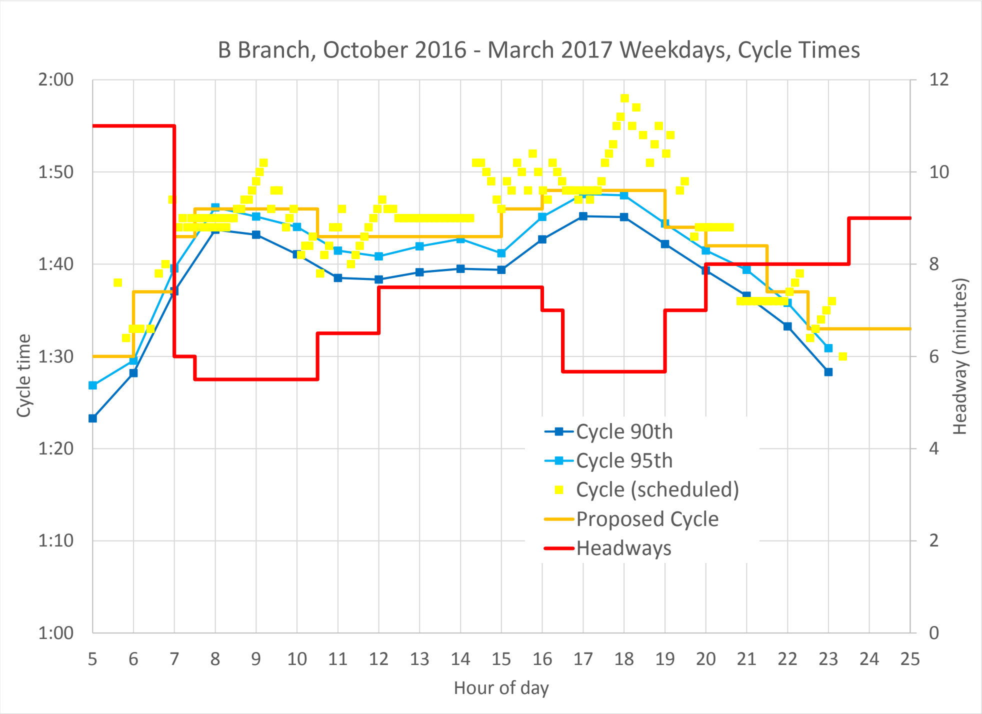

Figure E-1: 90th and 95th percentile running times, smoothed cycle times, and scheduled cycle times and headways on the B Branch for Fall 2016 and Winter 2017

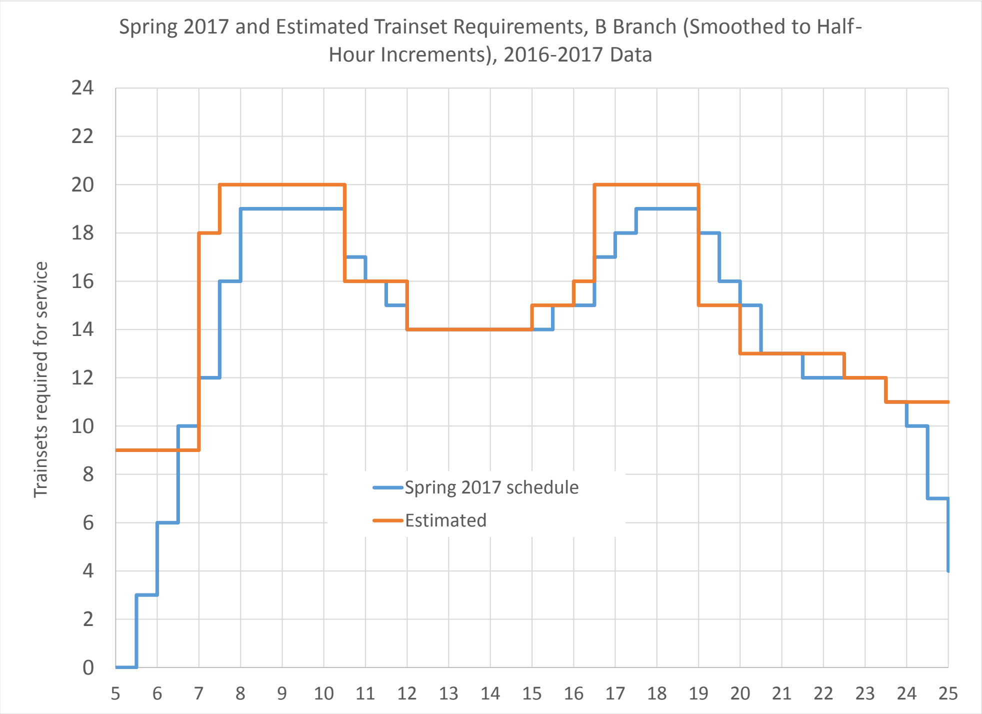

Figure E-2: Estimated trainset requirements on the B Branch

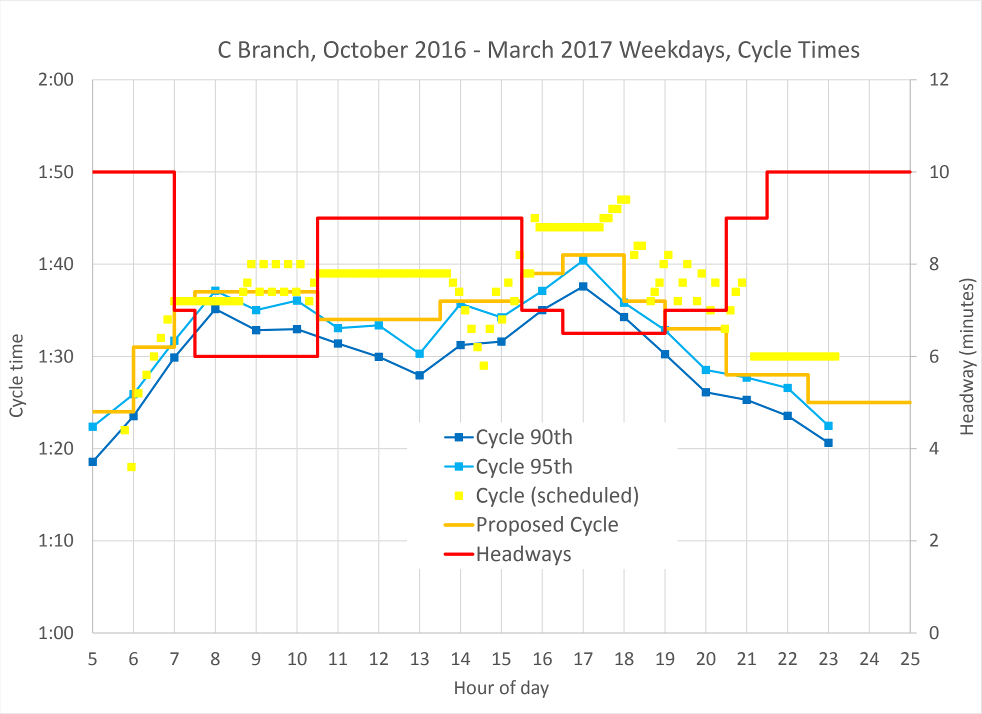

Figure E-3: 90th and 95th percentile running times, smoothed cycle times, and scheduled cycle times and headways on the C Branch for Fall 2016 and Winter 2017

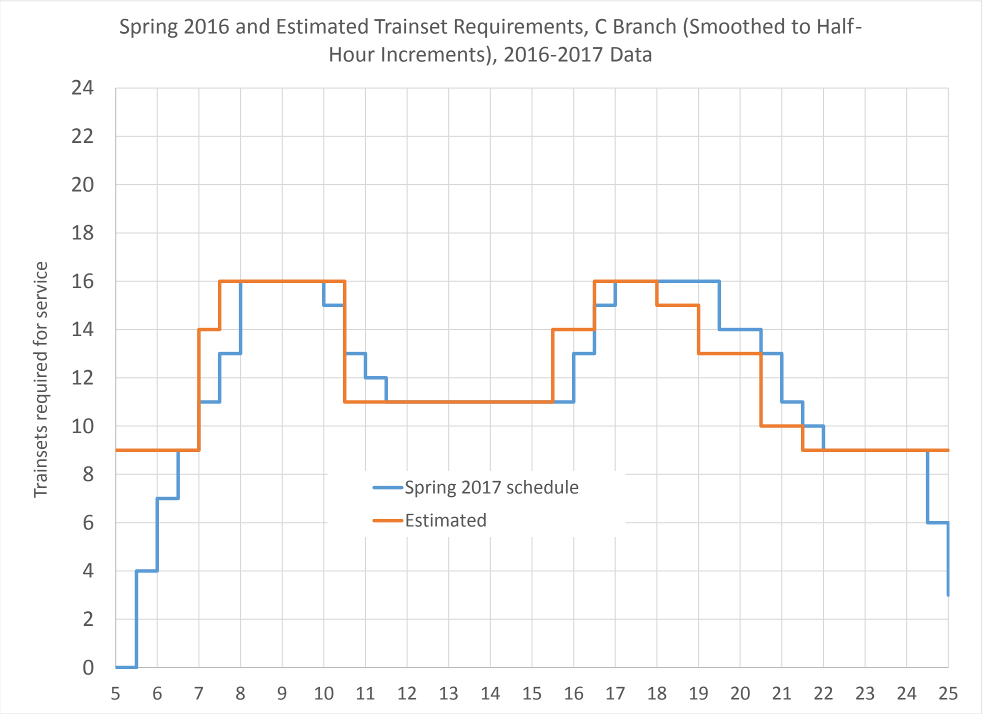

Figure E-4: Estimated trainset requirements on the C Branch

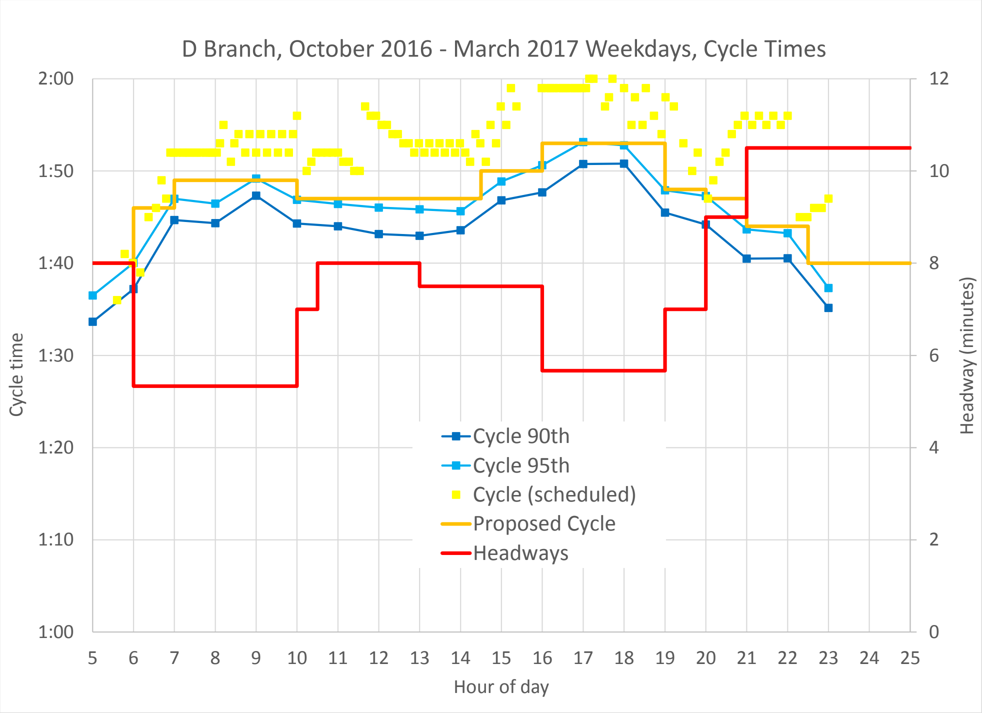

Figure E-5: 90th and 95th percentile running times, smoothed cycle times, and scheduled cycle times and headways on the D Branch for Fall 2016 and Winter 2017

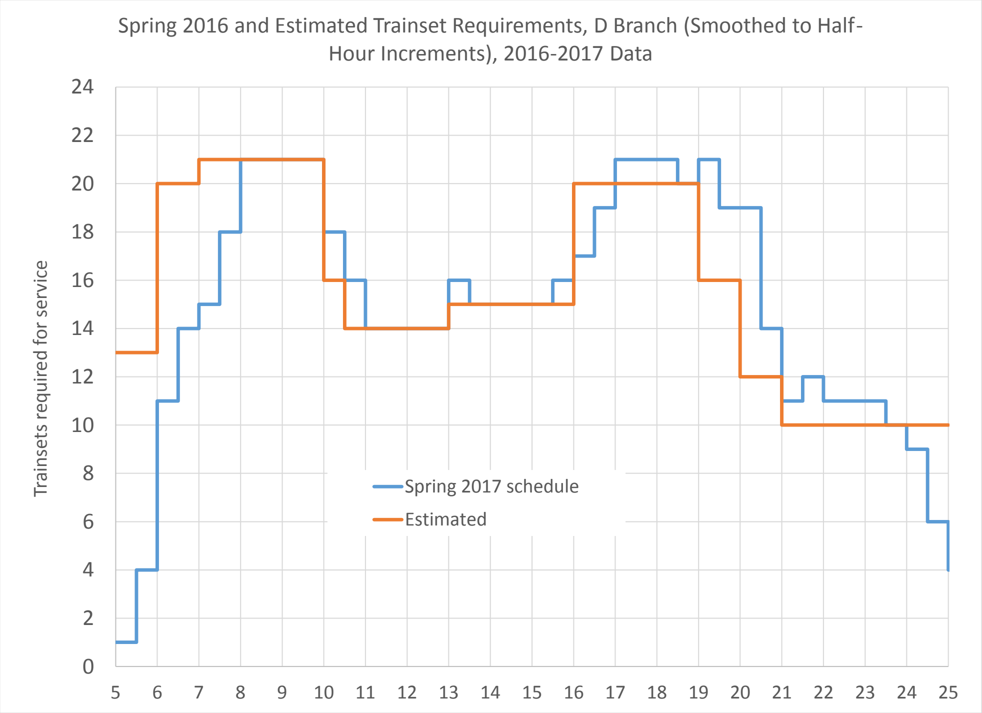

Figure E-6: Estimated trainset requirements on the D Branch

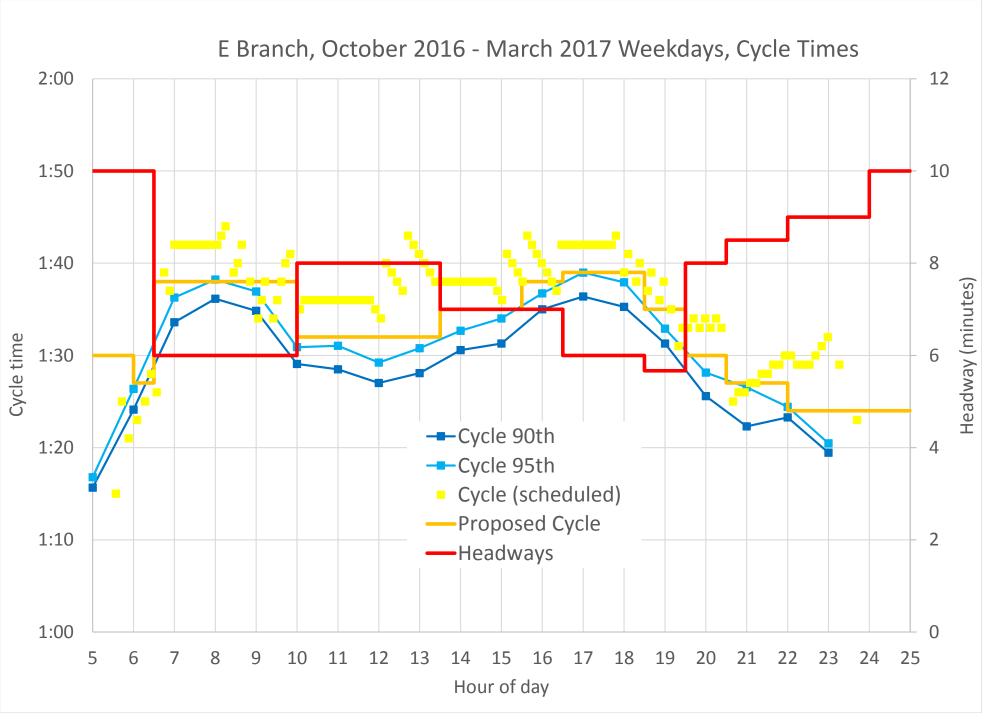

Figure E-7: 90th and 95th percentile running times, smoothed cycle times, and scheduled cycle times and headways on the E Branch for Fall 2016 and Winter 2017

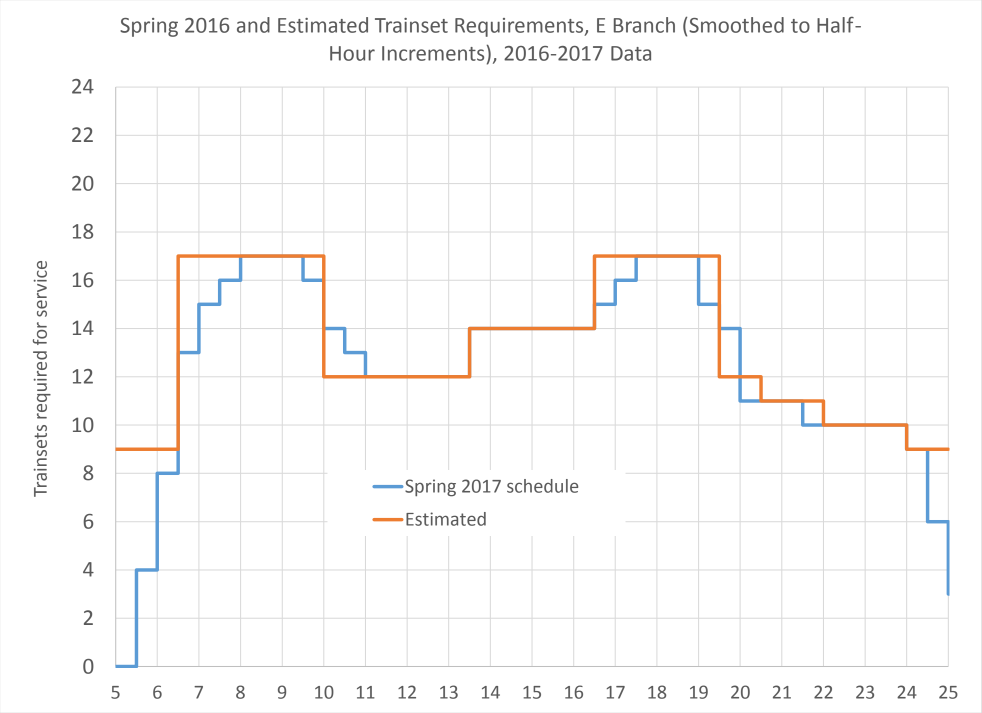

Figure E-8: Estimated trainset requirements on the E Branch

Appendix F

Headway distribution charts

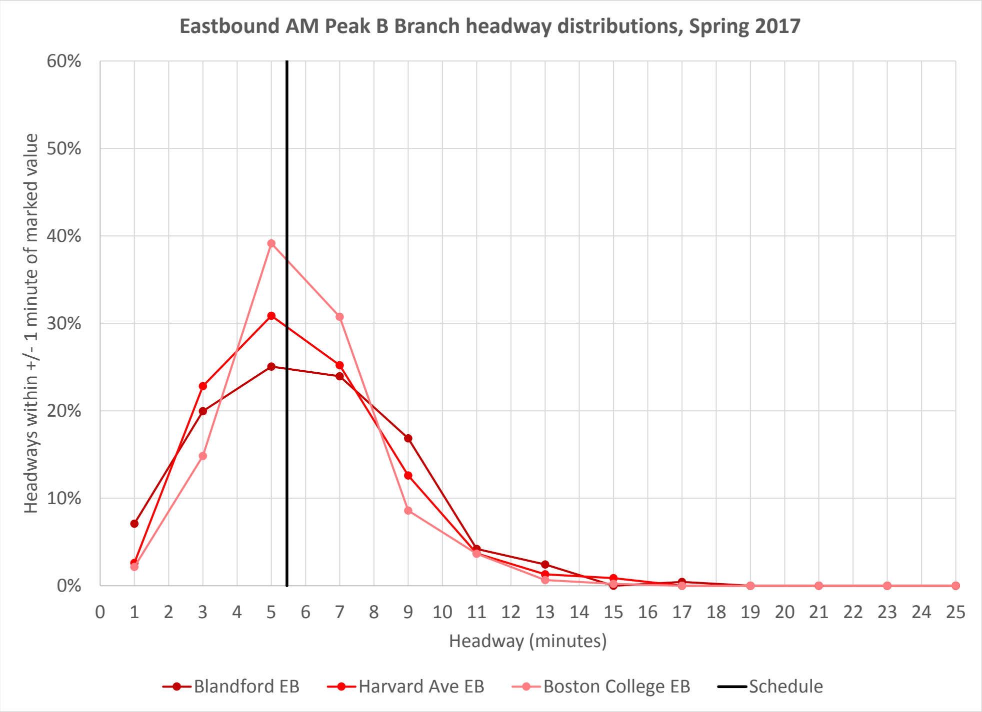

Figure F-1: AM headway distribution on the eastbound B Branch, Spring 2017

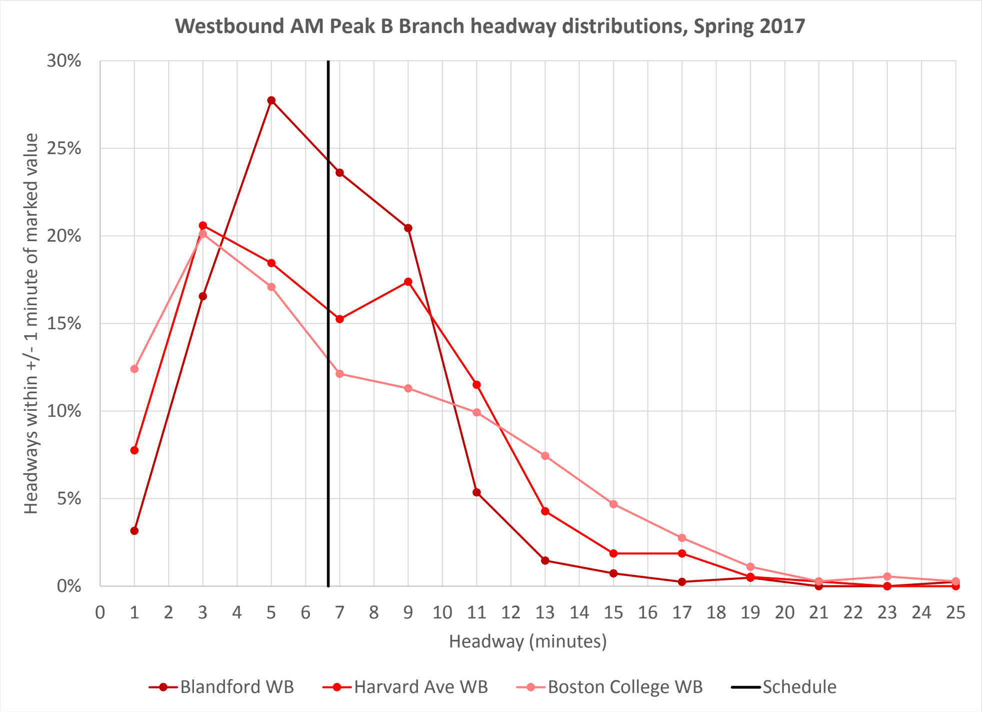

Figure F-2: AM headway distribution on the westbound B Branch, Spring 2017

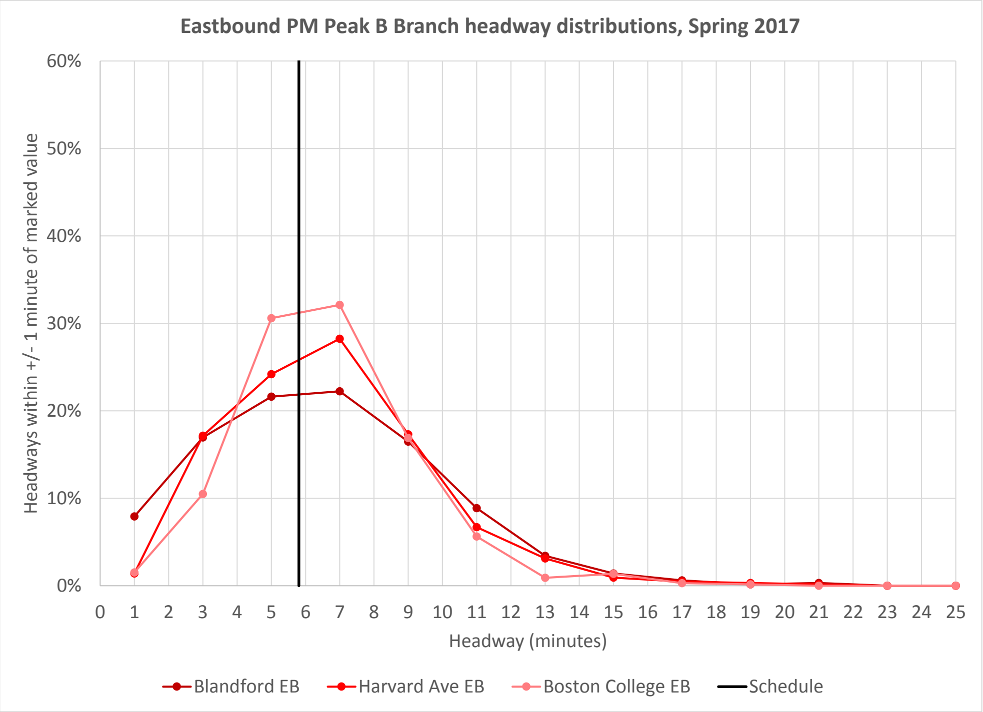

Figure F-3: PM headway distribution on the eastbound B Branch, Spring 2017

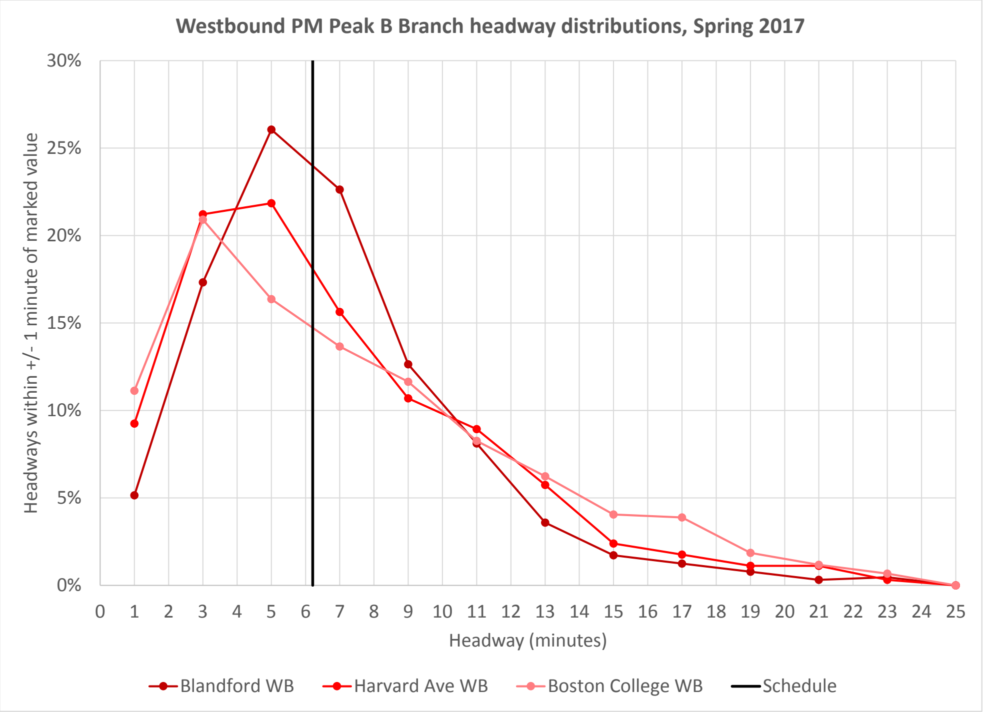

Figure F-4: PM headway distribution on the westbound B Branch, Spring 2017

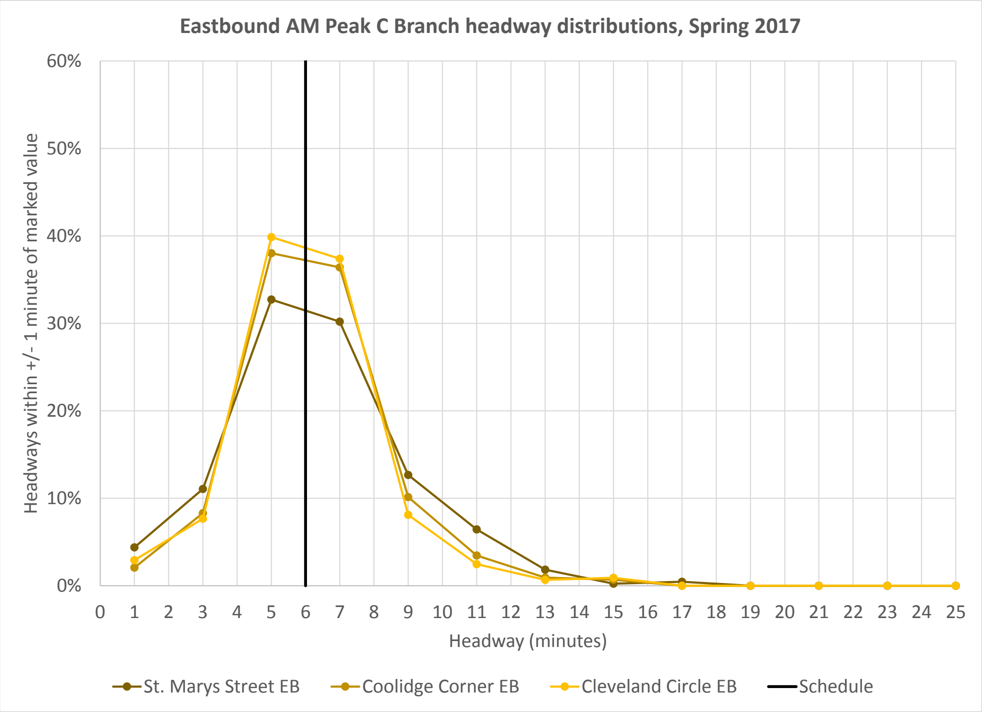

Figure F-5: AM headway distribution on the eastbound C Branch, Spring 2017

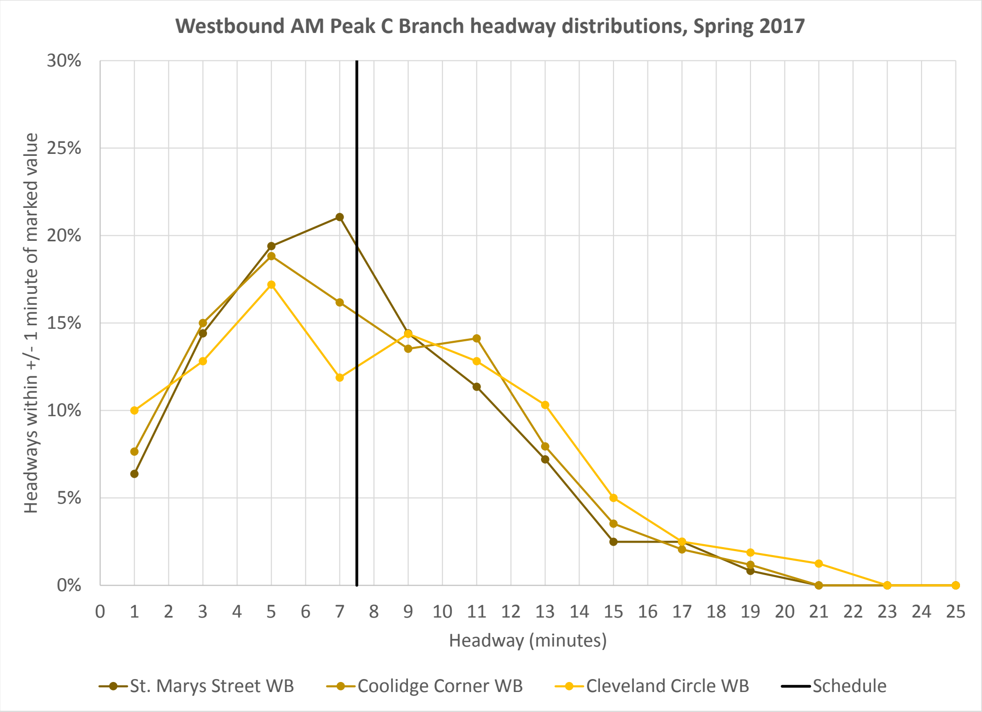

Figure F-6: AM headway distribution on the westbound C Branch, Spring 2017

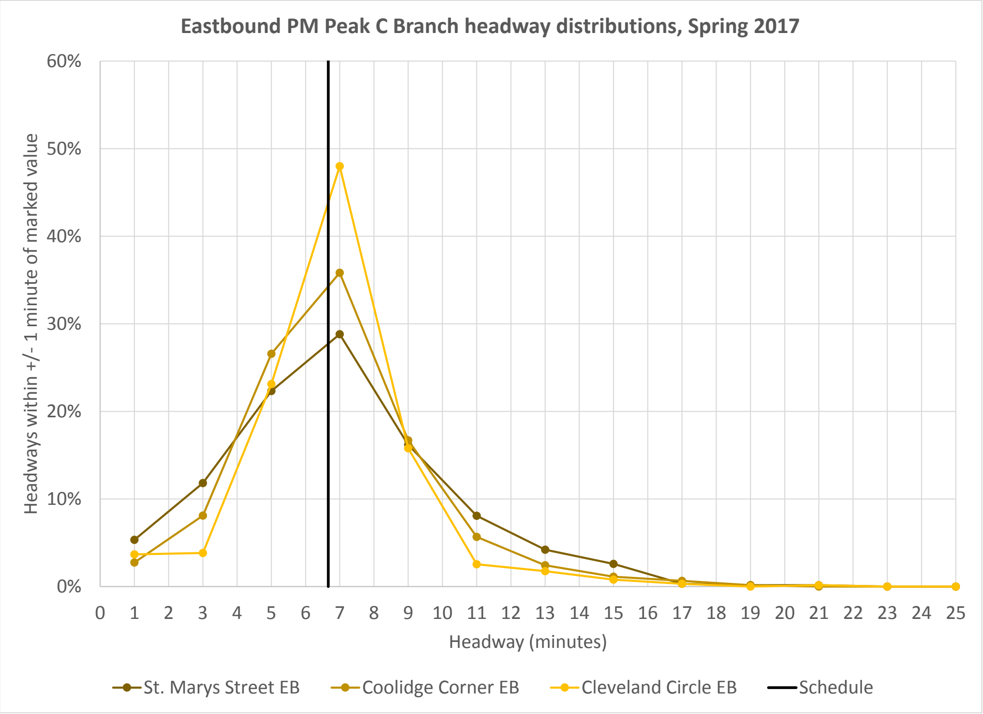

Figure F-7: PM headway distribution on the eastbound C Branch, Spring 2017

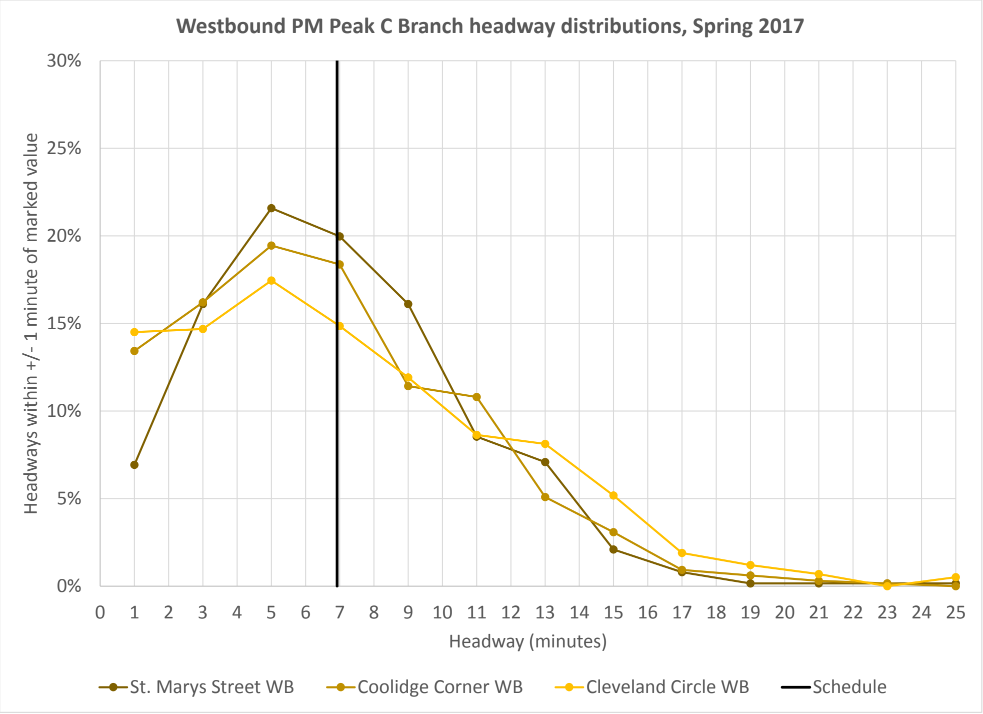

Figure F-8: PM headway distribution on the westbound C Branch, Spring 2017

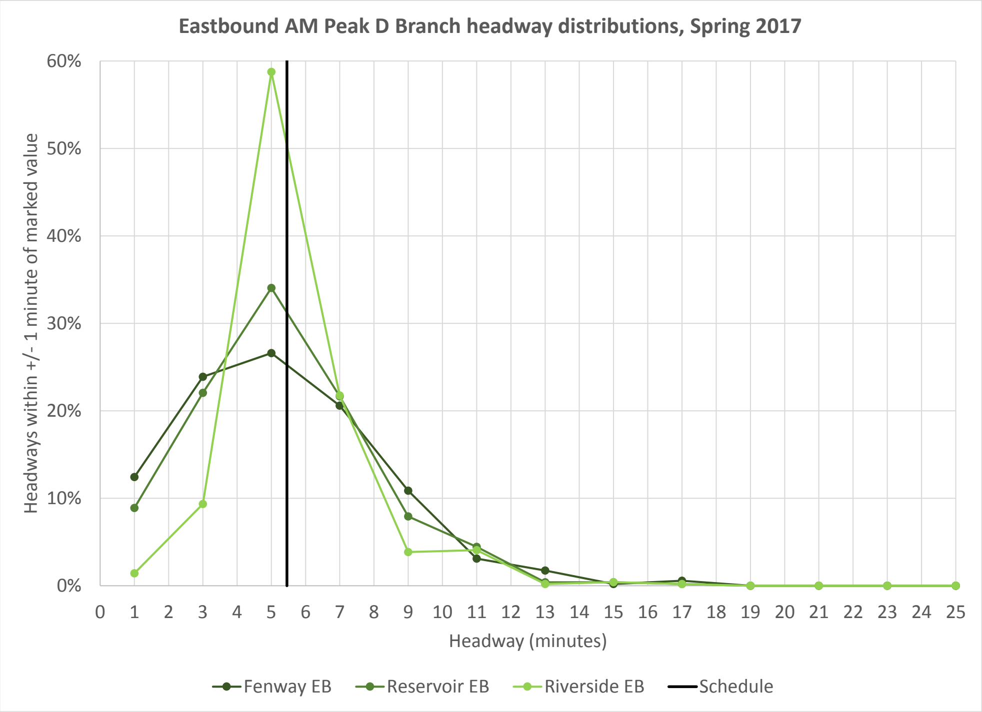

Figure F-9: AM headway distribution on the eastbound D Branch, Spring 2017

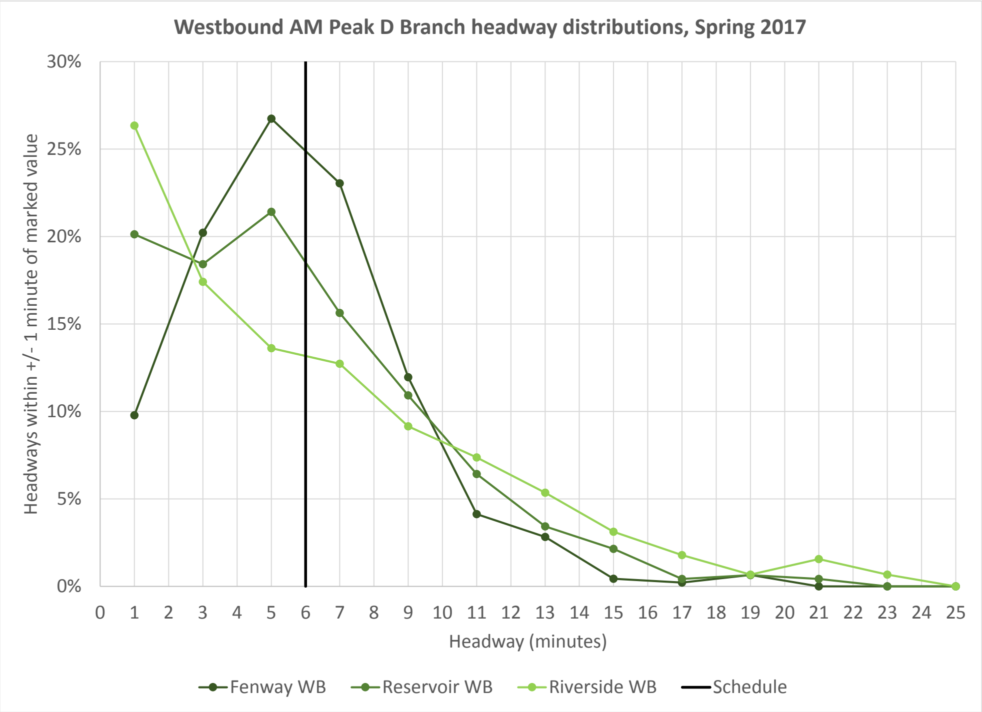

Figure F-10: AM headway distribution on the westbound D Branch, Spring 2017

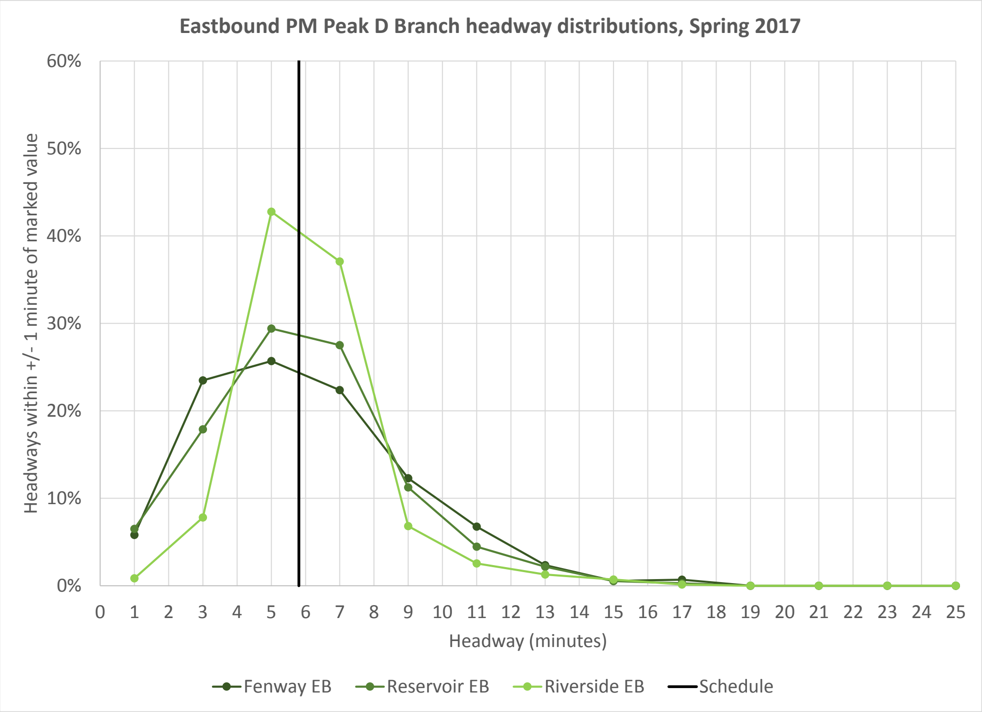

Figure F-11: PM headway distribution on the eastbound D Branch, Spring 2017

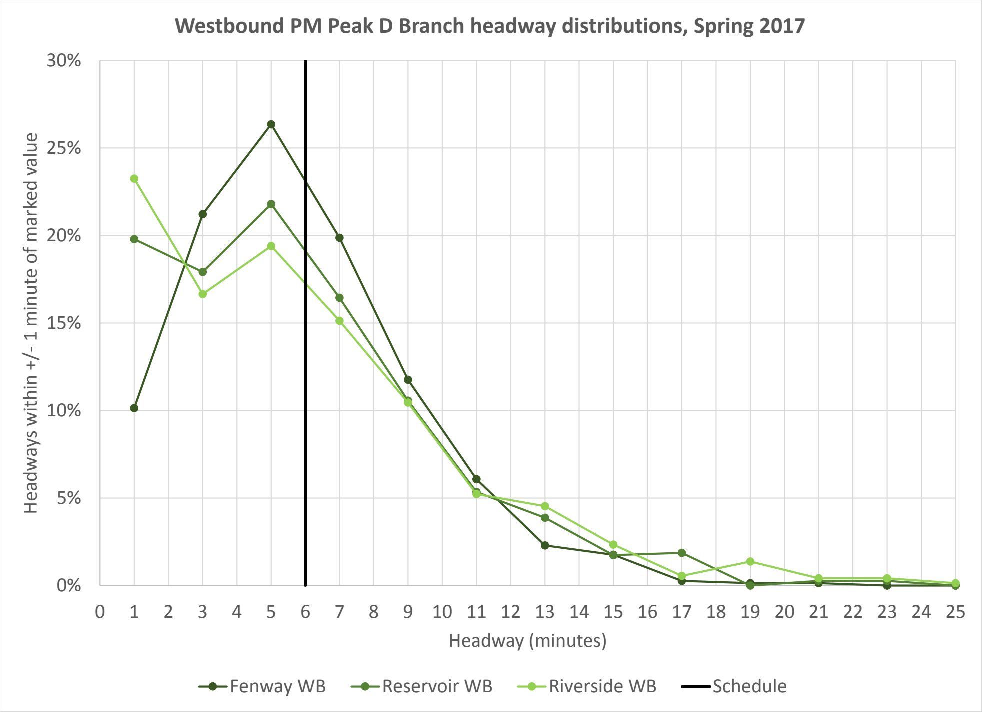

Figure F-12: PM headway distribution on the westbound D Branch, Spring 2017

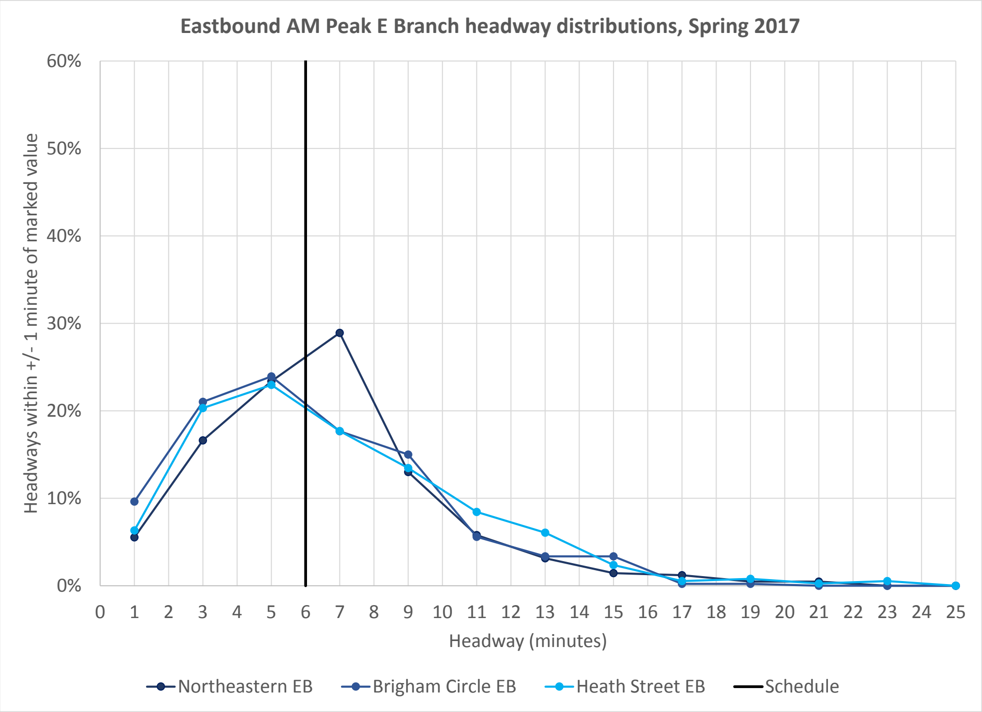

Figure F-13: AM headway distribution on the eastbound E Branch, Spring 2017

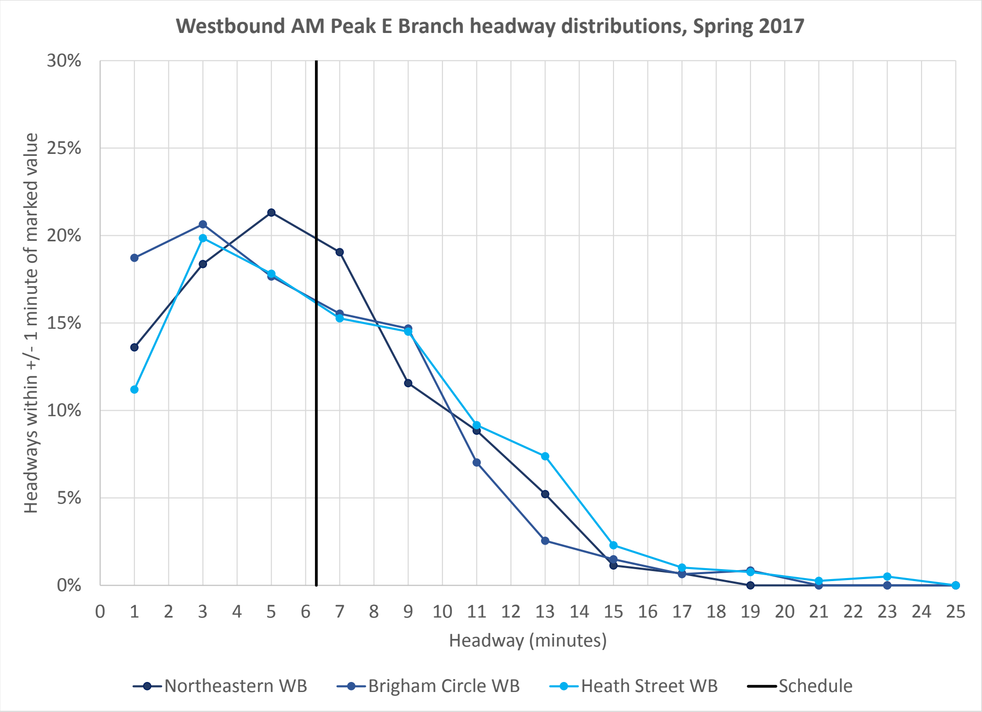

Figure F-14: AM headway distribution on the westbound E Branch, Spring 2017

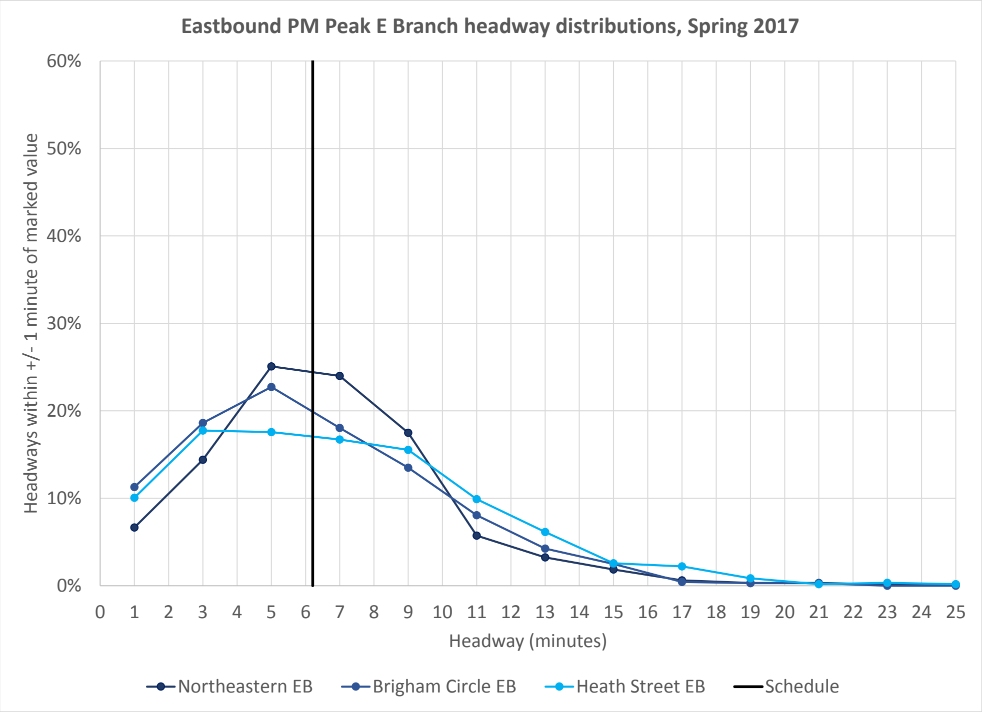

Figure F-15: PM headway distribution on the eastbound E Branch, Spring 2017

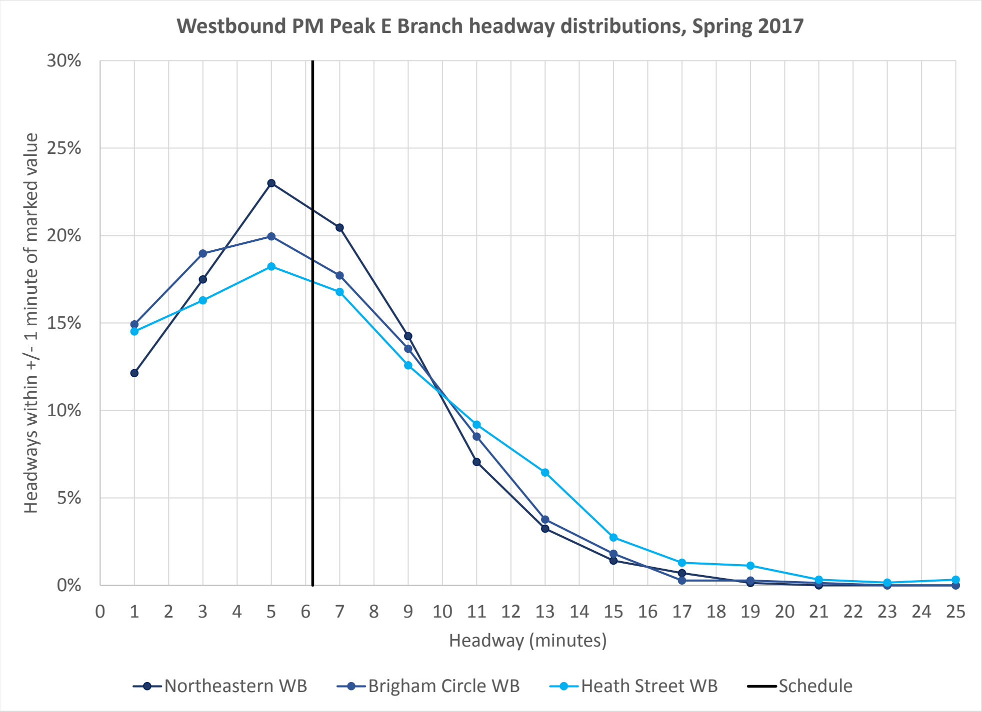

Figure F-16: PM headway distribution on the westbound E Branch, Spring 2017

Appendix G

Minimum Radius

G.1 Introduction

Minimum circular curve radius is a crucial limiting factor on vehicle design for light rail systems. Although smaller-radius curves can fit into tight city streets, they cause excessive wear on tracks and vehicles, and high-frequency 'wheel squeal' on tight curves can be disruptive or even hazardous.(Massachusetts Bay Transportation Authority, 1977) Additionally, tight curves require speed restrictions to avoid derailments, and designing vehicles with a small minimum radius can require sacrificing top speed. The Transportation Research Board "strongly discourage[s]" the use of circular curves with radii under 82 feet (25 meters), which was standardized by European tramway designs, and recommends minimum radii of 300 feet for revenue track and 100 feet for non-revenue track.(Parsons Brinckerhoff, 2012) Most light rail systems in the United States built since the light revival of the 1980s, and most extensions of legacy systems during that period, have minimum radii of 82 feet or greater.

However, legacy systems were constructed during an era of much smaller streetcars, which had to negotiate narrow streets in old city centers and could navigate curves as tight as 35 feet.(Parsons Brinckerhoff, 2012) Toronto's surface streetcar system still has a 36-foot minimum radius using modern light rail vehicles;(Booz Allen & Hamilton, 1995) Boston and San Francisco still have minimum radii of 42 feet. In order to have the widest possible choice of off-the-shelf vehicles, these systems would need to be rebuilt for 82-foot minimum radius. An intermediate level of 59-foot radius would allow use of some off-the-shelf designs.(Parsons Brinckerhoff, 2012) Even if these cannot be achieved, any increase in minimum radius is likely to increase the feasibility of relatively minor truck and body changes allowing use of an existing vehicle design. However, the fiscal and operational benefits of using an off-the-shelf design must be weighed against the cost of curve modifications.

G.2 Current radii and modification feasibility

This analysis includes all curves currently under 82 feet radius on the Green Line. Several curves with radii over 82 feet are also included, as they may act as permanent speed restrictions which affect throughput.

G.2.1 Central Subway

Lechmere Yard, constructed in 1922 between busy subway routes and less busy surface routes, has a pair of loop tracks with small radii. The outer loop, used by outbound terminating trains to return to the inbound platform, has a radius of 50 feet. The inner loop, used for car storage and to remove terminating trains from service, has a radius of 42 feet — the ruling radius for the entire line. Neither loop can be easily expanded without taking several residential structures, and converting to a stub-end terminal would reduce or eliminate the yard space (which is the only vehicle storage available for the E Branch). However, the Green Line Extension project will relocate Lechmere station and provide a new dedicated yard serving both new northside branches. If the current project timeline is met, the loops at Lechmere will be eliminated by 2021.

The Green Line makes two nearly-right-angle turns under the TD Garden complex between Science Park and North Station. This tunnel was constructed in 2004 as replacement for the Causeway Street Elevated and is thus built to modern clearances and curvatures.

Government Center Loop, a crucial downtown turnaround point, was new construction in 1963 and has no radii smaller than 99 feet. Brattle Loop, which allows trains from the north to reverse back towards Lechmere, has been out of service since the station was rebuilt in 2014-2016 but was formerly used for train storage during TD Garden events and to run Government Center — Lechmere shuttles. It has a 50-foot curve, with 74-foot and 76-foot curves preceding it. Brattle Loop lies entirely under City Hall Plaza; it may be possible to widen the 50-foot curve, but this would be an expensive proposition while maintaining full service to Government Center station on both levels (the Blue Line lies partially below the curve). Since it has not been used for regular service since brief periods in 2004 and 1997, it is likelier that the loop could simply be severed, with an additional crossover placed at the north end to allow the remaining stubs to be used for vehicle storage if needed.

The section of tunnel between Haymarket station and Government Center (ex-Scollay Square) station was rebuilt in 1963 to allow construction of Boston City Hall and the John F. Kennedy Federal Building. Because of the constraints of the building foundations and the small minimum radius of the PCC streetcars then in use, several tight curves were not straightened. The westbound track makes an 85-foot-radius turn off of Congress Street and a 60-foot-radius turn into Government Center station. (The eastbound track is spared from similar geometry.) The latter curve is constrained on its outside by the Blue Line emergency exit and possibly the JFK Building foundation, and on the inside by the Brattle Loop. Additionally, the Government Center Loop turnout is currently in the entrance spiral for the curve. However, if Brattle Loop is removed, it may be possible to increase the curve radius by widening it on the inside using part of the current Brattle Loop alignment and shaving off several feet of the platform.

Like Government Center, Park Street has a restricted westbound entrance; a compound s-curve has minimum radii of 74 feet and 93 feet on a right-hand curve followed immediately by a left-hand curve with 68-foot and 85-foot radii. The inner loop track has a radius of 49 feet for a complete half-circle, including a 50-foot-radius turnout providing access from the westbound main track to the fence track. Because of the proximity of the historic Park Street Church and the need to maintain access to the Red Line platforms below, it is likely not feasible to expand the loop. However, it may be possible to simply eliminate the loop, as the Green Line Extension would reduce the number of trains that need to terminate downtown.[1]

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[1] Even in a scenario with further expansion, the only plausible additional southside branches are a D Branch flank to Needham (likely to be through-routed to the GLX because its mostly-grade-separated route should provide high reliability) or reuse of the abandoned south fork of the Tremont Street Subway (which enters Boylston on the outer tracks and would not use the inner loop).

To do this, the eastbound fence track would be connected to the eastbound main track with a straightened curve and a new crossover. Installation of such a crossover (without curve realignment) has been programmed in MBTA Capital Investment Programs since at least FY 2005, with a cost of 3 to 4 million dollars. However, it has not been prioritized; the crossover alone would only provide modest operational benefits. In combination with curve realignments in both directions, though, it would allow the minimum radius at Park Street to be increased to 60 feet or more. Although the loop would no longer be in place to turn trains, being able to pass trains in the eastbound direction (as is currently done westbound) could add operational flexibility to compensate for the need for all trains to proceed to Government Center and beyond.

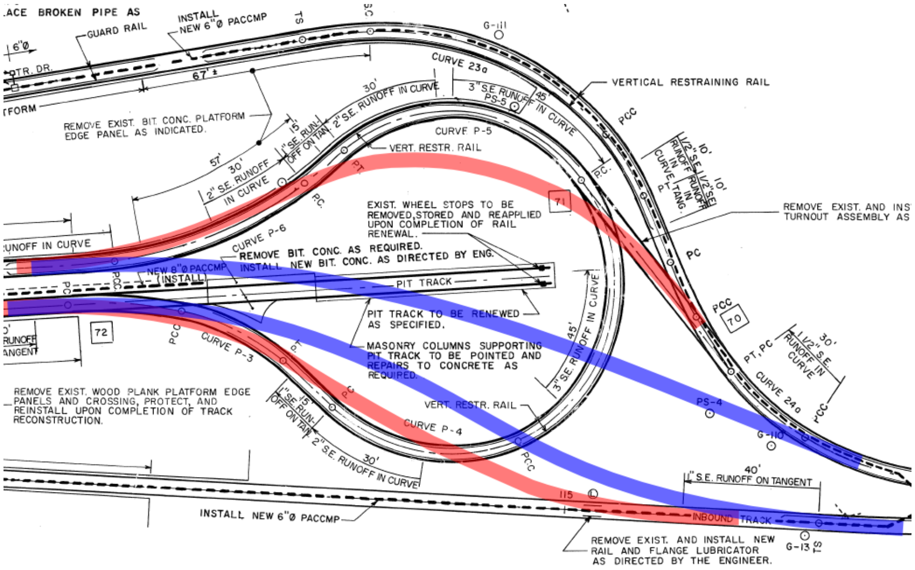

Figure G-1: Conceptual alignments for relocated center tracks at Park Street station, showing how the realignment could be designed for minimal changes to existing structures (pink) or smoothest curves (blue).

A conceptual sketch (Figure G-1) indicates that it may be feasible to reform this realignment without impeding on the existing exterior walls, platforms, or elevator shafts. A minimal relocation would require moving or replacing some electrical and pump rooms inside the loop, and some columns and walls near the eastbound crossover. Additionally, new columns or roof beams may be required on the Red Line level. More disruptive construction could allow even smoother curves. A trailing point crossover further to the west could even allow trains on the eastbound fence track to reverse onto the westbound fence track without fouling the wall tracks.

At Boylston station, there are s-curves located between the platforms, which were necessary to squeeze four tracks and two island platforms onto a narrow alignment. These curves have radii no smaller than 104 feet; however, they impact vehicle length because there are support columns located very near the tracks on both sides. Attempting to move these columns could incur legal complications, as this section of the Tremont Street Subway is a National Historic Landmark.

West of Boylston station, there is a tight, nearly-right-angle curve between Boylston Street and Tremont Street, where both tracks cross over a former branch to the south. This curve has minimum radii of 80 feet westbound and 90 feet inbound, causing a speed restriction and wheel squeal that is audible from outside the station. Although the public commonly perceives this as the tightest curve on the Green Line — and the wheel squeal issue certainly bears separate investigation — it would actually require little or no modification to meet the minimum radius of off-the-shelf vehicles. However, there may be narrow clearances which still limit vehicle length.

The Boylston Street Subway to just east of Kenmore Square was opened in 1914. The decision to connect it to the Tremont Street Subway was not made until relatively late in planning, and the new tunnel was built with much wider curves than the older tunnel, with no radii less than 400 feet. When Kenmore station was constructed in 1932, it was designed with plans to convert the Boylston Street Subway into a heavy rail line continuing under Commonwealth Avenue to the west. The Beacon Street line would have terminated at the station, using an overhead loop constructed east of the station. The loop is now used to short turn eastbound trains, to store trains during Red Sox games at nearby Fenway Park, and for non-revenue moves. Because it was built for streetcar use only, the loop has a radius of 55 feet. It would be inadvisable to eliminate the loop entirely, but is not clear how feasible it would be to widen the loop to a 60-foot or 66-foot radius.

G.2.2 B Branch

Except for the 1932-constructed connecting tunnel to the Blandford Street Portal, the B Branch was opened in stages from 1894 to 1900.(Clarke and Cummings, 1997, Engineering and Maintenance Department, 1981) Unlike the downtown tunnel segments, the surface lines were mostly laid out on wide, largely empty boulevards. The only significant curves on revenue trackage are at Packard's Corner and Chestnut Hill Avenue, both with 100-foot radii. The wye to non-revenue trackage on Chestnut Hill Avenue has a tighter radius, likely 75 feet.

The Lake Street Yard, first used around 1916 and reconstructed in 1930 and 1980, has several very tight curves. The outer loop has a 49-foot radius and the inner loop has a 45-foot radius; after the GLX opens, this will be the ruling radius for the line. There are also a number of short 50-foot curves and 50-foot crossovers in the yard. Relocation of the platforms to the median of Commonwealth Avenue was proposed in 2007 to reduce the number of trains having to cross travel lanes to enter the yard by almost 90%.(Massachusetts Bay Transportation Authority, 2012a) However, this would require widening the street, moving a stone wall, and other possibly disruptive changes. A compatible adjustment to this critical yard must be done as part of new vehicle procurement; any relocation of the platforms should be a secondary concern.

G.2.3 C Branch

Opened in 1888 and 1889 (again, except for the 1932-built portal), the C Branch has no tight revenue curves; the flying junction west of Kenmore and small s-curves on the surface all have radii of several hundred feet.

Reservoir Yard, which serves the B, C, and D branches, is located on a narrow parcel between Chestnut Hill Avenue, the D Branch, and commercial and residential properties lining Beacon Street. A single non-revenue track on Prendergast Avenue is used for several purposes: to loop outbound trains arriving at Cleveland Circle (for example, if the crossover is out of service), to pull trains from the yard into revenue service, or to send trains from the yard to Chestnut Hill Avenue and the B Branch. The curves from the northern two yard tracks — the "departure track" and "entrance track" both have 50-foot radii; the curves to the revenue tracks on Beacon Street are of similar tightness. The MBTA owns the parcel east of the alley; this would allow the track to be moved east and the curves to be straightened slightly, but would require demolition of part of the current operator's lobby.(City of Boston, 2017) The station should then be converted to an island platform; in conjunction with adding AVI control to the Ayr Road crossover, this would also increase operational flexibility at the station.

There are also several tight curves at the east end of the lower yard. The wye leading to the upper yard has two 70-foot curves, the departure track has a 65-foot curve, and Storage Track 2 has a 58-foot curve. These are all constrained by the carhouse to the west and Strathmore Road and a substation to the east; however, it should be possible to slightly reconfigure the curves to reach at least a 66-foot minimum.

G.2.4 D Branch

The D Branch is a former commuter rail line which was converted to light rail use in 1959. There are no revenue curves tighter than the 260-foot curves at Beacon Junction and the 200-foot turnouts to the Reservoir Yard (used for short turns).

Riverside Yard is populated primarily by 100-foot and 75-foot turnouts and curves. There is a single 70-foot curve on the south end of the inner loop, and a 57-foot curve on the north end of the same loop. Widening the 57-foot curve would be feasible but could require moving a yard building slightly; widening the 70-foot curve would require moving several crossovers on the loops and taking some of an MBTA driveway. Although it would be possible to widen even the numerous 75-foot curves, doing so would involve completely rebuilding both main ladders and is unlikely to be necessary.

G.2.5 E Branch

The curves at Copley Junction, built in 1941, have a minimum of 125 foot radius; no other curves in the Huntington Avenue Subway have radii under 200 feet. The surface section of the Huntington Avenue Line (E Branch) was laid out in sections between 1857 and 1903; the only tight revenue curves are at Riverway (approximately 75 feet in radius) and the loop at Heath Street (added in 1945 for the then-new PCC streetcars).

The Heath Street Loop has 50-foot radii on both inner and outer loops, which also limit the line to 2-car trains. This could be modified either by expanding the loop and moving some VA Hospital parking onto the current loop area, or turning it into a stub-end terminal. The VA owns both the current loop and the surrounding property; while this means that modifying the loop in any manner would require negotiating with the VA, they may be open to a proposal that improves their parking arrangement.(City of Boston, 2017) Alternately, the extension to Hyde Square proposed by neighborhood activists and the Go Boston 2030 plan would eliminate the need for the Heath Street loop entirely, as long as the extension was built to modern track geometry standards.

G.3 Conclusions

It is infeasible at this time to rebuild the Green Line for a standard radius of 82 feet. To do so merely for revenue trackage would require wholesale reconfigurations of Government Center and Park Street stations, with costs likely in the hundreds of millions of dollars. It would involve lengthy disruptions on the Green Line, and likely the Red and Blue lines as well. Including nonrevenue trackage would require all three major yards to be completely realigned, and both Brattle and Kenmore loops would be outright abandoned. The planning and construction time required for a project of this magnitude would be difficult to achieve by the planned arrival time of Type 10 vehicles. With off-the-shelf vehicles available from several major manufacturers that can navigate curves of 66 feet (20 meters) or less, the perfectionism of achieving 82 feet would not be cost-effective.

More limited efforts to increase the minimum radius, however, are possible and even likely to be cost-effective. Four plausible improvement packages with varying up-front costs and possible savings on vehicle procurement and maintenance are as follows:

- A 49-foot systemwide minimum radius would be halfway achieved by the planned replacement of Lechmere Yard. The only other required action would be to modify the loops at Lake Street to widen or eliminate the 45-foot curve on the inner loop. This would permanently eliminate all curves under 49-foot radius, likely cost no more than $1 million, and be easily achievable by the time the Green Line Extension opens.

Although this would not enable use of any off-the-shelf vehicles, it would likely decrease the cost of custom vehicles, or make it possible to make minor modifications to off-the-shelf models. For example, the Bombardier Flexity Outlook is capable of 36-foot radius but only 43 mph top speed; this might enable switching trucks for a 49-foot radius and 50+ mph top speed.

- A more ambitious change would be to achieve a minimum 60-foot radius in revenue service and 50-foot radius on non-revenue trackage. This may allow use of some off-the-shelf designs with 59-foot (18 meter) minimum radius if they can be approved for tighter curves in non-revenue service. The most significant modification required for this would be elimination of the inner loop at Park Street, including the new eastbound crossover and realigned center-track curves. Heath Street loop would be expanded, replaced with a stub-end terminal, or replaced by a Hyde Square extension.
- Using a fully off-the-shelf vehicle would be possible if non-revenue trackage was increased to a minimum of 60 feet as well. Significant changes (or abandonment) would be necessary for Brattle Loop, Kenmore Loop, Lake Street Yard, and Prendergast Avenue. One additional curve at each of the Riverside and Reservoir yards would need slight modification.
- The most ambitious modification likely to be feasible within the 2025 timeframe of a Type 10 procurement would be a systemwide 66-foot (20 meter) minimum radius, which would make possible other off-the-shelf vehicles. This would involve all the changes described for the first three scenarios, with all curve modifications made to the wider radius. Government Center would require the 60-foot entrance curve to be widened, likely including modifications to Government Center Loop and abandonment or significant realignment of Brattle Loop. One additional non-revenue curve at Reservoir Yard would need very slight modification.

Appendix H

Platform sizes

H.1 Introduction

Currently, only 21 of 53 surface stations and 10 of 13 underground and elevated stations are handicapped accessible with raised platforms. One additional station (Brookline Hills) has wooden mini-high ramps but not raised platforms. Four non-accessible surface stations on the B Branch are to be consolidated into two accessible stations, ADA renovations are planned for Hynes and Symphony, and the GLX will add 6 accessible stations. By 2025, that will make about 43 of 72 stations (60%) of the Green Line accessible for Type 8 and Type 9 vehicles. Any modifications to the remaining stations to permit use of new rolling stock will require rebuilding them to ADA specifications. Accessibility is desired wherever possible; however, in some cases, renovations may be expensive or difficult.

400 feet is used as the maximum station length in this analysis. This is sufficient to deboard passengers from one Type-9-sized triple pushing another, or for two doubles of longer standard stock. Except for rare cases where it is desirable to platform two trains simultaneously, longer platforms are unlikely to be necessary.

ADA regulations do not directly specify rail platform width; however, they specify a 5-foot clear width for bus stops which can be assumed to also be sufficient for the Green Line.(United States Access Board, 2013) Including separation from traffic and width of the train, this requires about eight feet from the edge of rail. With all-door boarding coming in 2019, island platforms using less total right-of-way width than facing side platforms may be possible where an individual situation demands.

Fire codes require that all platforms have two egress points in case the primary exit is blocked during an emergency. Some currently accessible surface stations built in the 2001-2003 era do not have this safety feature. It is also desirable, though not strictly essential, to have access to both platforms available either at a grade crossing or from surrounding streets, rather than at pedestrian-only grade crossings where both rail and auto drivers may be less watchful.

H.2 Analysis by Section

H.2.1 Central Subway

Twelve of the 15 underground and elevated stations are currently accessible. Symphony has planned renovations that are delayed due to the projected cost, as the station is adjacent to the historic Horticultural Hall and Symphony Hall, but it will eventually be modified. Renovations to Hynes are two-thirds funded by air rights development and may begin around 2019.

The stations west of Boylston were constructed in 1914 (Copley, Hynes), 1921 (Arlington), 1932 (Kenmore), and 1941 (Symphony and Prudential); they were designed for more rapid-transit-like service than the original subway and have platforms 300 to 350 feet long. The only likely candidate for substantial modifications not currently planned is Copley. An extension of the eastbound platform under Dartmouth Street and Copley Square would have no significant building impacts and would potentially allow two trains to platform at the station to reduce delays at Copley Junction. Such an extension would provide better direct access to Copley Square and present a unique opportunity for a headhouse that visually interacts with the historic buildings around the square.

Boylston and Park Street stations are part of the original section of the Tremont Street Subway, a National Historic Landmark, and Government Center and Haymarket may be included in the listing as well. The other stations have been heavily modified over the years, but Boylston has not except for the mid-century removal of two headhouses and blocking off the crossover passage. It represents something of a living museum — a 19th century station used in a 21st century light rail system. Modifications to the station would be extremely difficult to perform due to the historic designation. However, artful reconstruction of the missing headhouses for use as elevator shafts might be acceptable as a way to make the station accessible while restoring it closer to its original condition. Boylston is likely to remain the shortest platform in the subway, with useful platform lengths of about 250 feet eastbound and 300 feet westbound.

Science Park station has accessible 240-foot platforms that were extended to their current length in 2011; any further extension would be difficult due to the narrow width of the Lechmere Viaduct (a NRHP-eligible structure). It may be necessary to obtain a waiver to allow narrower-than-standard platform extensions. Lechmere station currently has a 175-foot platform and a 215-foot platform, both accessible. The station is expected to be replaced by the new GLX station by 2021.

H.2.2 B Branch

Currently, 5 of 18 surface stations on the B Branch are accessible. Commonwealth Avenue Phase 2 reconstruction around 2020 will combine the substandard four stops between Boston University West and Babcock Street into two fully accessible stops, improving this ratio to 7 of 16. All stations except Boston College currently have platforms 210 to 260 feet long. Of those 16 stations, 10 have sufficient space available for unlimited length. However, there is not always sufficient width for an accessible platform — Commonwealth Avenue was rebuilt in the 1950s to prioritize car traffic, with little consideration of transit needs.

Blandford Street is sandwiched between a grade crossing and the Blandford Street Portal, causing length and ADA slope concerns. Extending it past 220 feet — or even having enough platform for two current cars that is not too sloped for accessibility — may be problematic. It may be possible to necessary to eliminate the lightly-used grade crossing, which is only used by left turns from Sherborn Street and is redundant to the Granby Street crossing.

Boston University East is constrained by grade crossings, though it may be possible to narrow one or both crossings to extend the platforms slightly. Boston University Central is currently accessible, but does not have a redundant egress. Adding a new pedestrian level crossing or building paths to the University Road crossing would also improve transit access to the center part of BU's campus. Alternately, the two stations could be combined into a single stop on the longer block between Cummington Street and St. Mary's Street, sufficiently provisioned for the 5000+ daily riders such a stop would attract. If Boston University pursues air rights development over the Massachusetts Turnpike, a stop could be added in the future between Carlton Street and Mountfort Street.

Future Phase 3 reconstruction will reconstruct Packard's Corner, [currently accessible] Harvard Avenue, Griggs Street / Long Avenue, Allston Street, and Warren Street; consideration should be given to consolidating the latter three stops into two. All will require new crossings for redundant egress. Washington Street is currently accessible, but will require a new crossing at Melvin Avenue / Fidelis Way.

Sutherland Road has sufficient room for accessible platforms, but it is located on the side of a steep hill with a 5.4% grade, substantial cross slope, and superelevated tracks. It may be possible to move the platforms west (closer to the 1980-closed Leamington Road stop). Chiswick Road and Chestnut Hill Avenue are constrained by level crossings on both sides (and the non-revenue wye) and have extremely narrow platforms. Upgrading them to modern standards would require taking lane width, narrowing grade crossings, and adding a pedestrian crossing at Strathmore Road. South Street has sufficient length, but would require platform widening and a new pedestrian crossing.

Boston College is currently extremely constrained; only two cars can be platformed. As discussed in Appendix G, modifying the platform may be necessary in conjunction with improving or expanding the yard.

H.2.3 C Branch

Currently, 4 of 13 stations on the C Branch are accessible. All platforms except Cleveland Circle are between 205 and 260 feet, and most can be extended easily (although cutting down trees in the median may have pushback from residents).

The strings of non-accessible stations between Englewood Avenue and Tappan Street, and Saint Paul Street to Hawes Street, have very narrow inbound platforms. Taking lane width, or converting median parking spaces from diagonal to parallel, would be necessary to bring them to code. All would also require new pedestrian crossings or paths to the next grade crossings, which would also reduce instances of pedestrians crossing tracks and roads unsafely — and even walking along the tracks — to avoid the longer walk to the grade crossing. Some station consolidation — possibly removing Kent Street and Dean Road and realigning surrounding stations to replace access — should be further studied.

Winchester Street / Summit Avenue has sufficient space; extending platforms and paths to the existing Winchester Street pedestrian crossing will provide for the second egress. Fairbanks Street and Brandon Hall, currently just 500 feet apart, can likely be consolidated as a single station without significantly increasing walking distance to access trains.

The four currently accessible stations are still constrained on length and egress. Saint Mary's Street would require minor track realignment to extend platforms, and may need egress improvements (which would improve access to the busy commercial and residential district). The westbound platform at Coolidge Corner would be difficult to extend due to grade crossings. Both platforms have historically significant shelters that would be affected by raising the platforms, although they were safely raised previously.

Washington Square is limited to about 205 feet eastbound and 230 feet westbound by the dual U-turns just to the east. Extending the platforms may require eliminating one of the two, as the eastbound carriageway quickly drops below the westbound carriageway east of the station. A new pedestrian crossing at the U-turn lanes is also required for the second egress; it would also better serve residential blocks east of the station.

The eastbound platform at Cleveland Circle is limited in length by the Prendergast Alley wye; however, conversion to an island platform in conjunction with curve modifications would solve the length restriction. A new pedestrian crossing at Ayr Road — currently a heavily used but unsafe access route — would also be required.

H.2.4 D Branch

Currently, 7 of 13 stations on the D Branch are accessible, with a renovation at Newton Highlands planned. Current platforms vary from 205 to over 400 feet long. Because the D Branch is a converted commuter rail line rather than a boulevard median, even currently inaccessible stations have plenty of platform width.

All stations except two can easily fit platforms of 300 feet or greater. Riverside is constrained by the Grove Street bridge, and Reservoir by the yard leads; expanding either station much beyond 210-foot platforms would be more difficult than elsewhere. The bridge could be widened to extend the platforms, and relocating the snowplow siding at reservoir would allow moving the yard leads and extending the platforms.

Fenway has access from one point on one platform only, although passengers can exit onto the wide right-of-way west of the station in an emergency. Access to the Park Drive bridge and the bus stops is by a steep set of stairs; wheeled mobility device users have an arduous, winding quarter-mile route to the southbound bus stop, as shown in Figure H-1. A proposed project would add elevators to one or both sides of the bridge, vastly improving accessibility.

Brookline Hills has access from only one point; the MBTA is advised to acquire an access route to Brington Road during the planned development project there. Beaconsfield has good access routes to both sides, but the route to Dean Road is indirect. A renovation should consider including a path under the Dean Road bridge to the Jean B. Waldstein Park, providing handicapped access from Dean Road and several residential areas through the park.

Platform work at Newton Center and Newton Highlands would have to be compatible with the NRHP-listed stone station buildings, which are currently rented for commercial use. Modifications to Eliot may involve reconstruction of the ramp to the footbridge across Route 9, which was constructed around 1977 (although the original staircase was later replaced with the ramp) and will certainly require major reconstruction of the ramps to the north side of Route 9.

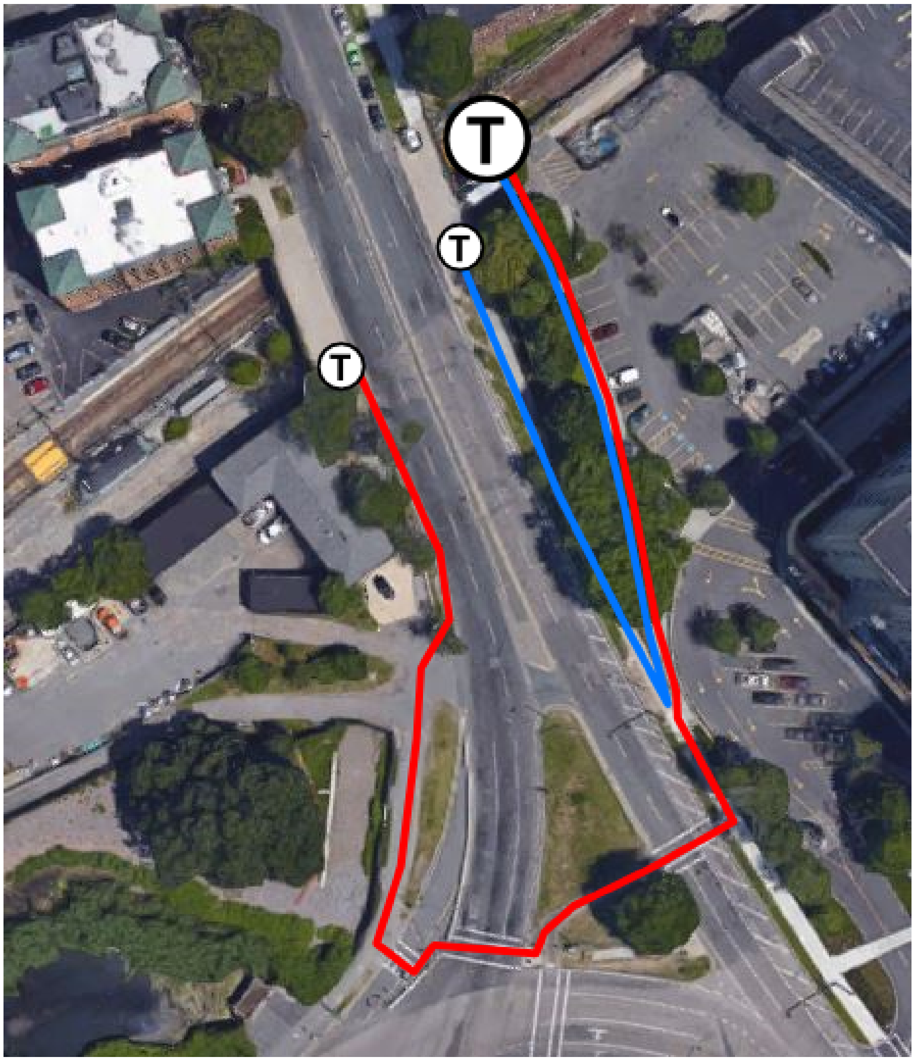

Figure H-1: Lengthy accessible routes from the platforms at Fenway to the northbound (blue) and southbound (red) bus stops. Overlay from Google Maps.

Both Waban and Woodland have access at one point only. A second access point connecting directly to the overpasses west of each station would likely be more feasible than connecting into the relatively private residential neighborhoods. Riverside also only has one access point; a second would be difficult to construct due to its elevation, but the Grove Street bridge may provide sufficient emergency egress.

H.2.5 E Branch

Currently, 5 of 9 surface stations on the E Branch are accessible. Four of those, reconstructed around 2002, have platforms from 250 to 400 feet with dual egress. Three are easily expandable and plenty wide; Brigham Circle has narrow staggered platforms. Parking and/or lane width should be carefully taken to allow for a full-length island platform, which would make short-turning at the station easier.

The four stops between Back of the Hill and Fenwood Road are located where the line runs in mixed traffic. There is no effective platform and no easy way to make the stations accessible; even adding shorter platforms on traffic islands would likely require major street construction and involve loss of travel lanes or parking, which would likely cause neighborhood resistance. One possible solution is the creation of "easy access" stops, which have been pioneered in Melbourne. Shelters and other passenger paraphernalia are built on the sidewalks, and the travel lane between curb and tracks is raised or tilted so that the pavement is level with the vehicle floor. Bollards are used to demark the 'platform' edge. A typical such stop is shown in Figure H-2. Some streetcar operators in Melbourne perceived the stops as unsafe because of frequent conflicts between pedestrians and cars, but this could be mitigated by proper signage and signals.(Farhana Naznin, 2017)

Figure H-2: "Easy access" stop (EAS) in Melbourne. The raised area left of the track serves as both travel lane and accessible platform. Photo by Public Transport Victoria.

Heath Street has a 130-foot platform and a 170-foot platform on the loop, currently limiting the line to 2-car trains past Brigham Circle and potentially causing issues with longer rolling stock. As mentioned in the minimum radius discussion, possible solutions include a stub-end terminal, a wider loop, or the extension to Hyde Square.

H.2.6 Green Line Extension

All six new GLX stations plus rebuilt Lechmere will have accessible island platforms at least 210 feet long. Although longer platforms were removed as part of cost-cutting measures, the stations will be built not to preclude extensions to at least 280 feet and raising for true level boarding.

H.3 Conclusions

A standard accessible surface platform length of about 220 feet, with about 250 feet of space between crossing car or pedestrian traffic, is an easy and achievable goal for systemwide standardization. This allows three current 74-foot vehicles, or three off-the-shelf 81-foot vehicles (which do not have a door adjacent to the driver), or two longer vehicles up to about 120 feet long, to have accessible boarding at all doors. This allows for a substantial increase in per-train capacity over what is currently provided, while needing relatively few stations to be lengthened. (A higher number, however, need raised platforms and/or additional platform width to meet standards.) Stations where this would require major work (other than minor widening and new pedestrian crossings) not currently planned are:

- Boston College: The current site is extremely constrained, but could be reconfigured during yard improvement.
- Cleveland Circle: As discussed above, an island platform is likely necessary in conjunction with track realignment.
- Washington Square: The station is sandwiched between Washington Street and a U-turn lane. For longer trains to platform without blocking the U-turn lane, it may be necessary to move the U-turn slightly to the east.
- Heath Street: Extremely limited loop designed for PCC streetcars; likely requires modification for curve radius anyway.

- E Branch street-running stops: Likely to remain inaccessible and without proper platforms unless a major street reconstruction is initiated to improve service on the E Branch and the route 39 and 66 buses.
- Boylston: Historic designation would make ADA renovations difficult; modifications must be carefully designed to avoid losing the best-preserved part of Boston's subway history. Any modifications should include consideration of reuse of the outer tracks and/or the completion of the "missing link" to the Silver Line Waterfront Tunnel.

A more aggressive goal for futureproofing is 290-foot accessible platforms on the B and D Branches, the inner E Branch, the Central Subway, and the Green Line Extension. This would allow triples of up to 100-foot vehicles (approximately a doubling of current capacity) to be operated on these branches to handle rush hour crowding. The recommended course of action is to obtain this length immediately when retrofitting stations when it is inexpensive to do so;[1] platform length will not be a substantial driver of cost at most stations compared to planning, roadway modifications, and so on. At stations where platform extensions to 290 feet would add substantial cost, care should be taken not to preclude future extension should future ridership demands longer trains.

Stations where this would require major additional work are:

- Chestnut Hill Avenue: Either eliminate the Strathmore Road grade crossing, or move the platforms west of Chestnut Hill Avenue (and move South Street west as well).
- Chiswick Road: Likely eliminated in favor of an expanded, slightly relocated Sutherland Road station.
- Harvard Avenue: Westbound platform flipped to farside of grade crossing.
- Boston University East: Combined with Boston University Central on intermediate block. Potential for new station west of University Road in conjunction with future air rights development.
- Blandford Street: Eliminate the lightly-used grade crossing.
- Riverside: Extend platforms across Grove Street bridge.
- Reservoir: Relocate yard leads to extend platforms.

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[1] There is precedent for this kind of futureproofing — longer-than-standard platforms were added at several D and E Branch stations during the early-2000s renovations, as the cost of extending the platforms was negligible compared to other costs of renovation.

- Brigham Circle: Relocate to island platform with extended length.
- Boylston: May require permanent exemption wherein not all doors can be platformed.
- Science Park: Extend platforms onto viaduct with minimal disruption to the historic structure.
- GLX: Extend platforms as made possible by design.

Appendix I

GLX flow tables

The GLX (including the relocated Lechmere station) is projected to have some 48,000 daily trips, representing an increase of about 36,000 trips — one-sixth of current ridership on all Green Line services. Most of these trips will continue south of Lechmere into the existing Central Subway, representing additional strain on the already crowded system. The Medford Branch alone is projected to have 24,000 daily trips north of Lechmere, which may stress the capacity of through-running trains on the branch.

Including these additional demands is crucial for determining the future throughput needs of the entire Green Line system. Additionally, they are needed to optimize vehicle allocation — and thus fleet size — to meet future capacity needs. Creation of a passenger flows matrix that incorporates approximate OD patterns for the GLX is thus necessary for all medium-term capacity planning.

This necessarily cannot be as accurate as measurement of real riders through AFC data, as exact boarding totals and the number of riders who switch from the Red and Orange Lines to the new Green Line stations cannot be precisely determined from modeling alone. This is not inherently problematic; vehicle allocation and frequencies — and even matching eastern and western terminals — can be revaluated after several months of data is collected when the lines open. However, a first-order approximation is useful to estimate the total vehicle counts and an initial operating pattern required to begin services on the Extension.

Lacking access to a detailed trip generation model, existing ODX data plus the projected per-station boarding totals was used to estimate future flows. It was first necessary to make a number of assumptions that allow simplification of the problem. One of these — that temporal distributions of trips beginning/ending in the GLX, and the spatial distributions of the other ends of the trips, can be approximated from current riders using Lechmere — is examined in some detail. Adding projected flows from the GLX to existing flows data was then done in two parts. Additional flows on the existing system caused by new GLX riders can be approximated by isolating current Green Line flows to/from Lechmere station itself and scaling them to match projected GLX ridership. Flows on the new sections of line (Lechmere-Union Square, Lechmere-East Somerville, and East Somerville-College Avenue) can be approximated by taking the current temporal distribution of bus ridership to/from Lechmere and applying that to projected GLX ridership.

I.1 Assumptions

Several assumptions inform this production of approximate flows. The GLX was assumed to consist of three independent parts: the relocated Lechmere station, the new Union Square Branch and Union Square station, and the new Medford Branch and its five stations. The Medford Branch was divided into two sections at East Somerville station, as some GLX plans have called for that station opening before the rest of the branch. The wording of this report assumes that Lechmere service is the sum of Union Square and Medford Branch services, without any Lechmere or East Somerville short turns. (This is because of the planned GLX carhouse design, which due to constrained rights-of-way does not have yard leads that can be reached from Lechmere without reversing.)(Massachusetts Department of Transportation, 2010)

It was assumed that there will be no significant ridership between Union Square and the Medford Branch, and between any pair of Medford Branch stations. A fixed percentage (for this report, 15%) of GLX branch riders were assumed to ride only between the branches and Lechmere - without entering the Central Subway - as riders commute from Somerville and Medford to jobs in East Cambridge and Kendall Square. As comparison, 15% of inbound Red Line riders boarding between Alewife and Central over several days in April 2016 got off no later than Central, and 11% got off at Kendall (14% of those who rode past Central). Lechmere has a similar mix of residential and employment density as Kendall, but the Medford Branch intermediates are primarily residential without the density of Davis, Porter, Harvard, and Central — and the Union Square Branch has no intermediate stops before Lechmere. If desired later, an approximation of the small intra-Medford-Branch and between-branches ridership can be done using bus ridership in the corridor. However, these minor corrections are secondary to ensuring that there is sufficient capacity to meet demand on constrained segments.

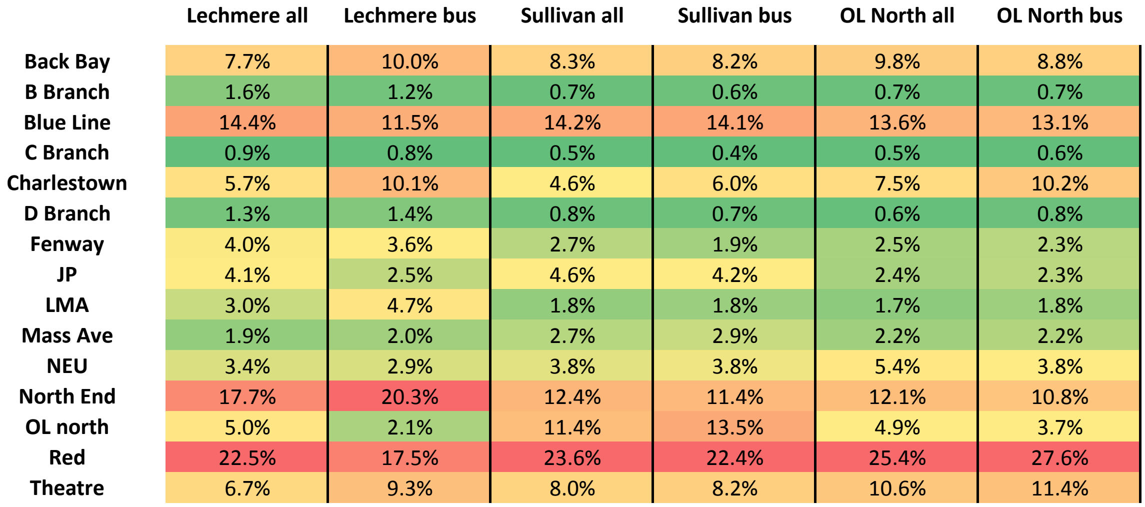
It was assumed that the destination and time of all inbound boardings at the new Lechmere station can be approximated by examining and scaling up existing boardings at Lechmere by riders who do not arrive by bus. Similarly, it was assumed that the destination and time of non-Lechmere-bound inbound boardings can be approximated by scaling up existing boardings from one of a selection of existing transit services (see next section) in the corridor. Finally, it was assumed that outbound ridership can be estimated in the same manner. This final set of assumptions can be examined with ODX data.

I.2 Temporal and spatial distribution comparison

To determine what ridership patterns should be scaled up for the new stations, OD patterns originating at Lechmere, Sullivan, and the Orange Line north of Sullivan (an area with similar demographics to the GLX corridor) were compared. OD patterns only of riders originating on bus routes serving the corridor (routes 69, 80, 87, and 88 to Lechmere; and routes CT2, 86, 89, 90, 91, 95, and 101 to Sullivan) or similar areas (routes 99, 100, 101, 106, 108, 131, 132, 134, 167, and 137 to the northern stations) and continuing by rail were also considered. Ridership for weekdays on the four weeks from April 4 to April 29, 2016 was used for this analysis. A number of the routes connected to Lechmere and Sullivan extended beyond the GLX corridor; no effort was made to only include riders actually boarding within the GLX coverage zone. However, all of those routes except the 80 and 95 intersect either the Red or Orange lines near their outer ends, so bus riders that are unlikely to use the GLX are likely already alighting buses at the heavy rail stations and so would be excluded from this count.

Destinations were aggregated approximately into geographic zones (shown in Figure I-1), roughly by how far the rider would travel if using the Green Line. Thus, all riders terminating at Park Street, Downtown Crossing, or transferring to the Red Line were considered equivalent; similarly, all riders terminating at Roxbury Crossing, Longwood Medical Area, Brigham Circle, or Fenwood Road were grouped together. Bus connections made after leaving rapid transit were not considered, but Orange and Green Line stations in the same zones generally served similar bus routes. Ridership to Orange Line stations north of Sullivan was not considered; from the GLX corridor, bus connections to Sullivan would generally be faster for such trips than using the Green Line at all.

Destination distributions for the six origin groups are shown in Table I.1.



	Lechmere all	Lechmere bus	Sullivan all	Sullivan bus	OL North all	OL North bus
Back Bay	7.7%	10.0%	8.3%	8.2%	9.8%	8.8%
B Branch	1.6%	1.2%	0.7%	0.6%	0.7%	0.7%
Blue Line	14.4%	11.5%	14.2%	14.1%	13.6%	13.1%
C Branch	0.9%	0.8%	0.5%	0.4%	0.5%	0.6%
Charlestown	5.7%	10.1%	4.6%	6.0%	7.5%	10.2%
D Branch	1.3%	1.4%	0.8%	0.7%	0.6%	0.8%
Fenway	4.0%	3.6%	2.7%	1.9%	2.5%	2.3%
JP	4.1%	2.5%	4.6%	4.2%	2.4%	2.3%
LMA	3.0%	4.7%	1.8%	1.8%	1.7%	1.8%
Mass Ave	1.9%	2.0%	2.7%	2.9%	2.2%	2.2%
NEU	3.4%	2.9%	3.8%	3.8%	5.4%	3.8%
North End	17.7%	20.3%	12.4%	11.4%	12.1%	10.8%
OL north	5.0%	2.1%	11.4%	13.5%	4.9%	3.7%
Red	22.5%	17.5%	23.6%	22.4%	25.4%	27.6%
Theatre	6.7%	9.3%	8.0%	8.2%	10.6%	11.4%

Table I.1: Rail destination distribution for six origin groups. Values are colorized green-to-red according to the proportion of riders that leave the rail system in that station group.

Overall destinations are relatively similar across the six origin groups. Over half of riders leave the two lines before or at the Red Line transfer stations, another 15-20

The largest difference between the Green Line and Orange Line origins is in Boston proper; more Green Line riders stay in the North End, while more Orange Line riders transfer to the Red Line. Based on this, the recommended scaling group for GLX riders is, as hypothesized, those who currently take buses from the corridor to Lechmere. This group more accurately represents the existing walkshed overlap with the Red Line, ease

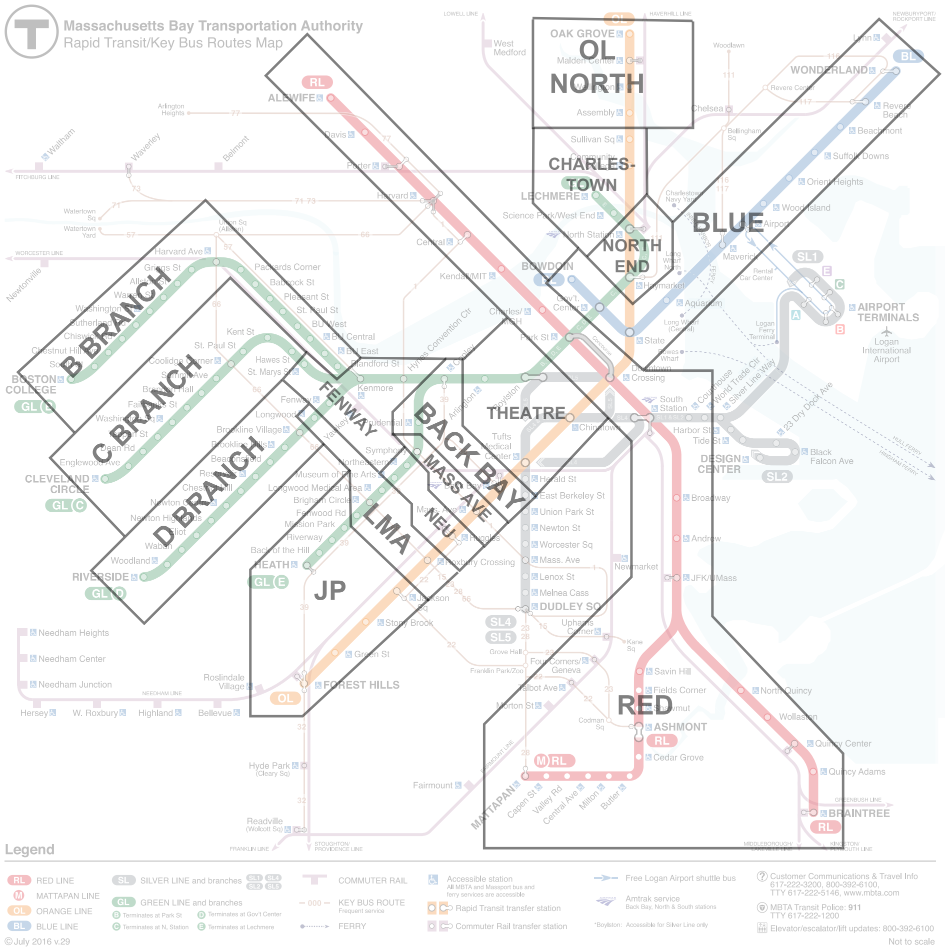


Figure I-1: Geographic zones used to group destinations among parallel stations on the Green and Orange lines. This map distorts geography, so some stops that appear far apart are actually within close walking distance.

of intra-Green-Line transfers, and AM-inbound/PM-outbound peak flow expected for the GLX.

I.3 Additional flows on existing system

Additional flows through the existing system were then approximated using the methodology that has been used to produce the existing passenger flow tables for the MBTA. By restricting the input dataset in several similar ways, four additional flow tables were created:

- Table A, consisting only of (daily average) M_A riders that begin their trips by rail at Lechmere and did not arrive by bus

- Table B, consisting only of M_B riders that take a bus to Lechmere and continue by rail
- Table C, consisting only of M_C riders that end their trips by rail at Lechmere and did not continue by bus
- Table D, consisting only of M_D riders that take rail to Lechmere and continue by bus.

Ideally, there would be $M_A + M_B = M_C + M_D = L$, the actual total number of current riders entering (or the total leaving) Lechmere station on a given day. However, the rail flow algorithm uses only trips with inferred destination; because ODX only infers about 75% of trips and this varies greatly by location, this equality will not work out in practice. In practice, L should be taken from the count of tap-ins at Lechmere, which is much more accurate.

GLX documentation estimates the following boardings:(Massachusetts Department of Transportation, 2011)

- X_U: Union Square boardings (3,570 daily)
- X_T: College Avenue, Ball Square, Magoun Square, and Gilman Square boardings (9,060 daily)
- X_E: East Somerville boardings (2830 daily)
- X_L: Lechmere boardings (8,820 daily)

This then gives $Y_G = X_U + X_T + X_E$, the projected daily boardings from beyond Lechmere, and μ, the percentage of those boardings that alight at Lechmere and do not enter the Central Subway. To this is added α, the proportion of estimated GLX ridership that actually occurs. This gives us $Y_L = \alpha \cdot X_L - L - \alpha \cdot \mu \cdot Y_G$: the number of new Lechmere-boarding passengers that enter the subway after GLX opens. (The $\alpha \cdot \mu \cdot Y_G$ term is subtracted to account for riders returning from Lechmere to Union Square or Medford Branch stations.) With these, four scaled load tables were created:

- Table AA: multiply Table A by $\frac{Y_L}{M_A}$ to get the new subway flow from new passengers that board at Lechmere
- Table BB: multiply Table B by $\frac{\alpha \cdot (1-\mu) \cdot Y_G)}{M_B}$ to get the new subway flow from new passengers that board north of Lechmere
- Table CC: multiply Table C by $\frac{Y_L}{M_C}$ to get the new subway flow from new passengers that alight at Lechmere

- Table DD: multiply Table D by $\frac{\alpha\cdot(1-\mu)\cdot Y_G)}{M_D}$ to get the new subway flow from new passengers that alight north of Lechmere

Adding tables AA, BB, CC, and DD to the existing loads table produced a full post-GLX loads table for the existing system. Because these scaling factors scale to the projected ridership, they will produce accurate results even if tables AA through DD are incomplete (as long as the incompleteness was evenly distributed).

I.4 Flows within the GLX

It was then necessary to compute flow tables for the 6 new segments (3 bidirectional sections), which do not have existing rail flow tables to scale. We approximated these using the assumption discussed above that existing bus services in the corridor offer a useful temporal distribution of ridership.

To obtain the projected southbound flows for the Union Square Branch, we took the temporal distribution of riders from group B above, binned to half-hour intervals, and multiply it by X_U. The same was done for the College Avenue-East Somerville segment using X_T and the East Somerville-Lechmere segment using $X_T + X_E$. Similarly, the temporal distribution of group D was used for the three northbound segments.

One possible issue with this approach is that unlike rail arrivals and departures — which are scheduled for every 5 to 15 minutes and thus stochastic for these purposes — the four bus routes operate on headways of 20 to 40+ minutes and thus are nonrandom. The 69, 80, and 87 have identical clockface schedules on 20-minute headways during the PM peak; this is ideal for passengers to remember that their buses always leave at :00, :20, and :40 past the hour. (The 88 leaves at :10, :30, and :50). However, it means that from 3 pm to 7 pm, each :00 to :29 bin has 7 outbound buses and each :30 to :59 bin has 5. At off-peak hours this problem can be even worse: there are only 2 departures between 10:30 and 10:59pm, but 4 between 11:00 and 11:29pm.

Three factors and actions can mitigate this. First, bus departures and arrivals have a degree of randomness beyond the schedule; all four routes had on-time performance between

57% and 64% by a 2012 measurement.(Massachusetts Bay Transportation Authority, 2012b) This induced variation is of course highest at rush hour, when passenger volumes are most critical. Second, we use the rail arrival and departure times to create the distribution, which adds an additional amount of randomness. Third, if there are still issues from binning, then smoothing can be performed to even out the peaks.

Scheduled arrivals and departures at Lechmere (for the Spring 2016 schedule), actual arrivals and departures (from AVL data) and the assigned flow distribution in the Lechmere-Brickbottom corridor are shown in Figures I-2 and I-3. There is broad correlation between frequency and flow, particularly in the AM peak, but there is not a substantial nonrandom element to flow caused by the bus schedules. (Strangely, actual and scheduled arrivals correlate more closely than do departures — indicating that many buses are arriving nearly on time but departing early or late.)

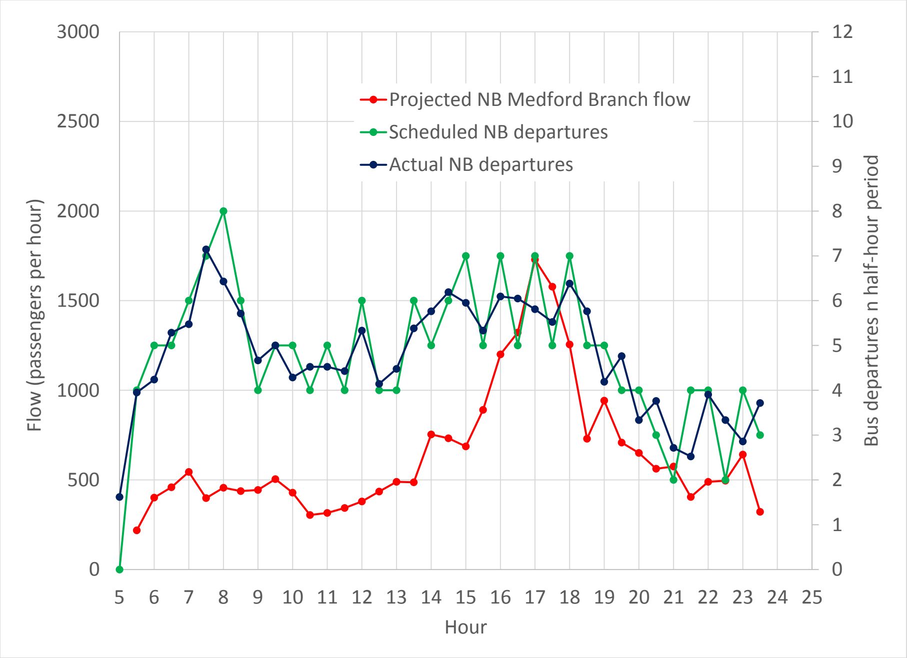


Figure I-2: Projected northbound Medford Branch flows versus scheduled and actual bus departures from Lechmere

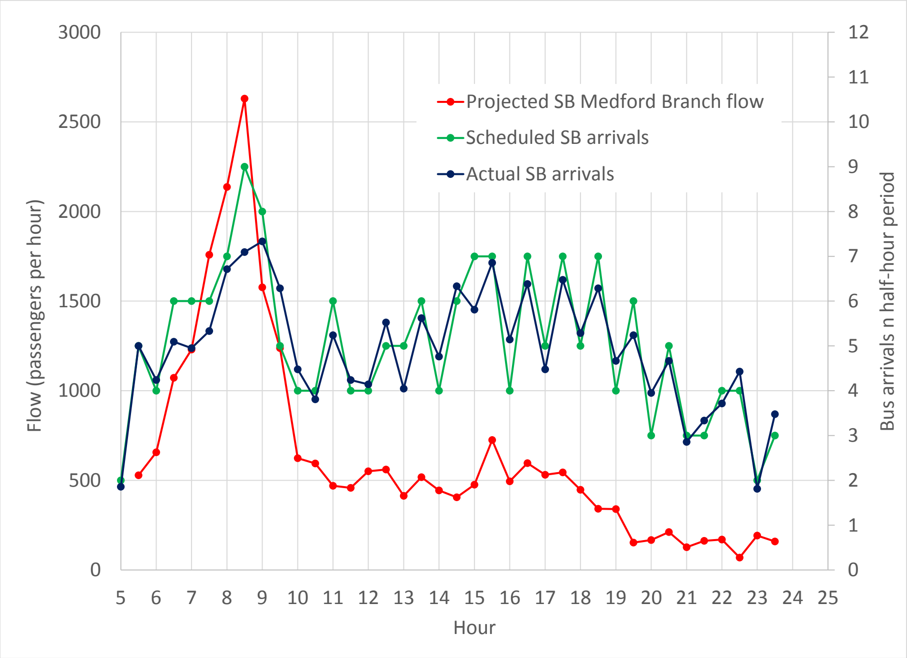


Figure I-3: Projected southbound Medford Branch flows versus scheduled and actual bus arrivals at Lechmere

I.5 Implementation

Cycle times for services after the Green Line Extension were estimated based on running times from GLX environmental documentation.(Massachusetts Department of Transportation, 2011) The cycle time increases used were as follows:

- B Branch: Extended to Government Center to eliminate need for the Park Street Loop. Add 1 minute in each direction (+2 minutes total)
- D Branch: Extended from Government Center to College Avenue. Add 9 minutes (8 running + 1 recovery) in each direction for Lechmere extension; add 11 minutes (9.5 running + 1.5 recovery) in each direction for College Ave extension (+40 minutes total).
- E Branch: Extended from Lechmere to Union Square. Add 5 minutes in each direction (4.5 running + 0.5 recovery) in each direction (+10 minutes total).

For calculations where the C Branch is also extended to College Avenue to handle demand, add 4.5 minutes (4 running and 0.5 recovery) in each direction for Lechmere extension; add 11 minutes (9.5 running + 1.5 recovery) in each direction for College Ave extension (+31 minutes total). For those where the B Branch is also extended to North Station, add 4.5 minutes (4 running + 0.5 recovery) in each direction (+9 minutes total, +11 minutes total including Government Center extension)

Cycle times were decreased uniformly by 5% from the results of this thesis, as Fabian and Sánchez-Martínez (2017) showed that real-time headway control (which the MBTA has indicated plans to pursue) can decrease running times by this much or more.

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