MBTA Green Line 3-Car Train Operating Plans to Enhance Capacity and Reliability

by

Alexandra A. Malikova

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Author ....
Department of Civil and Environmental Engineering
May 21, 2012

Certified by ....
Frederick Salvucci
Senior Lecturer and Research Associate of Civil and Environmental Engineering
Thesis Supervisor

Certified by ....
John P. Attanucci
Research Associate of Civil and Environmental Engineering
Thesis Supervisor

Accepted by ....
Heidi M. Nepf
Chair, Departmental Committee for Graduate Students

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Abstract

Transit agencies face a variety of challenges, from increasing ridership to changes in infrastructure, to system expansions, all of which require significant preparation to accommodate the changes without affecting passengers or the agency negatively. The MBTA Green Line, a Boston light rail system serving nearly 230,000 average weekday passengers, will be undergoing major changes in the next two decades, including nearly doubling of ridership and system expansion. In order to prepare for these changes, measures need to be taken to increase capacity and plan for operations on the new segment.

Starting in Fall 2010, the MBTA added to a 2-car train operation, and subsequently increased, a number of 3-car trains on three of the four Green Line branches, in order to begin to address the capacity issue. This thesis analyzes service performance before and after implementation of 3-car trains to find that although scheduled capacity increased slightly, the actual capacity of the system remained constant during the morning peak period and decreased during the evening peak period. Furthermore, there were some negative impacts with respect to passenger waiting time and running times, thus worsening the overall passenger experience. However, since 3-car trains will be required for increasing capacity on the Green Line, it is recommended that trials of 3-car trains continue, with the restriction that only 2- or 3-car trains operate on a branch. Furthermore, field observations at terminal stations on two of the branches show differences in operations management practices, which help explain some variability in service along the route, and point to strategies to improve service reliability.

Thesis Supervisor: Frederick Salvucci
Title: Senior Lecturer and Research Associate of Civil and Environmental Engineering

Thesis Supervisor: John P. Attanucci
Title: Research Associate of Civil and Environmental Engineering

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Chapter 1

Introduction

Public transportation systems face constant changes, from funding levels to system expansion, to changing ridership. Each change requires preparation to ensure that the impact of the changes is felt minimally, either to the passengers or the transit agency itself. The Massachusetts Bay Transportation Authority (MBTA) is one such agency that is preparing for significant changes. It operates the Green Line, the nation's busiest light rail system with over 232,000 average weekday passengers [1] (Dickens, 2011) and is facing a ridership increase of nearly 100% to over 457,000 average weekdays riders by 2030 (Federal Transit Administration and Commonwealth of Massachusetts, Executive Office of Transportation and Public Works, 2008). Furthermore, the line is facing an expansion to the north to the cities of Somerville and Medford, and a potential upgrade to the system's control. All of these changes will impact the system's ability to carry passengers quickly and reliably.

These significant changes require preparation to transition to more complex future operations, yet the existing state of Green Line is not well understood in terms of its operating effectiveness. The last academic operations study of the Green Line was completed in 1996 by Eberlein (Eberlein et al., 1998), and the last thorough analysis completed by the MBTA was done in 2008 by the service planning staff (Strangeways, 2012). In order to prepare for the future, the MBTA must understand current operations and challenges.

[1] The next highest light rail ridership is on the San Francisco MUNI, with 162,000 average weekday riders.

1.1 Motivation

In order to prepare for the future, the MBTA should create a plan to incrementally change operations to meet its future needs, which requires continuous evaluation by the agency and external contractors, if applicable. MBTA's promise to deliver quality service to its passengers requires service monitoring. According to the Service Delivery Policy 2010 the mission states:

> *The MBTA is a dedicated world-class transit system built upon customer service excellence, accessibility, reliability, state-of-the-art technology, and a diverse workforce that reflects our commitment to the communities we serve.*

In order to provide the reliability on the system, the MBTA needs to know first if it is meeting the goals of reliability defined in the Service Delivery Policy. However, due to limited information on the Green Line, the MBTA service planning staff is not always fully informed of the Green Line's ability to meet its passenger demands nor its efficiency in operating its services. Evaluation of the system is crucial for understanding present service levels and planning efficient short-term operating modifications and meeting the growing demand on the system.

Long-term operations are even more critical. The system is facing two major project completions within the next decade: the Green Line Extension project and Positive Train Control (PTC). The Green Line Extension into Somerville and Medford, now planned to be partially completed by 2018 and fully by 2020, will extend along two new branches in Somerville and add 4.3 new miles of track and 6 new stations. The extension is also predicted to have ridership with up to 52,000 average boardings per day (Commonwealth of Massachusetts, Department of Transportation, 2010), which will further increase the ridership in the core downtown section of the system. Moreover, PTC, a system for monitoring and controlling train movements to increase system safety, is being considered for implementation in the next decade. Depending on the type of system implemented, PTC will most likely require the minimum headways to increase from the current 30 seconds, achieved with line-of-sight operations. An increase in minimum headways will reduce the effective capacity of the system unless steps are taken to mitigate the reduction in train frequencies.

In addition to the service perspective, the Green Line is also important for the city's economy. The light rail system supports the City of Boston's economic strength by enabling commuting between Boston's economic centers and the surrounding towns. Mobility, defined as the ability to move around easily, is important for economic activity within cities (Rodrigue et al., 2009). Weak transportation links can limit economic development as it will constrain the number of people who can use those links to commute to the economic centers. The MBTA Green Line can become a weak link if it cannot accommodate increasing ridership of up to 100% by 2030. The challenge is understanding the present situation of the Green Line to determine where and how growth of the system can be accommodated continually over the next two decades.

Understanding of current operations will help conceptualize, test, and analyze short-term improvements to prepare for growing ridership and make it easier to transition to future changes. Analyzing operations can help the MBTA mitigate the inevitable operational challenges of these future changes.

1.2 Green Line Background

The Green Line is a four branch system that converges into a single trunk tunnel under Boston (Figure 1.1), serving Boston and its surrounding suburbs. The system covers 22.9 track miles, and has 66 stations. It connects to all the other major rail lines in the MBTA system, including the Red, Blue, and Orange lines, as well as the Silver Line bus network and the commuter rail system. Numerous bus routes also have connections to the Green Line. The light rail system is an integral part of Boston's public transportation network, not only carrying a large number of people but also creating important connections to the rest of the system.

The increase in ridership on the Green Line poses a strain on the system, which will require significant capacity increases. In addition the MBTA is considering modernizing its signalization system, which may require decreasing train frequency. In September and early October 2010, the MBTA operated all 2-car trains during weekdays. To prepare to meet these challenges, the MBTA began to experiment with 3-car trains in late October 2010. It must be noted that the introduction of 3-car trains can be done in two ways: one way is to switch all or some scheduled trips from 2-car trains to 3-car trains. Such a move would require additional fleet resources and operators, as the current operating policies require one vehicle operator per light rail car, but would increase capacity by up to 50%. The second

Figure 1.1: MBTA Subway and Key Routes Map

way is to consolidate all 2-car train operations into only 3-car trains, but without increasing the number of rail cars used. This scenario reduces train frequency, which will be important in the Central Subway if positive train control is implemented, but only maintains the same current total scheduled capacity of the system.

Having introduced 3-car trains into service on the B and D Branches, the MBTA was testing its ability to operate 3-car trains. The schedule change was publicized as a capacity increase to alleviate peak period crowding, which indicates that the intent was to increase the number of rail cars operated. However, because of resource constraints and system power concerns—namely that the total number of rail cars the system can accommodate is unknown—the strategy ended up maintaining the scheduled capacity, but reducing the frequency. This can be viewed as providing insight into the future PTC project. The scheduling change, along with the other motivating factors listed above, prompted the evaluation of the Green Line service. Monitoring of the operations continued as this experiment was further developed by the MBTA. Several additional schedule changes beginning in January 2011 include an increase in 3-car train trips and further changes in headways.

Most recently, on January 3, 2012, the MBTA announced proposals for significant fare hikes and service cuts in an attempt to close a $161 million operations deficit for Fiscal Year 2013 (Massachusetts Bay Transportation Authority, 2012b). The plans included cutting Green Line weekend service on the E Branch, as well as dozens of bus routes, weekend commuter rail service, and ferry service. The final accepted proposal was altered to reduce the fare increases and service cuts (Massachusetts Bay Transportation Authority, 2012a), though the financial constraints on the system are still prevalent, which call for greater operations efficiency.

1.3 Objectives

The primary objective of this thesis is to critically evaluate service offered on the Green Line and understand the consequences of adding 3-car trains into service on the MBTA Green Line, while using the lessons learned from the analyses to create operating scenarios that take advantage of the benefits of 3-car train operations. The before and after analysis will help determine if the test improved reliability and service, by studying the running times and headways, and increased capacity, by studying the system throughput capacity.

The evaluation will provide a methodological framework for future studies of the Green Line. Changes to the operations plan will be recommended, which will focus on short-term operational changes. The hypothesis is that MBTA can plan its Green Line service to take advantage of 3-car train operations to increase its capacity and improve its reliability.

1.4 Research Approach

The recent trends in automatic data collection at transit agencies have allowed agencies to better assess performance. In cases where automatic data is available, the following can be easily calculated for any period of time to help understand system performance:

running time - time for a train to complete a route segment between two points. It is used predominantly for scheduling purposes.

cycle time - time for a train to complete a round trip, including the extra "layover" time normally built into a schedule to allow the train to depart on-time for its successive round trip. Again, this is used for schedule making to ensure that the schedules reflect actual train performance.

headway - in a given direction, time between each successive train at a point on a route. This metric is useful for calculating passenger waiting time, which allows evaluation of passenger service levels.

ridership - number of passengers entering the system on a given route or combination of routes (additional information on passenger destinations can be inferred using assumptions about passenger travel behavior).

passenger flow - number of passengers per unit of time on a given point or segment on the line. Understanding passenger flow is important for scheduling purposes to ensure that enough trips are scheduled to accommodate the passenger demand at the peak load point.

vehicle load - number of passengers on a single train at a specific time.

On the Green line, two sources of data are used: Automatic Vehicle Identification (AVI) data as the primary source, and field observations of train performance at the Riverside Terminal as secondary.

Automatic data is collected using the Green Line's Automatic Vehicle Identification (AVI) system. Multiple AVI boxes are placed along the route and record the route number, date and time, AVI number (associated with a location), rail car numbers, and queue information as each train passes, which can then be retrieved for any length of time and be used for system evaluated.

There are a total of 28 active AVI sites located throughout the 22.9 miles of the Green Line. The Central Subway, defined as Kenmore Station to North Station, has the highest coverage while the surface portions have fewer, and thus lower granularity. The E Branch has no functional AVI points west of Brigham Circle, therefore thorough evaluation of the entire branch is not possible, though analyses of intermediate running times and headway analyses can still be performed.

Field observations are used to capture data not attainable by automatically collected data.

1.5 Thesis Organization

Chapter 2 describes previous work on rail transit capacity and service, and gives an overview on previous research of the Green Line. Chapter 3 will further discuss the Green Line by giving a more thorough background of the system, the system used for record keeping of the Green Line's movements, and identify problems on the Green Line that must be considered when recommending short-term improvements. Chapter 4 will discuss the methodology used to evaluate the service as well as describe findings for each branch. Chapter 5 will propose and evaluate operating plans for the Green Line based on lessons learned from Chapter 4. Lastly, Chapter 6 will summarize the findings as well as provide recommendations to the MBTA for short-term operational changes. Chapter 6 will also offer recommendations for future work.

Chapter 2

Literature Review

2.1 Introduction

This thesis focuses on transit light rail capacity and real time operations, therefore it is necessary to briefly introduce these concepts and review relevant research on each topic. A better understanding of capacity and real time operations will also provide guidelines for the research at hand, namely how to approach solving these issues on the MBTA Green Line.

2.2 Rail Transit Capacity

Although rail systems throughout the world face different operating conditions, there are a number of factors that control capacity on all rail systems, as discussed in the Transit Capacity and Quality of Service Manual (Kittelson & Associates, Inc. et al., 2003). When considering capacity on rail systems, with respect to train throughput, the following can be limiting: train control and signaling, dwell time, types of turnbacks, junctions, power supply and fleet availability. There are further capacity constraints particular to light rail, including traffic signal cycles at at-grade intersections. The line capacity dictates the passenger capacity, depending on the individual rail car capacity and rail cars per train set. However, a distinction must be made between theoretical capacity and practical person capacity, where the latter is usually less than the theoretical capacity. The main differences between the two are discussed further in the following sections.

2.2.1 Signaling System

The purpose of the signaling system is to ensure that trains keep a safe distance between each other. There are at least two types of signal systems: fixed block and moving block. Although there are additional types of systems, a lot of them can be categorized within the above two. The fixed block system, also called automatic block system (ABS), uses computer logic to relay to a train whether it must stop (usually red), can proceed with caution (usually yellow), or proceed at normal speed (green). In general, a minimum of two empty blocks seperate each train, allowing for enough room for a following train to stop safely. Figure 2.1 demonstrates a system using red/yellow/green signal convention, and each block's signal color, depending on the train location. In Figure 2.1, the second to bottom scenario demonstates that if a train occupies more than one block for a short period of time, then three full blocks are used for the safety buffer.

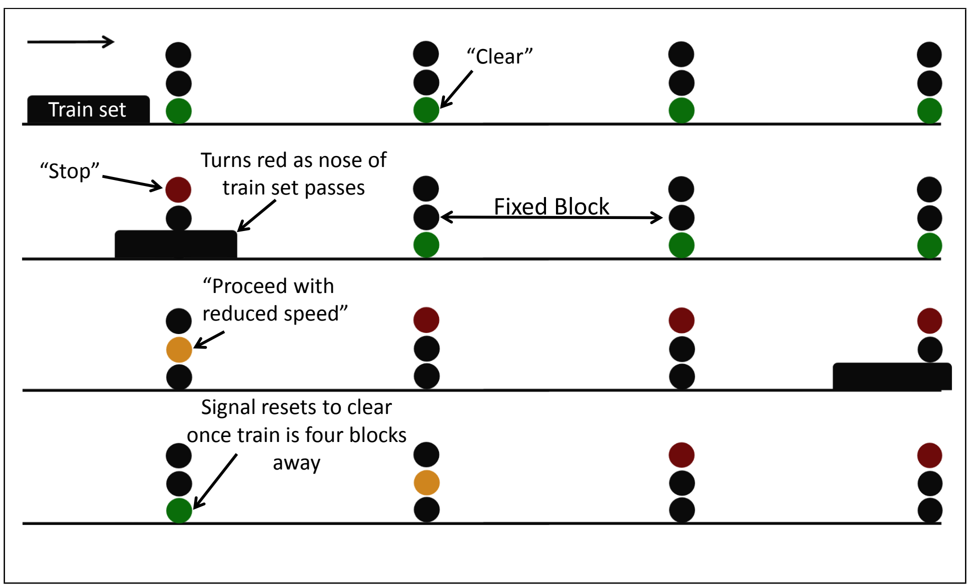

Figure 2.1: Example of Signal Display in Fixed Block System, with Respect to Train Location (Adapted from Kittelson & Associates, Inc. et al. 2003)

Some fixed block systems are able to control trains that violate the given signal aspects through Automatic Train Control (ATC). A computer onboard the train communicates with the signal system and ensures that the operator follows the given signals. For example, if an operator accidentally misses a red signal, the ATC will force the train to stop though the onboard computer.

The Green Line is an example of fixed block wayside signalling system (Farrell, 2012), though currently there are no controls to stop trains if any of the signals are violated. The lack of control allows the trains to easily switch to line-of-sight operations at stations, where operators manuever the train based on visual distances. Since some Central Subway stations on the Green Line allow two 2-car train sets to stop there, the trains can come to within feet of each other. However, due to a fatal accident on the Green Line in 2008 (Bierman et al., 2008), and a more recent non-fatal accident in 2009 (Valencia and Bierman, 2009), the National Transportation Safety Board has highly recommended that the MBTA install Positive Train Control (PTC) on the entire Green Line (National Transportation Safety Board, 2009). PTC, similar to ATC, will provide some automated control over trains to reduce the probability of crashes. However, depending on how the system is implemented, the capacity on the Green Line may be significantly reduced. Using the current fixed block system as the base system, the headways may increase to up to two minutes since conventional fixed block systems have a throughput of 30 trains per hour (Kittelson & Associates, Inc. et al., 2003).

Alternatively, a communications based train control (CBTC), or moving block, system may be installed to minimize the capacity reduction. In CBTC, rather than having blocks fixed at certain locations along the track, blocks are defined as the spacing around a train that would allow a following train safe braking distance. A moving block system requires onboard computers to allow trains to communicate with a central control (Pascoe and Eichorn, 2009).

Using simulation models, Gill and Goodman (1992) calculated theoretical headways for a steady state track section using a 4-aspect fixed block system and a moving block control system, with train speeds of 50-70 km/h. Keeping all other aspects of the system the same, they calculated a theoretical minimum possible headway of 95 seconds for the fixed block system and 64 seconds for the moving block system, thus showing that moving block systems can decrease theoretical headways, and thus increase capacity, by up to 33% (Gill and Goodman, 1992).

More recently, in 2008, the Madrid Metro introduced CBTC signalling system on top of their traiditional fixed block system on two of their lines. After the completion of the signalling system, Line 1 had a 38% (9 additional trains per hour) increase in throughput capacity and Line 6 had up to 50% (12 additional trains per hour) capacity increase on one of the tracks, even after the addition of a new station (Jeronimo, 2010).

2.2.2 Dwell Times

Dwell times make up a significant portion of the running time and headway variability on a train system. Increases in dwell time can negatively impact the overall capacity and service performance of the system. For example, prolonged dwell time at a station will increase the running times for all trains and decrease the overall system capacity, assuming a fixed number of available trains.

While dwell times depend on a large number of factors, the most important variables in determining dwell time include the number of passengers boarding and alighting, the number of doors used for boarding, and train crowding (Lin and Wilson, 1992). In addition, the dwell time depends on the heaviest used door(s) of the train set, so dwell time is also a function of the slowest car or door operator, assuming manual door operation.

On the Green Line, Lin and Wilson showed that the crowding on the Green Line is a significant explanatory variable for dwell time, especially nonlinear forms, thus suggesting that more crowding compounds delays. The study also focused on dwell time differences between 1- and 2-car trains. It showed that there is variability in dwell time between the two train sets, in large part due to uneven passenger movement and loading distributions. However, the dwell time constants for 2-car trains are consistently larger for various scenarios tested, thus suggesting that there are inherent differences between 1- and 2-car trains, most likely because of the requirement of coordination between 2 operators in a 2-car train, as opposed to one in the 1-car train.[1]

Other factors important for dwell time determination include ease of boarding, for example whether the rail car has mulitple stairs or a low platform, and type of payment. The majority of Green Line stops and stations currently require front door boarding and on-board payment. At stations that are particularly crowded, the dwell time can increase quickly. Eliminating the need to have passengers board at only the front door and pay on-board would speed up the boarding process. For example, a study on the the New York City Transit Select Bus Service Bx12, which also had front-door only boarding, has shown that switching to off-board payment reduced dwell time by up to 40% (Barr et al., 2010). Before off-board payment implementation, dwell time used to make up 27% of running time

[1] The MBTA requires one operator per each rail car.

but changed to 20% after implementation.

Overall, controlling the factors that impact dwell times can be an effective strategy for improving capacity. For example, enforcement of strict dwell times, such as done on the Moscow Metro (Kittelson & Associates, Inc. et al., 2003), could reduce variability in departure times, which in turn maintains more even headways and reduces crowding. Understanding the most important factors that contribute to dwell time is critical for knowing what areas of the service to target for improvement.

2.2.3 Turnbacks and Junctions

Physical infrastructure also is critical to rail capacity. First, the design of the turnback and related track configurations at termini that allow a train to turn around to return to service can be a capacity constraint to the system. If the headway is shorter than the time it takes for a train to turn around and prepare for departure, then there is an obvious problem if trains are running late (assuming that effective recovery time is zero). For example, a turn around may require unloading and loading of passengers, an operator changing train ends (or bringing the train around a loop), and inspecting the train, all of which may add significant delay to the turn around time. Turn arounds may be especially problematic for older systems that did not design for the higher required capacity on the system. The Transit Capacity and Quality of Service Manual suggests a cross over just before the terminal station to increase capacity. Figure 2.2 demonstrates the ideal operations for improving capacity.

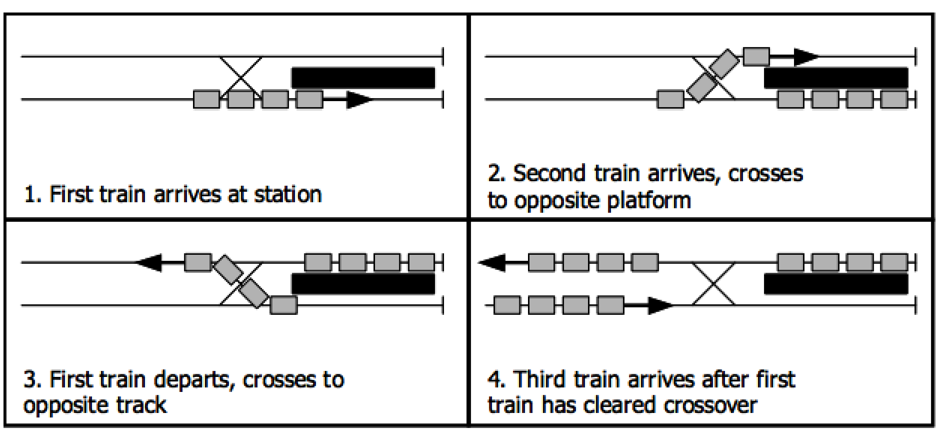

Figure 2.2: Turnback Operation with Crossover Located Prior to Terminal Station (Kittelson & Associates, Inc. et al., 2003)

In addition to turnbacks, junctions (track sections that overlap, merge or diverge) can impact service on systems that operate at less than 2.5-minute headways. The arrival of two trains at a junction requires that one of the trains moving through that section stop and wait for the other train to travel through the junction and the switch to reset. Furthermore, the waiting train loses time for decelerating prior to and accelerating from the junction. If more than two trains arrive at a junction, then the additional trains have to wait even longer while all the preceding trains travel through the junction. If the system has a frequency of 30 trains per hour or more, the junction may be creating a capacity constraint. Therefore, building a "flyover" junction, where conflicting tracks are grade separated, removes some interference between trains as they merge and diverge, and may be desirable to improve capacity.

2.2.4 Power System

A rail car requires a lot of power to accelerate (on the order of 500kW) from a full stop, and on average 150kW per rail car to operate at normal speeds (Kittelson & Associates, Inc. et al., 2003). Older systems may not be able to accommodate more trains than every three minutes, or an increased number of rail cars in operation (e.g. increasing to 3-car train sets from 2-car train sets). Having an up-to-date power system is vital for increasing the system's capacity.

2.2.5 Traffic Signal Delay

Many light rail systems, including the MBTA Green Line, operate in either mixed conditions or cross intersections at-grade. These operating conditions often require that trains obey the roadway traffic lights, which adds delay to a vehicle's running time, in turn affecting on-time performance and possibly leading to bunching. Traffic signals, more importantly, can dictate the line capacity. If the traffic light cycle time is greater than the minimum required headways, then train throughput, and thus capacity, is limited.

2.2.6 Passenger Capacity

As mentioned above, there are two types of passenger capacity: theoretical and person capacity, the latter of which is always less than the former. The theoretical capacity calculation assumes that all trains passing through a track section are at filled at capacity.

However, due to uneven loading and variable passenger arrival times, not all rail vehicles can actually operate at capacity, thus a person capacity is usually calculated. For example, rail cars closest to station entrances tend to be more crowded than rail cars away from the entrance (Kittelson & Associates, Inc. et al., 2003). Furthermore, passenger loadings vary within the peak hour, and there is generally a peak within the peak where the number of passengers is the greatest, referred to as the peak hour factor. Because of these variations, it is important to understand where and when, and to what extent, each of these variations occur, in order to accommodate the surges in passengers, and/or to plan station entrances that are placed at different locations along the platform.

2.3 Real Time Control

The goal of real time control on a transit system is to reduce service variability, including ensuring that headways remain as even as possible, and filling in gaps in service if delays or vehicle breakdowns occur. Sources of most of the service unreliability include road traffic, longer than expected dwell times, vehicle malfunctions, and type of driver (slow or fast) (Wilson, 2012). Monitoring routes prone to service delays on a daily basis can minimize the impact of each of the sources through real time intervention, with the exception of traffic, which can be improved through physical improvements, such as bus only lanes, and technology, such as transit signal priority.

Transit lines usually have field officials responsible for monitoring transit schedule adherence to ensure that the above sources disrupt service as little as possible using a variety of measures. Various measures used for getting vehicles back on schedule include expressing, deadheading, short-turning, and holding trains, each of which is explained below.

Short-Turning: Transit vehicles that turn around before their planned terminus are "short turned". This action is usually done to allow a transit vehicle to catch up to its schedule or to close a wide headway in the opposite direction. The decision usually decreases waiting time for passengers that are downstream from the location of the short turned train, but any passengers who intend to travel beyond the short turn location are inconvenienced by having to get off the train and wait for the next train. The unloading passengers also increase the dwell time of the train being short turned at the location of the short turn and increase the dwell time for the following train since more passengers will have to board that train.

Expressing: Transit vehicles are expressed past numerous consecutive stop to open a gap between leading and a succeeding vehicles that are too close to each other. The decision to express a train is announced at a stop to allow those traveling to intermediate stops to get off. Passengers on board the transit vehicle and at the station who are traveling to destinations to and past the next stop benefit by the reduced travel time, though those traveling to intermediate stops have to wait for the next vehicle in addition to the required travel time.

Deadheading: Similar to expressing, empty transit vehicles bypass one to many consecutive transit stops to open up a gap between the leading and following transit vehicle. Since no passengers are onboard the vehicle as the operation decision is made, fewer passengers are impacted by this service decision, although passengers located at stops not serviced by the deadheading vehicle have to wait longer for the following vehicle.

Holding: Transit vehicles are held at stations to lengthen gaps between vehicles that are bunched. Passengers onboard are negatively impacted by having to wait extra time in the vehicle, though those arriving during the holding period benefit because their waiting time is decreased since they do not have to wait for the next train. Usually, the number of passengers on the transit vehicle is much larger than those arriving to the stop during the holding period; thus, the overall passenger travel time may be worse compared to no holding.

These practices are common on the Green Line, as will be discussed in Section 3.3 (page 42). Significant research has been completed on the Green Line operations control decisions. Richard Macchi (1989) studied the impact of expressing decisions on passengers for various Green Line branches. By looking at the time saved or lost for all the passengers impacted by an expressed train, Macchi calculated the total time impact for the passengers by testing various headway scenarios on different branches. For example, on the D branch, a positive passenger time savings resulted if the preceding headway was 10 minutes and the following headway was 3 minutes or shorter. Although the model results varied from branch to branch, in general, Macchi found that the greater the following train headway is, the smaller the benefits of expressing are. Therefore, it is best to express a train with a short following headway and a long preceding headway, though of course that requires knowledge of the following headway.

Anthony Deckoff (1990) studied the passenger impact of short turning trains on the Green Line on the B and D branches. Deckoff determined the guidelines for short turning trains by determining which combinations of headways creates the largest positive passenger time savings. The B branch benefits from short turning if the two preceding trains were severely bunched or if there is a large gap between the preceding train and the arriving train. However, on the D branch, short turning is only beneficial if there is a wide gap (8 minutes or more before 6pm) between the preceding train and the arriving train.

Both Macchi and Deckoff pointed out that better real time information is needed in order to make beneficial operations decisions. Soon after the completion of their research, the MBTA implemented an Automatic Vehicle Location (AVI) system on the Green Line, which displayed train location throughout the system.[2] Fellows (1990) resarched the system and identified additional functions of the system that should be implemented in order to give MBTA staff better information to make better control decisions. Namely, Fellows identified the need for incorporating train headway information and schedule adherence, and suggested ways to implement this information into the AVI system. For example, the operating system controlling the AVI could be modified to calculate headways as trains pass each point that records train information. Alternatively, he proposed exporting the real time train information to a separate computer to calculate all of the desired information.

In addition to the above research, in 2005, the MBTA had implemented intermediate hold times, or “paddle times”, in order to minimize bunching on the B and C branches (Massachusetts Bay Transportation Authority, 2005). The memo sent to all the Green Line operations staff outlined locations where trains are to be held if ahead of schedule, unless directed otherwise by an authorized official. This directive required all operators to be aware of their scheduled arrival times at locations throughout the system. However, due to budgetary constraints, the number of enforcing officials had to be reduced, thus ending the program. Additionally, the practice could not be automated due to incomplete information of train location on the system (see Section 3.2 on page 41).

[2]See section 3.2 on page 41 for a detailed explanation of the system.

2.3.1 Dwell Times

Dwell time variability impacts service levels in addition to system capacity, perhaps even more so. Over longer distances, continuous small delays in dwell times can add up significantly to create large delays in running time. Furthermore, because of the buildup of passengers, which increases loading times, the vehicle continues to be delayed at each stop and falls further and further behind schedule, and increases its headway with respect to the preceding train. Unless the vehicle following the delayed train set is also delayed, it will find fewer passengers at each succeeding station, and gain on the train agead. Therefore it will have a shorter and shorter headway as the first train is delayed longer. Eventually the vehicles end up closely following each other in a bunched pair, which also adds a lot of variability in train arrival times.

As mentioned above, controlling dwell times as much as possible, for example, by introducing off board payment and enforcing a strict dwell time, can reduce the variability of the system.

2.3.2 Traffic Signal Delays

As mentioned above, traffic signal delays can not only constrain capacity, but can also add significant variability in travel time. For example, similar to station stops, delays at traffic lights introduce variability into the system, and if compounded over longer distances can add to running times.

Reduction in traffic light delay can be achieved through traffic signal priority, which gives transit vehicles priority for crossing the intersection. Traffic priority systems use a sensor to identify an approaching transit vehicle. Signal priority accommodates the transit vehicle by giving it a longer or early green signal, while signal preemption disrupts the traffic cycle to give instantaneous green to an approaching vehicle (Peter Koonce, 2008). Studies have shown that transit priority can reduce running time by 2-18% for buses (Kittelson & Associates et al., 2007).

2.4 Conclusion

The above research discusses the many factors affecting capacity and service levels. While there are different variables affecting each, both dwell times and traffic delays impact capacity and service levels. Reducing both of these will inevitably improve service and reduce constraints on capacity. However, increasing the number of rail cars operated can also worsen service levels. For example, increasing volume may result in more trains on the system and higher train throughput, but having trains closely spaced in the system makes the entire system more unstable, and any small delay can propagate through the system, thus delaying all trains. Furthermore, a higher concentration of trains within track sections generally results in slower service because of the signaling system. As discussed above, trains must have at least two empty blocks between each other, and trains following three blocks behind must travel at a reduced speed.

Ultimately, increasing capacity and improving service levels is a balancing act, where tradeoffs between each must be considered before implementing any interventions.

Chapter 3

MBTA Green Line

The Green Line light rail system in Boston and its nearby suburbs is complex with regards to its physical layout and operations. The system has four branches of various lengths and operating conditions that converge into a single trunk railway in the Central Subway. In order to evaluate the system's performance, automatically collected train tracking data is used, though it is incomplete and the analyses presented in this thesis depend on significant pre-processing of the available data. The Green Line also faces significant operating challenges due to upcoming extension, along with related power system, fleet, and passenger demand changes.

3.1 Green Line System Description

The Green Line provides commuter transportation for many working in Boston or attending one of many educational institutions along its length. As its four branches have various origins and destinations, not all trains serve all of the stations (Figure 3.1). The termini (located in Boston unless noted otherwise) for the four branches include:

- **B branch** - Boston College to Government Center, via Commonwealth Avenue
- **C branch** - Cleveland Circle (Brookline) to North Station, via Beacon St.
- **D branch** - Riverside Station (Newton) to Government Center, via Highland branch
- **E branch** - Heath St. to Lechmere (Cambridge) via Huntington Ave.

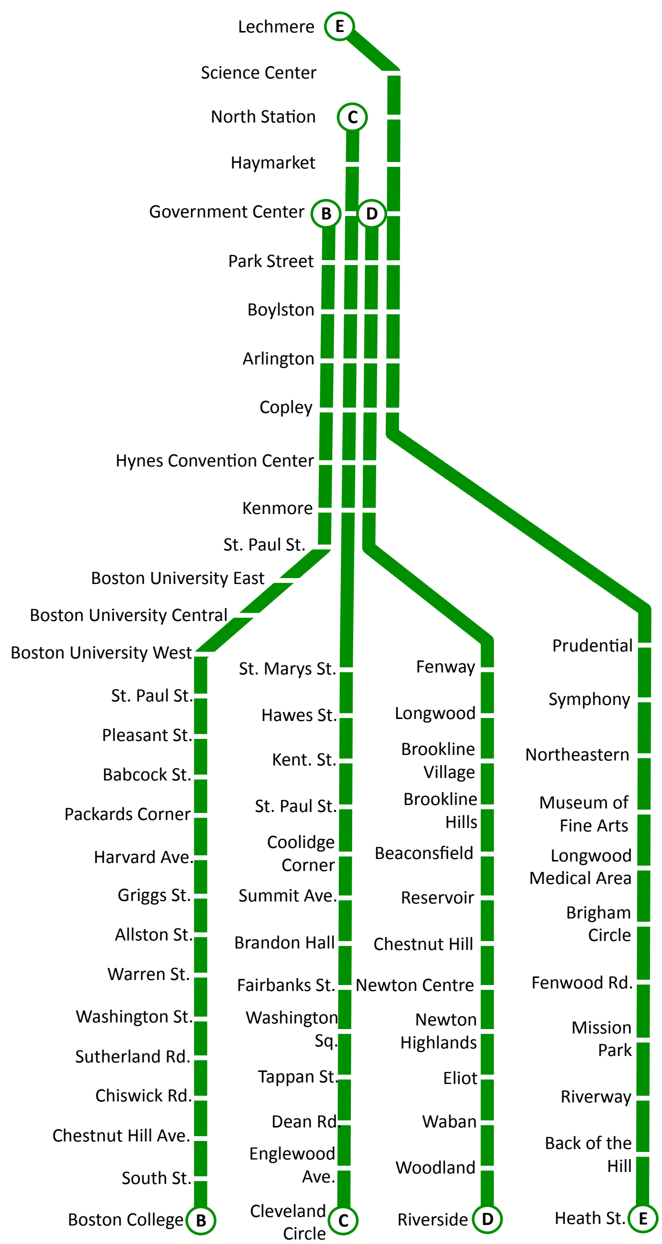

Figure 3.1: Green Line Routes

The Green Line operates in a variety of right-of-ways, ranging from a completely separated right of way in the Central Subway in Boston and on the D branch, to a full street car operating in general traffic, as done on the E branch south of Brigham Circle. On the majority of the segments, namely on the B, C, and a portion of the E branch, the trains operate separately in the median of the road, which include at-grade intersection crossings and general traffic signal regulation for light rail trains. Currently there are no portions of the Green Line that have traffic signal priority to minimize the time trains wait at traffic lights or to maintain headways.

There are two major storage yards with maintenance facilities on the system, and two smaller yards. Riverside Station, at the end of the D branch, has the largest train yard, with a capacity of up to 95 rail cars, while Reservoir Yard at Cleveland Circle, at the end of the C branch, has the second largest, with 79 rail cars. Two smaller yards are located at Boston College, at the end of the B branch, and Lechmere, at the end of the E branch. There are no storage facilities at the southern end of the E branch at Heath St. Furthermore, there is very little storage capacity in the Central Subway, where only seven rail cars can be accommodated at the North Station turnback, eleven rail cars can be stored at Government Center loop, and four at Kenmore loop, though any storage at the latter locations precludes the regular use of these loops.

The lack of off-line storage in the Central Subway does not allow the Green Line trains to easily layover (before proceeding westbound) in order to adjust their performance in accord with the schedule. Additionally, the Green Line has one track per direction in most of the system, except between Boylston and Park Street stations, where each direction has two tracks. The eastbound middle track in that segment is used only for short-turning trains at Park Street, therefore the two eastbound tracks cannot be fully used for trains traveling past Park Street.

Sidings located at a few points in the system (see Figure 3.2) can be used for storing vehicles, overpassing another vehicle, or short-turning trains. The sidings are located at Blandford Street on the B branch, at Northeastern University Station on the E branch, and at Reservoir Station on the D branch.

In addition to operating in various conditions, the Green Line has aging infrastructure that poses great challenges to daily operations. The original portion of the Green Line between Boylston and Park Streets was built in 1897, with the rest built in the following

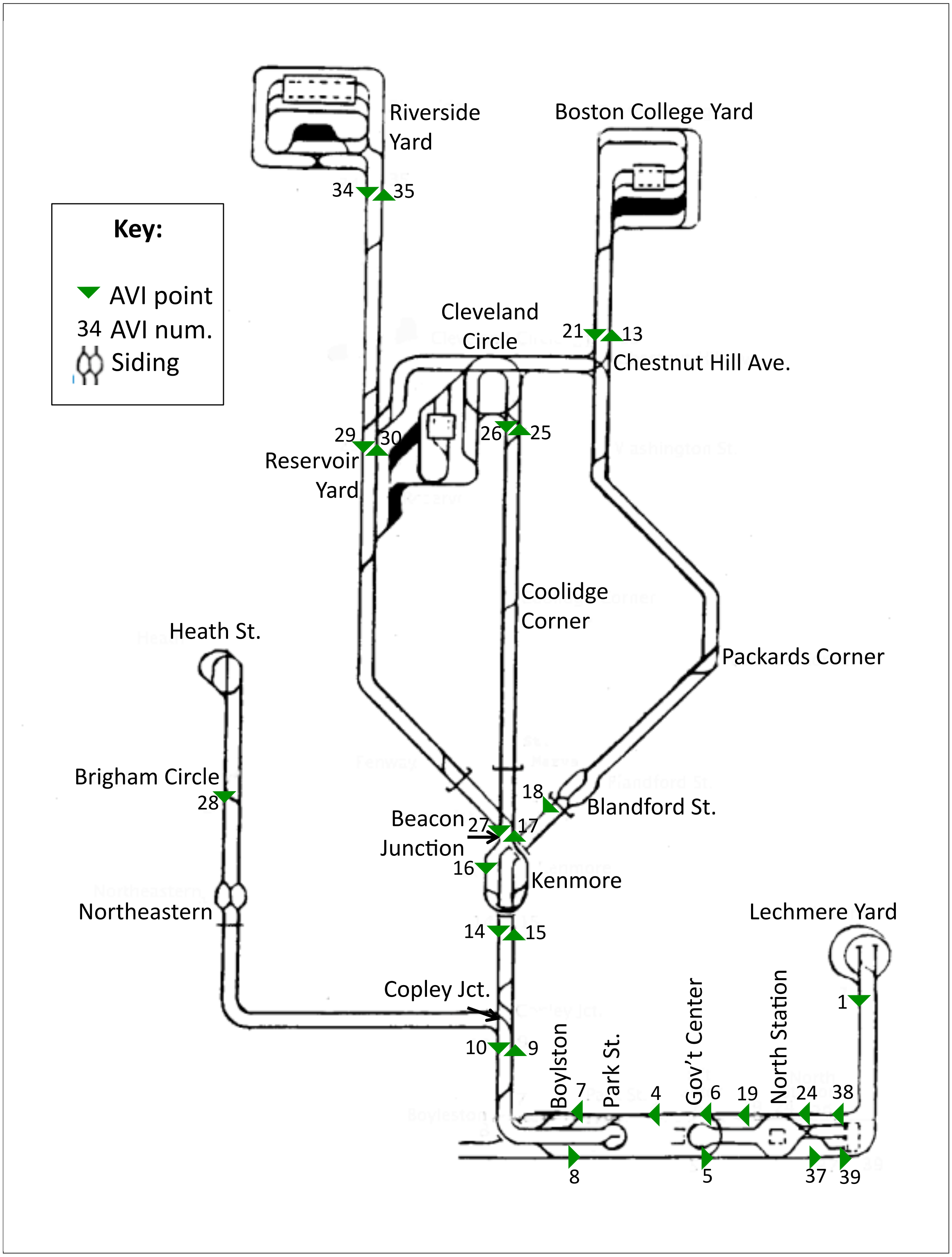

Figure 3.2: Green Line Track Map, with Locations of AVI Points, Rail Yards, and Sidings

decades. The original infrastructure contains tight curves at various locations on the Green Line, which slow down service and cause severe track and wheel wear, and harsh noise, especially at Government Center. Furthermore, the signaling system and the switches are extremely old. Either of them causes problems as often as a couple of days a week, which puts a strain on the system and impacts passenger service.

Ridership on the Green Line adds complexity as well. As the nation's busiest light rail system, the Green Line faces frequent crowding, as evident during peak periods and service delays, when, often visually, trains operate at crush capacity.[1] Uneven train and passenger arrival rates worsen on-board and platform crowding. Transfer stations, especially Park Street, with a connection to the Red Line, and Government Center, with a connection to the Blue Line, are particularly problematic since surges of transferring passengers from the higher capacity lines create significant crowding conditions that can temporarily overwhelm passageways, stairways, and the Green Line itself.

3.2 Automatic Vehicle Identification

Train movement on the Green Line is tracked using the Automatic Vehicle Identification (AVI) system. The AVI data is displayed at the Operations Control Center on a large Green Line system map, and it is also recorded in a central computer. The system consists of 28 AVI points placed throughout the routes that work in conjunction with sensors on board rail cars. Each rail car sensor stores its vehicle and route number. Every time a train set passes over an AVI point, the rail car component passes its information to the AVI, which then stores the train route, car numbers, the time and date of the event, and its own AVI unique identifying number. The information stored can be retrieved daily, weekly, or monthly for any time periods to use for performance analysis.

Currently, the AVI provides the best information for calculating Green Line performance without having to perform additional manual counts (with the exception of the E branch). After pre-processing, the AVI data can be used to evaluate the system's running times and headway distributions (see Section 4.1 for detailed methodology).

The greatest challenges in using the AVI data are the inaccuracy and incompleteness of

[1]Crush capacity is defined as 1.5 sq. ft./passenger by the MBTA (Webber, 2010), while the Transit Capacity and Quality of Service Manual defines "totally intolerable" capacity as 2.2 sq. ft./passenger (Kittelson & Associates, Inc. et al., 2003).

the current data set. Below, some of the issues with raw AVI data are identified:

1. **Low Resolution of AVI Locations** - There are only 17 locations on the Green Line that have either one or two AVI points. With 22.7 miles of track on the Green Line, this averages to 1.34 miles between each AVI location. However, coverage in the Central Subway is much tighter, with 11 AVI locations over a 3.4 mile stretch of track, while the remaining six locations are on the surface portions of the branches, with up to 6 miles between two AVI locations (on the D branch between Reservoir and Riverside Stations).

2. **Missing or Non-Working AVI Locations** - Some AVI's are disabled due to poor maintenance, while some are missing altogether. In particular, the E branch has no functioning AVI units south of Copley Junction in the outbound direction, and no units south of Brigham Circle in the inbound direction. Consequently, the E branch cannot be fully evaluated using AVI data alone.

3. **Incorrect Train Information** - AVI points may not record the correct train route or car numbers due to malfunctioning on-train equipment. The route may be recorded as an "Invalid Route" or "Unknown" route, and rail cars may be recorded with the default "9999" train identifier. Additionally, operators are responsible for inputting the correct on-board route information at the start of every trip, which creates opportunities for manual errors.

4. **Non-Recording of Trains** - Some AVI points work but do not record all of the information. A malfunctioning AVI can "miss" trains. This can also be a result of malfunctioning machinery on the train.

3.3 Operations Control Center and Real Time Control

The system operations decisions are made in real time by field staff, known as Inspectors, and off-site dispatchers, located at the Operations Control Center (OCC) at 45 High Street in Boston. At the OCC, the AVI system is used to monitor the Green Line train progression. There, two officials monitor the performance of Green Line trains on the four branches, provide information to the Green Line drivers about track work or operating conditions, and make operations decisions if deemed necessary. Officials at the OCC know which trains are between two consecutive AVI points, yet they do not know the true location of the train. If multiple trains are between two consecutive AVI locations, the officials do not know the spacing, and thus headways, between the trains. This poses problems since the dispatchers cannot make operations decisions to correct bunched trains or close long headways. In addition to the OCC officials, the Inspectors are placed throughout the Green Line system, namely at Lechmere, North Station, Government Center Station, Park Street Station, Boylston Station, Copley Station, Hynes Station (during rush hour), Kenmore Station, and Brigham Circle Station. The Inspectors work with the OCC to make operating decisions, such as short turning, expressing, or holding trains, based on field observations by the Inspectors and AVI information obtained by the OCC officials.

The Inspectors and operations control center can communicate via radio to make these operating decisions. If there is disagreement between the OCC staff and the Inspectors, the OCC has the final say. As of Fall 2011, the Inspectors at Park Street and Kenmore have access to the AVI data and can use the information to make decisions to short turn, hold, or express a train. These particular operations maneuvers are practiced as follows on the Green Line (for definitions of the terms, see Section 2.3 on page 31):

Short-Turning Trains

Trains on the Green Line are periodically short-turned at Park Street in order to correct headways. The decision is made by the Boylston Inspector since the track used for short turning at Park Street can only be accessed from Boylston, as that is where the tracks diverge (see Figure 3.2). The decision to short-turn at Park Street is generally made for about 2-3 trains on either the B or D branches. Occasionally east-bound trains are short-turned at Kenmore if there are significant problems, such as a signal outage, in the Central Subway.

Expressing Trains

Trains can be expressed at any point in the system, and by any field inspector or OCC dispatcher. Generally it is used as a last resort to regain scheduled headways or to recover from significant delays. On average, trains are expressed about twice per hour across all lines, and even more frequently following the evening rush hour.

Holding Trains

Holding is fairly common on the Green Line and can happen as often as every passing train on each branch. Trains can be held anywhere and field inspectors generally hold trains at their respective locations, such as Park St. in the Central Subway or at Brigham Circle, to adjust headways or to get the trains back on schedule.

3.4 Schedule Changes

The Fall 2010 schedule required all 2-car train operations on all branches. Trains on each branch operated with 5-6 minute headways during the peak periods, and 8-15 minute headways during off-peak periods. On October 25, 2010, the MBTA added a total of 13 3-car train round trips on the B and D branches (6 trips were operated on the B and 7 on the D). While the scheduled running times and headways remained the same for the C and E branches, the headways on the B and D branches remained at 5-6 minutes preceding all 2-car trains and increased to 9 minutes preceding all 3-car trains. The 3-car trains were scheduled as every other trip in the morning peak on the D branch, though only every 4th to 7th trip was a 3-car train on the B branch during both peak periods and the D branch during the PM peak period.

The Spring schedule increased the total number of 3-car train round trips to 30, with 13 round trips operated on the B branch, 13 on the D branch, and 4 on the E branch. 3-car trains cannot be operated on the street running portion on the E branch between Brigham Circle and Heath St.; thus all 3-car trains were operated between Brigham Circle and Lechmere. The headways remained similar to the winter schedule, with 9-minute headways preceding all 3-car trains. During the morning peak, the D branch operated 3-car trains for every other trip, while during the evening peak, and on the B branch for both peak periods, the 3-car trains were operated on every 3rd or 4th trips. The E branch operated the 3-car trains about 10 trips apart.

In Fall 2011, the number of 3-car train trips was increased to 32, and the preceding headways for 3-car trains changed to 7 minutes, while the headways for 2-car trains remained at 5-6 minutes. During the morning peak, the D branch was scheduled to operate 3-car trains on every 3rd trip, with sequence of 5-6-7 minutes headways for two consecutive 2-car train trips and a 3-car train trip. The evening peak on the D branch dispatches a 3-car trains trip every 4th or 5th trip, with the 5-6 minute headways preceding 2-car trains and 7 minute headways preceding 3-car trains. The B branch has more dispersed 3-car train operations, with 3-car trains running every 4th to 6th trip, though the headways remain the same as on the D branch. Lastly, the E branch has 3-car train trips scheduled as every 7th trip.

Table 3.1 summarizes the number of 3-car trains and trips operated during each season on 3 of the 4 branches (the C branch had no 3-car trains in service).

		B branch	D branch	E branch
Fall 2010	AM Peak	0	0	0
	PM Peak	0	0	0
Winter	AM Peak	2/4	3/3	0
	PM Peak	1/2	2/4	0
Spring	AM Peak	4/8	6/7	1/2
	PM Peak	4/5	4/6	1/2
Fall 2011	AM Peak	4/8	6/8	1/2
	PM Peak	4/6	4/6	1/2

Table 3.1: Number of Green Line 3-car trains/trips per schedule

3.5 Current Green Line Problems

As mentioned previously, the Green Line has many challenges, which may constrain proposed improvements. In addition to the problems and challenges stated above, there are a number of other problems facing the Green Line. Below is a summary of these problems and challenges.

- Ridership growth - As mentioned previously in Chapter 1, ridership is expected to increase by nearly 100% by 2030. Since the Green Line is already near capacity in the Central Subway, new strategies must be devised to accommodate some or all of this growth.

- Crowding that increases dwell time - Dwell time is a function of the number of passengers boarding and alighting, number of doors per rail car, rail cars per train set, and passengers on a vehicle. Lin and Wilson (1992) studied the impact of train crowding on dwell time and showed that on-board crowding contributes significantly to dwell time. They further showed that using non-linear forms of crowding improved their model, thus suggesting that the marginal increase in dwell time is greater with more crowding. This is especially problematic on the Green Line during peak periods.

- Poor train tracking capabilities - As mentioned above, while the AVI provides some information about the location of the trains, it does not provide precise train location information. If more than one train is located between two AVI points, they will appear to be bunched, which may not be the case.

- Positive Train Control (PTC) - The implementation of PTC, a system for monitoring and controlling train movements to increase Green Line safety, may impact the minimum headways, depending on the system chosen. Reducing the minimum headways will reduce the capacity of the system.

- At-grade intersections - On the B, C, and E branches, trains cross roadway intersections at-grade. Although most of the intersections are signalized, cars still occasionally block train movements. Traffic lights also slow trains down, adding running time. On some occasions, automobile accidents at these intersections temporarily disrupt service on the individual branches.

- On-board payment on surface portions - Only 14 stations on the system have prepaid fare areas, including all subway stations, as well as Riverside, Science Park, and Lechmere stations, and the remainder of the stations and stops require payment onboard the vehicle. This increases train dwell time by the time it takes all the passengers to interact with the fare box.

- Outdated power system - The power supply to the system is outdated, and overloads are more common than with modern systems. The actual limitations on the number of trains that a power section can accommodate is unknown. Therefore, the MBTA is conservative with the number of rail cars they schedule to reduce the probability of overloading the power system. A failure in one of the power sections can disrupt service on the entire system for hours.

- Outdated signal power system - Portions of the wayside signal system also rely on an antiquated power supply. Sectors within the system occasionally fail, thus requiring switching to manual operations, namely using radio communication to identify train positions within the failed sector. Manual operations require increased train separation, which decreases the train throughput capacity and impedes service levels. Although service continues, passengers can incur on average 10-20 minute travel delays within the impacted system segment.

- Train car constraint - Even if power sections allowed maximum throughput, the MBTA does not currently have enough trains to satisfy the increased demand requirements.

- Green Line Extension - The Green Line Extension to Somerville and Medford will increase the extent of the light rail system to the north. The Extension calls for 3 minute headways on the trunk portion of the extension and 6-minute headways on the two branches to Union Square and Medford. As of yet, the MBTA has not considered which of the four existing branches will be through-routed to the extensions, but this remains an important question since the decision will impact the branch service performance.

- New vehicles - The Green Line Extension will require the purchase of new rail cars, thus it is important to create specifications for procurement that reflects the future, as well as current, needs of the system. Consideration might be given to longer vehicles with larger throughput capacity and lower labor cost, and possibly wider doors to reduce dwell times.

This thesis will focus on the solutions to the capacity and reliability problems mentioned above. Listed below are possible solutions that should be or have been considered for light rail transit systems by previous studies.

- Ridership growth - Increasing the number of rail cars operated on the system will help accommodate some of the growth. Possibilities for increasing the number of cars include adding a car to all peak period 2-car train sets, depending on the ability of the power system to handle an increase in the power requirement and fleet availability. However, having 3-car trains operating throughout the entire route continuously will put some of this new capacity where it is not needed, such as at the western end of the branches. In order to save resources, the MBTA could split and join trains at key junctions. For example, single cars from the B, C, and D branches each could arrive at Kenmore Station and couple to become a 3-car train. A similar plan was operated in San Francisco on MUNI (Rosen and Olson, 1982). The operation plan required excellent coordination of the branches and customer information to relay these complex operations to customers to ensure passengers didn't board the wrong rail car. Alternatively, it may be possible to couple two 2-car trains from two of the four branches into one 4-car train. The headways should remain similar to current headways to increase the capacity. In the second case, coordination of train arrival will also be simplified since only two branches will have to meet, as opposed to three.

- Dwell time worsening with crowding - Increasing capacity is the primary solution to reducing crowding. A secondary solution is having trains run more reliably through better scheduling and field management, which in turn may even out passenger loading.

Other solutions that are beyond the scope of this thesis, but are important to consider when determining capacity and reliability are:

- Train car constraint - Purchasing new stock will help alleviate vehicle shortages, which is required to accommodate the ridership growth. Currently, the MBTA has started the procurement process for 24 new rail cars for the Green Line Extension. Furthermore, the procurement process should consider the future operations and project completions to define the vehicle specifications. Factors, such as increased ridership, should also be considered in the vehicle procurement, for example, by requiring the new vehicles to be longer.

- Positive Train Control - Implementing a system that allows short headways, such as communications based train control (CBTC, see Section 2.2.1 on page 26 for system explanation), will help maintain the capacity of the Green Line. Furthermore, the system should allow in-service coupling and uncoupling of the vehicles for either disabled vehicle management or the flexibility of allowing trains to couple from different branches.

- At-grade intersections - Implementing signal priority or preemption will allow Green Line trains to reduce time spent at traffic lights. Studies have shown that transit priority can reduce running time by 2-18% for transit vehicles that use signal priority (Kittelson & Associates et al., 2007).

- On-board payment on surface portions - Off-board payment could be implemented either through gated stations or through implementation of a proof of payment system. While the D branch has the option of off-board payment at many of the surface stations, it is rarely used.

- Poor train tracking capabilities - Increasing the number of AVI points, especially on the surface portions, will help improve the ability to track trains. Alternatively, positive train control will also give much better train tracking capabilities, though seeing as the project may only be completed towards the end of the decade, if at all, it would be prudent to increase the number of AVI points as soon as possible. Currently the MBTA is working on a project that will improve monitoring on the system through a yet undisclosed technology.

- Outdated power system - A Green Line power study is currently in progress. The results of the study will help determine the requirements for upgrading and perhaps replacing the system. Once upgraded, the MBTA should have a reliable power system adequate to handle larger train consists at the current frequency.

- Outdated signal power system - The signal department has plans for signal power system upgrades in the next five years, which should reduce the number of signal failures.

- Green Line Extension - Starting to plan for operations once the Green Line Extension opens will allow the agency to identify areas that will cause problems and potentially incorporate solutions to the identified problems into the construction plans.

Multiple other capital projects have been considered to improve Green Line operations and capacity. Although the projects are beyond the scope of this thesis, it is important to consider them for future Green Line studies:

- Park Street Connector - Currently the inner eastbound track between Boylston and Park Street stations can only be used for turning trains around at Park Street. However, the connector would link the inner track to the outer track at Park Street, thus allowing through trains to use the inner track in addition to the the currently constrained outer track (Massachusetts Bay Transportation Authority, 2011a).

- Silver Line Connector - Phase III of the Silver Line project proposed to build a direct Silver Line tunnel between South Station and Boylston, which would enable a direct connection between the Silver Line and The Green Line (Federal Transit Administration, 2003). This project was suspended, but would help improve passenger distribution and reduce pressure on Park Street, which is currently used as a transfer station for passengers traveling to South Station.

3.6 Conclusion

The Green Line is a complex system with four branches that converge into one trunk subway section. It operates in many conditions, including fully separated right of way, partially separated right of way, and on fully mixed traffic right-of-way throughout the system. Operations control is carried out by field staff and the operations control center, both of whom use the Automatic Vehicle Location (AVI) system to track train movement. Since the AVI data is stored, the data can be used for system evaluation, though with some limitations due to data imperfections.

Lastly, the Green Line faces many problems, ranging from infrastructure conditions to operations. Solutions for each of those problems are presented, some of which will be addressed by this thesis, and others considered by external studies. Understanding the problems that the Green Line is facing is important for operations since each listed problem creates constraints on system improvements in the short term. Any incremental Green Line improvements will require investment in one or more of the above solutions.

Chapter 4

Analysis of Three-Car Train Trials

The Green Line operating plan and schedule changes implemented in 2010-2011 can provide valuable insight into changes needed on the Green Line to address future challenges. The important questions to answer are: did the 3-car train trials achieve the first steps in preparing for the expected 100% increase in ridership by 2030, the Green Line Extension, and implementation of Positive Train Control? Furthermore, did the MBTA succeed in achieving those goals with minimal negative or even positive impact on passengers' experiences with respect to travel time and passenger waiting time? The latter is important to consider since hundreds of thousands of passengers use the service daily, and negative impacts would be felt widely.

Understanding the factors that contribute to service improvements or deteriorations is important for future service planning as well as management training. Service planning can use lessons learned to focus changes where they will provide the greatest benefit. In addition, operations manangement is crucial to implementing schedules and any service changes; service cannot be improved without focused and reliable operations management practices.

This evaluation of the Green Line used the AVI data stored by the MBTA, and can be used as a basis for developing a new methodology for regular AVI use at the MBTA. The methodology presented below describes the steps taken for headway, and running and cycle time calculations from AVI data. First, results from the evaluation of the B, C, D, and E branches are presented for Fall 2010 as a baseline, chosen since no 3-car train were scheduled for that time period. Results of the impacts of subsequent schedule changes on throughput capacity, running and cycle times are presented, followed by a discussion of the implications of the results. Only headway distributions are calculated for two locations on the E branch, since only a few AVI points function on the non-trunk portions of the branch and these do not provide enough information to calculate running times. In addition, field observations for the D and E branches are presented as support for the findings obtained from the AVI data.

4.1 Methodology

The methodology developed below is aimed at facilitating the evaluation process of the Green Line while providing as accurate a representation of the average daily Green Line performance as possible. Prior to 2010, the MBTA had developed a tool for evaluating Green Line on-time performance, though the change in the AVI data format in 2010 disabled the use of the tool. The methodology presented below focuses on schedule development through running and cycle time calculations, and measurements of passenger service quality though headway distribution analyses. The methodology can be applied on an ongoing basis to the MBTA service planning process to continue monitoring the performance of the system and the impact of various schedule and operational changes. The iterative process is especially important for developing a thorough understanding of factors and their impact on Green Line performance.

The primary data source used for Green Line evaluation is AVI data, complemented by field observations. In order to understand the delivered service levels of the entire Green Line, the throughput capacity in downtown Boston is calculated using AVI data, followed by the running and cycle times for the B, C, D branches, and headways for the B, C, D, and E branches. The running and cycle times are important for basic system scheduling, which should reflect the actual operating conditions throughout the day. Running time analyses also allow schedulers to determine the required slack time for vehicles throughout the day, which takes into account the travel time variability of vehicles throughout the day. Scheduled slack time reduces the probability of smaller delays propagating through the system. Furthermore, by analyzing route running time, the reliability and efficiency of the system can be determined: too little time allocated for a vehicle that has high variability in travel time adds unreliability to the performance of the route, while having too much time scheduled for a route creates inefficiencies and wastes resources.

Additionally, headway analyses are a proxy for passenger waiting time and train bunching. Train bunching is normally defined as trains that are spaced closer than scheduled, though for this thesis will be defined as trains that have headways of 3 minutes or less. Passenger waiting time (PWT) is dependent on the standard deviation and average headway, both of which are easily measurable (Equation 4.1). Increasing either of these variables increases passenger waiting time. Alternatively, bunching can be an indication of unreliability and degradation of the system performance. Studying bunching with respect to schedule changes allows the identification of factors that contribute to this phenomenon.

$$E[w] = \frac{E[h]}{2}\left(1 + \frac{\sigma_h^2}{E[h]^2}\right) = \frac{E[h]}{2}\left(1 + c.o.v.[h]^2\right) \tag{4.1}$$

Where:

$$\begin{aligned} E[w] &= \text{Expected passenger waiting time} \\ E[h] &= \text{Expected headway} \\ \sigma_h^2 &= \text{Headway variance} \\ c.o.v.[h] &= \text{Coefficient of variation of headway, } \frac{\sigma_h}{\mu_h} \end{aligned}$$

Furthermore, field observations are important for understanding the operations of the Green Line that cannot be understood by analyzing automatically collected data. These include the interaction of the staff with each other and train maneuvers made within yards or between AVI points, though the field observations in this thesis focus only on yard operations. Although operations control practices cannot be understood fully using AVI data, their impact on service can be. Therefore, field observations are important to separate the impact of schedule changes versus operations control strategies.

Using all of the above methodologies, the results are used to understand the Green Line performance over a year time period. The operational baseline, when no 3-car trains were scheduled to be operated, can be used to compare the impacts that various schedule changes had on the performance of the Green Line. The C branch will be used as a control for comparing schedule impact since it did not have any scheduled 3-car trains. For example, seasonal changes may result in service impacts on all branches, while schedule changes may be evident only on the branches that incurred the schedule change.

4.1.1 Reference Time Assignment for AVI Data

Reference time is the time at which the train passes the AVI detector at Boylston Street Station inbound in the Central Subway. For example, if a D branch train left Riverside Station at 7:00am and passed inbound Boylston Station at 7:40am, then the reference time is 7:40am. This allows comparison of the same trains across various points along the system when analyzing them by time period. Boylston was used since it is the closest AVI to Park Street inbound, one the busiest stations on the Green Line system and an important interchange to the Red Line subway line.

Apart from the reference time, the analyses for running time and headway distributions use the actual time at each of these locations.

4.1.2 Data Description

Four sets of AVI data were used for the analyses, which contain the following dates:

- **Fall 2010**: September 18, 2010 - October 8, 2010
- **Winter 2011**: January 7-21, 2011
- **Spring 2011**: April 4-15, 2011
- **Fall 2011**: September 18, 2011 - October 8, 2011

The analyses focused only on weekday data. In the case of Winter 2011, additional days were removed: January 17 since it was Martin Luther King Jr. Day, and January 12-13 due to a blizzard.

Furthermore, field observations were conducted on the D and E branches at their respective terminal locations, Riverside and Lechmere stations. The Riverside Terminal field visits were performed on October 3 and 17, 2011 during the morning peak. The Lechmere Terminal field visit was performed on March 28, 2012 during the morning peak.

4.1.3 Throughput Capacity

In order to understand the change in the number of passengers that can be carried at the busiest point in the system from season to season, the throughput capacity is calculated. First, the number of rail cars that are scheduled to pass Boylston Station inbound in the morning peak, and Boylston Station outbound in the evening peak are counted. Then, using AVI data, the actual number of trains are counted at the same locations for the morning and evening peak to compare to the schedule. Since Boylston Station is served by all branches, all trains are counted irrespective of their route.

4.1.4 Running and Cycle Times

AVI Data

As mentioned before, AVI is used since it has time stamps that allow running and cycle time calculation. The round trip running time is based on departure from and arrival at the surface portion western terminus for each branch. Table 4.1 lists the corresponding branch termini used in the analyses. The E branch is now shown in the Table because running times were unable to be calculated for that branch.

Branch	Western Terminus
B	Boston College
C	Cleveland Circle
D	Riverside

Table 4.1: Surface Termini for Green Line branches

The reference time used for each calculated running time is Boylston Station inbound, so, for example, while the data used are recorded at Riverside, the reference time (for purposes of classifying the time of day) is downtown Boston.

The calculations for running time for the B and D branches includes the turn around time at Government Center, which takes approximately 4 minutes. The running time for the C branch excludes the turn around time at North Station. Although the turn around takes about 4 minutes as well, where the operator has to get out of the vehicle and move to the opposite end of the train set, it was not included since trains can be, and are occasionally, held there.

Since the C Branch has the possibility of being held at North Station, the running time was calculated as the sum of the running times in each direction between Cleveland Circle and North Station.

The B Branch AVI locations are approximately 0.69 miles east of the terminus, thus an extra 5 minutes were added to the running time to adjust for the AVI location, as taken from MBTA's schedule. A more accurate running time between the two locations could be calculated if AVI points were located at Boston College.

The running times for each branch are then parsed for reasonable running times, defined as within 1.5 times of the average of the running times for a branch in a season. Parsing data eliminates running times with excessive delays caused by vehicles disabled for a long periods, or an incorrect AVI recording or running time calculation. Some vehicle delays of 10-20 minutes are still included in the analyses because it is difficult to differentiate running times due to congestion rather than a problematic vehicle.

Once the round trip running times are calculated for each branch and season, the 50th and 90th percentiles are calculated for each service hour, from 5am until 1am. The 50th percentile represents the required scheduled running time while the 90th percentile represents the required cycle time in order for 90% of the trains to depart on time.

When comparing the running and cycle times for all the branches, the 50th and 90th percentiles are compared to the schedule to provide insight on the appropriateness of the existing schedules.

Schedules

The current MBTA scheduled running and cycle times on a per trip basis were accumulated for the analysis. To make the schedule more comparable to the AVI data, the scheduled trips were averaged by hour, with the reference time defined at Boylston Station. The scheduled cycle times were determined as the running times plus the scheduled layover time for each branch at their respective terminals.

4.1.5 Running Time Statistical Analyses

The running and cycle time results varied between seasons. To determine if the differences in running times were significant, Welch's t-test was used, which allows testing of samples with unequal sizes and unequal variances. The t-statistic and degrees of freedom are calculated as follows:

$$t = \frac{\overline{X}_1 - \overline{X}_2}{\sqrt{\frac{s_1^2}{N_1} + \frac{s_2^2}{N_2}}} \tag{4.2}$$

$$\nu = \frac{\left(\frac{s_1^2}{N_1} + \frac{s_2^2}{N_2}\right)^2}{\frac{s_1^4}{N_1^2 \cdot (N_1 - 1)} + \frac{s_2^4}{N_2^2 \cdot (N_2 - 1)}} \tag{4.3}$$

Where:

$$\begin{aligned} t &= \text{t statistic} \\ \overline{X}_i &= \text{Sample mean} \\ s_i &= \text{Sample standard deviation} \\ N_i &= \text{Sample size} \\ \nu &= \text{Degrees of freedom} \end{aligned}$$

The t-statistic and degrees of freedom are used to determine the probability that the hypothesis that the average Fall 2010 running time in a given hour is the same as the average running time for Winter 2011, Spring 2011, or Fall 2011 in the same hour. Fall 2010 is chosen as the base to compare the other seasons to because there were no 3-car trains scheduled to be operated throughout the day. The alternative hypothesis is that the Fall 2010 average running times are different than the Winter 2011, Spring 2011 or Fall 2011 average running times.

$$H_0 : \overline{X}_{Fall2010} = \overline{X}_i$$

$$H_a : \overline{X}_{Fall2010} \neq \overline{X}_i$$

Where i = Winter 2011, Spring 2011, Fall 2011

The hypothesis that the two season averages are the same was rejected if the probability is less than 10% ($p < 0.1$). In other words, if the calculated t statistic from Equation

4.1.5 is greater than 1.67, given that each season sample size has 40 observations, then the hypothesis can be rejected with a 90% level of confidence.

4.1.6 Headways

The calculation of a headway from AVI data is defined as the difference between the time that the current train passes and the time that the previous train passes a specific AVI point. On the B, C, D, and E branches, the AVIs studied are located at or near the termini. Furthermore the B, C, and D branches include AVI points near the Beacon Junction to the Central Subway on the surface portion. Figures 4.1, 4.2, 4.3, and 4.4 show the location of the AVI points used in the analyses for each branch, where the AVIs are indicated by a numbered diamond. From the AVI data, the headway distribution can be calculated near the terminus and along the route, to see how progression of a train along the route impacts the headways.

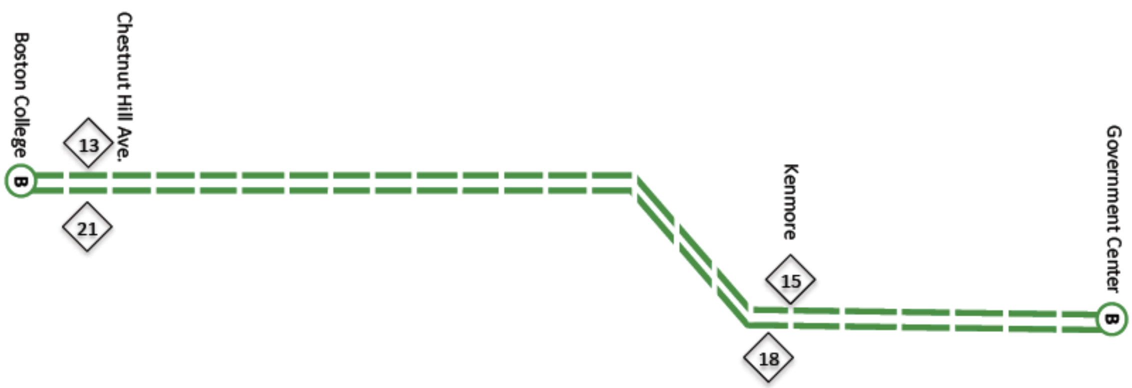

Figure 4.1: Location and Identifying Number of AVI Points Along B Branch

By studying the headways, it is possible to see an expected deterioration as the vehicle progresses along a route. For example, Figure 4.5 shows the theoretical probability distribution of the headways for a transit vehicle as it progresses along a congested route. Towards the end of the route, the curve is very flat, meaning that the headway variation is great, and there is a peak for very short headways, indicating bunching.

Using the AVI data for each point, the headway of every succeeding recorded train is calculated, regardless of whether a train has a reference time or not. Then the train records

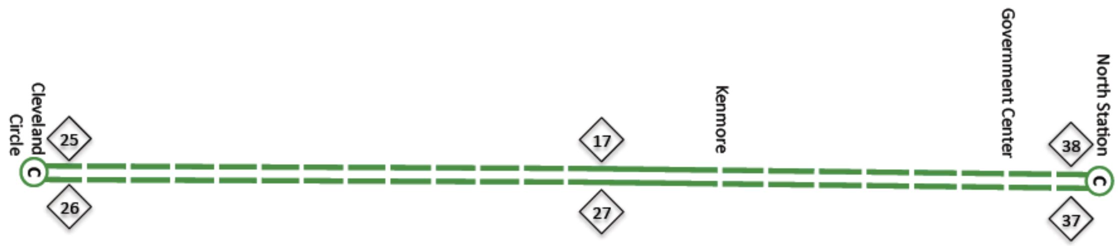

Figure 4.2: Location and Identifying Number of AVI Points Along C Branch

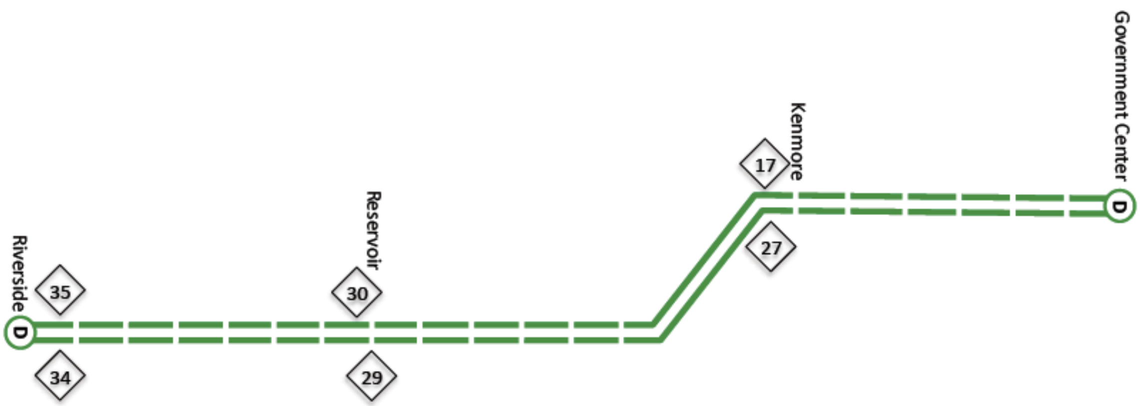

Figure 4.3: Location and Identifying Number of AVI Points Along D Branch

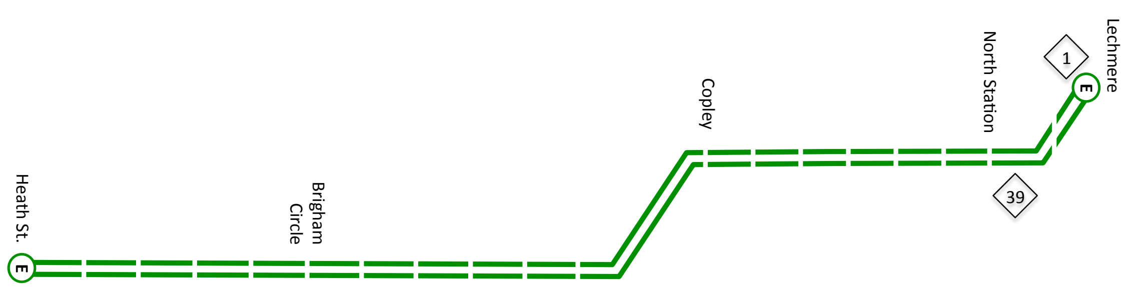

Figure 4.4: Location and Identifying Number of AVI Points Along E Branch

that have a reference time and headway information are retained for the analysis, while the records with headways but no reference times are discarded. The headways are then split by time period to isolate the peak headways from the non-peak period headways. The

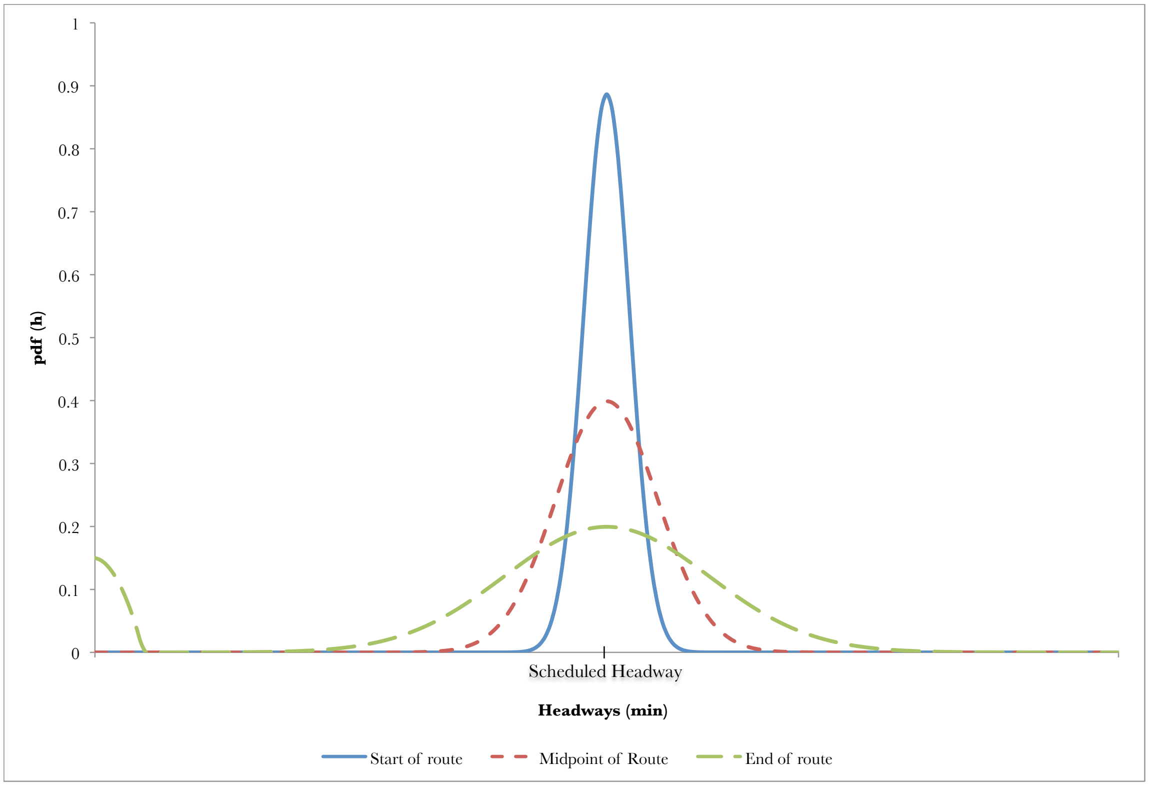

Figure 4.5: Theoretical Example of Headway Distribution Deterioration Along a Congested Route (Adapted from Wilson 2012)

frequency of each headway is calculated to create a headway distribution; each frequency bin is one minute and is the upper bound, meaning that a headway between 3 minutes and 1 second, and 4 minutes will be counted in the 4-minute frequency bin. This is done to give accurate percentages when determining what percentage of passing trains had headways less than or equal to a given headway, since the distributions were normalized by turning the frequencies into percentages of the total sample.

Since passenger waiting time is dependent on the mean and standard deviation of a headway distribution, examining the headway distributions along the route and by season allows analysis of the passenger service quality impacts. Ideally, headways are supposed to have a mean close the scheduled mean, and a variance of zero or close to zero. In this analysis, variations from the baseline headways will be noted and passenger waiting times presented. The baseline will establish the status quo, and the resulting seasons will be compared to see if headway variability improved or worsened.

4.1.7 Field Observation

The field observations focused on Riverside Terminal operations at the end of the D branch and on Lechmere Terminal operations at the end of the E branch. This analysis was performed after two days of field observations at Riverside, October 3 and 17, 2011, and one day at Lechmere, March 28, 2012. Although both days spend at Riverside were Mondays, it is assumed that they are representative of the typical service day, since no significant delays were reported. The Lechmere observation was on a Wednesday, and again, no significant delays were reported on the E. On all occasions, the observations focused on train arrivals and departures from the Terminals during the morning peak (7:40-8:50am). On October 17 and March 28, the yard operations were also observed.

For each trip at Riverside, the times of arrival at, and departure from, the platform were recorded, along with rail car numbers. This allowed monitoring of train sets from their arrival at to their departure from Riverside, enabling calculation of layover times. The departure times of the trains were compared with the scheduled departure times, as were scheduled and actual headways. The Lechmere observations were complemented with AVI data for that departing day, and were used to calculate schedule adherence of all departing trains. This was possible because the Lechmere AVI point is located just after the inbound platform, which records departure time down to the second. The AVI detectors at Riverside were not used because they are located well beyond the platform edge[1], thus the exact travel time between the platform edge and the AVI detector is unknown.

4.2 Results of 3-Car Train Analyses

The results of the data analyses and field observations are presented below, starting with the baseline. Notable changes in Winter, Spring and Fall 2011 will be quantified and highlighted first on the D branch, which had the greatest changes, and then on the B, C, and E branches, which had smaller changes. Many of the resulting graphs and tables from the data analyses

[1]The precise location of the AVI detector is not known, though it is known to be located close to the departing platform right across the Grove St. bridge. Although the precise location for the AVI detector does not matter for running time, where a few seconds do not significantly impact the overall calculated running time, the location is more important for schedule adherence because it is more sensitive to small time differences.

are presented below, although Appendix A contains the complete set of the analyses figures. The discussion section, following the results, will identify the implications of the observed results.

4.2.1 Baseline - Fall 2010

The first step in understanding the impact of the trials with the schedule changes is to establish a baseline of when no 3-car trains were scheduled and compare the succeeding service of when 3-car trains were scheduled. Although the trial has many uncontrollable variables, the C branch will be used as the control throughout the analyses since scheduled headways and running times had only minor changes (for example, the headways are the same throughout the day across the seasons except one or two trips that have headways differing by 1-2 minutes), although it must be kept in mind that other external variables remain, such as variations in ridership and staff performance. Lastly, all notable differences between the actual and scheduled running and cycle times are marked with dashed circles on the graphs.

Looking at the results for running time, the B branch's actual running and required cycle times most closely resembled the schedule, meaning that the actual train operations closely follow the existing schedule (Figure 4.6). The largest variation is during the PM peak period, where the estimated cycle time is about 5-9 minutes lower than the schedule. Some adjustments should be made to running time during the midday since it is greater than the scheduled running time by up to five minutes. The variation in the median running time is large, with the running time varying between 73 and 101 minutes, and the greatest running time occurring during the evening peak.

The baseline C and D branches' actual operations show larger differences from their schedules, most notably the cycle time on the C branch during the midday (Figure 4.7) and the cycle times on the D branch during the morning and evening peak periods (Figure 4.8). The C branch scheduled cycle times exceed the estimated required cycle time by up to 8 minutes (19:00-20:00), which is greater than the scheduled 8-minute headway for that time period, indicating one less train set can be operated on the C branch. The D branch also has significant differences in the morning and evening peaks of up to 20 minutes, which, if eliminated, can reduce train set requirement by three units. Alternatively, the frequency during the peak periods could be increased if the power system permits.

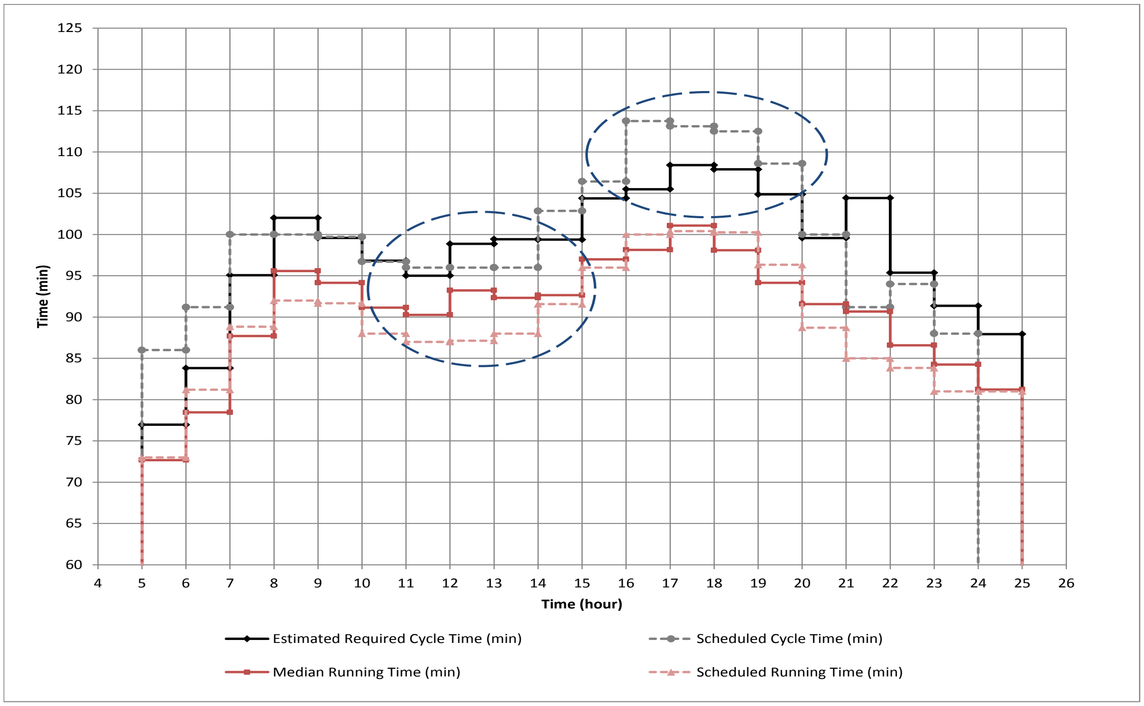

Figure 4.6: B Branch Running and Cycle Times (Sept.-Oct. 2010)

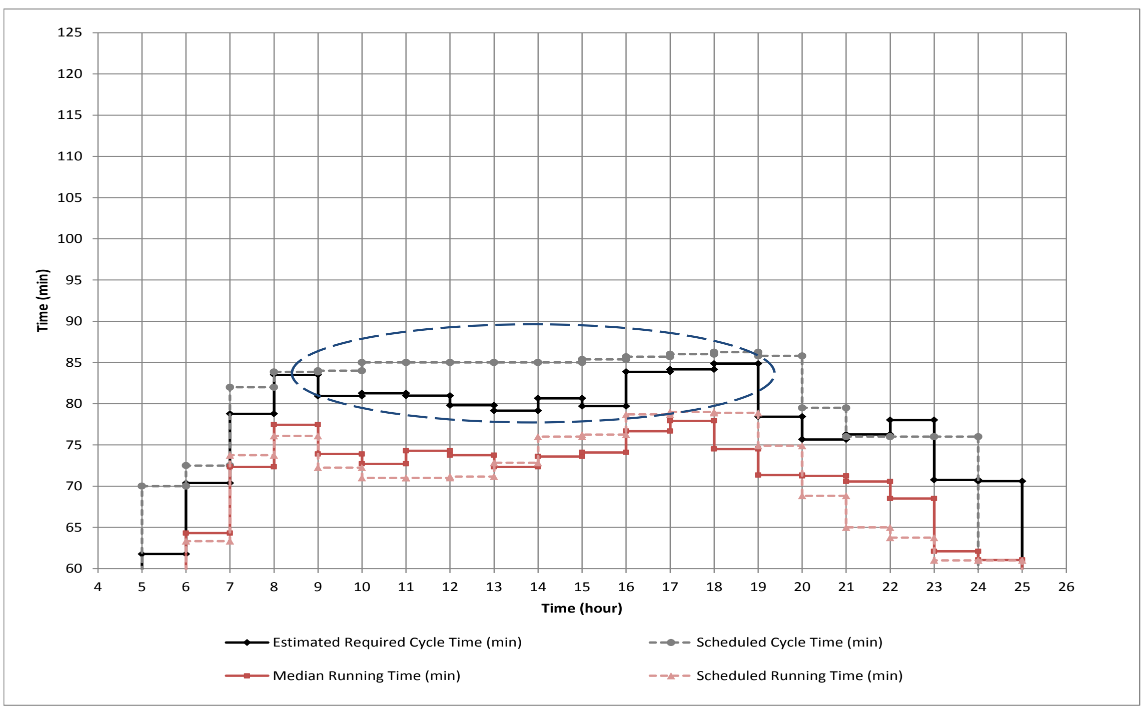

Figure 4.7: C Branch Running and Cycle Times (Sept.-Oct. 2010)

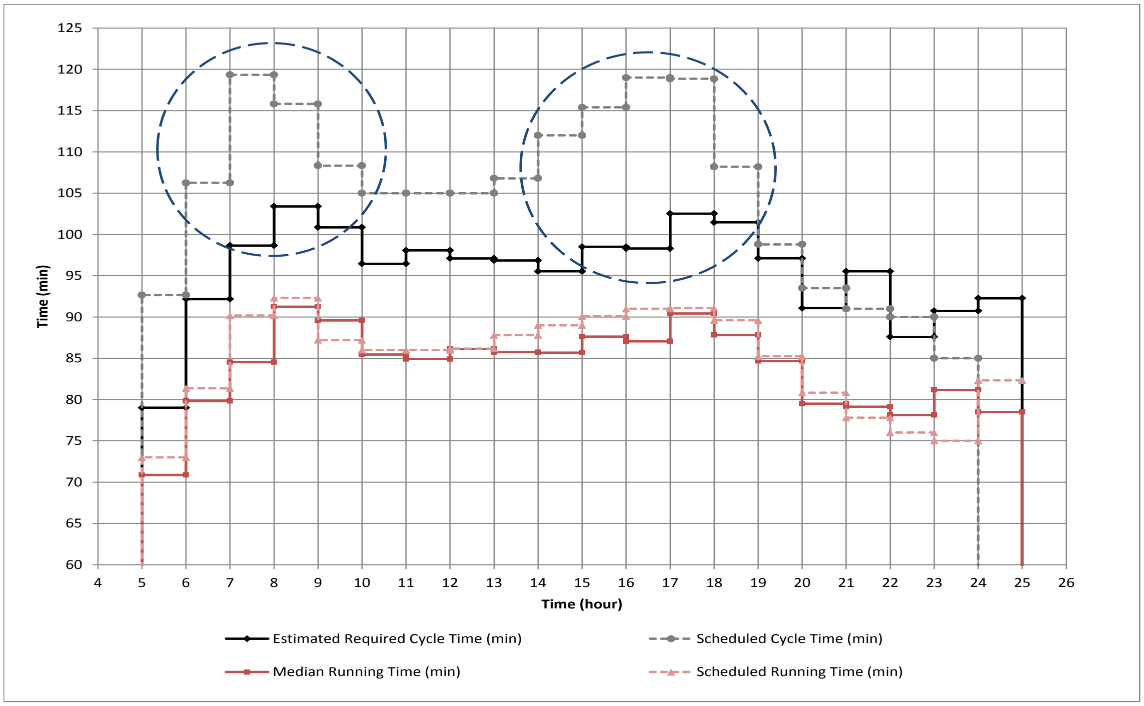

Figure 4.8: D Branch Running and Cycle Times (Sept.-Oct. 2010)

Unlike the B branch, the running times on the C and D branches vary less throughout the day: C branch running times range between 64 and 78 minutes and D Branch running times range from 71 to 91 minutes. The high variability in the B branch running times could be accounted for by the length of the route, the high ridership and number of stops, and high number of street crossings. In particular, Harvard Avenue, Packards Corner, and the Boston University stops contribute the largest number of passengers to the system (Webber, 2010).

Next, the baseline headways are determined. When analyzing the headway distribution as trains progress along their route, in general, headways vary more the further along a route a train is, which can be seen as the flattening of a curve in the cumulative distribution graphs. (See Figure 4.9).

Although the analyses aim at having as comprehensive an evaluation of each branch as possible, the variability in AVI functionality prevents full analysis in some data periods. In particular, AVI 35, at Riverside Station on the outbound direction, was not fully functional during Fall 2010, thus other data sets cannot be compared to the arrival of trains at Riverside in Fall 2010. Also, AVI 13 at Chestnut Hill on the outbound B branch was not functional

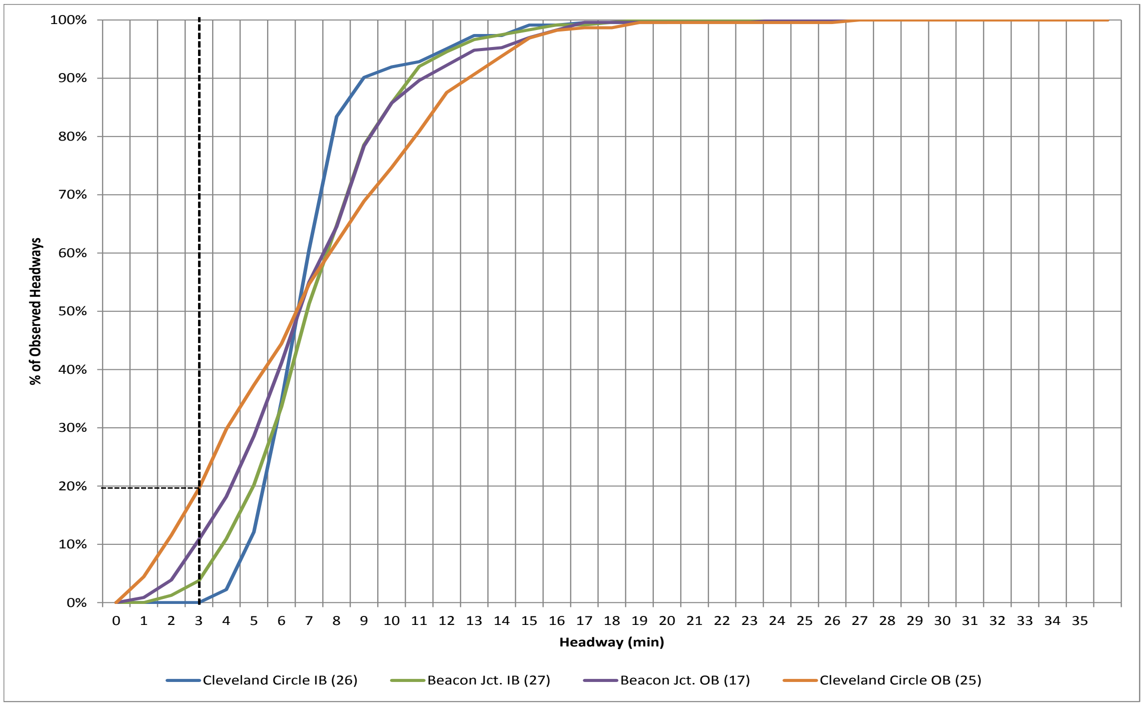

Figure 4.9: C Branch Headways, AM Peak (Sept.-Oct. 2010)

during Fall 2011. In addition to the malfunctioning AVI points, train operations added complexity to the analysis, especially on the B branch. A portion of B branch trains traveling inbound during the morning peak are scheduled to depart from Reservoir Yard at Cleveland Circle. The location where trains join the B branch from Reservoir is east of the AVI point closest to the Boston College terminal (AVI 13). At least 3 out of 18 scheduled trips during the morning peak originate from Reservoir Yard. Since these trains do not pass the western-most AVI point, the headways recorded at that AVI get inflated by at least 23% and, therefore, that AVI data cannot be reliably used for analyses during periods when trains are scheduled to depart from Reservoir.

During the morning and evening peaks, the headways on B and D branches are scheduled for 6 minutes, and 7 minutes on the C branch, which is also reflected in the average actual headways calculated from the data. However, the variation increases as the train progresses along the route, thus passengers going outbound have a longer expected waiting time according to Equation 4.1. Additionally, train bunching, again, defined as trains having a 3-minute or less headway, increases as the train progresses along the route. The B branch has the highest incidence of bunching at the end of the route, where nearly 38% of trains arrive at Chestnut Hill within 3 minutes during the PM peak period (Figure 4.10). The C branch has a smaller number of bunched trains, with up to 20% of trains arriving at Cleveland Circle within 3 minutes (Figure 4.11).

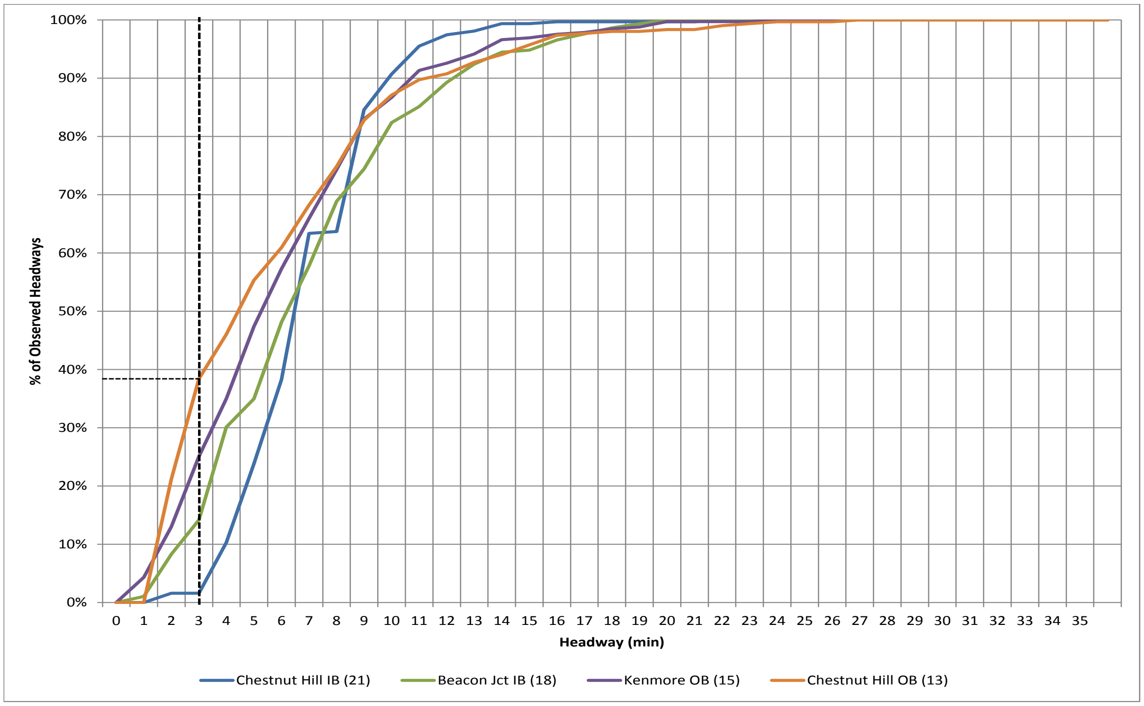

Figure 4.10: B Branch Headways, PM Peak (Sept.-Oct. 2010)

Within each branch, differences can be observed between the AM and PM peaks. The B branch trains arrive to Chestnut Hill with a slightly tighter headway distribution fit during the evening peak compared to the morning peak, with 90% of trains arriving within 11.5 minutes in the evening, compared to 90% of the trains arriving within 12.5 minutes in the morning. The C branch has significant variations in departure times from Cleveland Circle: during the morning peak, 90% of the trains depart within 8.5 minutes, while 90% of trains depart within 11 minutes during the evening peak. The D and E branches have little departure headway variation between morning and evening, at each of the AVI points.

4.2.2 Trial Evaluation

The evaluation of the addition of 3-car trains will focus on the change in throughput capacity, running time comparisons, and changes in headways, with respect to the average, standard deviation, and passenger waiting time. The trial on the Green Line was prompted

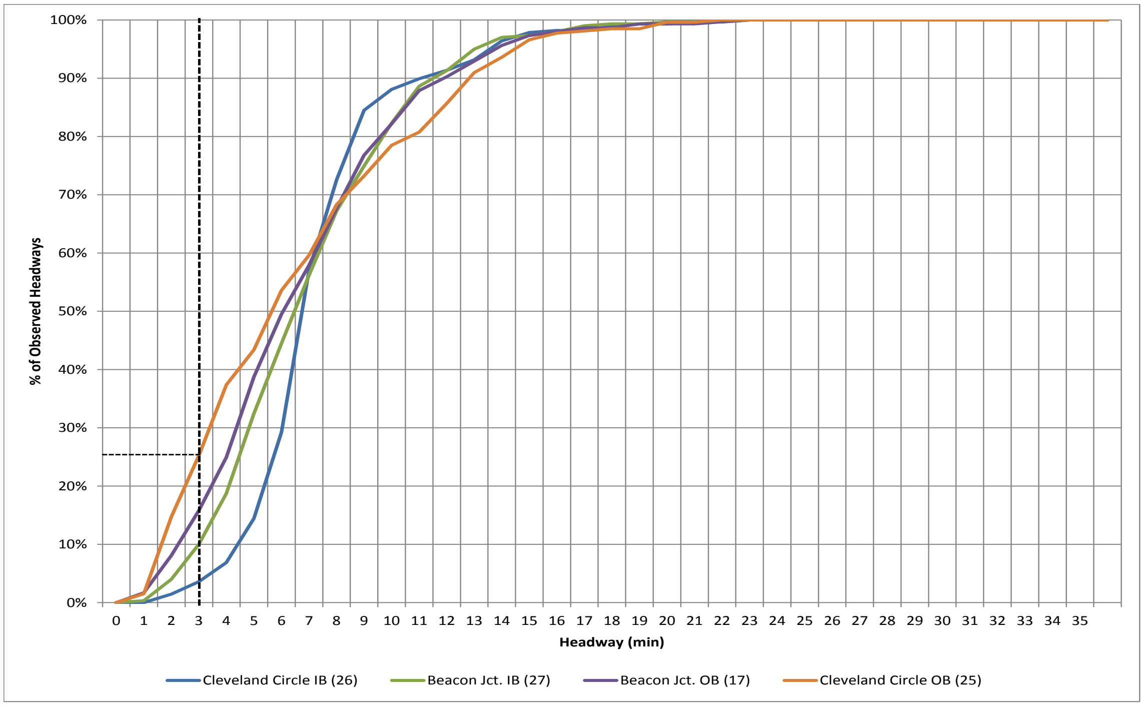

Figure 4.11: C Branch Headways, PM Peak (Sept.-Oct. 2010)

as an increase to the capacity of the system (Pesaturo, 2011). However, an equally important objective was to observe the impact of using more 3-car trains in light of the possible transition to Positive Train Control on the line.

Table 4.2 summarizes the scheduled and actual throughput capacity, or the effective passenger carrying capacity, at Boylston inbound in the morning peak period, 7:00-9:00 am, and Boylston outbound in the evening peak period, defined as 4:00-7:00 pm, for each of the branches for all data periods. The actual number of rail cars are counted for each day in the data set and then averaged over the number of days within each data set. According to the schedule, the throughput in number of rail cars did not increase during the morning peak, but increased in the evening peak. However, according to the actual throughput, there was a decrease in rail car throughput during the evening peak from Fall 2010 to all succeeding periods. Furthermore, the morning peak actual throughput did not change from Fall 2010 to succeeding periods, with the exception of Winter 2011, which had a significant decrease in the car throughput. It must also be noted that the actual throughput is almost always lower than the scheduled throughput for corresponding peak periods, except for the PM peak period in Fall 2010, where the actual rail car throughput was on average 4 rail cars (two 2-car trains) greater than the scheduled rail car throughput.

Table 4.2: Scheduled and Actual Throughput (Rail Cars) at Boylston During AM Peak (7:00-9:00 am) and PM Peak (4:00-7:00 pm)

	Scheduled Throughput		Actual Throughput	
	Total AM Peak	Total PM Peak	Total AM Peak	Total PM Peak
Fall 2010	170	234	160	236
Winter 2011	169	239	142	212
Spring 2011	165	242	163	233
Fall 2011	170	251	162	223

Running Times

Figures 4.12, 4.13, and 4.14 show scheduled and actual round trip running and cycle times for Winter, Spring, and Fall 2011 for the D branch. The figures also show the number of three car trains that were operated during each time period (in blue). It must be noted that for the last two trips of the night for each branch, all trains are held at Park Street Station until the next to last and last Red Line trains arrive, therefore inflating the running and cycle times for all branches and seasons.

In general, the actual running times are similar to the scheduled running times for all three periods, though Winter has about a five minute difference between the scheduled and actual running times during the morning peak and right before the evening peak. Furthermore, from Figures 4.13 and 4.14, it can be seen that the evening peak running times are greater than the schedule by up to five minutes in the peak hour.

The cycle times in Winter and Spring are much greater than the estimated required cycle time, however the Fall 2011 schedule has reduced scheduled cycle times, due to MBTA's adjustment of the schedule. The Fall estimated required cycle times follow the scheduled cycle times much more closely than in Winter and Spring, though there is still excess scheduled cycle time in the first half of the day of up to 11 minutes. Eliminating this excess time can reduce the fleet requirement by at least one train set or could result in slightly more frequent service.

In comparing the Fall 2010 running and cycle times on the D branch to the other seasons, it can be seen that most running and cycle times increase during the AM and PM peak periods, with Winter having the greatest increases of up to 4.5 minutes and 10 minutes for

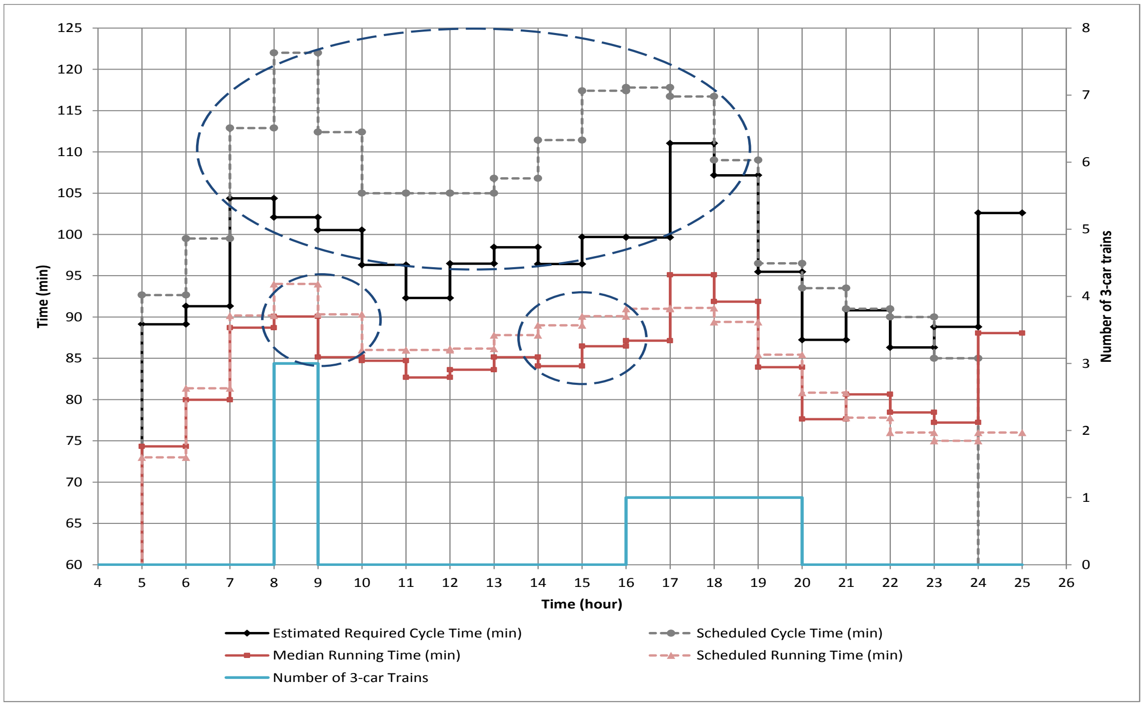

Figure 4.12: D Branch Running and Cycle Times (Winter 2011)

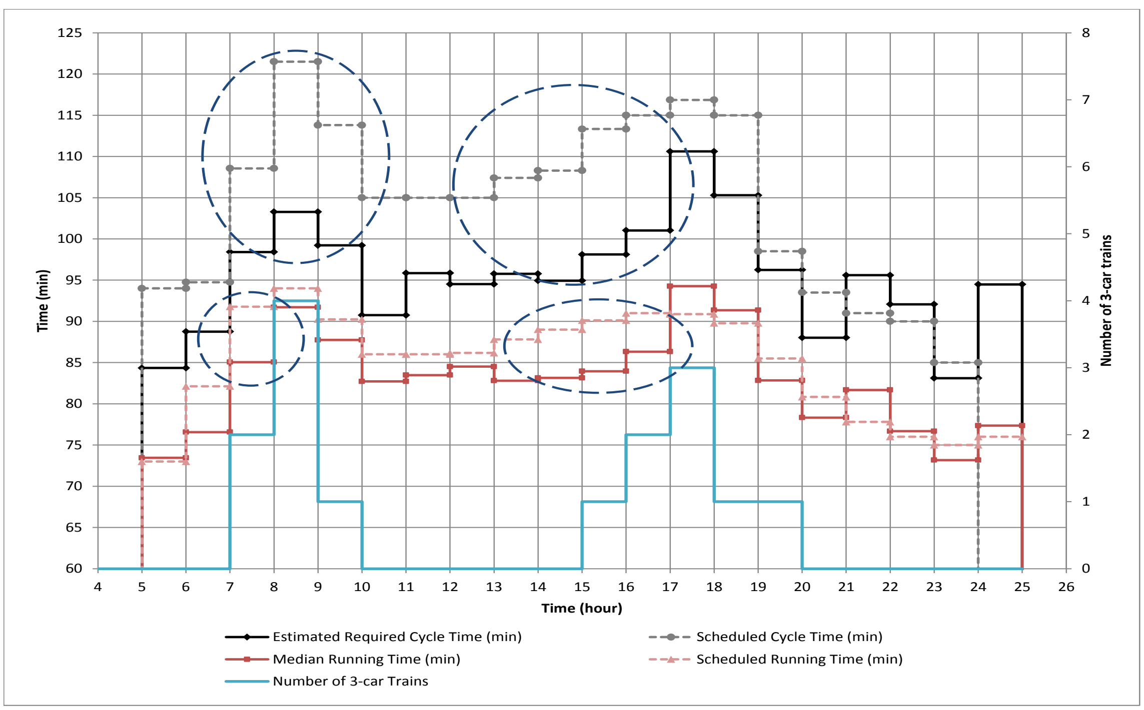

Figure 4.13: D Branch Running and Cycle Times (Spring 2011)

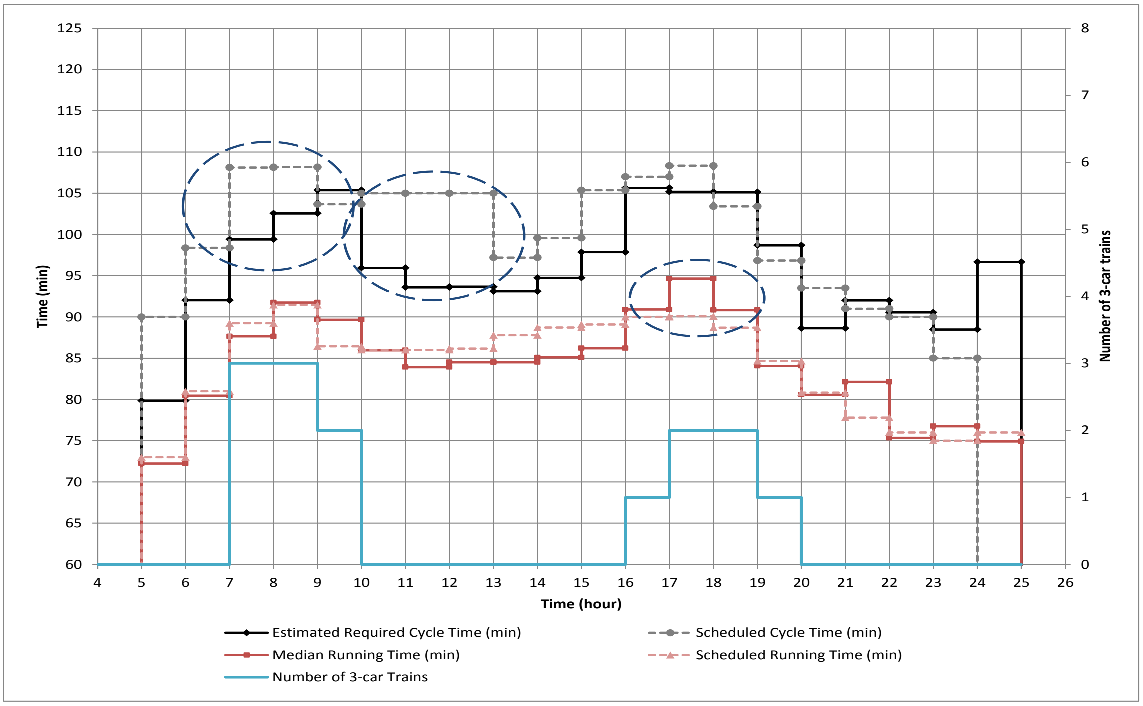

Figure 4.14: D Branch Running and Cycle Times (Fall 2011)

the running and cycle times, (Figure 4.15), respectively, both with statistical significance. The running and cycle times decreased, however, during the midday during all seasons, up to 4.5 minutes for the running time in Winter 2011 (Figure 4.15) and 5.5 minutes for the cycle time (Figures 4.15 and 4.16). In general the increases indicate that the schedule changes, including the addition of 3-car trains, had an impact on the performance of the branch.

Comparing the C branch estimated running and cycle times to the schedule in Figures 4.18 and 4.19 shows that the estimated cycle time is lower than the scheduled cycle time in Winter 2011 by up to 10 minutes (Figure 4.18) and by up to six minutes in Fall 2011 (Figure 4.19). The scheduled running time in Fall 2011 should be increased during the morning peak by about 4 minutes since it is shorter than the actual estimated running time. Since the headways are 8 minutes during the midday, reducing the cycle time may reduce fleet requirement by one train set, or improve the service by slightly increasing the frequency. It must be noted that the C branch running and cycle times for Spring 2011 are not presented because of a non-functioning AVI point at Cleveland Circle (termini for C branch) for this season.

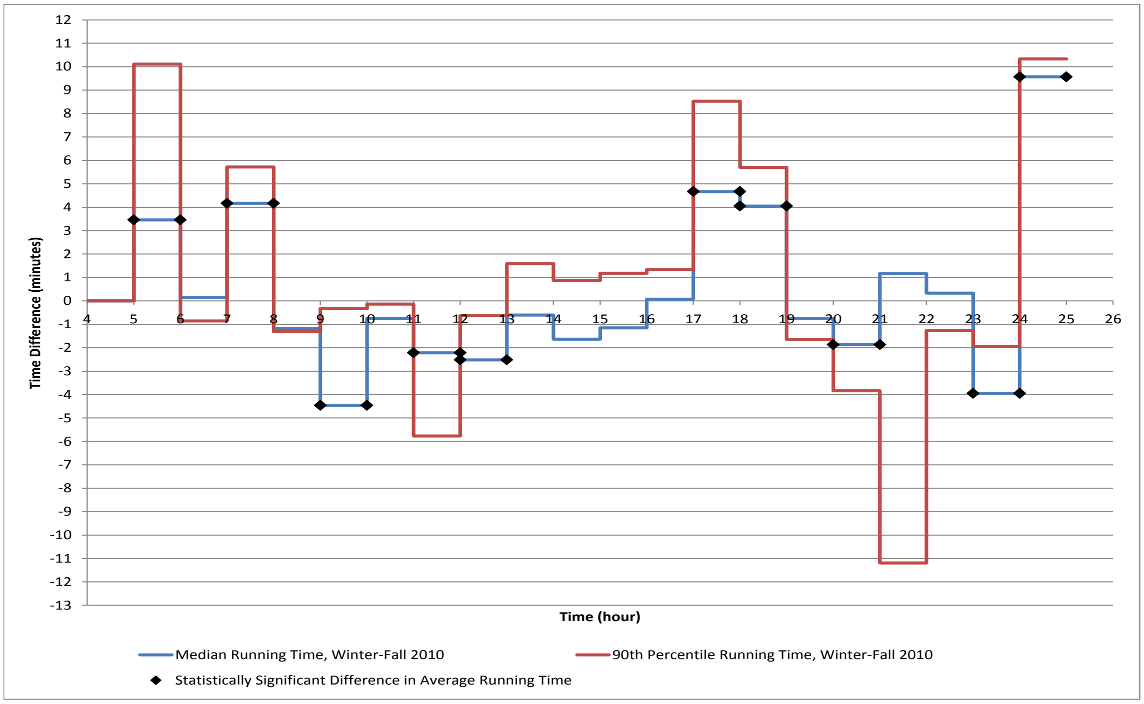

Figure 4.15: Change in Running and 90th Percentile Running Times on D Branch, from Fall 2010 to Winter 2011

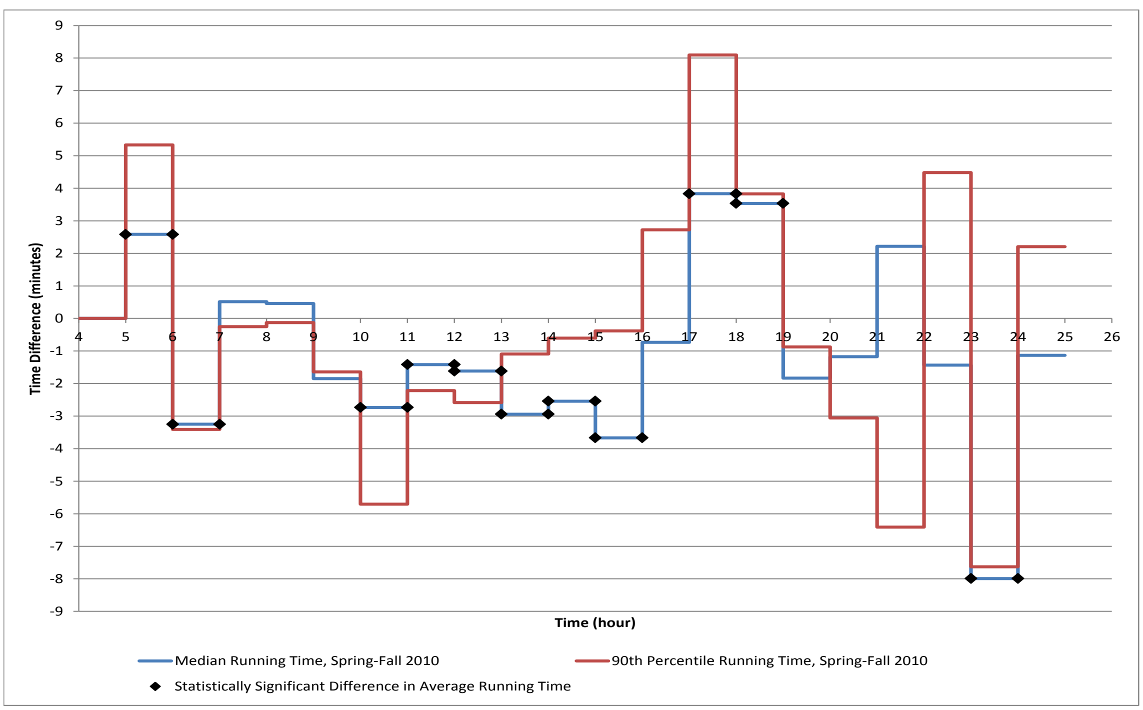

Figure 4.16: Change in Running and 90th Percentile Running Times on D Branch, from Fall 2010 to Spring 2011

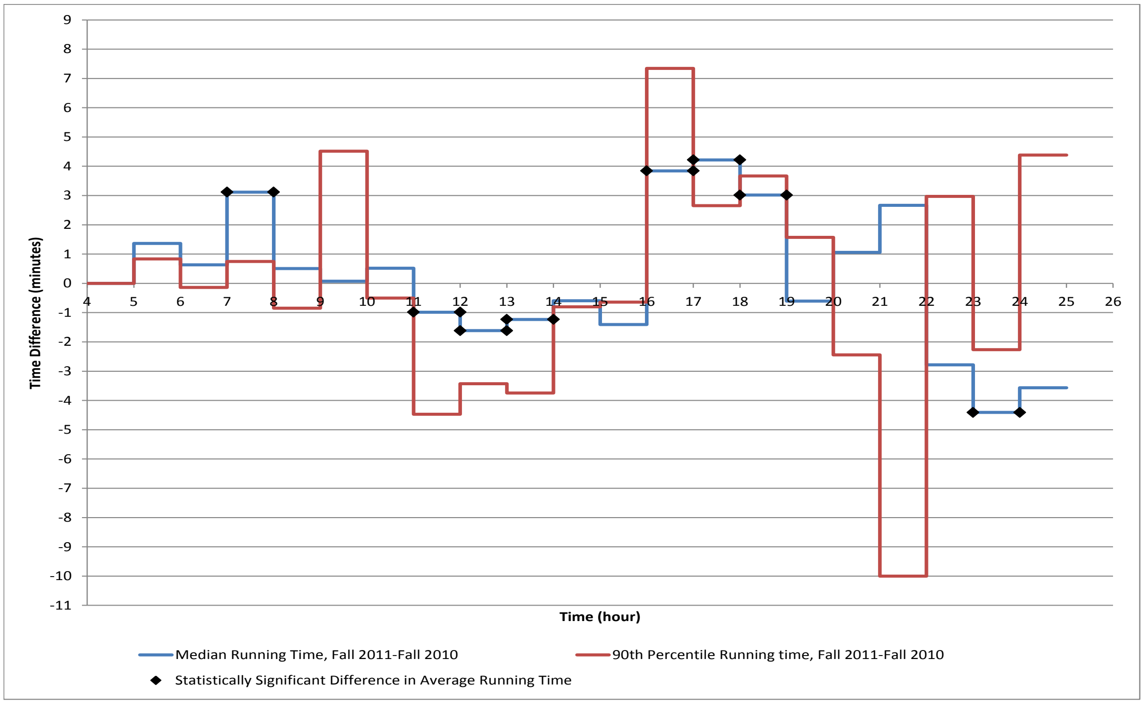

Figure 4.17: Change in Running and 90th Percentile Running Times on D Branch, from Fall 2010 to Fall 2011

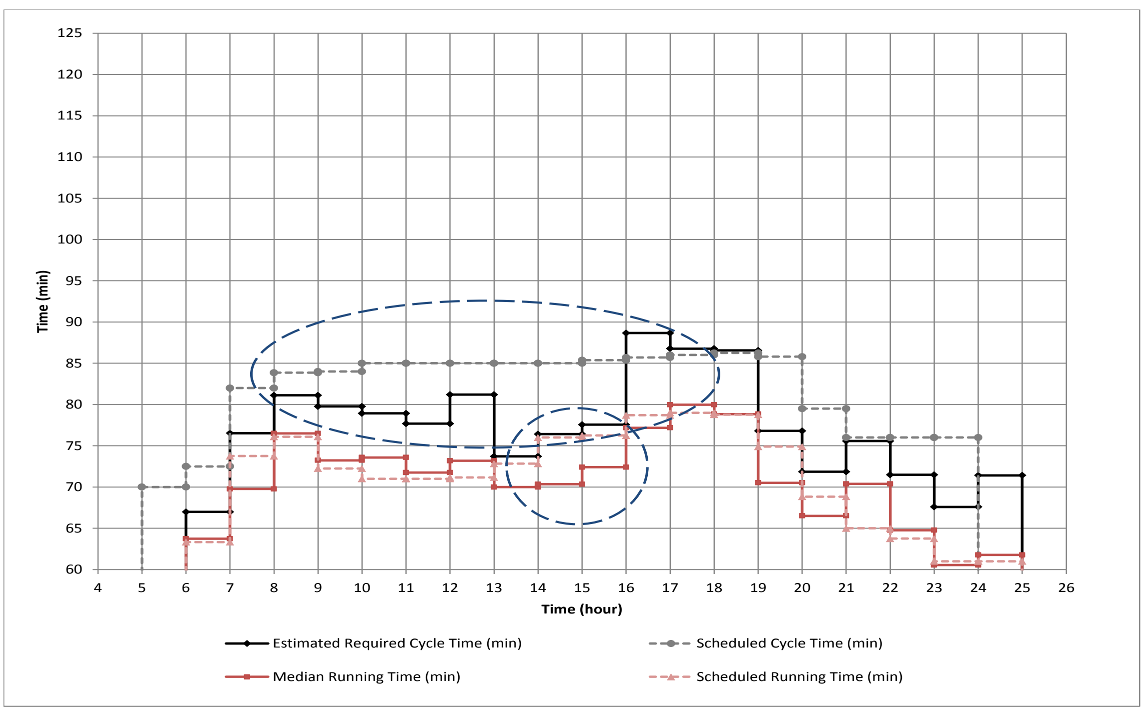

Figure 4.18: C Branch Running and Cycle Times (Winter 2011)

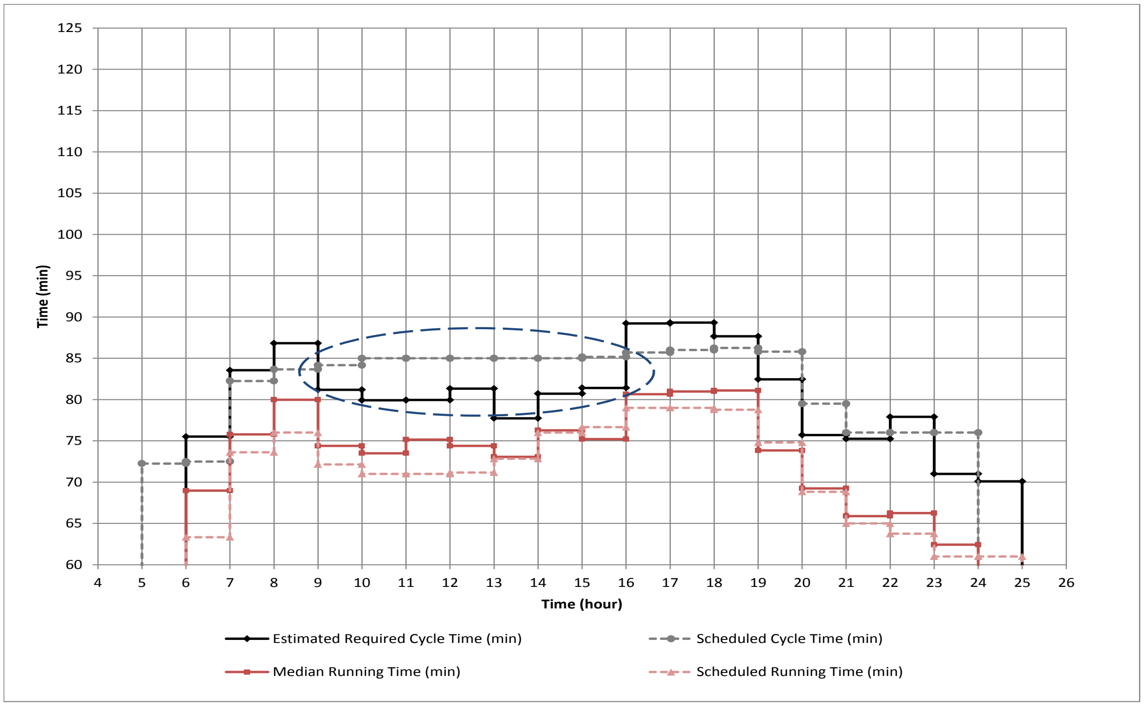

Figure 4.19: C Branch Running and Cycle Times (Fall 2011)

When comparing the C branch Winter and Fall 2011 running and cycle times to those in Fall 2010, it can be seen that the running times increased with statistical significance during the PM peak period by up to 4.2 minutes in Winter 2011 (Figure 4.20), and then during both AM and PM peak periods by up 6.5 minutes in Fall 2011 (Figure 4.21), again with statistical significance. However, during the midday, the running and cycle times decreased from Fall 2010 to Winter 2011 and Fall 2011 by up to 3.5 minutes and 5.8 minutes, respectively. Since the 3-car trains were only scheduled on the other branches during the peak periods, these results suggest that the C branch operations in the peak periods may have been adversely impacted by the slower operations of the 3-car trains in the subway.

The B branch Winter running and cycle times follow the schedule very closely (Figure 4.22), with at most a five minute difference between either the estimated running or cycle time, and the schedule. The Spring and Fall 2011 running and cycle times vary more from the schedule, however, with up to 7 minute difference between the scheduled running time and estimated running time, and up to 12 minute difference between the scheduled cycle time and estimated required cycle time (Figure 4.23). The elimination of the excess time can reduce the fleet requirement by at least one train set during the off peak periods, and

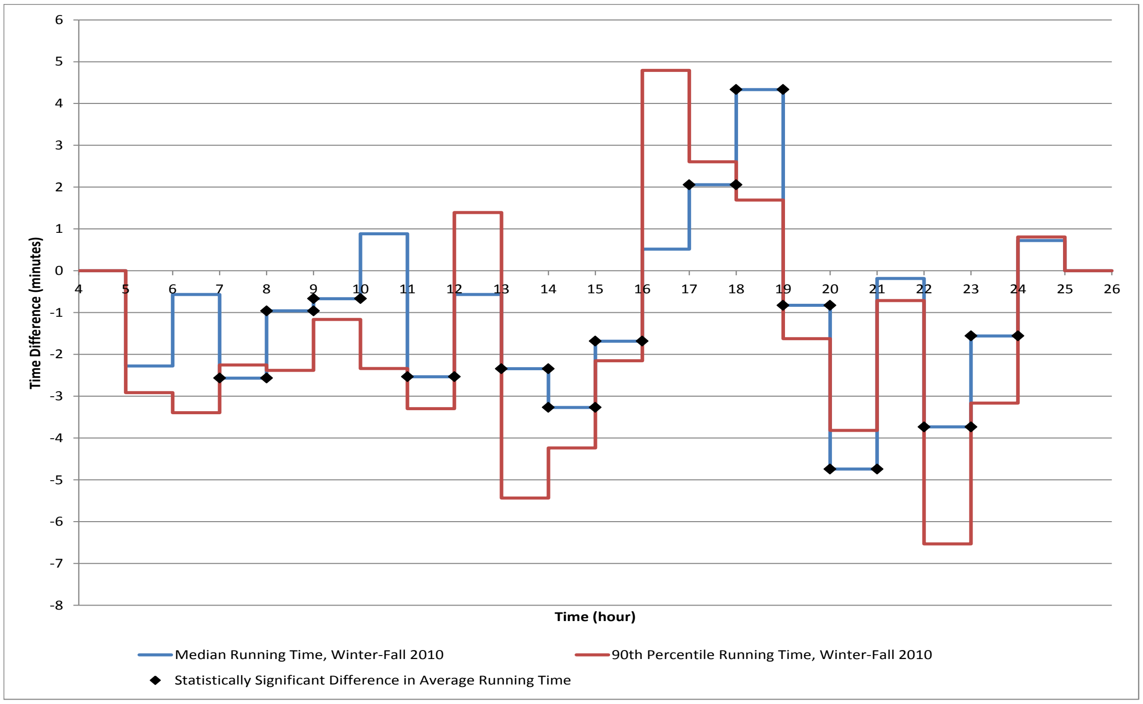

Figure 4.20: Change in Running and 90th Percentile Running Times on C Branch, from Fall 2010 to Winter 2011

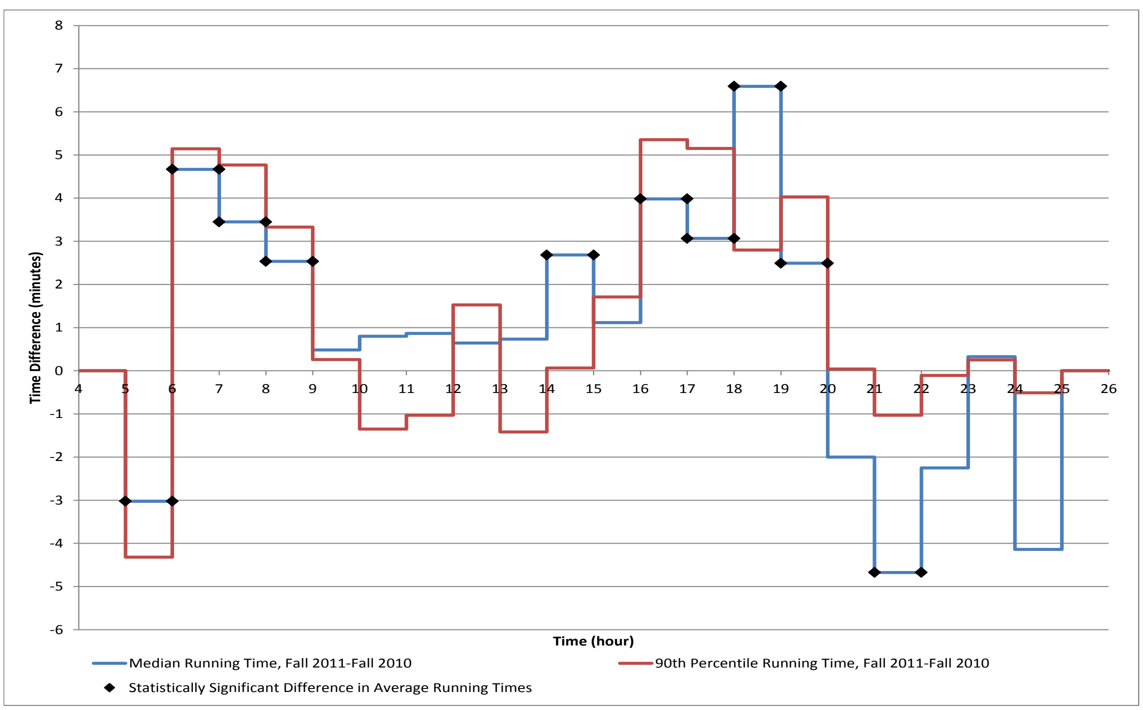

Figure 4.21: Change in Running and 90th Percentile Running Times on C Branch, from Fall 2010 to Fall 2011

up to two train sets during the peak periods. Alternatively, the number of trains operating in the peak period may be increased to provide higher frequency, pending on the power system's ability to handle the increase.

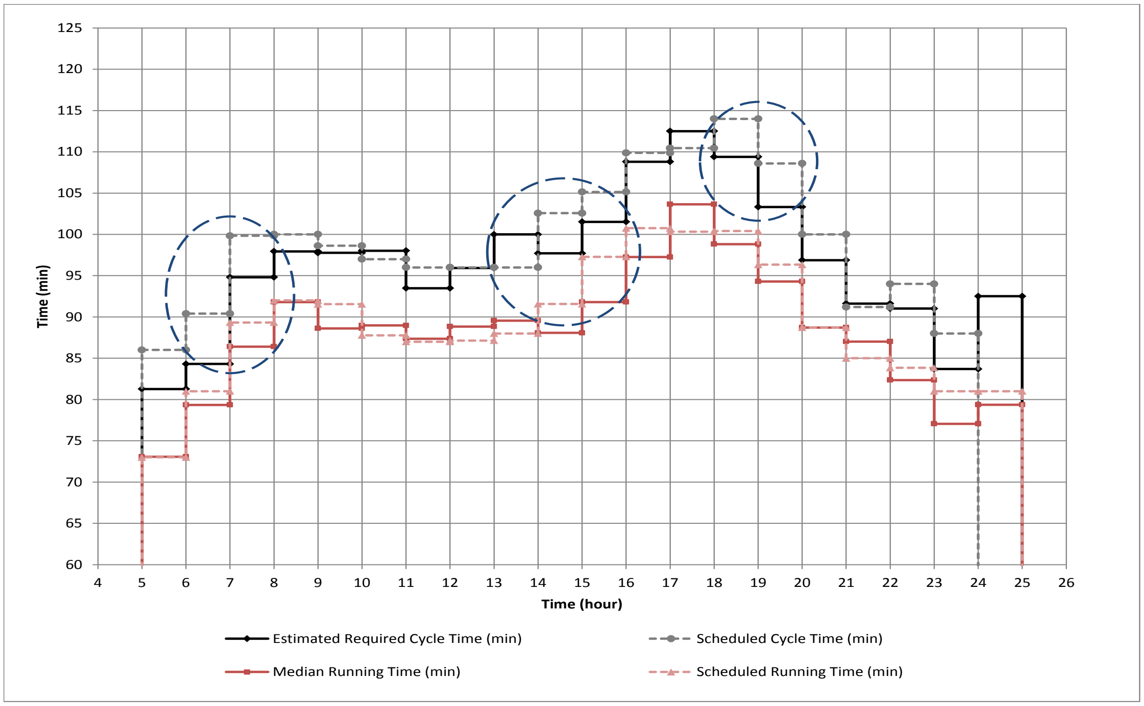

Figure 4.22: B Branch Running and Cycle Times (Winter 2011)

Overall, Figures 4.25, 4.26, and 4.27 show that the running and cycle times on the B branch decreased from Fall 2010 to Winter, Spring and Fall 2011 of up to seven minutes of running time in Spring 2011 and up to 13 minutes in estimated required cycle time, in Winter 2011. There were increases in running times in Winter 2011 during the evening peak (Figure 4.25), but they were not statistically significant.[2]

Discussion of Running Time Changes

The initial evaluation of Fall 2010 performance shows that the schedules required some adjustment to increase the efficiency of train utilization, particularly on the C branch during midday and the D branch over the entire day. The MBTA explained that the excess slack

[2]The reduction in running time on the B branch was restricted to the surface portion of the branch, as will be shown in the Discussion of Running Time Changes section starting on page 80. The running time within the Central Subway actually increased slightly on the B branch, thus showing results that are consistent with the C branch.

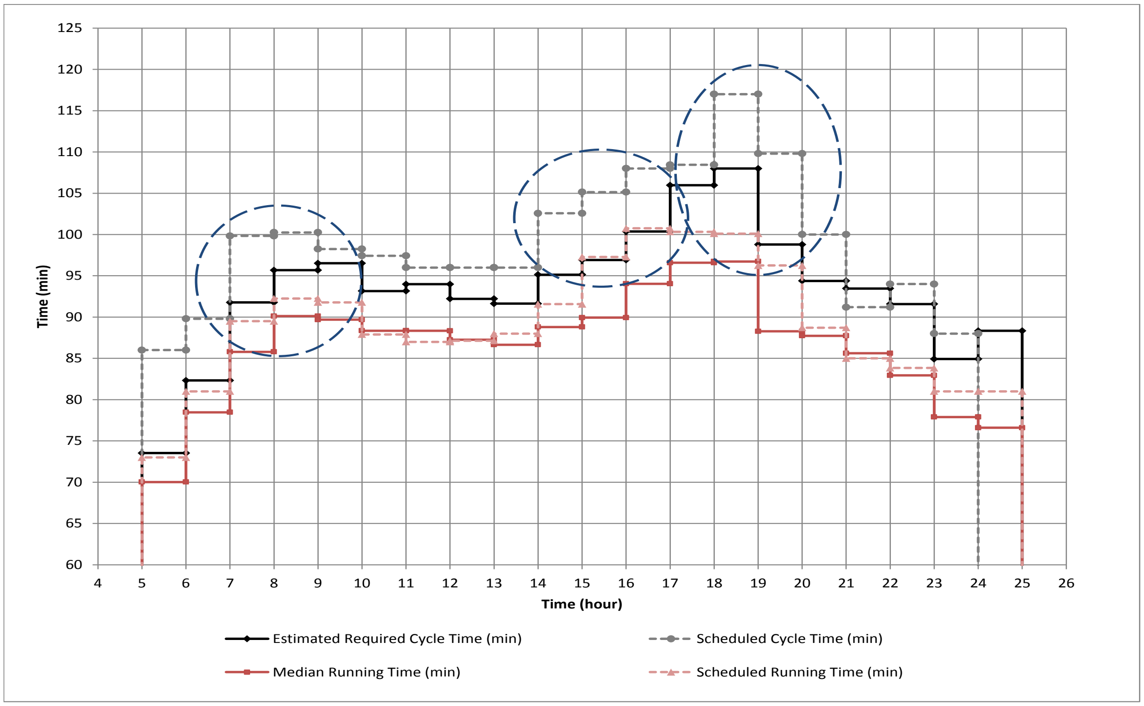

Figure 4.23: B Branch Running and Cycle Times (Spring 2011)

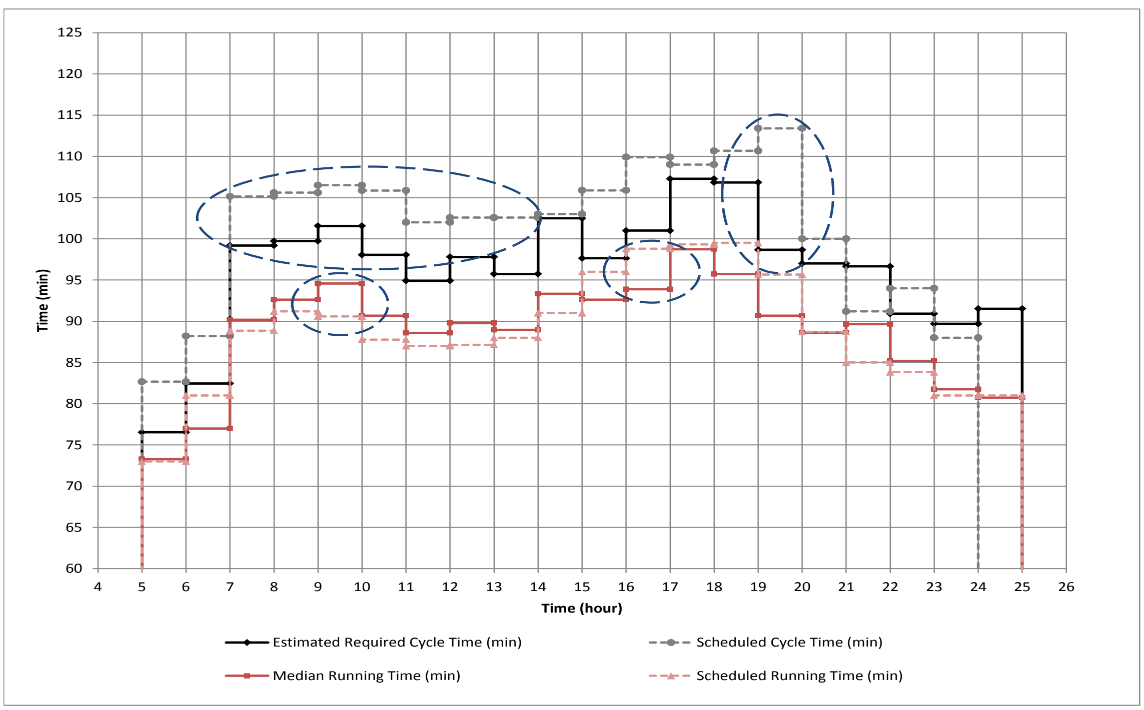

Figure 4.24: B Branch Running and Cycle Times (Fall 2011)

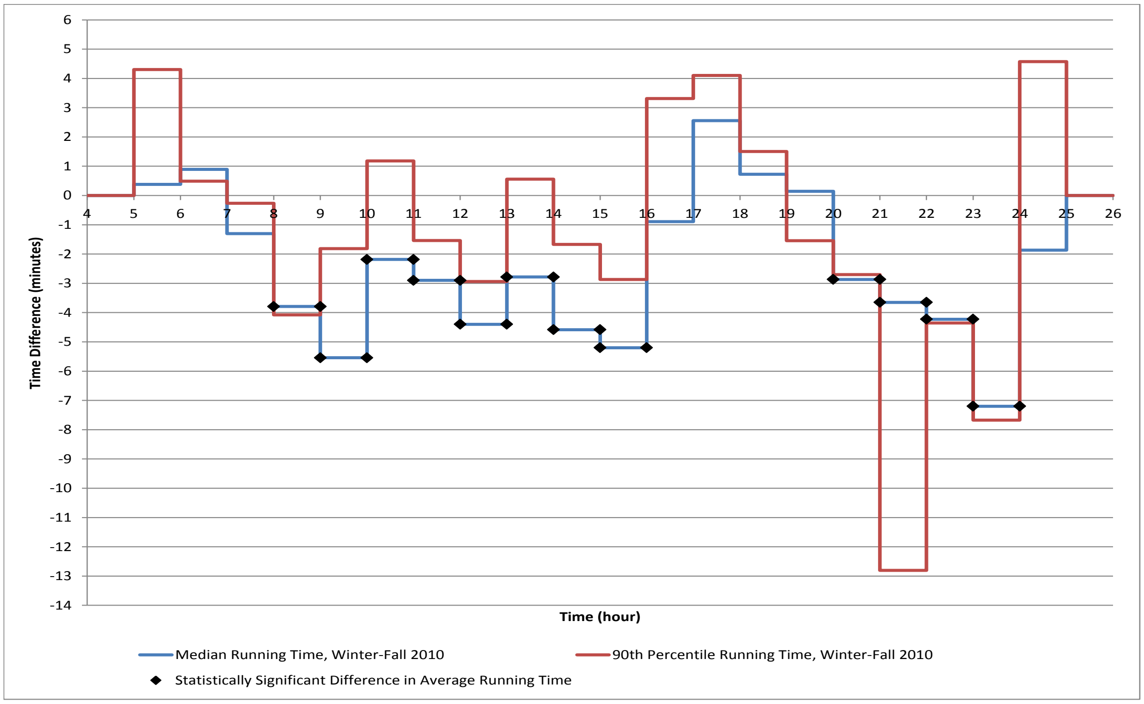

Figure 4.25: Change in Running and 90th Percentile Running Times on B Branch, from Fall 2010 to Winter 2011

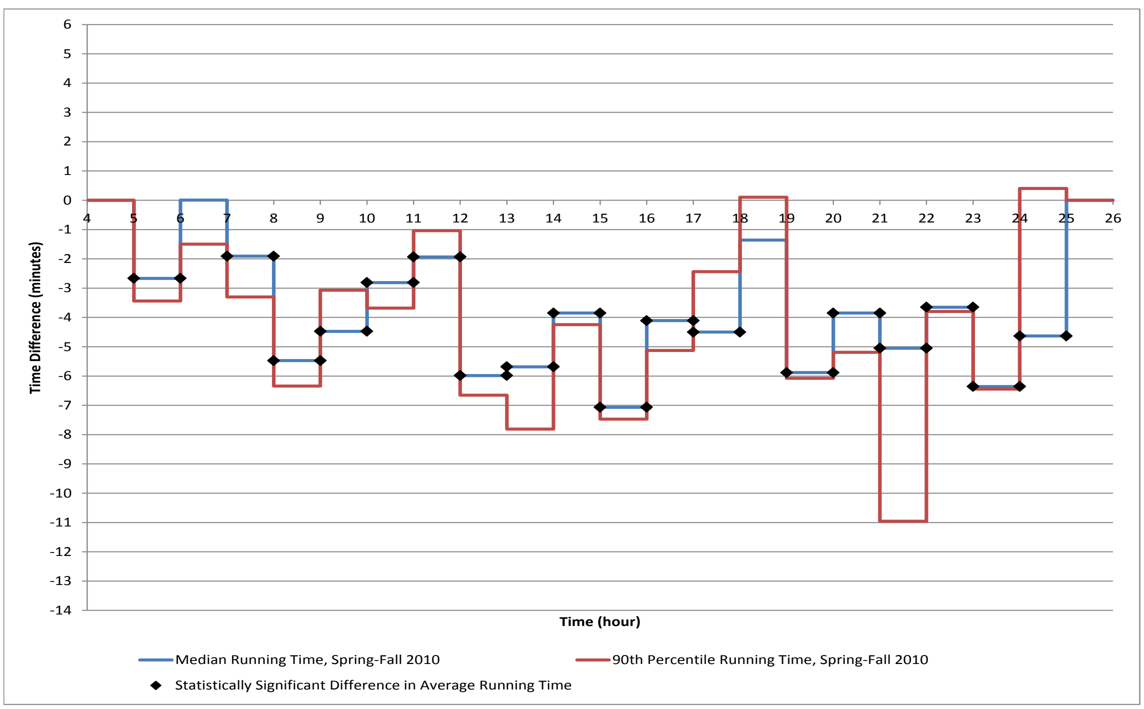

Figure 4.26: Change in Running and 90th Percentile Running Times on B Branch, from Fall 2010 to Spring 2011

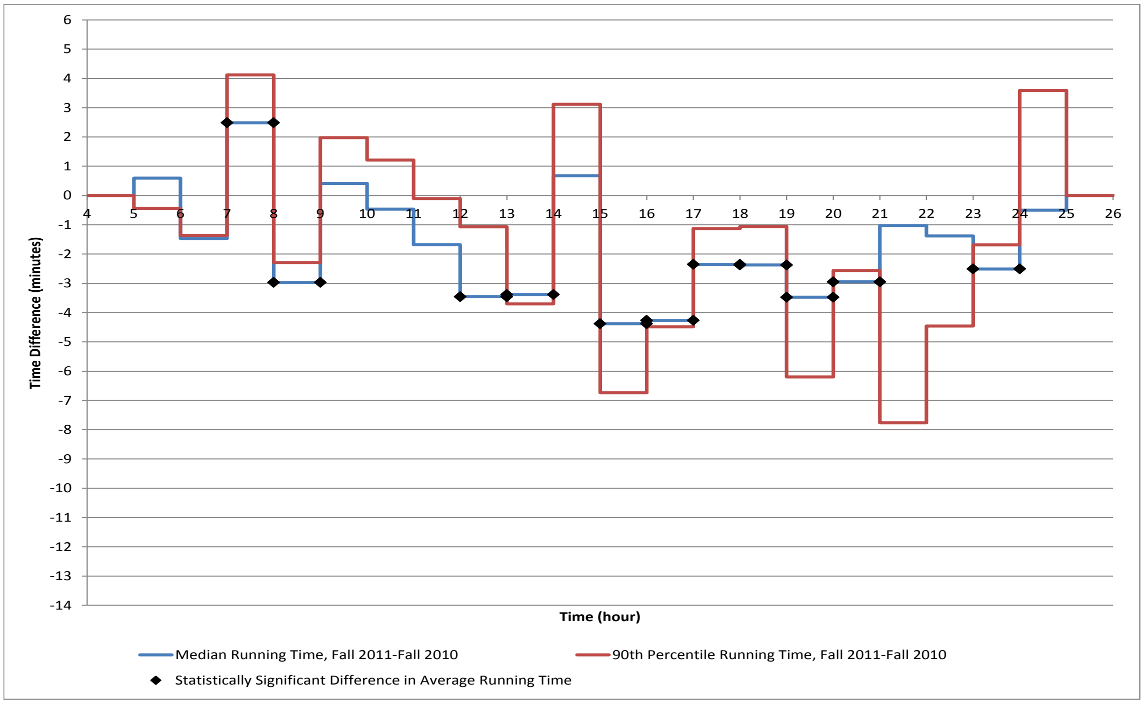

Figure 4.27: Change in Running and 90th Percentile Running Times on B Branch, from Fall 2010 to Fall 2011

time on the D branch was added shortly after the accident on the branch in Newton, to adjust the increases in running time due to more safety restrictions on the branch. However, after the initial temporary increases in the running time, the schedule was not re-evaluated to reflect the service operations after a partial easing of the safety restrictions. During Summer 2011, the D branch running times were evaluated for the Winter and Spring 2011 data sets and results were presented to the MBTA. After similar disparities, as compared to Fall 2010, were identified between schedule and actual performance, the MBTA adjusted their schedule for the D branch to eliminate most of the excess slack time. In Fall 2011, there is much less excess time, though the cycle time exceeded the scheduled cycle time by about 10 minutes in the morning peak and right after the morning peak (see Figure 4.14). Furthermore, on the C branch, eliminating the excess time during the midday may save a train, since the excess time is about 8-10 minutes, which is equivalent to the midday headways. Alternatively, the frequency can be slightly increased.

The changes in actual running and cycle times on all the branches in the subsequent seasons show how service has changed. Of interest is the C branch, which had increases of up to six minutes in running time in the evening peak in Fall 2011, compared to Fall 2010, even though no 3-car trains were in service on that branch. Since the data periods reflect the same season, seasonal affects could be eliminated. While many factors could have contributed to the increase in running times, a possibility is that operation of 3-car trains on the other branches influenced the overall system performance since the C branch trains still have to interact with the 3-car trains in the Central Subway.

The key question is: did the 3-car trains impact the service on the Green Line? If they impacted service, to what extent was the change a result of the addition of 3-car trains. There are two possibilities of how 3-car trains impacted running time: 1) 3-car trains are inherently slower compared to the 2-car trains, most likely due to greater coordination required between operators when closing doors and increased dwell time since passengers cannot anticipate the arrival of a 3-car train, and thus wait to board the first two cars, and 2) the way 3-car train service was implemented, for example, the uneven scheduled headways may have contributed to the difficulty of dispatching the trains on schedule. The goal is to understand which one of these, if any or both, is driving the change.

The increase in running time on the D branch, after the implementation of the 3-car trains, suggests at first that the cause is the inherent slowness of the train. However, other factors cannot be ruled out. For example, ridership grew slightly between Fall 2010 and Fall 2011 (Figure 4.28), and could have had an impact on the overall travel time.

However, the running time increased on the C branch, which further suggests that it is the impact of the 3-car trains. No 3-car trains were operated on the C branch, yet running times still increased during the times when 3-car trains were operated on the other branches. Since the C branch interacts with 3-car trains in the Central Subway, a reasonable conclusion is that the 3-car trains interfered with the 2-car trains on the C branch and impeded their service. To clarify if this is the case, the running times on the C branch were broken down into segments, with the surface portion (Cleveland Circle to Beacon Junction) analyzed separately from the subway segment (Beacon Junction to North Station). Figures 4.29 and 4.30 show that the running times for Fall 2010, Winter 2011, and Fall 2011 on the surface portion had little change, with the exception of the decreases in the median running time from Fall 2010 to Winter 2011 during midday. However, Figures 4.31 and 4.32 show that the running times in the subway had increased, especially on the inbound direction, thus confirming that the increases on the C branch are likely due to the interaction of C branch

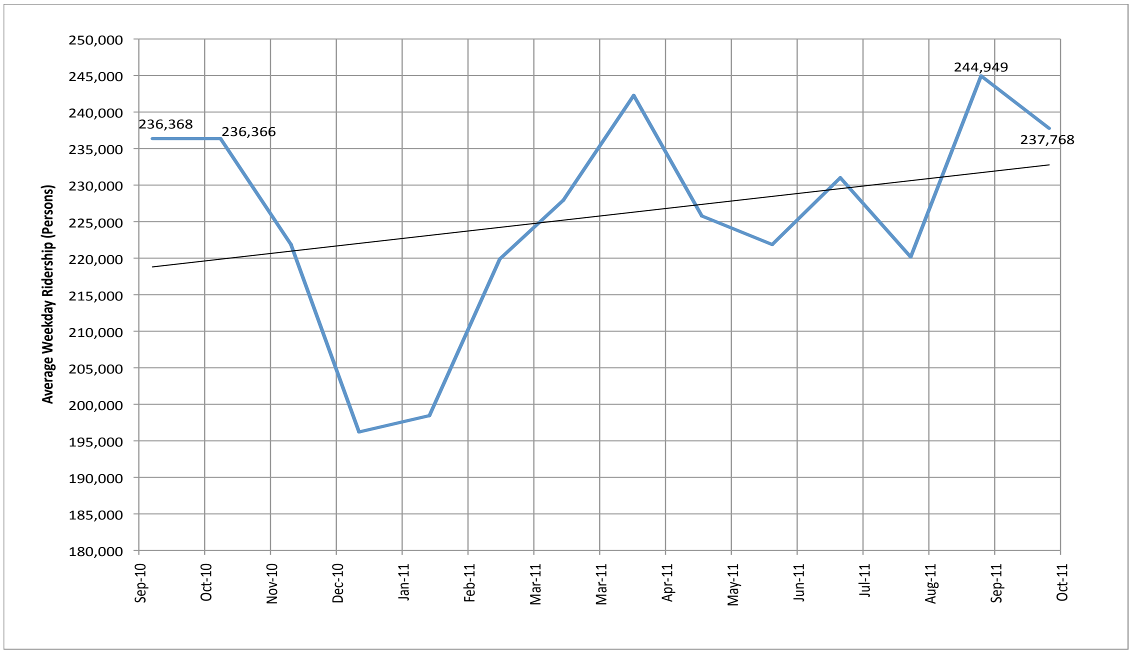

Figure 4.28: Green Line Average Weekday Ridership (Massachusetts Bay Transportation Authority, 2011b)

trains with the 3-car trains.

On the B branch, the running times did not increase, and even decreased from Fall 2010 to Fall 2011. Similar to the above analyses for the C branch, it is important to consider the location of the changes in running times, namely whether the changes occurred predominantly on the surface portion (Chestnut Hill to Blandford St) or in the Central Subway (Blandford St. to Government Center), where the B branch interacts with the other branches. Figures 4.33 and 4.34 show that there is a decrease in the median running time of up to 4 minutes between Fall 2010 and Winter 2011 in the inbound direction and up to 3.5 minutes in the outbound direction on the surface portion only of the B branch. Figure 4.35 shows that the running times in the Central Subway on the B branch decreased by at most 2 minutes from Fall 2010 to Winter 2011, and even increased by 2 minutes from Fall 2010 to Falll 2011, thus indicating that the decreases in running times occurred only on the surface portion of the B branch.

Some of the lack of change in the Central Subway suggests that either the introduction of 3-car trains did not impact the running times of the B branch significantly, or that since

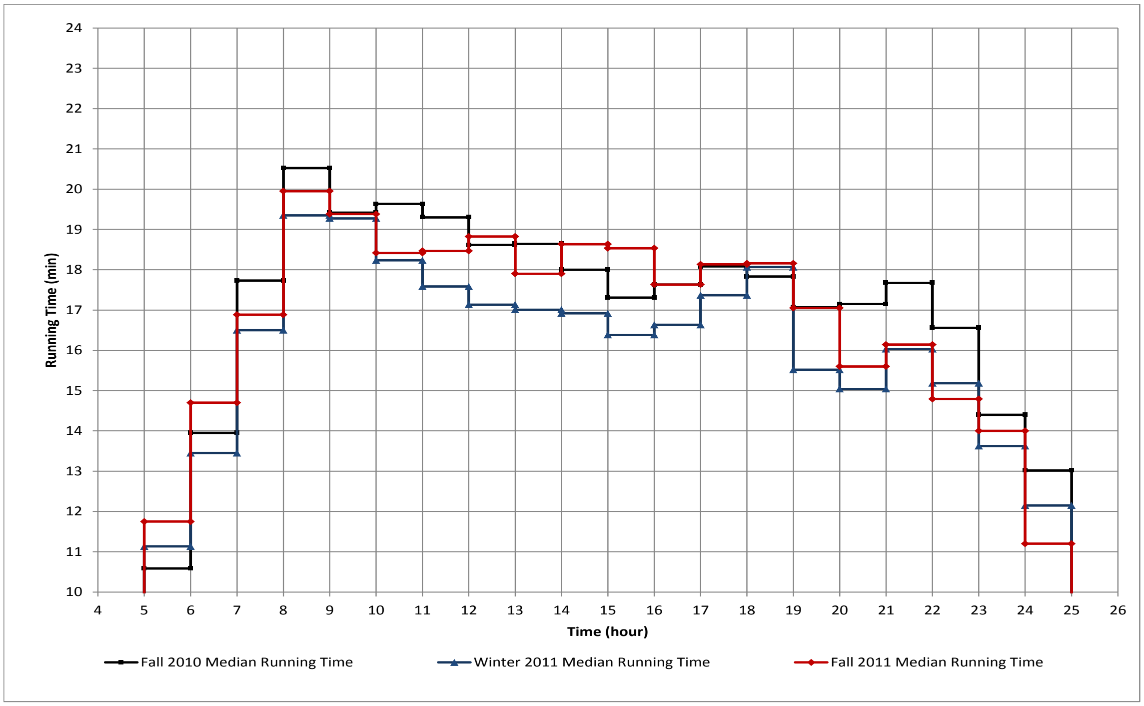

Figure 4.29: C Branch Median Running Times Between Cleveland Circle and Beacon Junction, Inbound

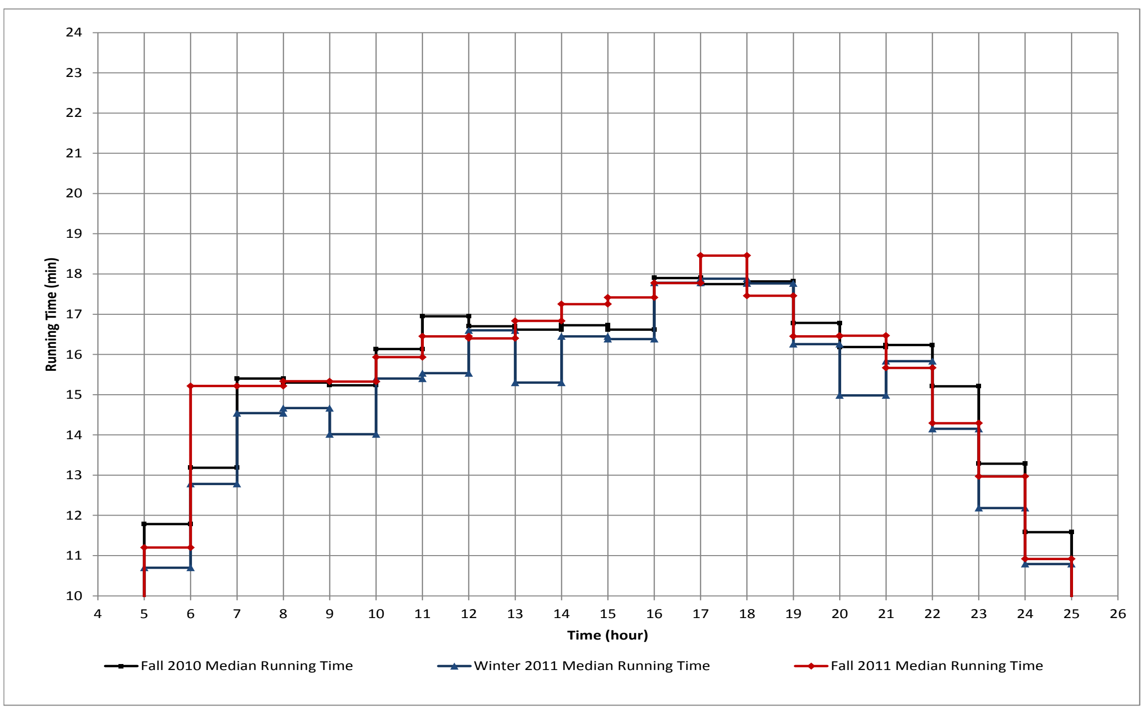

Figure 4.30: C Branch Median Running Times Between Cleveland Circle and Beacon Junction, Outbound

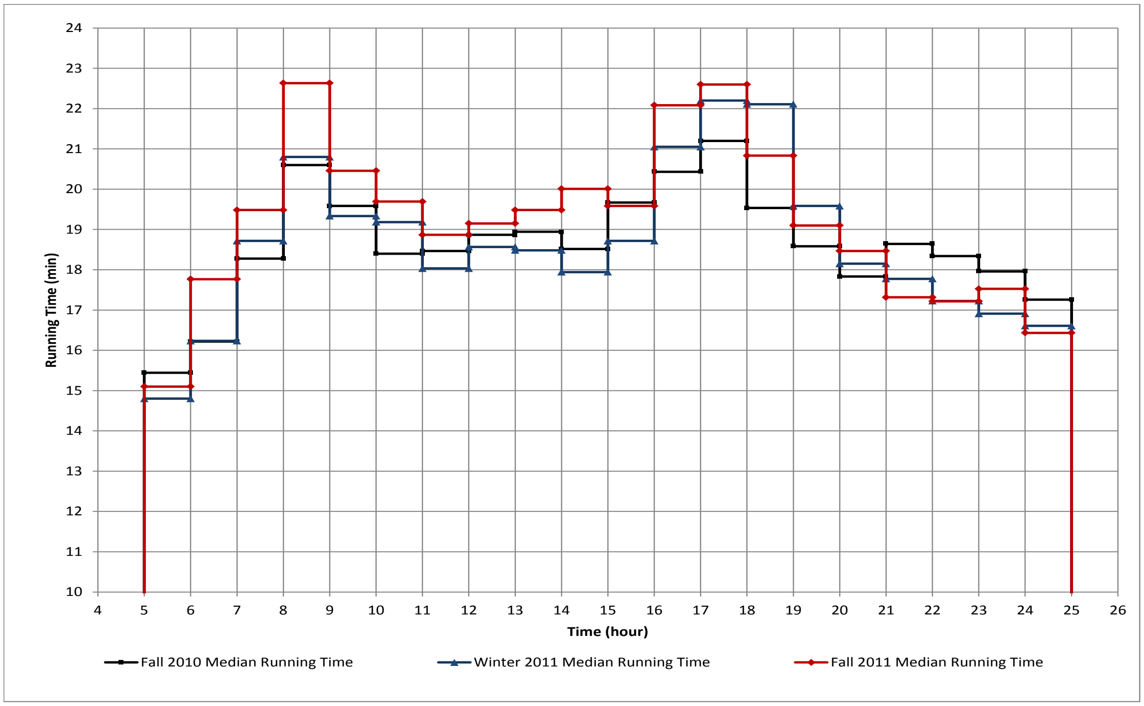

Figure 4.31: C Branch Median Running Times Between Beacon Junction and North Station, Inbound

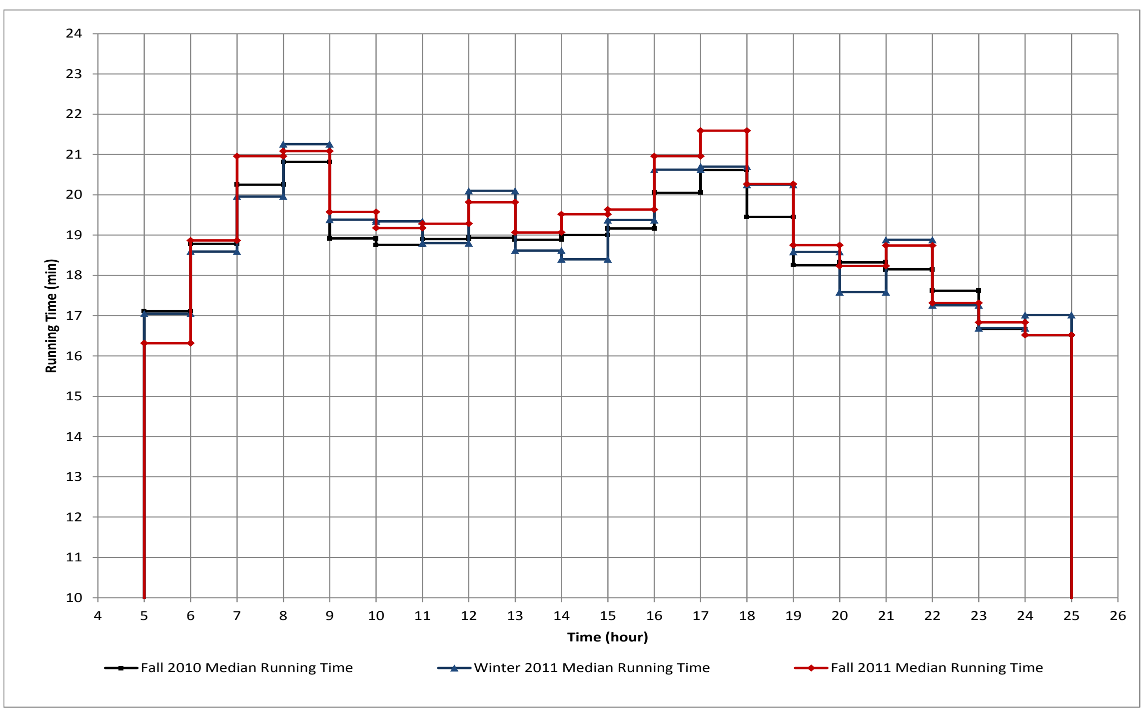

Figure 4.32: C Branch Median Running Times Between Beacon Junction and North Station, Outbound

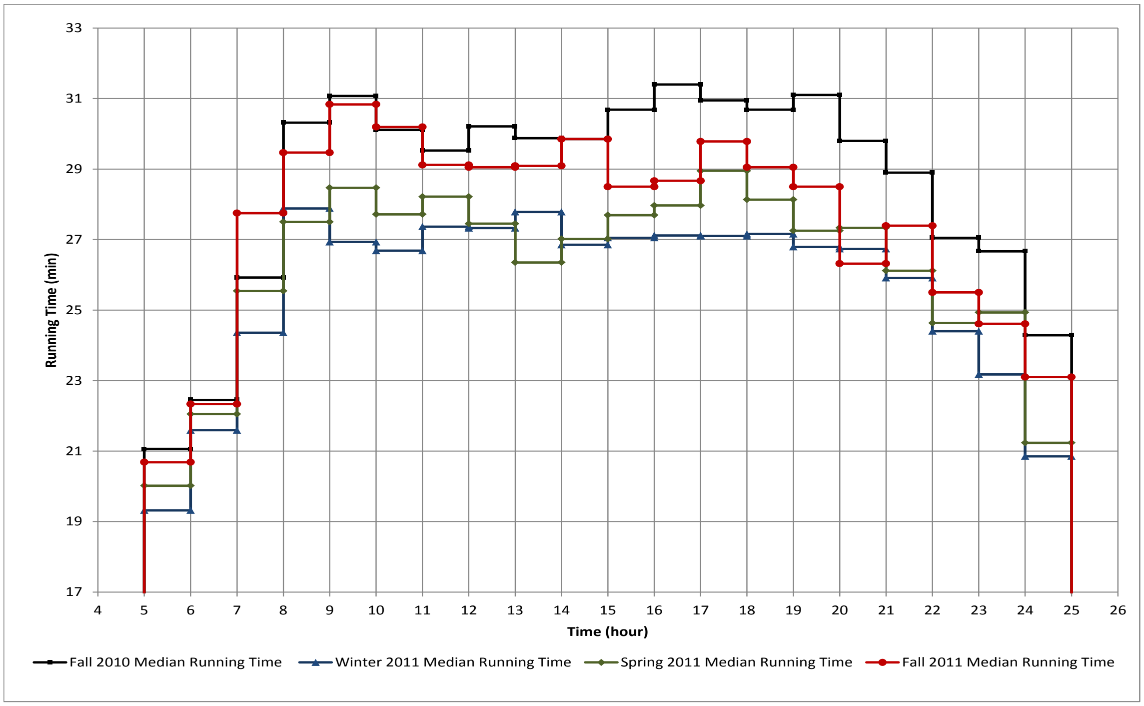

Figure 4.33: B Branch Median Running Times Between Chestnut Hill and Blandford St., Inbound

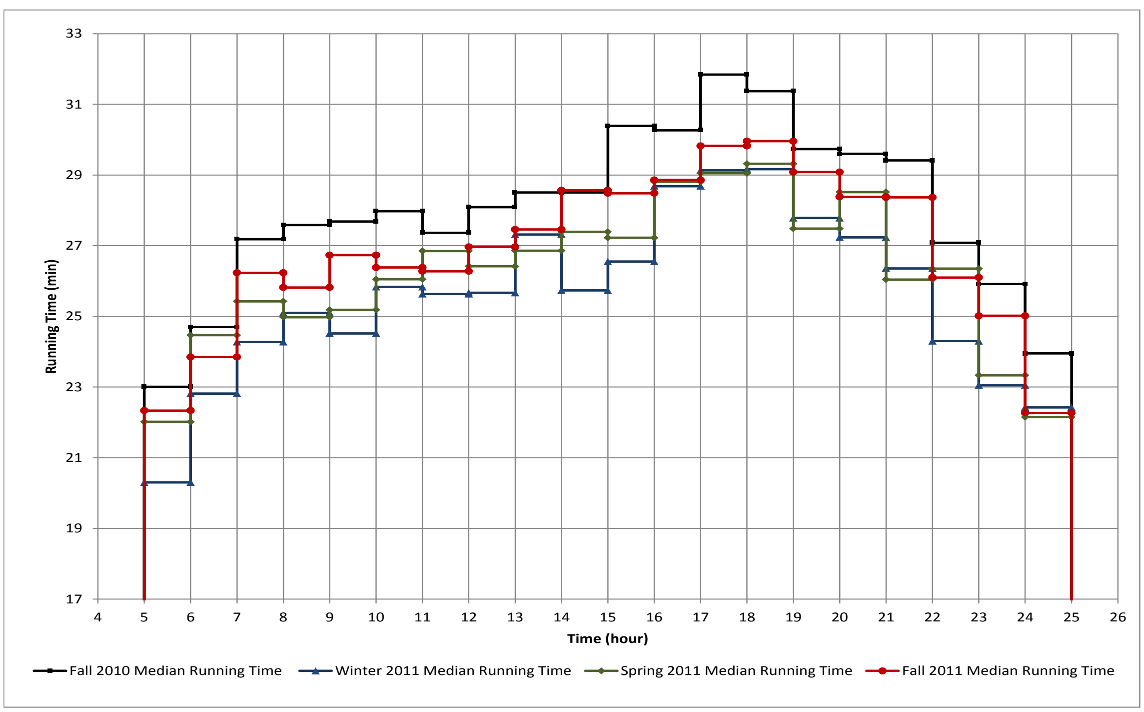

Figure 4.34: B Branch Median Running Times Between Blandford St. and Chestnut Hill, Outbound

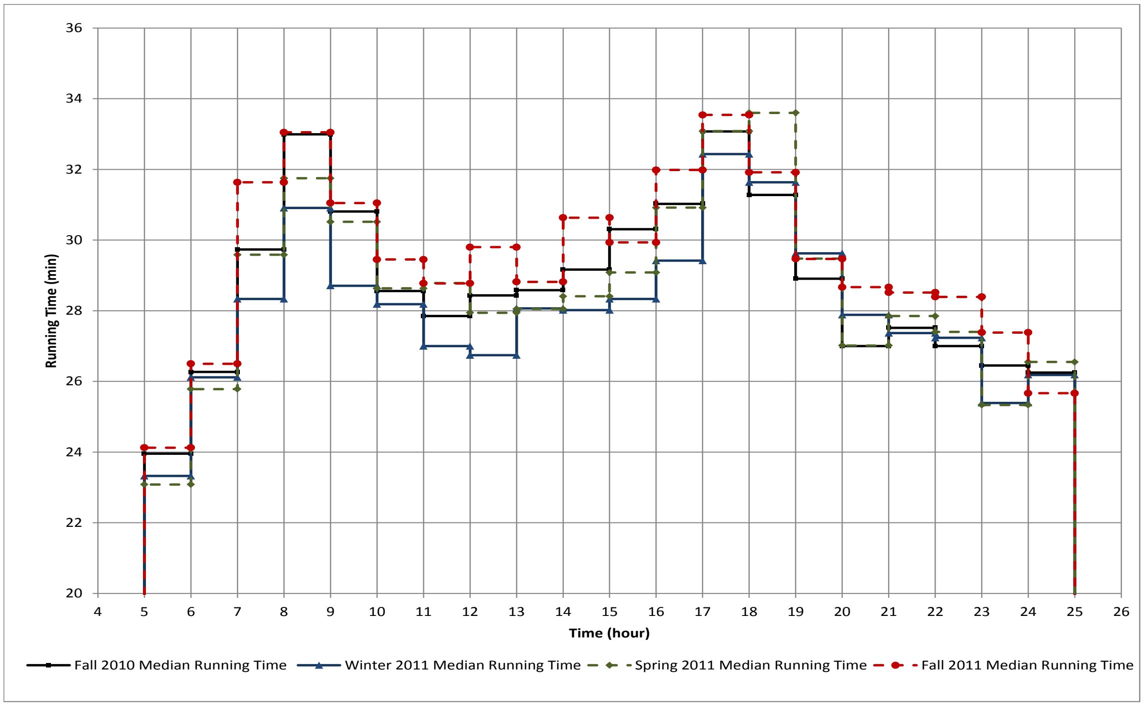

Figure 4.35: B Branch Median Running Times in Central Subway, Between Kenmore and Government Center

the baseline B branch already had so much variability, that adding 3-car trains did not make a difference in the median running time. The decreases on the surface portion suggest that 3-car trains improved service on the surface portion of the B branch. One explanation of why this happened is because of the occasional practice of all-door boarding on this branch: with the addition of 3-car trains, and thus more doors per train set, dwell times may have been reduced on some of higher usage stations, such as Harvard Ave, Packards Corner, Boston University Central, and Boston University East (Central Transportation Planning Staff, 2010).

Headway Analyses and Passenger Waiting Times

The headway analyses for each of the branches is presented below, with average and standard deviations of headways, as well as the resulting passenger waiting time (in minutes), and percentage of observed headways that are less than three minutes. Data that is not available due to some AVI's not working properly during certain data sets is indicated as "N/A" in the tables. References to the percent of trains with observed headways less than three minutes will be shortened to "bunched trains", and passenger waiting time to "PWT".

The discussion below will focus on PWT, which relies on the average and standard deviation of the headway. An increase in the average or standard deviation increases the PWT; therefore, the increases in the scheduled headway from Fall 2010 to Winter 2011, Spring 2011, and Fall 2011 will result in increased PWT, unless the standard deviation decreased significantly to compensate for the average headway increases.

The results for the D branch show that after the implementation of 3-car trains in Winter 2011, the PWT increased by up to 1 minute and the percent of bunched trains increased in the AM and PM peak (Tables 4.3 and 4.3), which is as expected due to addition of 9-minute headways for all 3-car trains. Similarly, the Spring PWT increased from Fall 2010 as well, again since every third or fourth train was operated with a 9-minute headway.

Lastly, Fall 2011, which transitioned to 7-minute headways for all 3-car trains, had increases in the PWT in the morning peak, and of bunched trains in the evening peak, though the PWT decreased by about 0.1 minutes in the PM peak.

Table 4.3: D Branch Headway Analyses Results, AM Peak

		Riverside St. IB (34)	Beacon Jct IB (27)	Beacon Jct. OB (17)	Riverside OB (35)
Average Headway (min)	Fall 2010	5.6	5.4	5.5	N/A
	Winter 2011	6.1	6.1	6.5	6.5
	Spring 2011	6.4	6.9	6.8	7.3
	Fall 2011	6.4	6.4	6.4	6.6
Standard Deviation (min)	Fall 2010	2.0	3.5	3.3	N/A
	Winter 2011	2.4	N/A	4.5	4.6
	Spring 2011	2.4	3.8	4.0	5.6
	Fall 2011	2.4	N/A	3.9	5.6
Expected Passenger Waiting Time (min)	Fall 2010	3.2	3.7	3.6	N/A
	Winter 2011	3.5	4.7	4.3	4.9
	Spring 2011	3.7	4.6	4.6	5.8
	Fall 2011	3.7	4.4	4.5	5.7
% Observed Headways Less Than 3 Min	Fall 2010	3.8%	26.4%	19.8%	N/A
	Winter 2011	8.1%	28.7%	18.3%	31.4%
	Spring 2011	3.3%	17.7%	14.5%	26.5%
	Fall 2011	4.4%	19.4%	17.8%	33.2%

The C branch, which did not have any scheduled headway changes, had slight increases in PWT of up to half a minute during the morning and evening peak periods (Tables 4.5 and 4.6). This increase is attributed to the large increases in standard deviation of the

Table 4.4: D Branch Headway Analyses Results, PM Peak

		Riverside St. IB (34)	Beacon Jct IB (27)	Beacon Jct. OB (17)	Riverside OB (35)
Average Headway (min)	Fall 2010	6.2	6.1	6.1	N/A
	Winter 2011	6.8	6.4	6.9	6.5
	Spring 2011	6.6	6.4	6.4	6.6
	Fall 2011	6.1	6.0	5.9	6.2
Standard Deviation (min)	Fall 2010	2.4	N/A	3.6	N/A
	Winter 2011	3.0	N/A	3.9	5.6
	Spring 2011	3.2	5.0	4.6	5.2
	Fall 2011	2.4	3.4	3.4	5.7
Expected Passenger Waiting Time (min)	Fall 2010	3.6	4.1	4.4	N/A
	Winter 2011	4.1	4.4	5.3	5.7
	Spring 2011	4.1	4.8	4.4	5.3
	Fall 2011	3.5	3.9	4.3	5.7
% Observed Headways Less Than 3 Min	Fall 2010	3.4%	19.3%	22.7%	N/A
	Winter 2011	2.7%	23.9%	25.5%	34.4%
	Spring 2011	7.6%	28.9%	20.0%	29.4%
	Fall 2011	6.2%	21.5%	28.3%	38.8%

headways of up to a minute. The percent of bunched trains decreased at the beginning of the route at Cleveland Circle, but increased along the rest of the route, during the AM and PM peak periods.

From Fall 2010 to the other seasons, the B branch had increases in PWT 0.7 minutes between Fall 2010 and the other seasons in the morning peak (Table 4.7). The evening peak had increases of up to 0.8 minutes from Fall 2010 to Winter or Spring 2011, though from Fall 2010 to Fall 2011, the PWT decreased by nearly 0.4 minutes on the inbound direction (Table 4.8). The increase of PWT from Fall 2010 to Winter 2011 and Spring 2011 is consistent with the increases in headways to 9 minutes for all 3-car trains. The bunched trains decreased by nearly 7% at Beacon Junction inbound, in the AM peak, but increased by up to 6% on the outbound direction at Kenmore (Table 4.7). However, this was conversely true to the PM peak, where the bunched trains increased at Beacon Junction inbound, by up to 6%, and decreased at Kenmore outbound, by up to 5.7%.

The E branch headways locations were examined at Lechmere inbound and North Station outbound (referred to as North Station eastbound to reduce confusion, since outbound changes direction in the Central Subway). North Station eastbound is the closest functioning AVI point to Lechmere, the E branch terminus. Furthermore, Fall 2011 is omitted

Table 4.5: C Branch Headway Analyses Results, AM Peak

		Cleveland Circle IB (26)	Beacon Jct. IB (27))	Beacon Jct. OB (17)	Cleveland Circle OB (25)
Average Headway (min)	Fall 2010	7.0	7.2	7.0	7.0
	Winter 2011	6.8	7.1	6.9	6.4
	Spring 2011	7.2	7.3	6.9	N/A
	Fall 2011	7.1	7.1	7.0	N/A
Standard Deviation (min)	Fall 2010	2.3	2.8	3.4	4.3
	Winter 2011	2.5	2.9	3.9	4.1
	Spring 2011	2.5	3.4	3.8	N/A
	Fall 2011	3.0	3.4	4.3	N/A
Expected Passenger Waiting Time (min)	Fall 2010	3.9	4.1	4.3	4.8
	Winter 2011	3.9	4.1	4.6	4.5
	Spring 2011	4.0	4.5	4.5	N/A
	Fall 2011	4.2	4.4	4.8	N/A
% Observed Headways Less Than 3 Min	Fall 2010	N/A	3.8%	10.8%	19.6%
	Winter 2011	3.1%	4.7%	12.4%	21.9%
	Spring 2011	4.2%	9.6%	17.3%	N/A
	Fall 2011	1.4%	8.6%	17.7%	N/A

Table 4.6: C Branch Headway Analyses Results, PM Peak

		Cleveland Circle IB (26)	Beacon Jct. IB (27))	Beacon Jct. OB (17)	Cleveland Circle OB (25)
Average Headway (min)	Fall 2010	7.3	6.9	6.7	6.5
	Winter 2011	7.5	7.2	7.2	N/A
	Spring 2011	7.1	6.8	6.7	N/A
	Fall 2011	7.6	7.2	6.8	6.2
Standard Deviation (min)	Fall 2010	3.0	3.5	3.8	4.3
	Winter 2011	3.5	4.3	5.0	N/A
	Spring 2011	2.8	3.3	4.4	N/A
	Fall 2011	3.4	4.5	4.6	4.5
Expected Passenger Waiting Time (min)	Fall 2010	4.3	4.3	4.4	4.7
	Winter 2011	4.6	4.9	5.3	N/A
	Spring 2011	4.1	4.2	4.8	N/A
	Fall 2011	4.6	5.0	4.9	4.7
% Observed Headways Less Than 3 Min	Fall 2010	3.6%	10.0%	15.8%	25.3%
	Winter 2011	4.4%	15.4%	17.5%	N/A
	Spring 2011	1.5%	13.6%	21.4%	N/A
	Fall 2011	1.1%	19.4%	21.4%	26.8%

Table 4.7: B Branch Headway Analyses Results, AM Peak

		Chestnut Hill IB (21)	Beacon Jct IB (18)	Kenmore OB (15)	Chestnut Hill OB (13)
Average Headway (min)	Fall 2010	N/A	5.9	5.9	5.9
	Winter 2011	N/A	6.6	6.3	6.3
	Spring 2011	8.4	6.1	6.0	5.9
	Fall 2011	7.3	6.6	6.5	N/A
Standard Deviation (min)	Fall 2010	N/A	3.3	3.1	4.3
	Winter 2011	N/A	4.1	3.5	4.8
	Spring 2011	2.8	2.9	3.4	3.8
	Fall 2011	3.1	3.6	3.7	N/A
Expected Passenger Waiting Time (min)	Fall 2010	N/A	3.9	3.8	4.5
	Winter 2011	N/A	4.6	4.2	5.0
	Spring 2011	N/A	3.8	4.0	4.2
	Fall 2011	4.3	4.3	4.3	N/A
% Observed Headways Less Than 3 Min	Fall 2010	N/A	20.4%	15.1%	35.7%
	Winter 2011	N/A	15.8%	18.1%	37.4%
	Spring 2011	N/A	13.5%	20.2%	25.1%
	Fall 2011	1.4%	12.9%	21.2%	N/A

Table 4.8: B Branch Headway Analyses Results, PM Peak

		Chestnut Hill IB (21)	Beacon Jct IB (18)	Kenmore OB (15)	Chestnut Hill OB (13)
Average Headway (min)	Fall 2010	6.9	6.8	6.0	5.7
	Winter 2011	7.2	7.0	7.0	N/A
	Spring 2011	7.2	7.1	6.8	6.8
	Fall 2011	6.3	6.5	6.5	N/A
Standard Deviation (min)	Fall 2010	2.5	3.9	3.9	4.4
	Winter 2011	2.7	4.1	4.7	N/A
	Spring 2011	2.4	5.0	4.2	5.1
	Fall 2011	1.9	3.5	3.8	N/A
Expected Passenger Waiting Time (min)	Fall 2010	3.9	4.5	4.2	4.6
	Winter 2011	4.1	4.7	5.1	N/A
	Spring 2011	4.0	5.3	4.7	5.3
	Fall 2011	3.5	4.2	4.4	N/A
% Observed Headways Less Than 3 Min	Fall 2010	1.6%	14.2%	25.1%	38.4%
	Winter 2011	1.4%	14.8%	22.4%	N/A
	Spring 2011	2.2%	20.4%	19.8%	30.7%
	Fall 2011	1.6%	15.4%	19.4%	N/A

because trains were not running past North Station due to construction at Science Park (located between North Station and Lechmere), therefore no trains were recorded at these locations for this time period.

The PWT did not change much from Fall 2010 to Winter 2011 during the AM and PM peak periods (Tables 4.9 and 4.10), changing by at most 0.4 minutes from Fall 2010 to Spring 2011. However, from Fall 2010 to Winter 2011, there were PWT decreases of up to 0.9 minutes in the morning peak. The bunched trains in the morning peak also increased by over 12% from Fall 2010 to Winter 2011 at North Station EB, though they increased by 0.8% in the PM peak, at the same location.

Table 4.9: E Branch Headway Analyses Results, AM Peak

		Lechmere IB (1)	North Station EB (39)
Average Headway (min)	Fall 2010	6.4	6.9
	Winter 2011	5.9	5.6
	Spring 2011	6.5	6.7
Standard Deviation (min)	Fall 2010	2.5	4.4
	Winter 2011	2.1	3.7
	Spring 2011	1.7	4.4
Expected Passenger Waiting Time (min)	Fall 2010	3.7	4.9
	Winter 2011	3.3	4.0
	Spring 2011	3.5	4.8
% Observed Headways Less Than 3 Min	Fall 2010	3.49%	20.67%
	Winter 2011	2.86%	32.89%
	Spring 2011	2.41%	17.05%

Discussion of Headway/PWT Changes

The addition of 3-car trains on the branches had a noticeable affect. The increases in scheduled headways for all 3-car trains in Winter, Spring, and Fall 2011 translated to increased average headways, as evident from increases in PWT on the B and D branches. The C branch also had increases in PWT even though no 3-car trains were scheduled on the branch. The E branch had very small changes in the PWT, and even some decreases. Overall, PWT increased by up to 1 minute (as seen on the D branch in the morning peak (Figure 4.3)). Although the increases seem not very significant, it must be noted that waiting time is generally more onerous than in-vehicle travel time, thus an increase in PWT

Table 4.10: E Branch Headway Analyses Results, PM Peak

		Lechmere IB (1)	North Station EB (39)
Average Headway (min)	Fall 2010	6.4	6.7
	Winter 2011	6.8	6.6
	Spring 2011	6.1	6.5
Standard Deviation (min)	Fall 2010	2.8	4.6
	Winter 2011	2.6	4.4
	Spring 2011	3.2	4.1
Expected Passenger Waiting Time (min)	Fall 2010	3.8	4.9
	Winter 2011	3.9	4.8
	Spring 2011	3.9	4.5
% Observed Headways Less Than 3 Min	Fall 2010	7.3%	26.7%
	Winter 2011	3.3%	27.5%
	Spring 2011	6.7%	22.1%

will be felt more negatively than increases in travel time.

The question, again, is how was service affected by 3-car trains as opposed to scheduled changes or external factors, such as operations management? Aside from the expected changes in the averages of the branch headways due to increases in scheduled headways for all 3-car trains, it is also important to look at the interaction of all the trains, which is shown as the percentage of observed headways less than 3 minutes. As the control branch, the C had a reduction in the number of bunched trains from Fall 2010 to the rest of the seasons at the beginning of the route at Cleveland Circle inbound, in the morning and evening peak hours, which suggests improvements in management control of train departures. However, the number of bunched trains increases from Fall 2010 to Winter, Spring, and Fall 2011 all along the route after Cleveland Circle, for both AM and PM peak periods. Since the change in bunched trains happens at locations before and after the C branch trains enter the Central Subway, any number of factors could have influenced the changes, including ridership or operations management. The B and D branches also had increases of bunched trains along their respective routes, for both the AM and PM peak periods, while the E had a reduction.

One method of identifying the impact of 3-car train on the service is to separate headways into multiple categories: headways of 3-car trains and headways of 2- or 3-car trains following 3-car trains. The results (see Figures 4.36 and 4.37) show, as expected, that the trains following 3-car trains had an even higher incidence of bunching compared to the overall average during the peak period, while 3-car trains had less bunching than average during the peak period. For example, when comparing Figure 4.36 to Figure 4.37, the percent of bunched trains is about 10% higher for trains following 3-car trains than for actual 3-car trains.

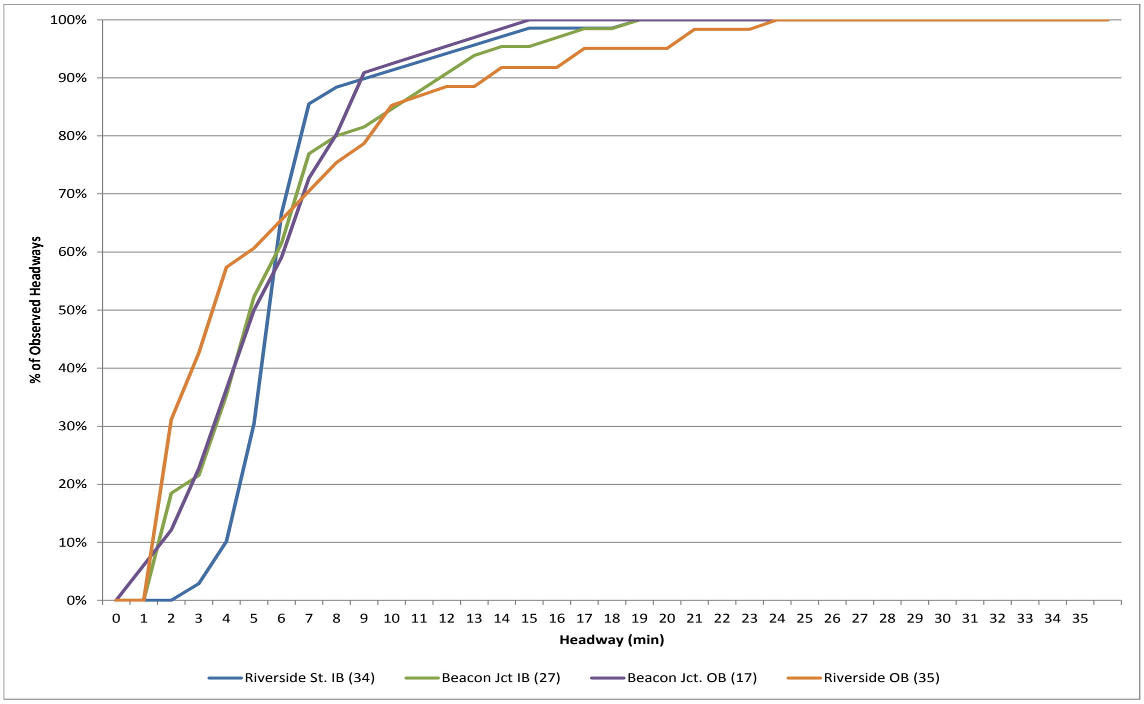

Figure 4.36: D Branch Headways of All Trains Following 3-Car Trains, AM Peak (Fall 2011)

The results suggest that either 3-car trains tend to fall behind schedule more consistently than the 2-car trains, or that more trains following the 3-car trains (as compared to trains following 2-car trains) catch up to the leading train. Either way, there is a tendency of trains following 3-car trains to bunch with the leading 3-car trains, which poses difficulties for operations management to maintain headways and creates more variability in PWT.

Field Observations

The data analyses using AVI are complemented by field visits to the D branch terminal at Riverside Station on October 3 and 17, 2011, and E branch terminal at Lechmere Station, on March 28, 2012. This provided the opportunity to understand the operational practices

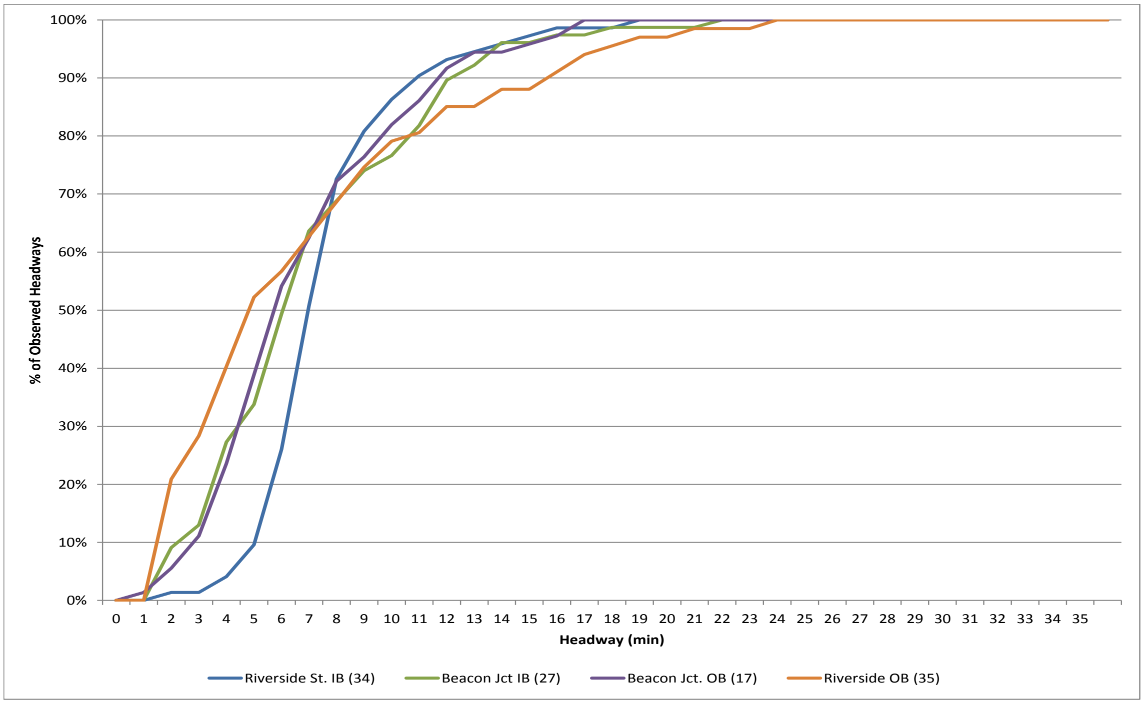

Figure 4.37: D Branch Headways of All 3-CarTrains, AM Peak (Fall 2011)

at a major and minor Green Line terminal, and the implications of the operations decisions practiced at each location. The field observations focus on the deviation from the scheduled departure times and headways, as well as yard operations. In the analyses presented below, the deviations from the scheduled departure time and scheduled headways can be either positive or negative, meaning that trains can depart before or after their scheduled trips. These deviations were averaged and will be referred to as average deviation. With average deviation, an average of zero minutes does not necessarily mean that all trains departed on time, but only that the sum of the deviations divided by the total sample is close to zero. To improve understandability of the observed performance, the standard variation around the mean deviation is used, which shows the variability of the deviation. The greater the standard deviation, the greater the variability in schedule adherence. Conversely, if the standard deviation is close to zero, then the variation in deviation is very small. Thus if the standard deviation and the average deviation are both zero, then all trains followed the schedule perfectly.

D Branch On October 3, the average deviation was 2 minutes, meaning that trains departed on average nearly 2 minutes later than scheduled. The standard deviation of 1.5 minutes implies that many trains were departing outside of the average deviation. On October 17, the average deviation was about 0 minutes, thus creating the false impression that the trains were departing on schedule. However, the standard deviation of 1.4 minutes is similar to that on October 3, meaning that the trains were departing with similar variability around the average on both days.

Deviation from		**Oct. 3, 2011**	**Oct. 17, 2011**
Scheduled departure time	Average	1.9 min	0.1 min
	Abs. Dev.	1.5 min	1.4 min
Scheduled headway	Average	0.0 min	0.1 min
	Abs. Dev.	2.4 min	1.7 min

Table 4.11: Summary of deviations from schedule at Riverside Terminal

Figure 4.38 shows the visual summary of the deviation from the scheduled departure time by scheduled trip. Dark colored points represent 3-car trains, positive deviation means that the train departed later than scheduled, and conversely, negative deviation means that trains departed early. Although 3-car trains were scheduled for the 7:48 and 8:06 trips on October 17, 2-car trains made these trips.

On October 3, the two trains with the highest deviation from the schedule were 3-car trains. For both days, 3-car trains had a higher average deviation from schedule (2.1 minutes) than 2-car trains (1.1 minutes). This suggests that 3-car trains were less likely to depart on schedule, possibly because of the greater coordination needed between three, as opposed to two, operators.

When comparing headway adherence, the average headway for October 3 and 17 is about 5.5 minutes, with a standard deviation of 2 minutes. Table 4.38 shows that the average deviation from the scheduled headway for both days is zero minutes, but the standard deviation is 2.4 minutes on October 3, and 1.7 minutes on October 17. It can be interpreted that on average the trains departed with the scheduled headways, however there is significant variability in headways. The trains on October 3 had a larger spread of deviation from the scheduled headways than the October 17 trains. Figure 4.39 graphically displays train headway adherence versus the scheduled headways for both days. Again, the dark colored points represent the 3-car trains.

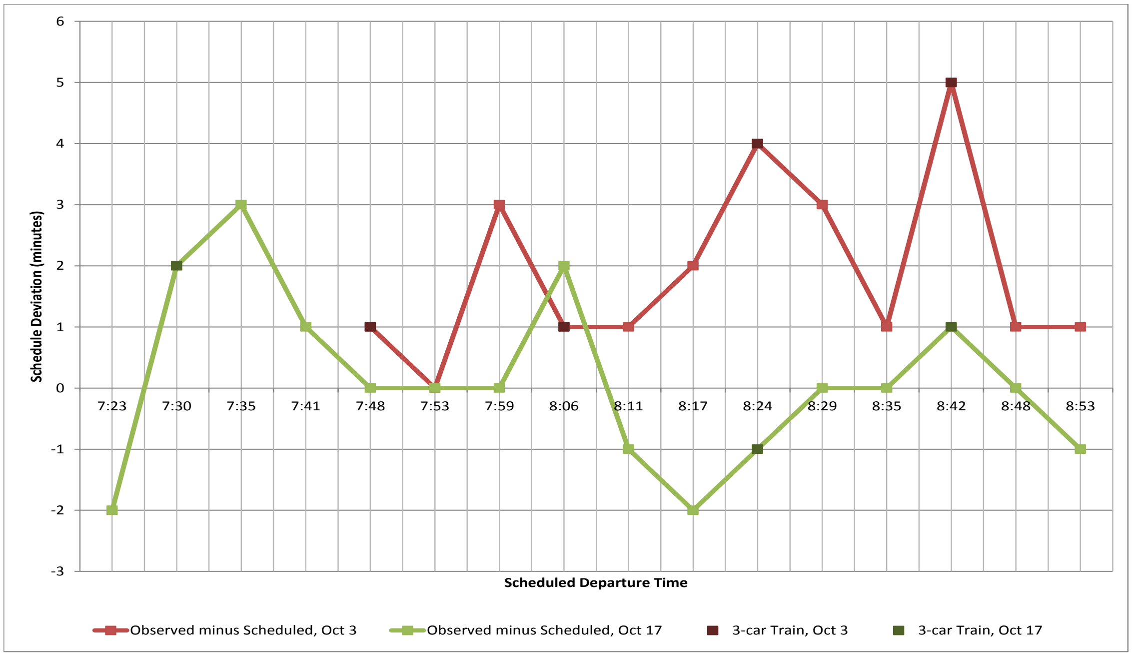

Figure 4.38: Deviations from Schedule During Field Observations at Riverside Terminal

In Figure 4.39, the 3-car train headways are longer than the scheduled headway, except for the 8:06 trip on October 3, which departed 2 minutes earlier than the scheduled headway. However, this short headway could be explained by the longer than scheduled headway of the preceding trip, since it seems that the official on duty was attempting to return to schedule rather than maintain scheduled headways. In general, it can be observed that all very long headways (greater than 8 minutes) were followed by very short headways (shorter than scheduled, except the 7:35 train), which again seems to be an effort by the operation staff to return to scheduled departure times.

Note: The observed differences in the scheduled departure and headway adherence between the two days are maybe due to different inspectors on the two days, as well as the awareness of the researcher team's presence on October 17. Although the reasons may not represent a significant portion of the differences in our observations, it is still important to consider when comparing the two days.

D Branch Yard Operations In addition to train arrivals and departures, yard operations were also observed. During the entire morning peak on October 17, there were 6 or

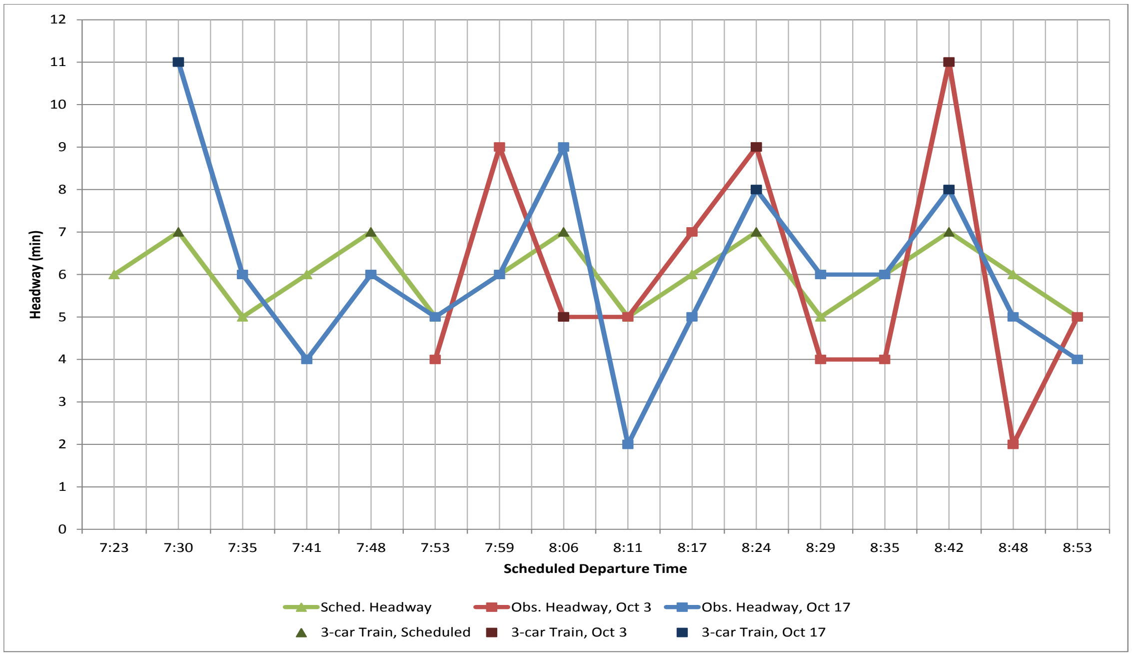

Figure 4.39: Scheduled and Actual Headways During Field Observations at Riverside Terminal

7 trains in the yard, seemingly ready for departure. Although this provided the Riverside crew flexibility in operations, this also may represent poor vehicle utilization. Furthermore, it was observed that trains at Riverside used the Riverside Yard loop for the majority of turn-arounds, as opposed to using the cross-over near the Riverside Station platform. Using the loop, as opposed to the cross-over, during the peak hour can add up to four minutes to a vehicle's cycle time. Although it is important to add some buffer time to the schedule in the peak hour to absorb any lateness, it is also important to create as efficient a schedule as possible.

The layover times were also observed. The average layover time on October 3 was 17 minutes with a standard deviation of 5 minutes, and 23 minutes with a standard deviation of 15 minutes on October 17. The observed average layover with the average headway of 6 minutes dictate that the yard should have 3 to 4 trainsets ready for departure (when using $N = \lceil \frac{C}{h} \rceil$), which is less than observed. It is presumed that 2 or 3 trains were extras to be used only in severe service disruptions.

E Branch The summary of the deviation of the departing observed trains and adherence to headways are presented in Table 4.12. AVI data from the AVI detector at Lechmere was used to compare the actual departure to the schedule since the AVI detector is located at the station.

The average deviation from scheduled departure time within the observed time period is 1 minute, meaning that trains departed on average 1 minute later than the schedule. However, the standard deviation of 0.9 minutes shows that the variation in departure is fairly small, so there is much more consistency in how close to the schedule trains depart from Lechmere. Figure 4.40 shows the deviation from schedule visually. It must be noted that there were no 3-car trains operating on the E branch at the time of the field visit, so observations can only be made about 2-car trains and the operational practices at Lechmere. Furthermore, the 7:55 trip was not made, therefore it is left out from analysis and related figures. From Figure 4.40, it can be seen that no trains departed before the scheduled departure time, and that the greatest delay was 3 minutes for two of the scheduled trips at 8:34 and 8:52. Additionally, 11 out of 16 (69%) of the trips at Lechmere departed within 1 minute and not before the scheduled departure time, compared 7 out of 12 trips (58%) on October 3, and 8 out of 16 trips (50%) on October 17 at Riverside Terminal.

Deviation from		**March 28, 2012**
Scheduled departure time	Average	1.0 min
	St. Dev.	0.9 min
Scheduled headway	Average	0.5 min
	St. Dev.	1.4 min

Table 4.12: Summary of deviations from schedule at Lechmere Terminal

The headway adherence statistics in Table 4.12 show that on average, the actual headways deviated from the scheduled headways by 0.5 minutes, and that the standard deviation of the difference between the actual and scheduled headways is 1.4 minutes, indicating that although the actual headways don't follow the scheduled headways perfectly, they vary from the schedule less than at Riverside.[3] In other words, Lechmere had better headway adherence compared to Riverside. One possibility of the better adherence is that the scheduled headways are more consistent and do not alternate between two or more headways

[3] The headway for the 8:00 trip, which followed the missed trip, was determined as the difference of its departure minus the previous departure as opposed to the difference of its departure and the previous scheduled trip.

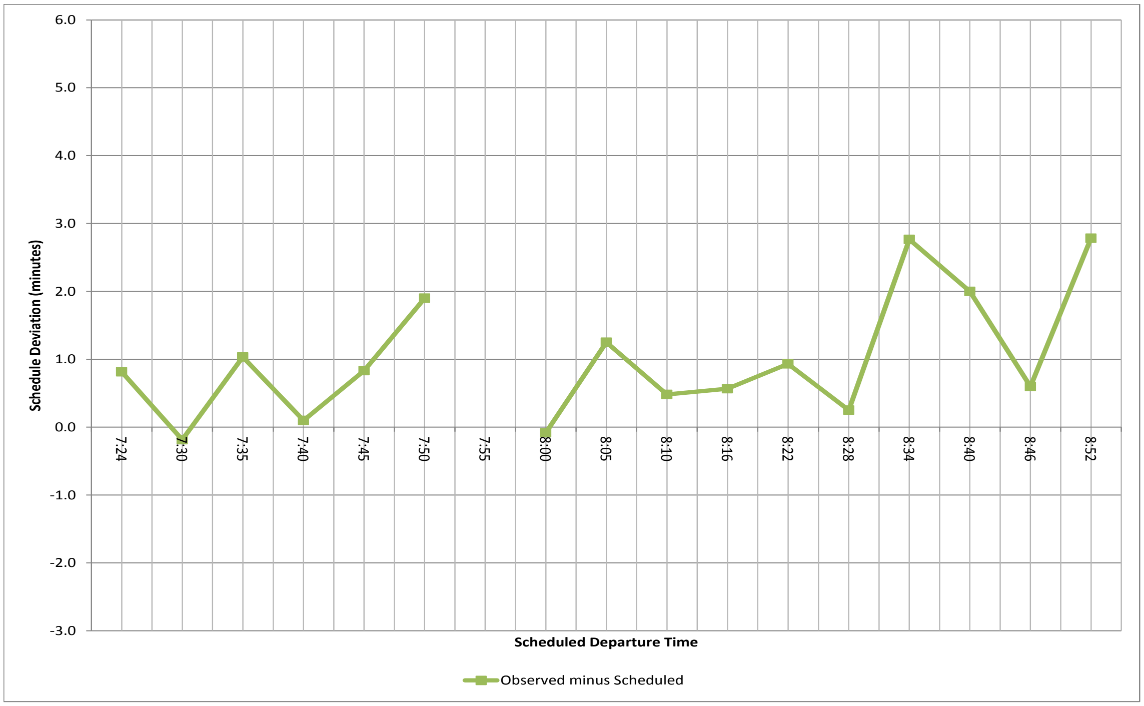

Figure 4.40: Deviations from Schedule During Field Observations at Lechmere

throughout the period of observation. Additionally, the practice of sending trains with very short headways if the preceding headway was longer than scheduled is practiced at Lechmere as well. As Figure 4.41 shows, for example, the 7:35 trip departed with a headway larger than scheduled, and the following trip departed 1 minute earlier than the scheduled headway. However, that following trip also departed on schedule, according to Figure 4.40, thus showing that there is an attempt at adhering to schedule, and not headways.

From the field visit, it was observed that the inbound trains wait at the departure platform until scheduled departure time, with the operators in the train vehicles and the doors open. It seems that this operations practice minimized the probability of delay, especially from having to prepare the vehicle and assemble the crew in a short time before scheduled departure. Also, by allowing passengers to board the train for the duration of the headway reduces the additional time needed for passengers to board if the train were just to pull up to the platform. This practice may reduce the variability in departure times as well as reduce delay overall.

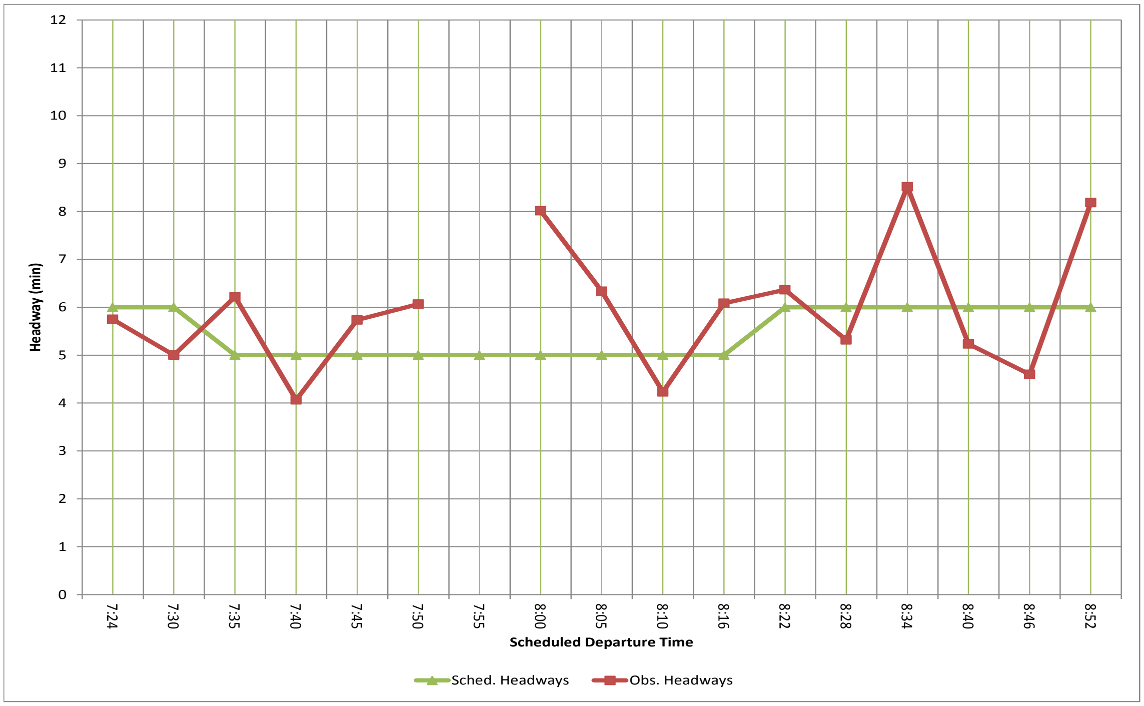

Figure 4.41: Scheduled and Actual Headways During Field Observation at Lechmere Terminal

Conclusions About Field Observations

The results presented above indicate that trains were not always departing on schedule, and headway management was not practiced when train departures deviated significantly from schedule. In most cases, when a train departed with a headway significantly longer than scheduled, it seems the operations staff tried to adjust for the deviation by dispatching the next train with a very short headway. The longer than scheduled headways tended to happen a lot with 3-car trains at Riverside, thus demonstrating that the management of 3-car train operations was creating some problems with keeping trains on schedule. Furthermore, Figure 4.42 shows the progression of the trains observed at Riverside on October 3, and the impact of the short or long headways on train bunching further up the route. In particular, a train departure with a greater than the scheduled headway, followed by a train departing with a shorter than scheduled headway results in bunching. Thus, 3-car trains alone cannot be attributed to greater bunching or the worsening running time, but operations practices as well.

The above mentioned deviations from scheduled departure were small, but deviations at

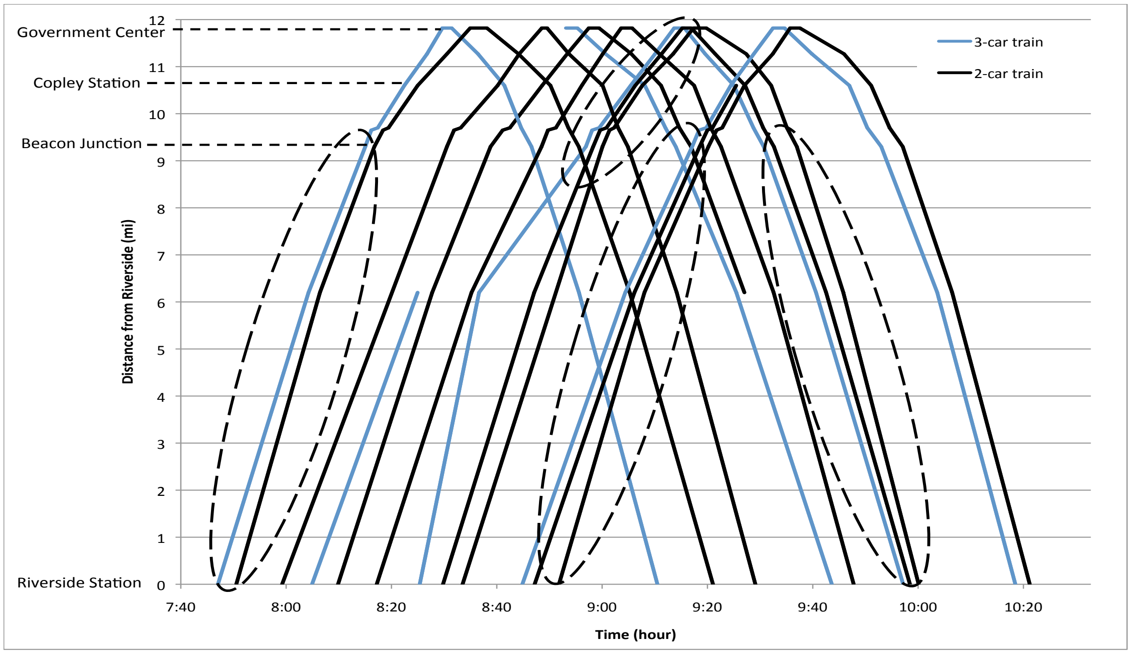

Figure 4.42: Space Time Diagram of Progression of Trains on the D Branch, Observed at Riverside on October 3, 2011

the terminal often magnify further along the route, as circled in Figure 4.42. It seems that the operations practice at Lechmere helps minimize departure delays, and the even headways helps reduce variability in train departure, therefore the practices should be more widely practiced throughout the Green Line. The reduction in train departure variability due to even headways also suggests that headway management should be practiced when trains deviate too much from schedule, as opposed to attempting to return train departures back to schedule. Furthermore, because of the possibility of the delays worsening further along the route, the terminal should be subjected to stringent schedule or headway adherence standards.

Although the field observations allow the identification of best operational practices, it must be noted that the above results are from only three days of observations, which is a limited sample. More samples should be collected to understand the scope of the improvements of switching from the operations practiced at Riverside to those practiced at Lechmere.

4.3 Conclusions from the 3-Car Train Trials

Ultimately, by Fall 2011, the scheduled throughput capacity, in number of train cars per hour on the system, increased during the PM peak, but decreased when measuring actual throughput. Additionally, the actual capacity during the morning peak remained the same, thus showing that changing some of the trips to 3-car trains did not increase capacity, as had been originally announced.

With respect to the impact on passenger service, there were some positive and some negative outcomes, all of which cannot be confidently attributed simply to 3-car trains. The increases in running times on the C branch in the Central Subway and on the entirety of the D branch during the peak periods slowed travel time for passengers by a few minutes, and the greater variation of headways for the B and D branches increased passenger waiting time, thus worsening service for passengers on these branches. However, the decrease in running times on the surface portion of the B branch suggest that service has not worsened appreciably there after the addition of 3-car trains, possibly because of the current boarding practices on the surface portion.

Through field observations, it can be seen that terminal operations management is crucial for the performance of trains. Slight deviations from schedule at the terminal can magnify over the length of the route and compound into serious delays. Although there are external factors that impact service performance on each branch, it is important to minimize the influence of the factors that are under the MBTA's control, which includes terminal departure management. **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.** Furthermore, having consistent (i.e. uniform) scheduled headways, as well as switching to headway departure management when train departures deviate significantly from schedule, may reduce the variability of scheduled departure adherence, while allowing departing trains to wait at the departing platform can minimize delays on departure.

The 3-car train trials may have had negative impacts on the Green Line performance, but it is still important continue trials of 3-car trains, as it is one of the ways the MBTA can increase capacity on the Green Line. The 3-car train trials may have to go through multiple iterations before desirable results are achieved, namely with increased capacity and improved service.

Lastly, one of the most important observations is that evaluation of the Green Line was incomplete due to either poor AVI data or missing AVI points. In order to have a more thorough system evaluation, more AVI points are needed.

Chapter 5

Green Line Operating Scenarios

The results of analyses of AVI data and field observations in the previous chapter suggest that the introduction of 3-car trains did not increase capacity, as had been expected, and that service levels worsened on the C and D branches, though improved slightly on the B branch. While there are some exogenous variables that could be affecting the service performance, such as increases in ridership or variability in operator behavior, there is evidence showing that the introduction of 3-car trains contributed to many of the changes. There are three aspects of the MBTA's 3-car trains operations that need to be addressed:

- It seems that the mix of 2- and 3-car trains operated causes increased dwell times through uneven passenger distribution at platforms. A study by Pettersson (2011) showed that passengers stand closer to the location where their desired rail car will stop, based on experience or information of train stopping location obtained at the train station. Furthermore over a third of the waiting passengers who were not aware of the availability of information of train stopping location (40% of all passengers) and did not have experience about exact train stopping location, had waited for the train in a location where they thought their desired car would stop, showing that there is a desire for passengers to wait at their boarding locations. Although the study was done for intercity rail passengers, it is likely to be valid for daily commuters, who take transit as often as twice per day. Through daily transit use, passengers gain experience about train stopping positions and thus are likely to wait near the boarding location.

  Applying the concept to the Green Line, in the past, commuting passengers were conditioned to expect 2-car trains and thus waited at the boarding locations of the

2-car trains. However, the implementation of 3-car trains does not seem to have conditioned passengers to wait at the stopping location of the third car in a 3-car train, most likely due to the inconsistency of 3-car train arrival and lack of advance information about the length of the next train. Having a more consistent stopping location and size of train consist will allow passengers to better position themselves in anticipation of a train arrival. This is aggravated by increased headways for 3-car trains, which increases the number of passengers at the station, assuming a uniform passenger arrival rate, and by the need for increased coordination of between the three separate operators who operate the doors independently.

- Currently, the mix of 2- and 3-car trains on three of the four branches uses variable headways, which creates a greater challenge for schedule adherence at terminal stations. Operations management, in particular at the terminals where it is most important for trains to depart on schedule, needs to be stricter to better regulate train departures. Increasing information availability to the operations staff may help increase awareness of lateness and desire to improve service.

- To compensate for the above two operating conditions that tend to slow down service and potentially impact its reliability negatively, a net increase of overall train car capacity is needed to more successfully implement 3-car train operations on the Green Line. As witnessed on the B branch, service on the surface segment actually improved after the implementation of 3-car trains there. Since these trains stop at more consistent locations and allow all door boarding, the addition of 3-car trains may have sped up the boarding at heavily used stations, thus improving service. Having consistent 3-car train arrivals may help isolate the cause of the decreases in running time of 3-car trains.

5.1 New Operating Scenarios

In order to improve passenger distributions along platforms on the surface portions and to decrease the variability in headways on all the lines, perhaps the MBTA should not operate a mix of 2- and 3-car trains during the peak periods on the same branch. Instead, a new trial should be designed to operate all 3-car trains on at least one of the branches during the peak periods and all 2-car train operations on the other branches. While there will still be a mix of 2- and 3-car trains in the Central Subway, studying the service and capacity impact on just the surface portion will help pinpoint the actual impact of 3-car train operations. Furthermore, restricting operations to all 3-car trains during the peak periods will eliminate the headway variability at terminals and possibly increase schedule adherence.

Two branches were considered for concentrating 3-car train operations in the peak periods: the D and E branches. The D branch was considered because of its completely separated right of way, which provides ideal conditions for running the trial due to a significant reduction in external variables, and high ridership (over 19,000 passengers use the surface portion of the D branch daily according to Central Transportation Planning Staff (2011)), which would benefit from higher capacity. The E branch is also proposed due to its shorter route, ideal for testing more complicated operating scenarios, as described below.

As mentioned already, the goal is to have only 3-car train operations during the peak periods. For the D branch, two scenarios for such operations are proposed: Scenario 1, where the number of rail cars available in Fall 2010 are reformed into all 3-car trains during the peak periods, but at reduced frequency (larger headways), assuming that additional resources will not be available; and Scenario 2, where additional resources are provided and the 3-car train frequency, while not as high as Fall 2010 levels, does not decrease nearly as much as it does under Scenario One. In this way, the first scenario can be considered an "operator friendly" alternative, while the second scenario clearly provides new capacity and improves overall passenger service by theoretically reducing crowding levels along the branch.

The proposed E branch operating scenarios are more complicated. The proposal is to operate train sets in a continuous loop from Lechmere to Brigham Circle, where trains can use the crossover between Longwood Medical center and Brigham Circle to reverse direction, just as was recently done for all 3-car trains on the E branch. All 3-car trains will operate during the peak periods and 2-car trains at all other times. Furthermore, a number of single rail cars will operate from Northeastern University to Heath St. throughout the day, using the siding just west of Northeastern University station to reverse direction (see Figure 5.1). Both of the segments will operate at the same headways. The Heath St. bound train will travel half a headway ahead of the Lechmere bound train to allow passenger to connect between the two segments with enough time, but also allow the trains to clear any crossovers without interference from the other trains. Two scenarios of this operating plan are also analyzed. Scenario 3 will limit the number of rail cars operated on the two segments to the number of rail cars operated on the E branch in Fall 2010. Scenario 4 examines the service impact of using all of the Fall 2010 E branch fleet on the longer 3-car segment, from Lechmere to Brigham Circle, but adding more rail cars to operate the shorter one-car segment. This results in a capacity increase on the Lechmere to Brigham Circle segment since the same number of rail cars will operate on a shorter route than the current E branch.

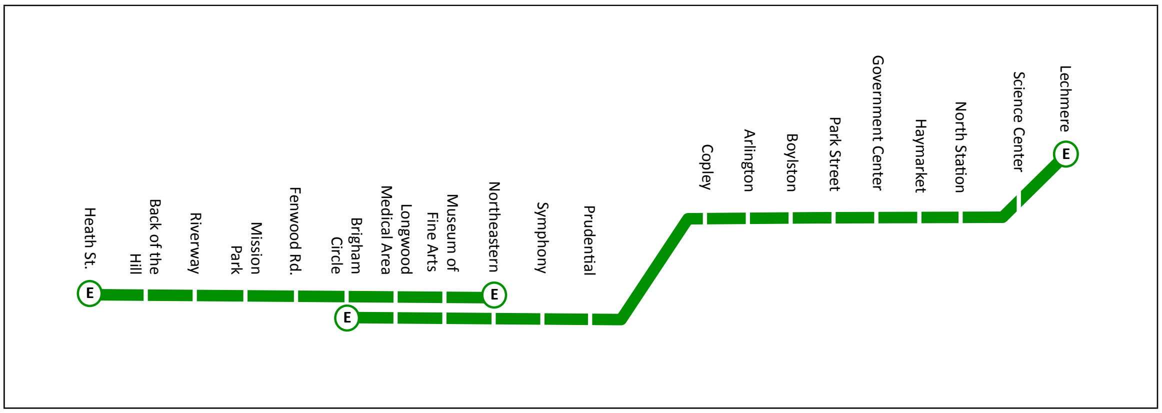

Figure 5.1: Proposed Operation on the E Branch

Furthermore, the proposed E branch scenarios are considered because, since the street running portion of the E branch creates a lot of variability in service, elimination of the street running portion from most of the service will help improve reliability for the largest number of passengers. The two segments overlap for four stations to give passengers the opportunity to transfer between the two "subroutes". As the shorter segment terminates at Northeastern, passengers traveling from stations between Heath St. and Brigham Circle to Longwood Medical Center, Museum of Fine Arts, and Northeastern University will maintain a single-seat ride.

5.2 Methodology

In the above scenarios, it is possible to estimate resources requirements and service impacts by using Equation 5.1. The estimations presented below are only meant to give an understanding of resource and scale of service level impacts upon implementation of the scenarios. The analyses for the plans are broken down by hour. However, it must be noted that changes occur within some hours, with respect to headway and fleet transitions, thus making the system more dynamic than presented below. Furthermore, there are many external variables affecting service on the Green Line, most of which are not accounted for in the analyses below due to the complexity of the interactions of these variables with each other and the Green Line.

$$TU = \frac{C_t}{h} \tag{5.1}$$

Where

$$TU = \text{Number of transit units (vehicles or train sets)}$$
$$C_t = \text{Cycle time (min)}$$
$$h = \text{headway (min)}$$

For all operating scenarios, Fall 2010 data is used, including the maximum number of rail cars in service per hour (for the fleet constrained scenarios), most common scheduled headways within each hour (for the additional services scenarios), the estimated required running and cycle times for the D branch, and scheduled running and cycle time for the E branch. Fall 2010 data was used because it represents the highest level of service, with respect to frequency, and does not have any 3-car train operations.

The assumptions made include:

1. As discussed by Lin and Wilson (Lin and Wilson, 1992), longer train sets are inherently slower than shorter train sets, since more operators need to coordinate door closure, regardless of the number of passengers boarding. Therefore, switching any 2-car train set to a 3-car train set will increase dwell time at each station by 1.5 seconds on average.

2. Resources are available to the MBTA for scenarios requiring more rail cars than operated on the D or E branches in Fall 2010.

5.2.1 Fleet Constraint Scenarios

Under the fleet constraint, the following methodology is followed:

1. Determine the maximum number of rail cars operated at each hour, starting from 5

am to 1 am.

2. From the maximum number of rail cars, determine how many 3-car train sets can be formed during the peak hours. For the D branch, Equation 5.2 is used.

$$TU_D = \frac{N_D}{3} \tag{5.2}$$

Where:

$$TU_D = \text{Number of train sets available on the D branch}$$
$$N_D = \text{Total numbers of rail cars available on the D branch}$$

The number of 3-car trains on the E branch Brigham Circle to Lechmere segment is calculated using Equation 5.3, assuming that the headways on the Brigham Circle to Lechmere and Northeastern University to Heath St. segments are the same.

$$TU_{BL} = \frac{N_E}{\frac{C_{NH}}{C_{BL}} + n} \tag{5.3}$$

Where:

$$TU_{BL} = \text{Number of train sets available on the Brigham Circle to Lechmere portion}$$
$$N_E = \text{Total numbers of rail cars available on the E branch}$$
$$C_{NH} = \text{Cycle time between Northeastern University and Heath St stations (min)}$$
$$C_{BL} = \text{Cycle time between Brigham Circle and Lechmere stations (min)}$$
$$n = \text{Number of rail cars in a train set, 3 for 3-car train set (in the peaks)}$$
$$\text{and 2 for 2-car train set (in the off-peak)}$$

The number of single cars for the Northeastern University to Heath St. segment is then calculated using Equation 5.4.

$$TU_{NH} = N_E - n \cdot TU_{BL} \tag{5.4}$$

Where:

$$TU_{NH} = \text{Number of train sets available on the Northeastern University and Heath St. portion}$$

$$N_E = \text{Total numbers of rail cars available on the E branch}$$

$$n \text{ and } TU_{BL} = \text{As defined and calculated above}$$

3. Round the number of train sets to the nearest whole number so that there is at most an increase or decrease of one rail car required.

4. At this point, there is an unrealistic assumption that 2- and 3-car trains do not operate together at any hour, even though 3-car trains cannot replace all 2-car trains in service at any given moment. 2-car trains must be somehow coupled to a third car so there must be a transition period where 2-car trains operate together with 3-car trains, therefore, the number of 2- and 3-car trains are recalculated for each hour before and after the peak periods, to reflect this transition, while keeping the fleet constrained.

5. Determine the resulting headways, using $\hat{h} = \frac{C_{2010}}{TU}$, where $\hat{h}$ is the estimated headways, C_{2010} is the scheduled E branch Fall 2010 cycle time, and TU is the maximum number of train sets operated within the hour.

6. Round headways to nearest half minute.

7. Adjust cycle times to reflect the resulting rounded headways, using $C_T = \hat{h}_{round} \cdot TU$.

5.2.2 Additional Service Scenario 2 on D Branch

The second D branch scenario maintains similar levels of service as in Fall 2010, as the headways are the same or greater by one minute compared to the minimum scheduled headways in Fall 2010. The fleet requirement for operating 3-car trains during the peak periods is calculated as follows:

1. Determine the number of train sets needed, using Equation 5.1, for operations at every hour between 5 am and 1 am, while maintaining the same or slightly increased minimum scheduled headways (same or reduced frequency) as operated in Fall 2010. The

exact frequencies were determined using judgement so as to require some additional resources, but not an unrealistic level.

2. Round the required number of trains sets.

3. Allocate all 3-car trains to peak periods, a mix of 2- and 3-car trains during each hour before and after the peak period, and all 2-car trains at all other hours.

4. Determine the additional number rail cars needed compared to Fall 2010 operations.

5. Recalculate cycle time due to rounding of train sets.

5.2.3 Partial Fleet Constraint Scenario 4 with Additional Service on E Branch

Lastly, the improved capacity scenario on the E branch has a partial fleet constraint, where the fleet is constrained on the longer Brigham Circle to Lechmere segment, which results in frequency similar to the Fall 2010 operations, and additional vehicles are added on the Northeastern University to Heath St. segment. The methodology is as follows:

1. Determine the maximum number of rail cars available for operations at every hour between 5 am and 1 am.

2. Determine the number of 2- and 3-car train sets that can be made on the Brigham Circle to Lechmere segment using the numbers from (1). 3-car train sets are calculated for the peak periods and 2-car trains during all other times. The resulting number of train sets is then rounded to the nearest whole number.

3. Add transition periods where 2- and 3-car trains operate at the same time as above.

4. Determine the resulting headways, using Equation 5.1.

5. Round headways to nearest half minute.

6. Calculate the number of single cars needed to operate on the Northeastern University to Heath St. segment, using the Fall 2010 scheduled running time between the two stations, the rounded headways from (5), and Equation 5.1.

7. Adjust the cycle times to reflect the rounded headways.

5.2.4 Passenger Capacity

For each scenario analyzed, the change in passenger throughput capacity at Boylston Station inbound is calculated, expressed as passengers per hour. The throughput capacity indicates the theoretical number of passengers that can be carried by the rail vehicles at a certain point in the system. For example, if the schedule calls for 2 minute headways in the Central Subway, then someone standing at Boylston inbound will see 30 train sets pass them, which translates to about 60 rail vehicles passing that point within that hour, assuming 2-car trains. Furthermore, if assuming MBTA's vehicle loading standard during peak periods of 101 passengers per vehicle (Webber, 2010), the theoretical passenger throughput at Boylston is about 6,000 passengers for one hour.

The capacity is estimated using Equation 5.5 and expresses the difference in the passenger throughput between the scenarios tested and Fall 2010. The vehicle capacity of 101 passengers per rail car is used.

$$\begin{aligned}
\Delta_p &= C_{Scenario} - C_{Fall2010} \\
\Delta_p &= \frac{60C_v \cdot n_{Scen}}{h_{Scen}} - \frac{60C_v \cdot n_{F10}}{h_{F10}}
\end{aligned} \tag{5.5}$$

Where:

$$\begin{aligned}
\Delta_p &= \text{Difference in passenger capacity (passengers/hr)} \\
C_{scenario} &= \text{Passenger throughput capacity in scenario (passengers/hr)} \\
C_{Fall2010} &= \text{Passenger throughput capacity in Fall 2010 (passengers/hr)} \\
C_v &= \text{Vehicle capacity (passengers/veh)} \\
n_{Scen} &= \text{Number of rail cars in train set in specific hour, in scenario} \\
h_{Scen} &= \text{Headway in specific hour, in scenario} \\
n_{F10} &= \text{Number of rail cars in train set in specific hour, in Fall 2010} \\
h_{F10} &= \text{Headway in specific hour, in Fall 2010}
\end{aligned}$$

For time periods where a mix of 2- and 3-car trains are operated, n_{Scen} is weighted by the number of 2- and 3-car trains operated.

$$n_{Scen} = \frac{N_2 \cdot 2 + N_3 \cdot 3}{N_2 + N_3} \tag{5.6}$$

Where:

n_{Scen} = Number of rail cars in train set in specific hour, in scenario

N_2 = Number of 2-car trains operated in hour

N_3 = Number of 3-car trains operated in hour

5.3 Results of Scenario Analyses

5.3.1 Scenario 1: D Branch, Fleet Constraint

Scenario 1 analyzes the headway impact on the D branch by limiting the fleet used on the branch to the number of rail cars scheduled for operation in Fall 2010. It is assumed that 3-car trains will operate during the peak hours, and 2-car trains will operate during off peak hours. Since it is difficult to change all 2-car trains to 3-car trains at a given time, there is a transition period before and after the peak hours, where a mix of 2- and 3-car trains are operated. Table 5.1 shows the results.

5.3.2 Scenario 2: D Branch, Additional Service

In Scenario 2, the operation of 3-car train during the peak period is similar to Scenario 1, but with increased capacity and slightly lower frequencies than scheduled for Fall 2010. The results are presented in Table 5.2.

Table 5.1: Scenario 1: D Branch, Fleet Constraint

Time	Estimated running time (min)	Estimated cycle time (min)	Maximum Fall 2010 rail car total	# Train sets reorganized			Possible headways (min)	Change in capacity (pass/hr)	Fall 2010 published headways (min)
				2-car trains	3-car trains	Additional rail cars needed			
5-6	70.9	79.0	14	7	0	0	11.5	-48	11.0
6-7	80.2	92.2	30	9	4	0	7.0	-426	5.0
7-8	84.9	98.7	42	0	14	0	7.0	173	5.0
8-9	91.7	103.4	42	0	14	0	7.5	0	5.0
9-10	90.0	100.9	38	7	8	0	6.5	-62	5.0
10-11	85.5	96.5	28	14	0	0	7.0	519	10.0
11-12	84.9	98.1	20	10	0	0	10.0	0	10.0
12-13	86.1	97.1	20	10	0	0	9.5	64	10.0
13-14	85.7	96.9	20	10	0	0	9.5	64	10.0
14-15	85.7	95.5	30	15	0	0	6.5	-155	6.0
15-16	88.0	98.5	40	5	10	0	6.5	62	5.0
16-17	87.5	98.3	42	0	14	0	7.0	173	5.0
17-18	90.8	102.5	42	0	14	0	7.5	0	5.0
18-19	88.2	101.5	42	0	14	0	7.0	173	5.0
19-20	85.1	97.1	34	6	7	-1	7.5	31	6.0
20-21	79.5	91.1	22	11	0	0	8.5	214	10.0
21-22	79.5	95.5	18	9	0	0	10.5	-58	10.0
22-23	78.1	87.6	14	7	0	0	12.5	-40	12.0
23-24	81.2	90.7	14	7	0	0	13.0	0	13.0
24-25	78.5	92.3	12	6	0	0	15.5	-26	15.0

Table 5.2: Scenario 2: D Branch, Additional Service

Time	Estimated running time (min)	Estimated cycle time (min)	Maximum Fall 2010 rail car total	# Train sets reorganized			Possible headways (min)	Change in capacity (pass/hr)	Fall 2010 published headways (min)
				2-car trains	3-car trains	Additional rail cars needed			
5-6	70.9	79.0	14	7	0	0	11.0	0	11.0
6-7	80.2	92.2	30	11	4	4	6.0	-135	5.0
7-8	84.9	98.7	42	0	17	9	6.0	606	5.0
8-9	91.7	103.4	42	0	17	9	6.0	606	5.0
9-10	90.0	100.9	38	10	7	3	6.0	12	5.0
10-11	85.5	96.5	28	10	0	-8	10.0	0	10.0
11-12	84.9	98.1	20	10	0	0	10.0	0	10.0
12-13	86.1	97.1	20	10	0	0	10.0	0	10.0
13-14	85.7	96.9	20	10	0	0	10.0	0	10.0
14-15	85.7	95.5	30	16	0	2	6.0	0	6.0
15-16	88.0	98.5	40	10	7	1	6.0	12	5.0
16-17	87.5	98.3	42	0	17	9	6.0	606	5.0
17-18	90.8	102.5	42	0	17	9	6.0	606	5.0
18-19	88.2	101.5	42	0	17	9	6.0	606	5.0
19-20	85.1	97.1	34	8	6	0	6.0	433	6.0
20-21	79.5	91.1	22	11	0	0	10.0	0	10.0
21-22	79.5	95.5	18	10	0	2	10.0	0	10.0
22-23	78.1	87.6	14	7	0	0	12.0	0	12.0
23-24	81.2	90.7	14	7	0	0	13.0	0	13.0
24-25	78.5	92.3	12	6	0	0	15.0	0	15.0

5.3.3 Scenario 3: E Branch, Fleet Constraint

This scenario focuses on changing to all 3-car train operations between Lechmere and Brigham Circle during peak periods (as defined above) and 2-car trains at all other times. Furthermore, a single rail car will operate between Northeastern University and Heath Street in a continuous loop and operate at approximately the same headway as the main portion of the line to allow easy transfer to the end of the line. The change in headways is shown in Table 5.3.

5.3.4 Scenario 4: E Branch, Partial Fleet Constraint with Additional Service

This variation constrains the number of trains for the Brigham to Lechmere portion to not exceed the number of rail cars operated on the E branch in Fall 2010, but extra rail cars on the Brigham Circle to Heath Street segment are added. The change in the headways and any additional required train cars for this operation are presented in Table 5.4.

5.3.5 Passenger Impact

In addition to the changes in capacity in the scenarios, current passengers on the E branch may be impacted by the segmentation of the branch. Passengers traveling from the street running portion of the E branch (including Heath St., Back of the Hill, Riverway, Mission Park, and Fenwood Road stations) to stations past Northeastern University and into Downtown Boston will have to transfer, thus making the journey less attractive. Table 5.5 shows the number of passengers boarding on the street-running portion in Fall 2010, according to the CTPS manual counts. Nearly 2,000 passengers travel beyond Fenwood Road station, the last stop on the street-running portion. However, some of those passengers may be headed to stations between Brigham Circle and Northeastern University, thus not needing to transfer. However, still about 1,900 passengers will be impacted by the change and will have to transfer in order to get to their destination. This represents a little over 16% of all passengers (11,820 total passengers) boarding on the surface portion of the E branch inbound.

On the outbound direction, 1,738 passengers travel beyond Brigham Circle, thus would have to transfer to reach their final destination if traveling from stations east of Northeast-

Table 5.3: Scenario 3: E Branch, Fleet Constraint

Time	Maximum Fall 2010 rail car total	# Train sets reorganized				Possible headways (min)	Fall 2010 published headways (min)	Change in capacity (pass/hr)	Adjusted Cycle Time, Lech-Brig (min)	Adjusted Cycle Time, NUniv-Heath (min)
		2-car trains, Brig-Lech	3-car trains, Brig-Lech	Single car, NUniv-Heath	Additional rail cars needed					
5-6	14	6	0	2	0	9.5	10.0	64	57.0	19.0
6-7	26	4	5	4	1	6.5	6.0	363	58.5	26.0
7-8	32	0	9	4	-1	7.5	5.0	0	67.5	30.0
8-9	34	0	10	4	0	8.0	6.0	253	80.0	32.0
9-10	34	4	7	4	-1	6.5	5.0	34	71.5	26.0
10-11	26	11	0	4	0	6.5	6.0	-155	71.5	26.0
11-12	20	8	0	3	-1	8.5	6.0	-594	68.0	25.5
12-13	20	8	0	3	-1	8.5	8.0	-89	68.0	25.5
13-14	22	9	0	4	0	8.0	8.0	0	72.0	32.0
14-15	24	10	0	4	0	7.5	7.0	-115	75.0	30.0
15-16	26	4	5	4	1	8.5	7.0	91	76.5	34.0
16-17	30	0	9	4	1	8.5	7.0	407	76.5	34.0
17-18	34	0	10	4	0	7.5	6.0	404	75.0	30.0
18-19	32	0	9	4	-1	8.5	6.0	119	76.5	34.0
19-20	26	3	5	4	-1	7.0	6.0	253	56.0	28.0
20-21	18	8	0	3	1	8.5	8.0	-89	68.0	25.5
21-22	12	5	0	2	0	12.0	9.0	-337	60.0	24.0
22-23	10	4	0	2	0	14.0	13.0	-67	56.0	28.0
23-24	10	4	0	2	0	13.5	13.0	-35	54.0	27.0
24-25	10	4	0	2	0	12.0	12.0	0	48.0	24.0

Table 5.4: Scenario 4: E Branch, Partial Fleet Constraint with Additional Service

Time	Cycle time: Brig-Lech (min)	Maximum Fall 2010 rail car total	# Train sets reorganized				Possible headways (min)	Fall 2010 published headways (min)	Change in capacity (pass/hr)	Adjusted cycle time: Brig-Lech (min)
			2-car trains, Brig-Lech	3-car trains, Brig-Lech	Single car, NUniv-Heath	Additional rail cars needed				
5-6	56.5	14	7	0	3	3	8.0	10.0	303	56.0
6-7	58.8	26	7	4	4	4	5.5	6.0	584	60.5
7-8	69.7	32	0	11	4	5	6.5	5.0	373	71.5
8-9	80.4	34	0	11	4	3	7.5	6.0	404	82.5
9-10	73.6	34	5	8	4	4	5.5	5.0	458	71.5
10-11	68.8	26	13	0	4	4	5.5	6.0	184	71.5
11-12	71.0	20	10	0	4	4	7.0	6.0	-289	70.0
12-13	70.6	20	10	0	4	4	7.0	8.0	216	70.0
13-14	71.0	22	11	0	4	4	6.5	8.0	350	71.5
14-15	74.0	24	12	0	4	4	6.0	7.0	289	72.0
15-16	77.1	26	4	6	4	4	7.5	7.0	369	75.0
16-17	75.0	30	0	10	4	4	7.5	7.0	693	75.0
17-18	75.6	34	0	11	5	4	7.0	6.0	577	77.0
18-19	78.8	32	0	11	5	6	7.0	6.0	577	77.0
19-20	74.9	26	4	6	4	4	7.5	6.0	81	75.0
20-21	66.5	18	9	0	3	3	7.5	8.0	101	67.5
21-22	59.8	12	6	0	2	2	10.0	9.0	-135	60.0
22-23	60.2	10	5	0	2	2	12.0	13.0	78	60.0
23-24	57.8	10	5	0	2	2	11.5	13.0	122	57.5
24-25	49.8	10	5	0	2	2	10.0	12.0	202	50.0

Table 5.5: Passenger Boarding and Alighting Counts on E Branch Inbound, Single Day in Fall 2010

Station	Ons	Offs	Volume
Heath St.	801	0	801
Back of the Hill	35	0	836
Riverway	475	9	1,302
Mission Park	506	11	1,797
Fenwood Rd.	197	68	**1,926**

ern University, although some of these passengers may be traveling from stations between Brigham Circle and Northeastern University. Table 5.6 shows the boarding and alighting passengers at Brigham Circle and all street running stations.

Table 5.6: Passenger Boarding and Alighting Counts on E Branch Outbound, Single Day in Fall 2010

Station	Ons	Offs	Volume
Brigham Circle	81	2,544	**1,738**
Fenwood Rd.	16	102	1,652
Mission Park	19	534	1,137
Riverway	8	343	802
Back of the Hill	0	54	748
Heath St.	0	748	0

5.3.6 Implications of Scenarios

The resulting headways and fleet requirement are summarized in Table 5.7. Scenarios 1 and 3 use the existing fleet to reconfigure 2-car trains into 3-car trains, which results in longer headways (lower frequency) and similar capacity levels. Scenarios 2 and 4 presented above increase capacity through addition of rail cars during the peak periods, which in turn reduces the headways (increases the frequency) of trains on the D and E branches. Both Scenarios 2 and 4 are favorable to Scenarios 1 and 3 because of increased capacity and more similar (but not the same) frequencies of service as scheduled in Fall 2010, when all 2-car trains were operated, without increasing the rail car requirement by an unreasonable amount.

Furthermore, it is important to increase capacity to continue to absorb future ridership increases that are forecast. Therefore it is recommended that the MBTA continue its trials of 3-car trains, including one or more of the operating scenarios proposed here.

5.4 Operations Management

In order for the above scenarios to work, there must be more stringent compliance with field operations management procedures. As shown by the field observations in Chapter 4, coordination for preparation for departure between three, as opposed to two, operators may delay train departures. In order to minimize any such possible delays, it will be necessary to have strict schedule adherence at terminals once the above scenarios are implemented, primarily to make sure that the delays do not propagate along the route and create bunching.

First and foremost, some of the problems with real time management is lack of information. Currently, there is no succinct way of showing the management team the service performance of a particular branch or at a particular station. With timely information, the management team is not only more informed of their service performance, but the information may also spur willingness to improve performance. This will require daily or weekly Green Line system evaluation, which in turn requires a stream lined process for AVI data analyses. Furthermore, presentation of the data is important since it has to be simple yet informative. A suggestion for how the data can be displayed at a terminal is presented in Figure 5.2.

Figure 5.2 shows the number of trips that departed from the terminal with shorter than scheduled, equal to (± 1 minute), or later than the scheduled headway. The headways are emphasized because of the desirability of headway management, as opposed to schedule management, when train departures deviate significantly from schedule. Using the headway distributions discussed in Chapter 4, the percentage of trips departing within a certain headway are expressed as trips to relay the on-time performance in a clear understandable manner. 9 out of 10 trains is chosen as a goal because this translates into 90% on-time departure performance. Furthermore, the poster contains information reminding operators to prepare for their departure well in advance to ensure that they are ready to depart on time.

The information should be displayed throughout the operator break room at the terminals, allowing all operators to see the cumulative performance of the operators at the terminal. Ultimately, however, the schedule adherence depends on the terminal staff's abil-

Table 5.7: Summary of Headway and Train Car Requirements for Scenario Testing During Peak Periods

Time	Scenario 1		Scenario 2		Scenario 3		Scenario 4	
	Achieved Headways (min)	Additional Rail Car Requirement	Achieved Headways (min)	Additional Rail Car Requirement	Achieved Headways (min)	Additional Rail Car Requirement	Achieved Headways (min)	Additional Rail Car Requirement
7-8	7.0	0	6.0	9	7.5	-1	6.5	5
8-9	7.5	0	6.0	9	8.0	0	7.5	3
16-17	7.0	0	6.0	9	8.5	1	7.5	4
17-18	7.5	0	6.0	9	7.5	0	7.0	4
18-19	7.0	0	6.0	9	8.5	-1	7.0	6

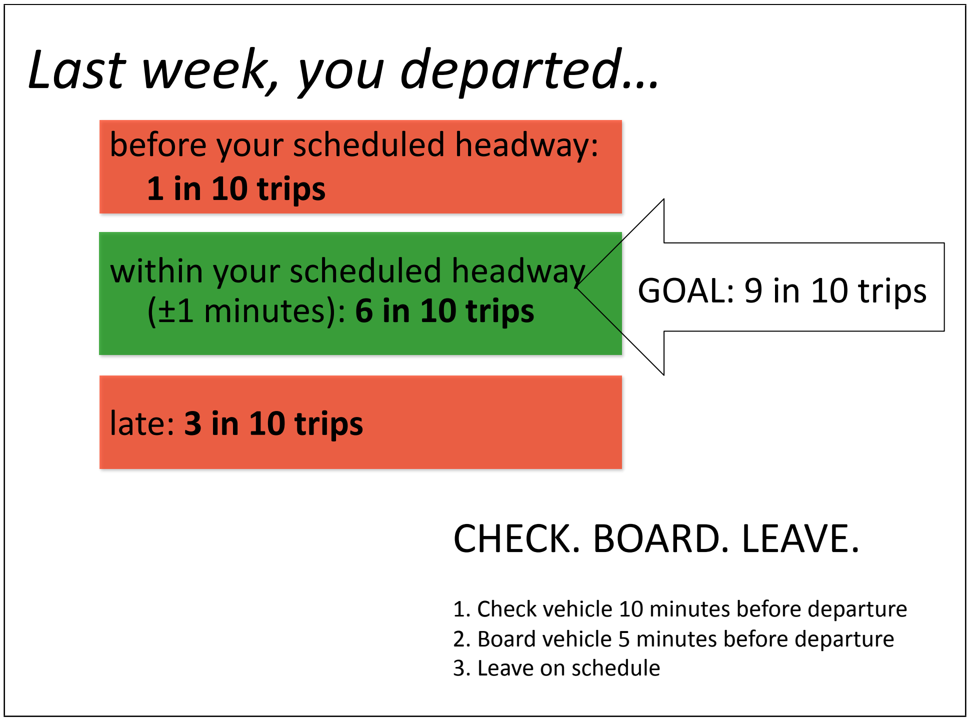

Figure 5.2: Example of Information Displayed to Operators at Terminals

ity to rally everyone to depart on schedule and ensure that the scheduled headways are adhered to. Furthermore, communicating with the operators well in advance of departure time about the assigned vehicle is also important for making sure that the operators are prepared to depart on schedule.

Second, different officials have various operations practices, at terminals or along the lines. The MBTA should identify best operational practices within its own system and apply them throughout the system where appropriate. For example, as witnessed at Lechmere, the practice of having trains wait at the departure platform improves on-time performance.

5.5 Conclusion

The tradeoffs between capacity increases and passenger service quality can be seen in the scenarios presented above. Scenario 1 proposes all 3-car train operations during the peak periods on the D branch, while not using more rail cars than operated in Fall 2010. It showed the resulting headways of reforming all 2-car trains into 3-car trains, which maintains throughput capacity at Fall 2010 levels and increases waiting time due to increased headways. However, the operations of only 3-car trains will remove the variability in the scheduled headways, as seen in Winter, Spring, and Fall 2011, thus improving the ability to practice more stringent terminal departure management.

The second scenario demonstrated the capacity increase and the additional rail car requirement on the D branch when operating service at a similar frequency as operated in Fall 2010. At most nine additional rail cars are needed to operate at the similar level of service as in Fall 2010, with 6 minute headways. This creates an additional carrying capacity of over 600 passengers on the system during the peak periods.

The third scenario splits up the E branch into two segments: a single rail car operating between Northeastern University and Heath St., and 2- or 3-car train sets operating between Brigham Circle and Lechmere. The headways are calculated for this operations scenario with the constraint that no more rail cars operate than in Fall 2010. The capacity impact is at most an additional carrying capacity of 400 passengers during the peak period, and there is a reduction in carrying capacity during the off-peak periods. Furthermore the frequency decreases (headway increases) slightly compared to those in Fall 2010.

Scenario 4 has a similar operation as in scenario 3, where the E branch is split into two segments, but there is a fleet constraint on the longer segment (Brigham Circle to Lechmere), and additional rail cars are added on the shorter segment (Northeastern University to Heath St.). This adds additional carrying capacity on the longer segment for the entire day, ranging from 100 passengers to nearly 700 passengers, and even increases frequency during the 12:00-15:00 time period, though most frequency changes are decreases.

While scenarios 1 and 3 simply even out the headways to reduce operations problems at terminals, Scenarios 2 and 4 also add throughput capacity to the peak periods. Although additional resources are needed for Scenarios 2 and 4, having additional capacity can help reduce the already crowded conditions on the Green Line, which in turn may reduce dwell times. Eventually, to accommodate the growth in passenger ridership, the goal is to increase the overall carrying capacity of the system to all 3-car trains during the peak periods, operating at similar frequencies as operated in Fall 2010.

It must be noted that although the above scenarios will create consistency of 3-car train arrivals on the surface portions of the D and E branches, there will still be variation in 2- and 3-car train arrivals in the Central Subway, therefore eliminating the opportunity for all passengers to position themselves according to the boarding location along a 3-car train.

Furthermore, the above results are theoretical. They assume that trains will be operated perfectly on schedule, which requires impeccable operations management and no influence from external factors, such as uneven passenger arrival and train malfunctions. Therefore it is necessary to take a next step and simulate these scenarios that allow for interaction of outside factors, to see how service is impacted and if capacity can really be increased.

That said, even with outside factors impacting Green Line service on a daily basis, stringent operations management is vital for improving service on the Green Line. Terminal operations must be strict because delays originating from the beginning of the route can compound over the length of the route to create more significant delays. Improving operations can be done through providing better information to the crew and supervisors at each terminal, as well as by improving required communications between officials and train operators. The information, which will be generated from AVI data, will likely require streamlining AVI data processing and improved AVI data recording.

Chapter 6

Conclusions

Transit operations often relies on the interplay between capacity and reliability: improving one may worsen the other. For example, increasing the number of vehicles operated in a system to increase capacity may actually reduce the quality of service because of longer required running times.

The MBTA Green Line is facing an estimated 100% passenger ridership growth by 2030, a rail extension into Somerville and Medford, and possible implementation of Positive Train Control, a system for increasing train safety through train control. All these factors will impact the capacity of the system negatively. Furthermore, the Green Line has many external factors, such as at-grade crossings and an outdated power system that impact its service reliability, which in turn further reduces the capacity of the system.

The MBTA introduced 3-car trains on the B and D branches in October 2010, and then on the E branch in March 2011, to increase capacity of the system, which is a necessary step to take to prepare the Green Line operations for the upcoming changes. This thesis set out to evaluate the impact of the 3-car trains on the system capacity and passenger service. Furthermore, the lessons learned from the system evaluation have been applied to develop alternative operating scenarios for the D and E branches, and provide recommendations for the Green Line system.

6.1 Research Summary

The goal of this thesis was to evaluate the Green Line with respect to carrying capacity and passenger level of service, from before 3-car train implementation in Fall 2010, to the subsequent schedule and operating plans, including 3-car train implementation, in Winter 2011, Spring 2011, and Fall 2011.

Methodology was presented for using AVI data for evaluation of the running times on the B, C, and D branches on the Green Line, which was then compared to the scheduled running and cycle times. Running time data was also used for evaluating the changes in running time between each of the seasons to understand the impact the various schedule changes had on the Green Line performance. Furthermore, AVI data was used to calculate the headways along the surface portions of the B, C, D, and E branches, which in turn was used to calculate the passenger waiting time in each of the seasons studied.

Field observations were also conducted to understand Green Line operations that were not captured by the AVI data, such as interaction between field officials, operators, and rail car activity in the rail yard. Lessons learned from the analyses were used to plan operating scenarios that better utilized 3-car trains.

6.2 Research Findings

The framework developed by this thesis showed that information from an Automatic Vehicle Identification (AVI) system can be used to evaluate the Green Line, not only for scheduling purposes but for evaluation of passenger service levels, including passenger waiting time.

6.2.1 Throughput Capacity

After the implementation of 3-car trains in October 22, 2010, the scheduled throughput capacity, measured in number of rail cars passing Boylston Street inbound in the morning peak and Boylston outbound in the evening peak, increased slightly during the PM peak, though remained the same during the morning peak. However, the actual capacity during the same time periods, as calculated using AVI data, shows that the throughput capacity actually decreased during the evening peak and remained constant during the morning peak, as compared to the actual capacity available before 3-car trains were introduced. This suggests that attempting to increase throughput by scheduling more car throughput actually decreased throughput because of the slower speed required for trains traveling so close to each other. This may be because of inadequate schedule management, inadequate increase in scheduled capacity, or both.

6.2.2 Running and Cycle Times

The analyses of the running and cycle time from before and after the addition of 3-car trains show that the schedules on the B and C branches could be adjusted to better reflect the actual train performance on these respective branches. Adjustment of cycle times on each of the branches could result in a savings of one or two train car sets each, or alternatively, an increase in frequency.

Furthermore, the analyses showed that from Fall 2010 to the subsequent seasons, the running times had increased on the D branch throughout the day, increased during the peak periods on the C branch, and decreased throughout the day on the B branch. The increases in running time on the C branch only during the peak periods were surprising, since there were no scheduled or known operational changes on that branch, and no 3-car trains were operated on the branch. Upon closer examination, the running time for the C branch increased solely in the Central Subway, but remained constant on the surface portion, which suggests that the C branch performance is impacted by the interaction with the other branches, specifically 3-car trains on those branches, since the increases in running time occur only during the times that 3-car trains are operated.

Furthermore the decreases in running time on the B branch occurred only on the surface portion, though remained constant or increased in the Central Subway, both of which can also be explained by the implementation of 3-car trains. The decreases are most likely attributed to the all-door boarding practices and consistent stopping locations of the trains on the B branch.

The overall conclusion is that 3-car trains slowed down service in the Central Subway, and thus increased running times in that segment, most likely due to the variation in arrival of 2- and 3-car trains, which in turn impacted the boarding behavior of passengers and thus increased the dwell time.

6.2.3 Headway Analyses

The headway analyses showed that passenger waiting time increased on the B, C, and D branches after the introduction of 3-car trains, with the exception of the PM peak period on the B branch, which had slight decreases in the passenger waiting time from Fall 2010 to Fall 2011. The passenger waiting time did not change much on the E branch. The changes in the passenger waiting times are a result of the schedule changes, which increased the average passenger headways on the B and D branches, though there was also greater variability in the headways, which contributed to the increases. Although the increases in passenger waiting time were limited to half a minute in most cases, it is important to note that in general, waiting time outside the vehicle is considered at least twice as onerous as in-vehicle travel time, thus any increases in waiting time will be widely felt. The longer scheduled headways, and greater variability in both the scheduled and actual headways then had noticeable effects on passengers. Reducing the headways, as well as making them more uniform, will result in shorter passenger waiting time, and thus improved passenger service.

6.2.4 Field Observations

Two sites were observed over three field visits: Riverside Terminal at the end of the D branch, and Lechmere terminal at the end of the E branch. It was found that the scheduled departure and headway adherence was better at Lechmere compared to Riverside. The changes in the adherence were most likely a result of the differences in operations management practices at the two terminals and differences in the variability in scheduled headways: the D branch had 3-car trains scheduled more frequently than the E branch. Furthermore, operations at Lechmere allowed next-to-depart trains to sit at the departure platform while accepting passengers on board until scheduled departure time, while the trains at Riverside Terminal were pulled into the station shortly before scheduled departure. Allowing trains to wait at the platform eliminates the variability of dwell time due to waiting for a surge of passengers boarding at the terminal station, and ensures that operators and the train are prepared for departure.

Having stringent control practices at terminals is important for overall service since any small delays or schedule deviations at the terminal are often compounded to become significant delays further down the route. Thus as many deviations as possible should be eliminated at the time of terminal departure.

6.2.5 Scenario Planning

In order to prepare for increasing ridership and major project completions, the MBTA will have to continue developing scenarios to implement 3-car trains, as that may be the most feasible method of improving the Green Line capacity. It was concluded that further 3-car train operation scenarios should be developed and tested, in particular scenarios where all 3-car trains are operated on a branch during the peak periods, as having consistent 3-car train arrivals with uniform headways will allow randomly arriving passengers to position themselves on the platform for 3-car train boarding locations.

Possible scenarios proposed include operating all 3-car trains during the peak periods on the D and E branches, and 2-car trains on the other branches. D branch 3-car trains will operate on the current D branch route, while the E branch was split into two segments, with 2- or 3-car trains operating between Brigham Circle and Lechmere, and a single rail car operating between Heath St. and Northeastern University. For each branch, headways and fleet requirement were calculated for two alternatives, where one alternative preserved the available resources used in Fall 2010, when all 2-car trains were operated, and another where additional resources were added to increase peak period capacity.

It was found that by increasing the rail car requirement by nine vehicles, theoretically, about 600 extra persons per hour can be accommodated on the D branch, and about 500 extra persons per hour can be accommodated on the E branch with 4 extra rail cars. Both of these increases improve capacity while maintaining a train frequency similar to but slightly less frequent than Fall 2010 levels.

6.2.6 Recommendations

The analyses provided in this thesis indicate opportunities for improving the passenger service and capacity, and provides a start in preparing the Green Line to accommodate the foreseeable changes, including increasing ridership and the Green Line Extension to Somerville. The following recommendations outline the short-term next steps needed to prepare for these changes on the Green Line.

The recommendation are split into two categories: those that may help the MBTA with managing its system and improving operations, and those intended to help the increase passenger capacity. The first set of recommendation listed applies to improving service:

1. More AVI points should be placed throughout the system, especially on the surface portion, to allow the MBTA to gather better information about the Green Line and do more thorough analyses, as is done for the other heavy rail lines. While this thesis attempted to evaluate the entire system for four different time periods, some

segments of the Green Line were impossible to evaluate because of missing AVI data and not enough AVI locations. Having a higher AVI resolution will help the MBTA better evaluate the Green Line, and in turn identify problems on the Line that need most improvement, analyze impacts of various schedule changes, and isolate most problematic areas of the Green Line in need of capital improvements.

2. With an improvement in Green Line tracking data, a method for data processing should be established to provide regular reports of the Green Line performance, such as on-time performance, headway variability and passenger waiting time, and running times. The process could be automated and posted regularly to allow for easier access by all Green Line staff.

3. Since terminal schedule adherence is extremely important for the performance of a train along its route, having strict schedule adherence at terminals through stringent departure management is important. Having information about the cumulative performance of the operators at a terminal is important to encourage operators to improve, often through unstated peer pressure. The MBTA might even consider sponsoring friendly on-time performance competitions among the various Green Line branches.

4. At terminals, when train departures start to deviate too much from schedule, headway management should instead be implemented, especially during peak hours. It is understandable that problems arise at terminals that cause difficulties in adhering to scheduled departure times. However, by forcing trains to get back on schedule by sending them with headways that are shorter or longer than the scheduled headways, the terminal management ensures that trains will become bunched further along the route, as demonstrated in Figure 4.42 on page 99.

5. Trains departing from terminals should wait at the departing platform to ensure a more timely departure, by allowing passengers to board before scheduled departure, and ensuring that the train operators are ready to depart on time.

6. The power system should be upgraded as soon as possible. A weak and unstable power system significantly impacts the capacity of the system, as pointed out by Kittelson & Associates, Inc. et al. (2003). The ability to increase the Green Line passenger capacity hinges on the power system's ability to handle additional rail cars.

Suggestions intended for improving passenger capacity include:

1. Continue operating 3-car trains in service, though consider operating all 3-car trains on one or two branches at slightly lower uniform frequencies as scheduled during Fall 2010, as outlined in Scenarios 2 and 4 in Chapter 5. Operating all 3-car trains on just one branch will further spread out the arrival of 3-car trains in the Central Subway (as opposed to having the probability of two 3-car trains arriving into the Central Subway at the same time from two different branches), where there is the greatest concern over the total number of rail cars operating within one sector at a time.

2. Until power reliability can be improved so far as 3-car trains can be operated on all branches, passengers should be given better information about the consist size of the next arriving train in the Central Subway, for example, through larger "3-car train" signs. Furthermore, the train stopping location should be consistent among all 2-car trains and among all 3-car trains.

3. The coupling and uncoupling of trains in service should be considered. As done previously on the San Francisco MUNI light rail system, trains can couple at major junction points to allow higher throughput in the Central Subway (through longer train consists), while eliminating excess resources on the surface portions of the branches. This will further the goal of operating only 3-car, or even 4-car, trains consistently within the Central Subway.

6.3 Future Research

While this thesis analyzed recent changes on the Green Line, there are various ways in which this work can be expanded. This thesis is intended to be the first in a series of research to be done on the Green Line to accommodate ridership growth and the Green Line Extension into Somerville and Medford. These are the proposed recommendations for future work:

- The most obvious recommendation for future research on the Green Line is to look at medium- and long-term improvements and changes needed on the Green Line, including which infrastructure changes are needed most, which fare payment policies will result in greatest time savings, and further studies of operations, including operating scenarios for the Green Line extension.

- Operations planning research should focus on simulating the scenarios presented in this thesis. The scenarios presented are only hypothetical thus do not include the variability in running and dwell time times, nor the impact of external factors, such as traffic, variation in operator performance, and operations management along the route. By simulating the scenarios, the impacts of the external factors will be identifiable. Furthermore, it is also important to implement the trials and monitor their outcome. Monitoring should include AVI data analyses and qualitative evidence from operators, officials, and passengers.

- A study should be completed on the best alternatives for operating plans focusing on coupling and uncoupling rail cars in service, as was done on the San Francisco MUNI.

- Additional operations research must be done on the E branch, as no full running times could be calculated for the branch. Evaluation of the E branch using manual observations or AVI data, if the AVI points are added to the branch, would help improve the E branch schedule and assessment of its service.

- Any future Green Line changes in operations must be monitored and evaluated. The implementation of the suggested trials will allow isolation of the causes associated with worsening or improvement of service, since the variability of operating 2- and 3-car trains at the same time will be eliminated. The analyses will help the MBTA further refine their operations, especially since consequences of operating all 3-car trains on a branch are not known. Furthermore, for any operations, passenger impact must be examined, including the number of passengers impacted positively and negatively by various operational changes.

- Since the new rail vehicle is important for the operations of the Green Line in the extension as well as accommodating increasing ridership demand, it is important to understand the impacts of various Green Line vehicle designs. These various designs should be incorporated into future operating plan studies.

Appendix A

Headway Distributions on B, C, D, and E Branches

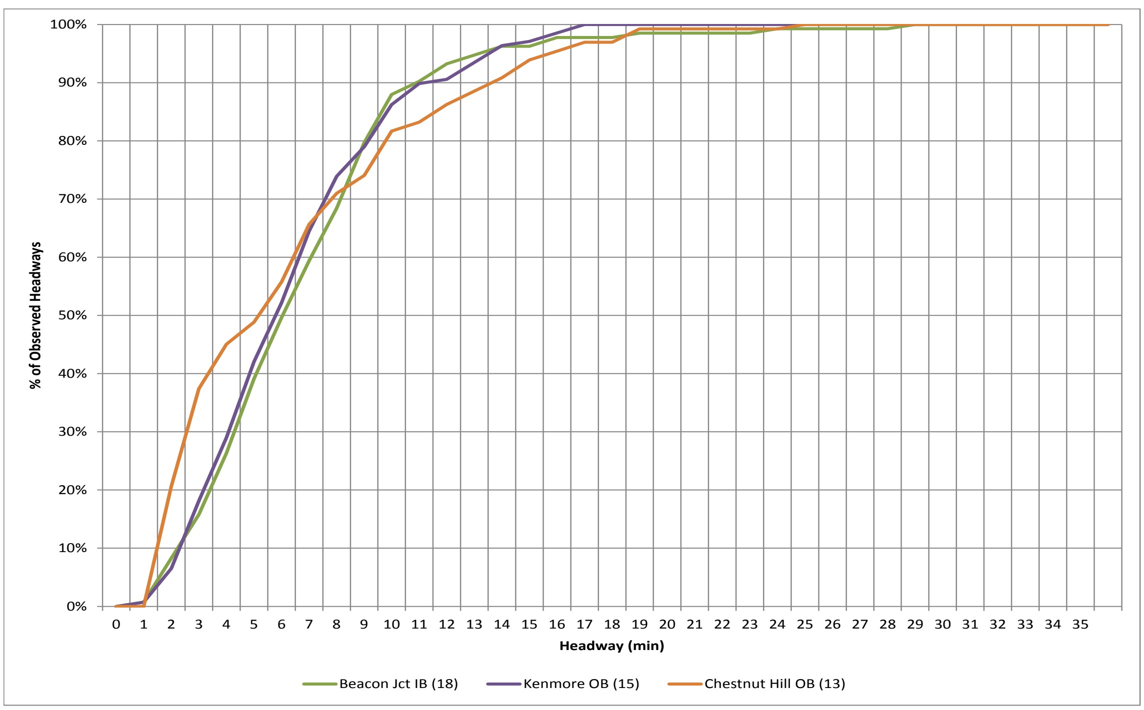

Figure A.1: B Branch Headways, AM Peak (Winter)

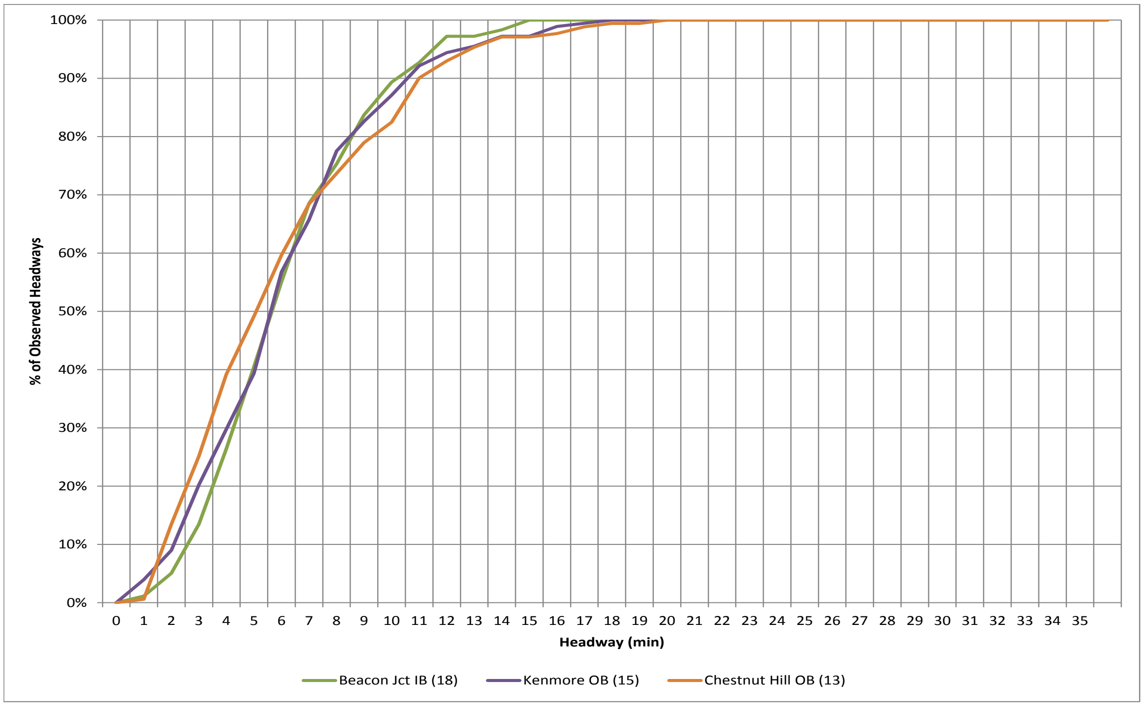

Figure A.2: B Branch Headways, AM Peak (Spring)

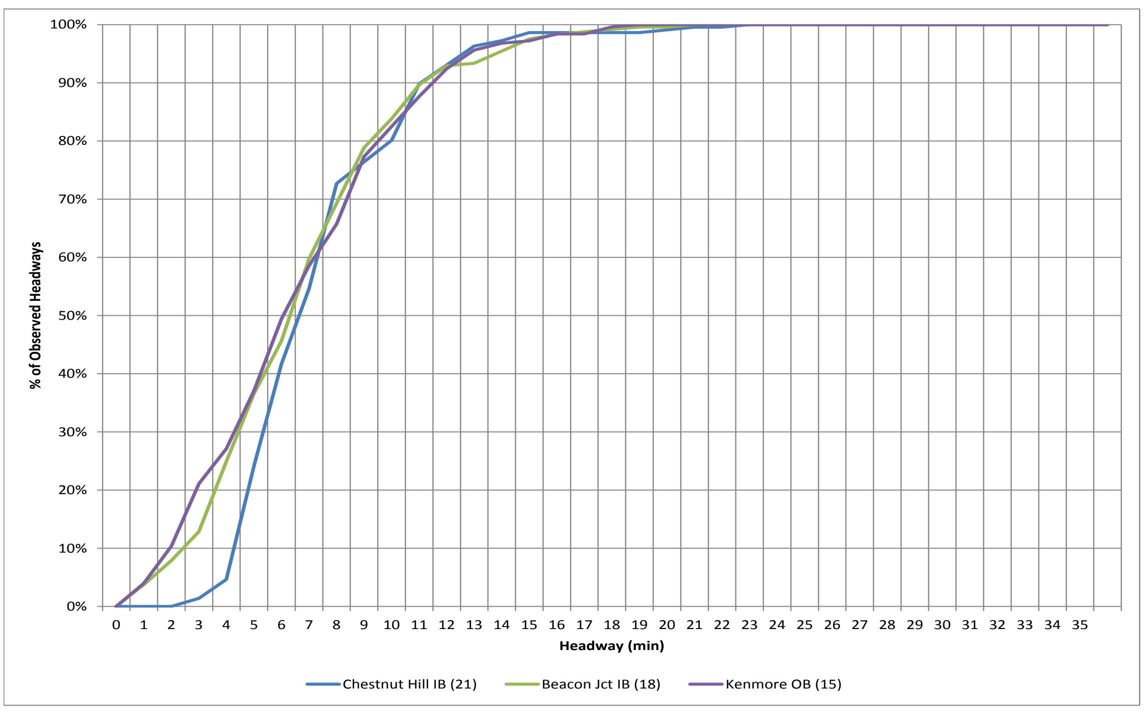

Figure A.3: B Branch Headways, AM Peak (Sept.-Oct. 2011)

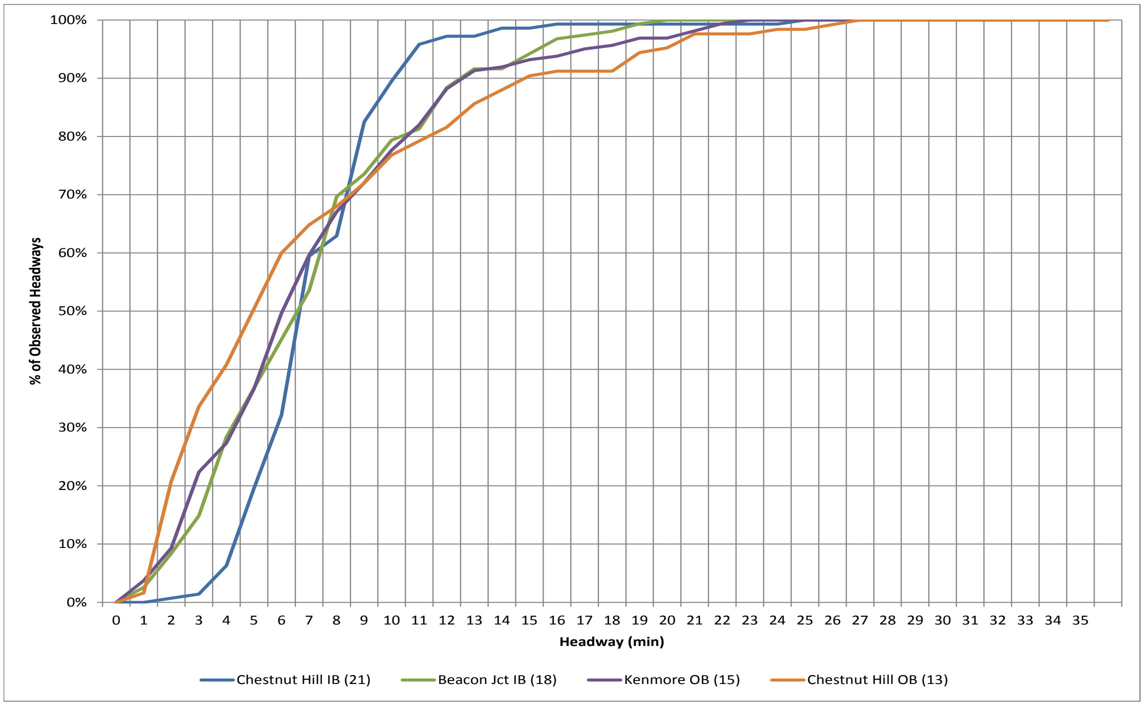

Figure A.4: B Branch Headways, PM Peak (Winter)

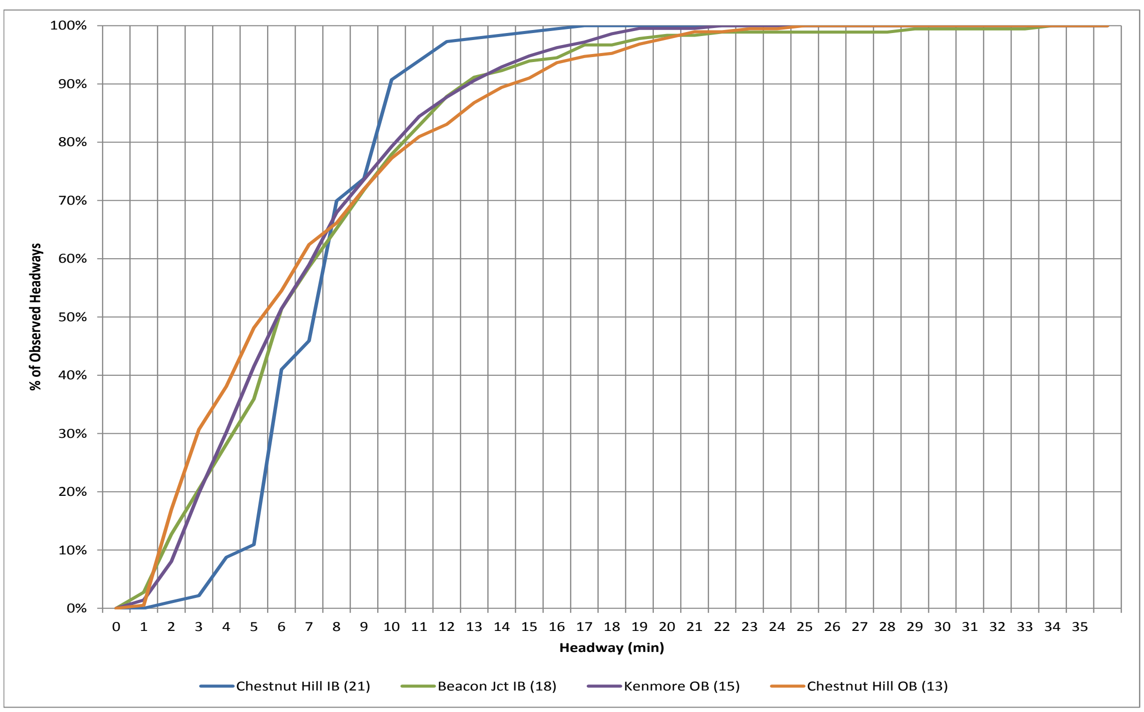

Figure A.5: B Branch Headways, PM Peak (Spring)

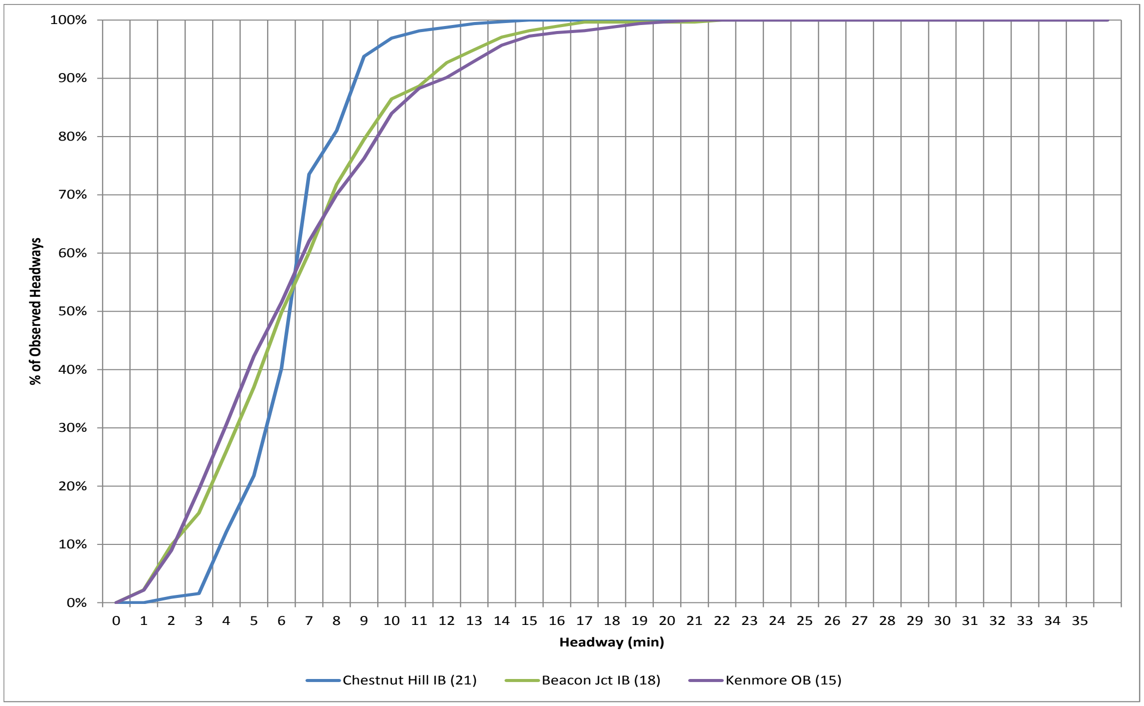

Figure A.6: B Branch Headways, PM Peak (Sept.-Oct. 2011)

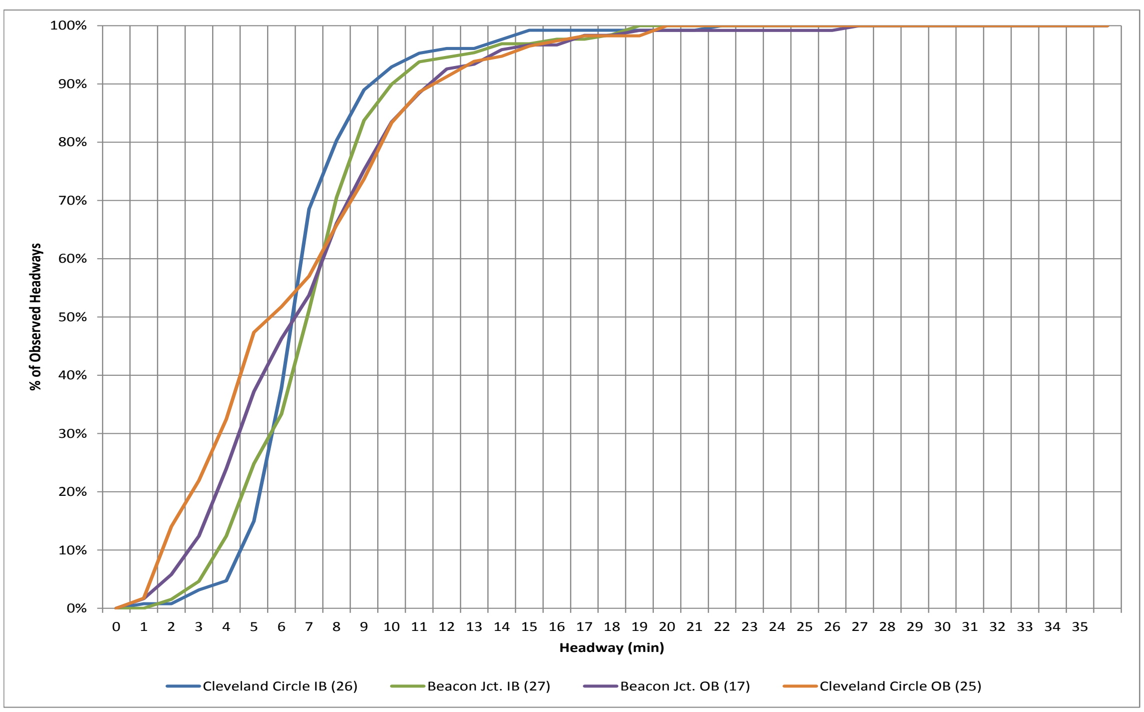

Figure A.7: C Branch Headways, AM Peak (Winter)

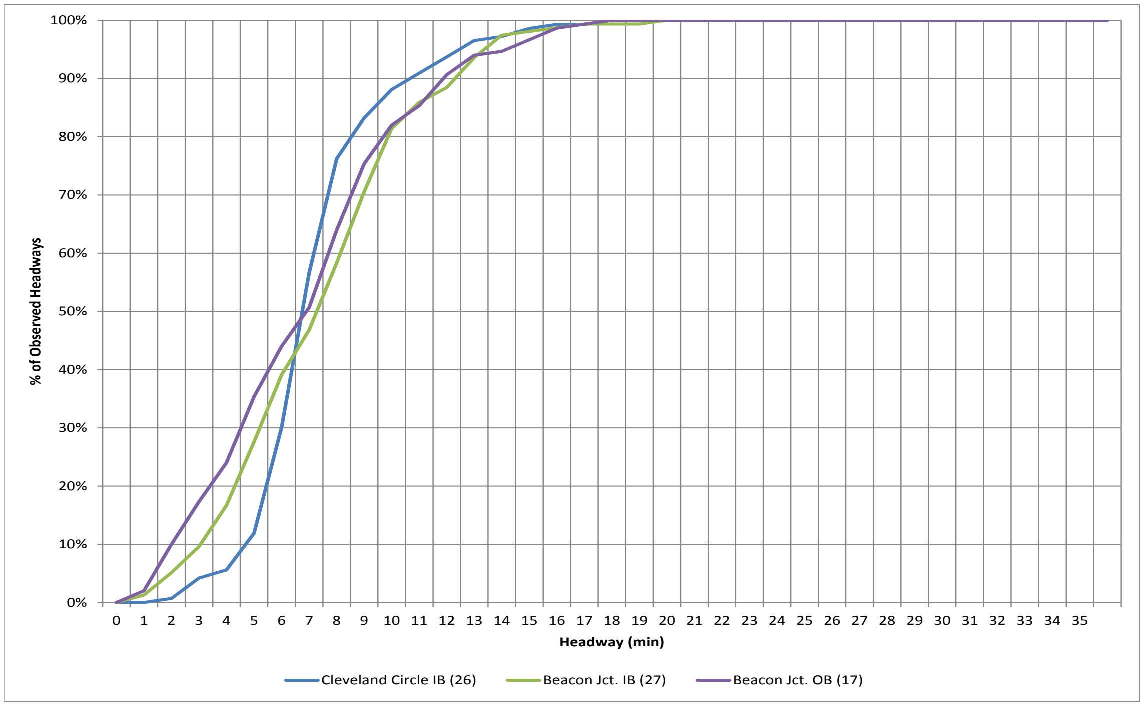

Figure A.8: C Branch Headways, AM Peak (Spring)

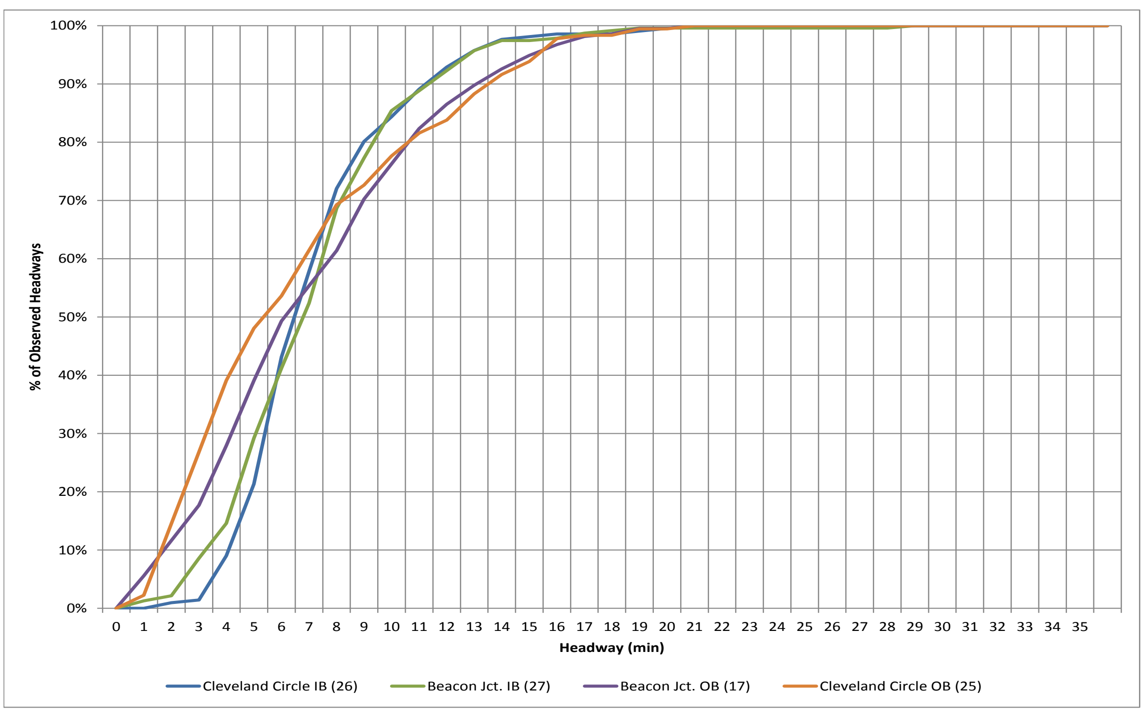

Figure A.9: C Branch Headways, AM Peak (Sept.-Oct. 2011)

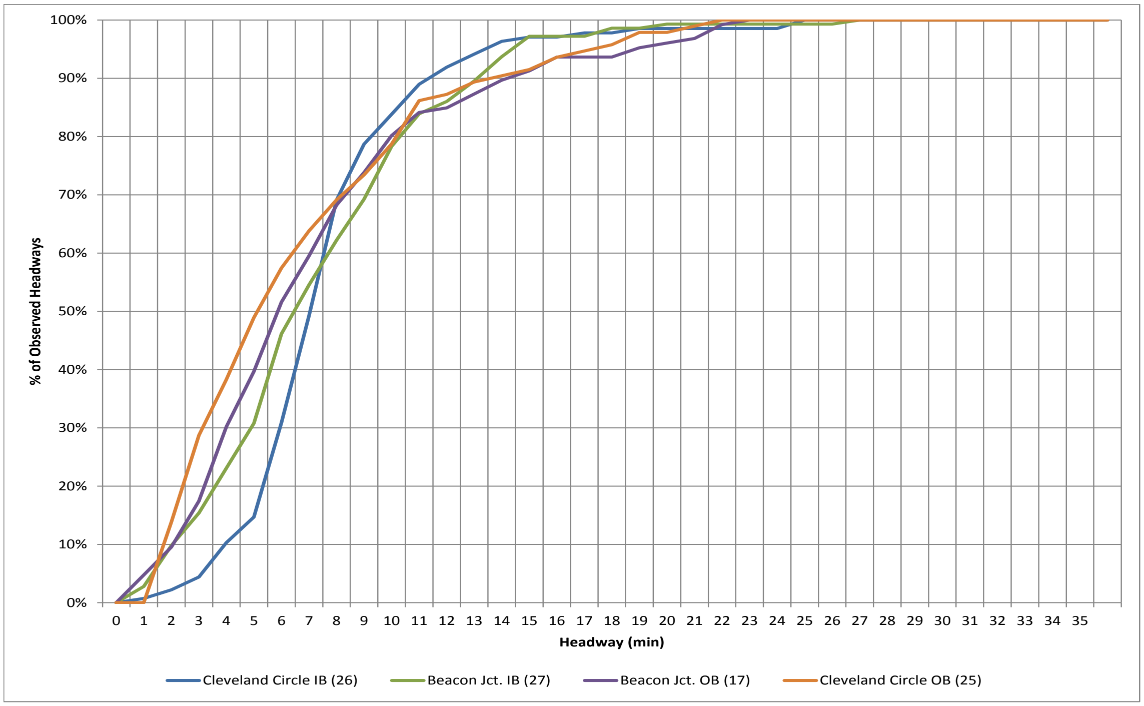

Figure A.10: C Branch Headways, PM Peak (Winter)

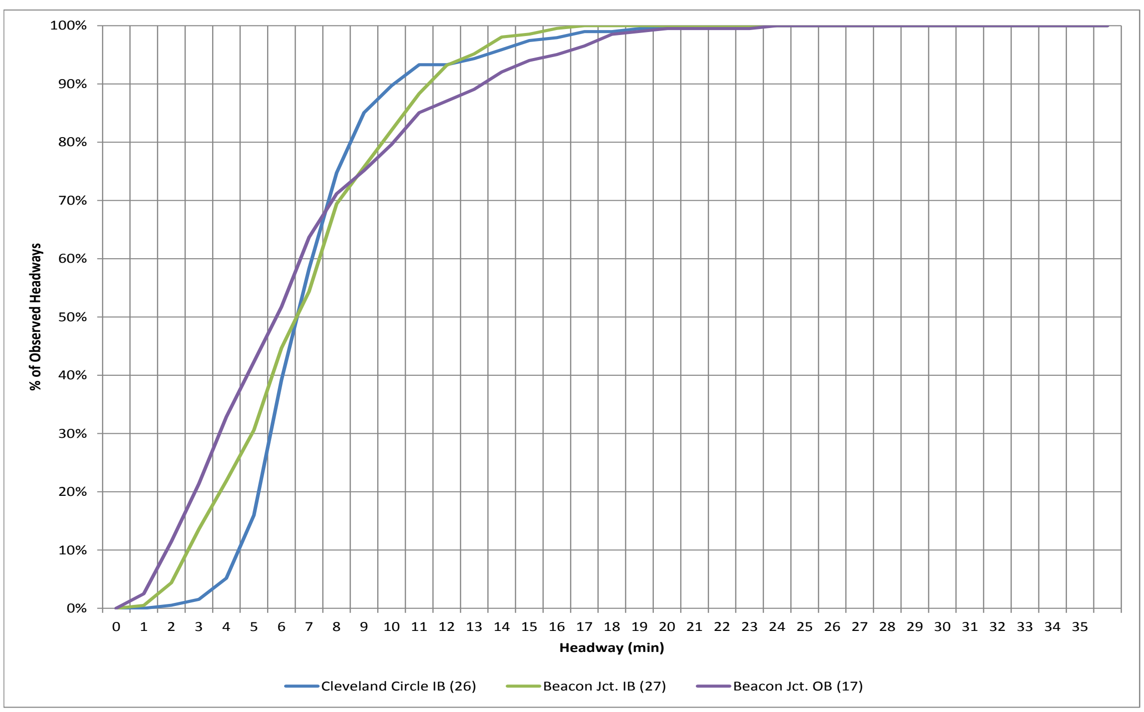

Figure A.11: C Branch Headways, PM Peak (Spring)

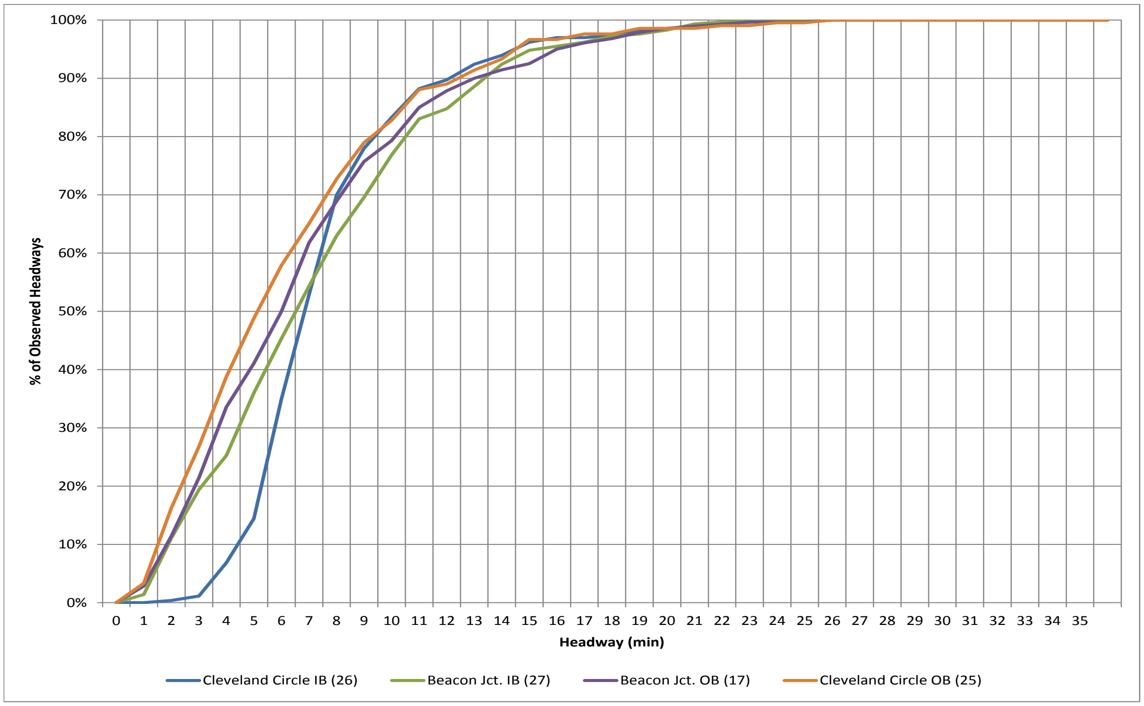

Figure A.12: C Branch Headways, PM Peak (Sept.-Oct. 2011)

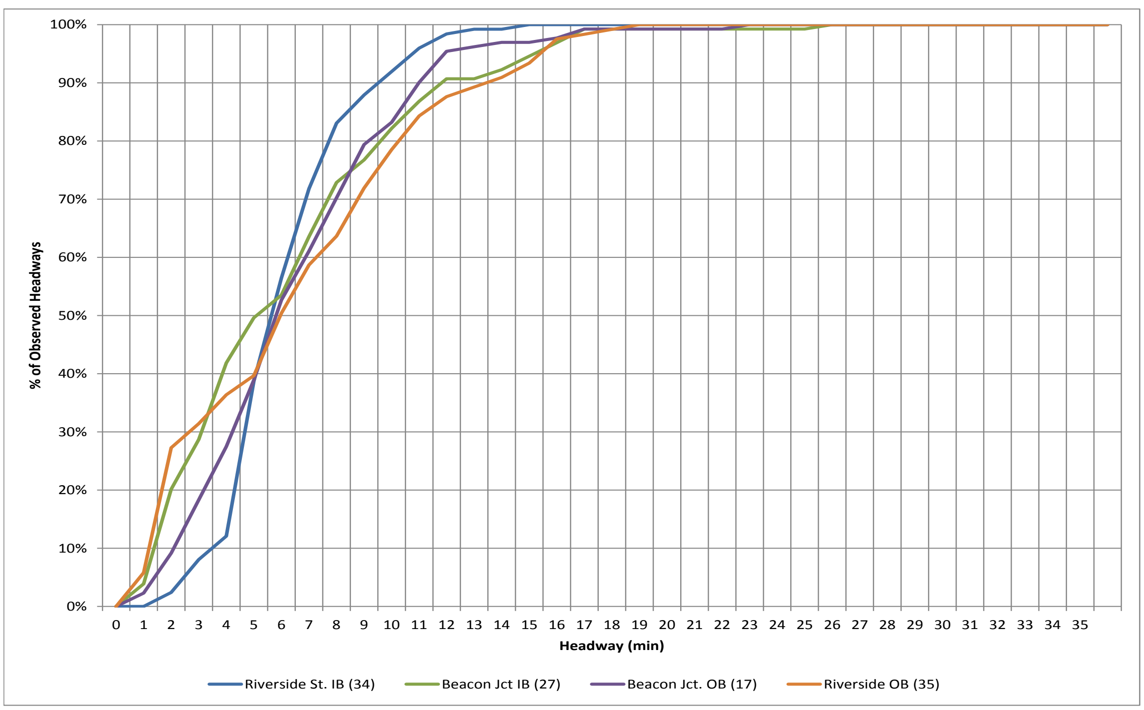

Figure A.13: D Branch Headways, AM Peak (Winter)

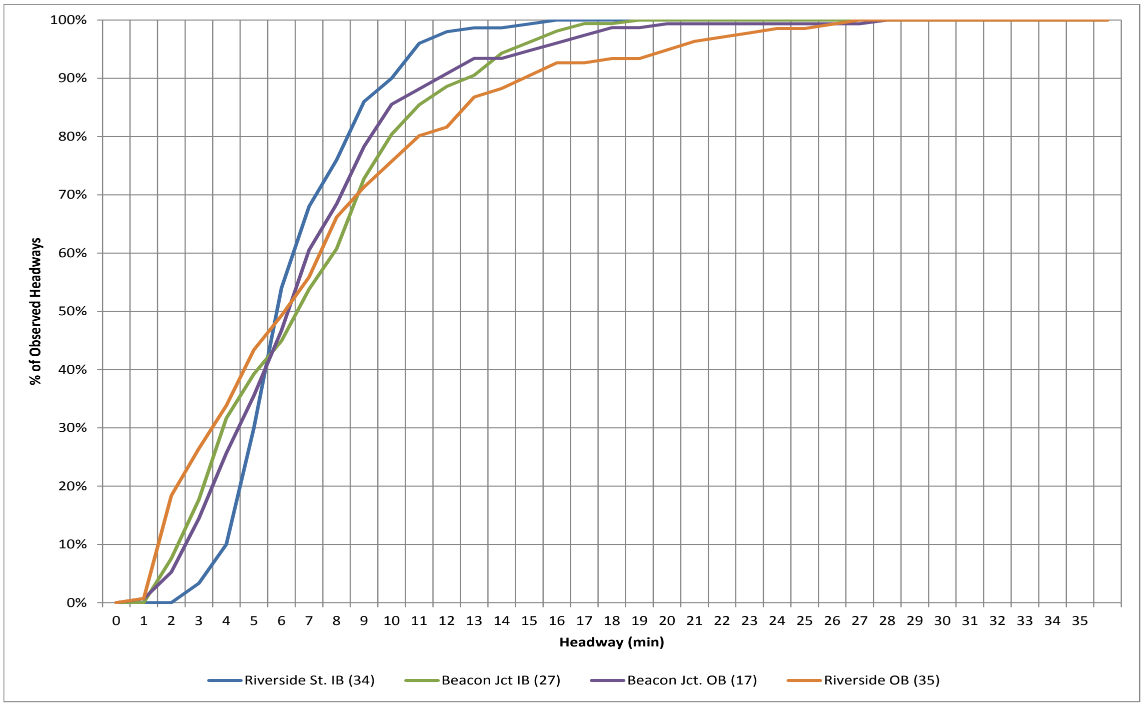

Figure A.14: D Branch Headways, AM Peak (Spring)

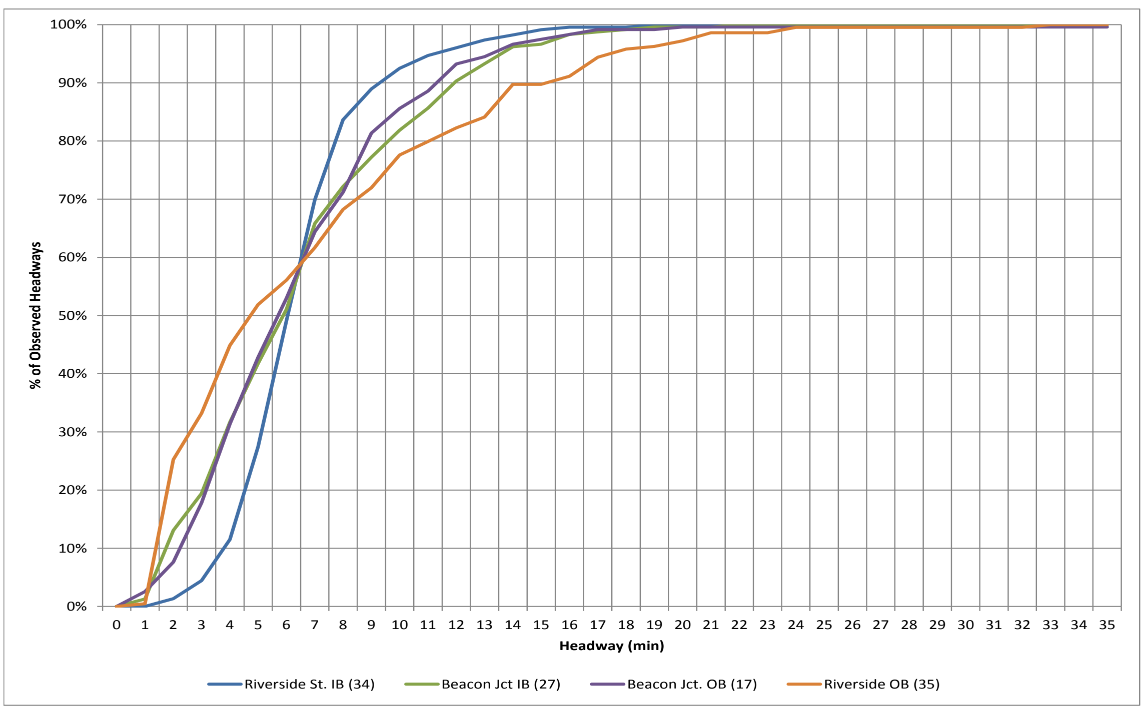

Figure A.15: D Branch Headways, AM Peak (Sept.-Oct. 2011)

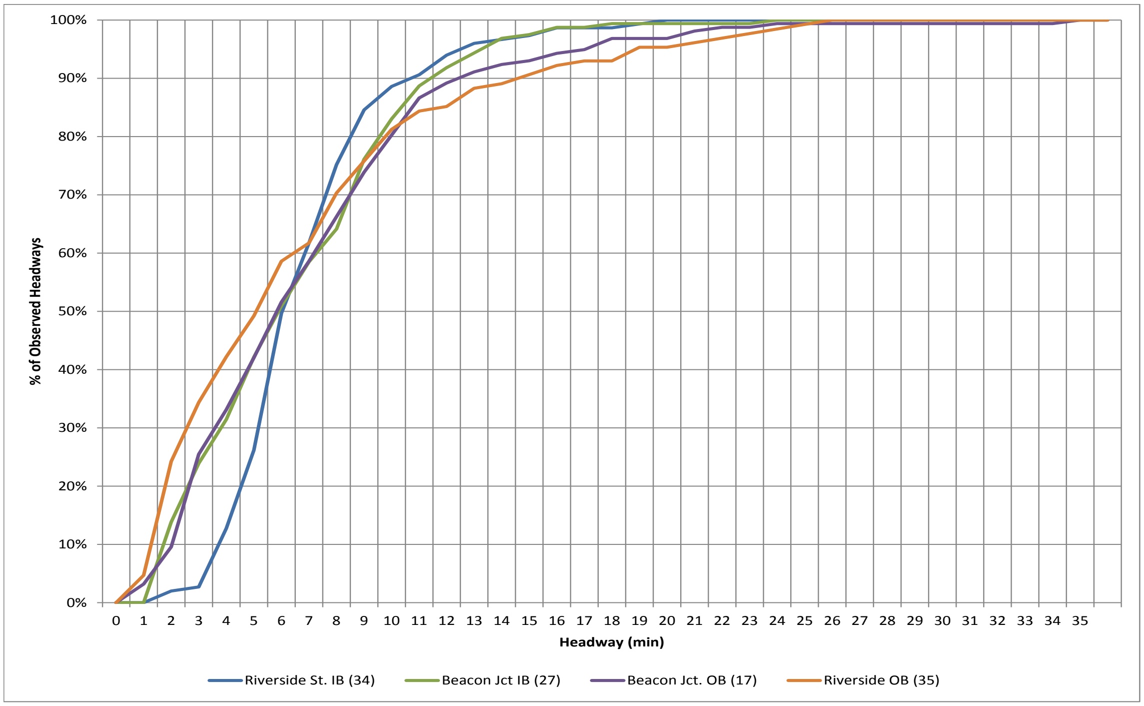

Figure A.16: D Branch Headways, PM Peak (Winter)

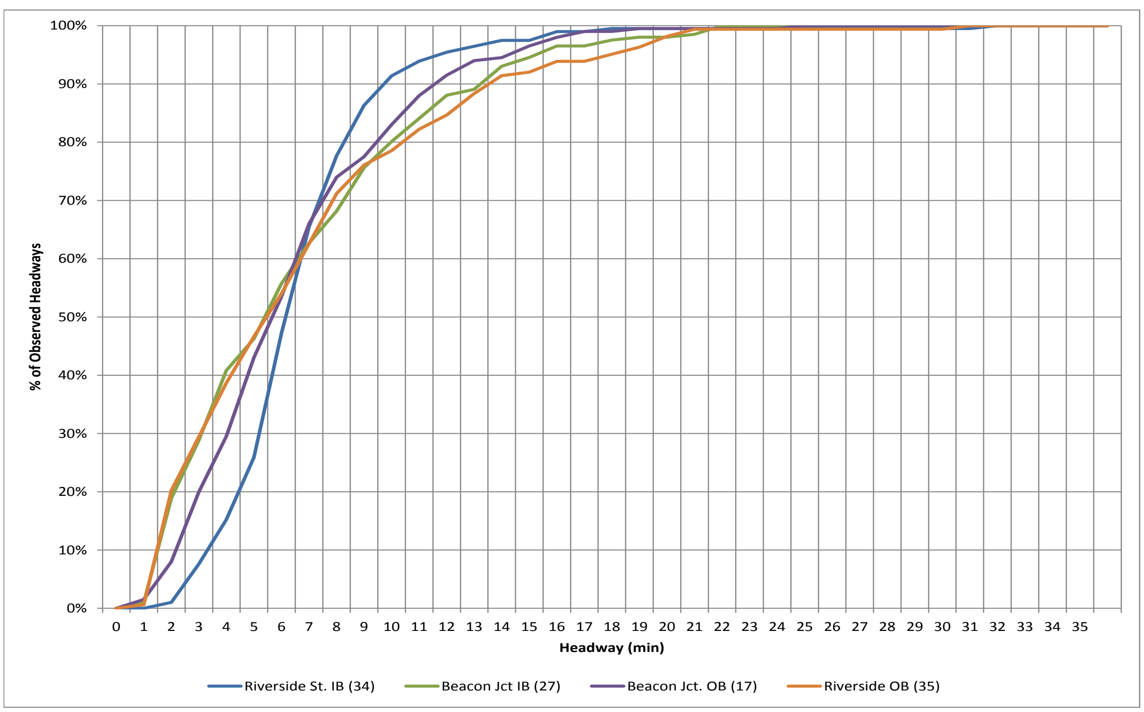

Figure A.17: D Branch Headways, PM Peak (Spring)

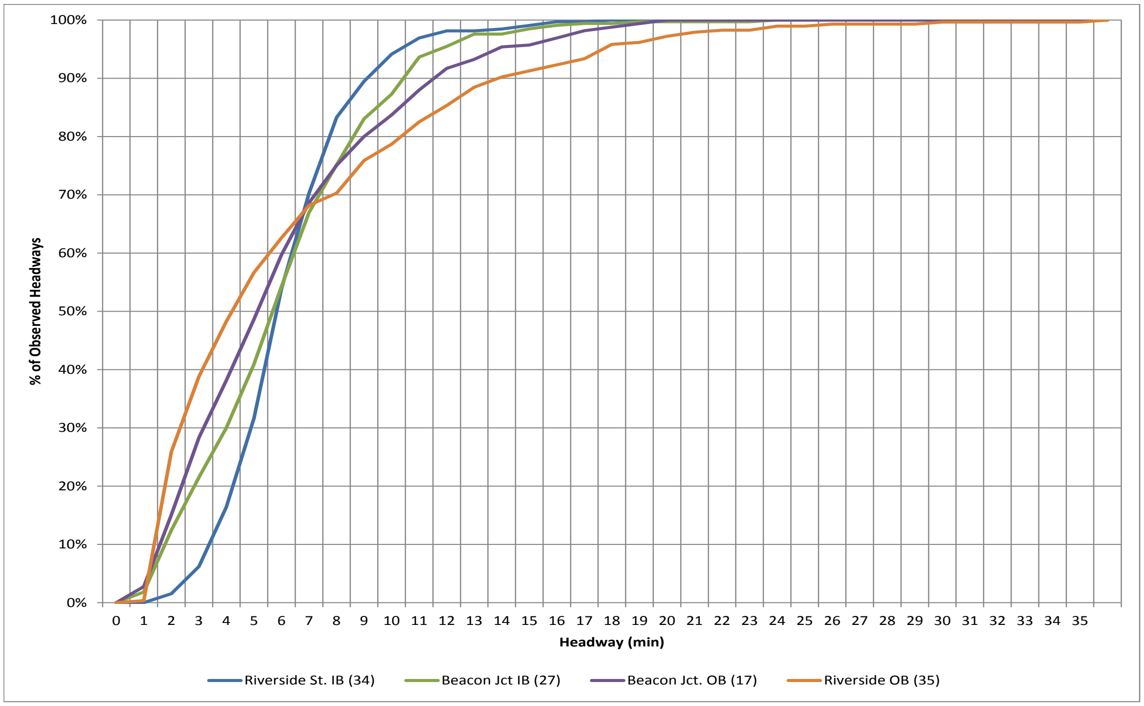

Figure A.18: D Branch Headways, PM Peak (Sept.-Oct. 2011)

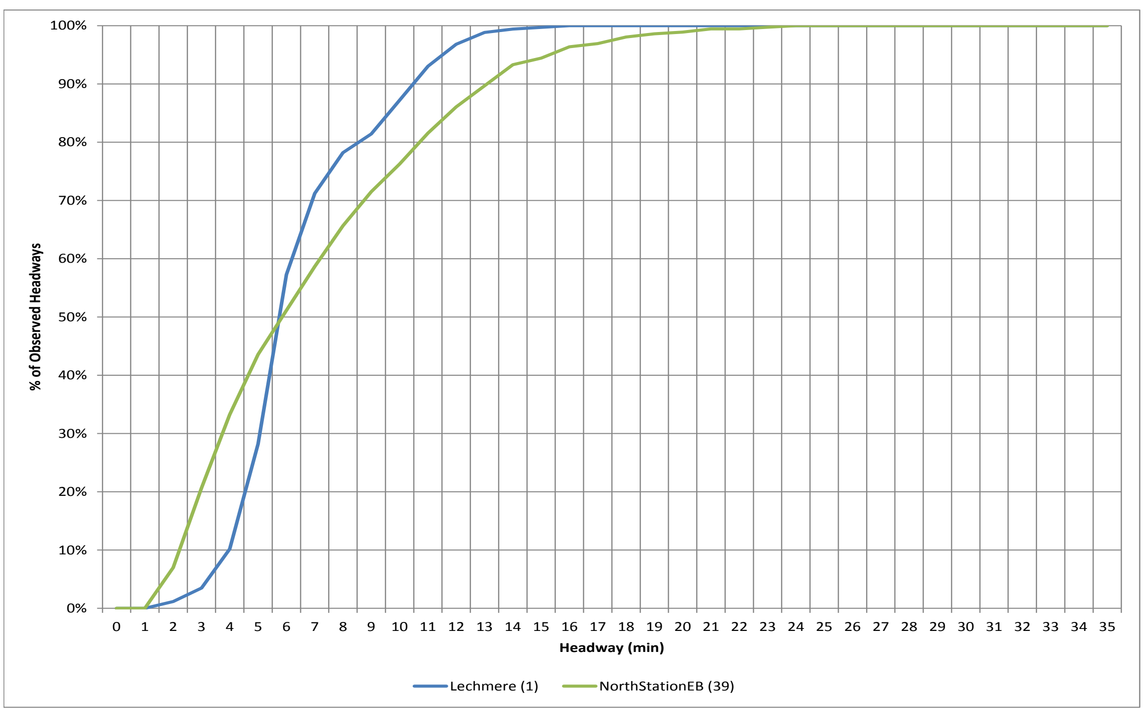

Figure A.19: E Branch Headways, AM Peak (Sept.-Oct. 2010)

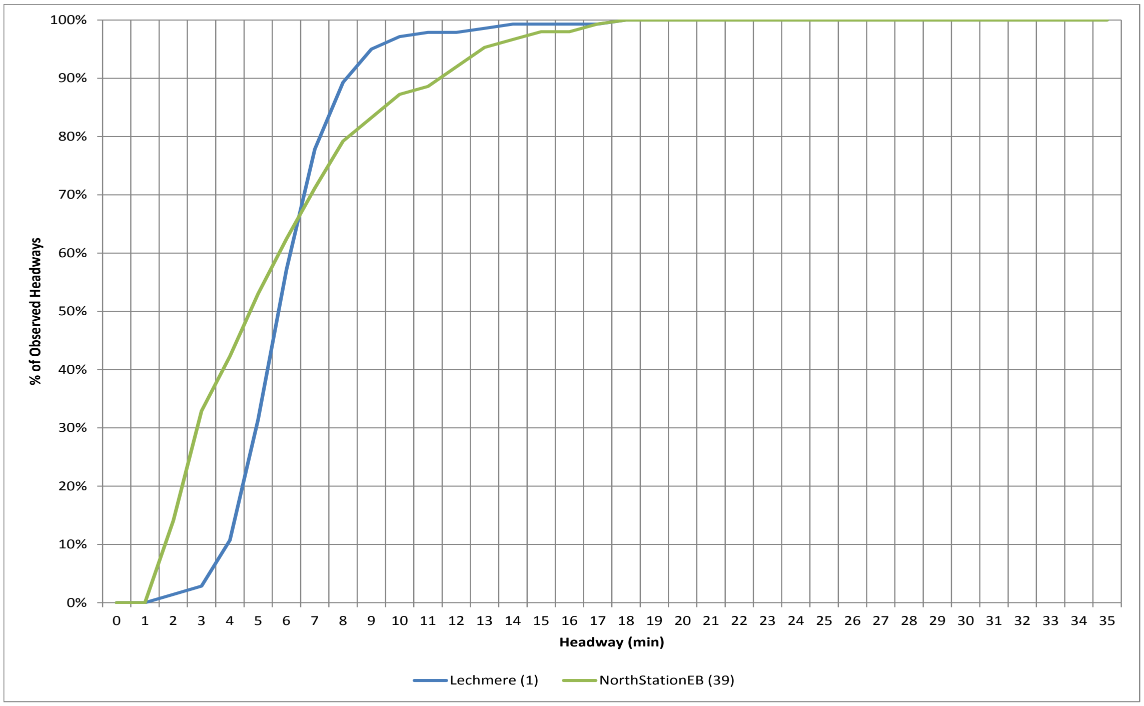

Figure A.20: E Branch Headways, AM Peak (Winter)

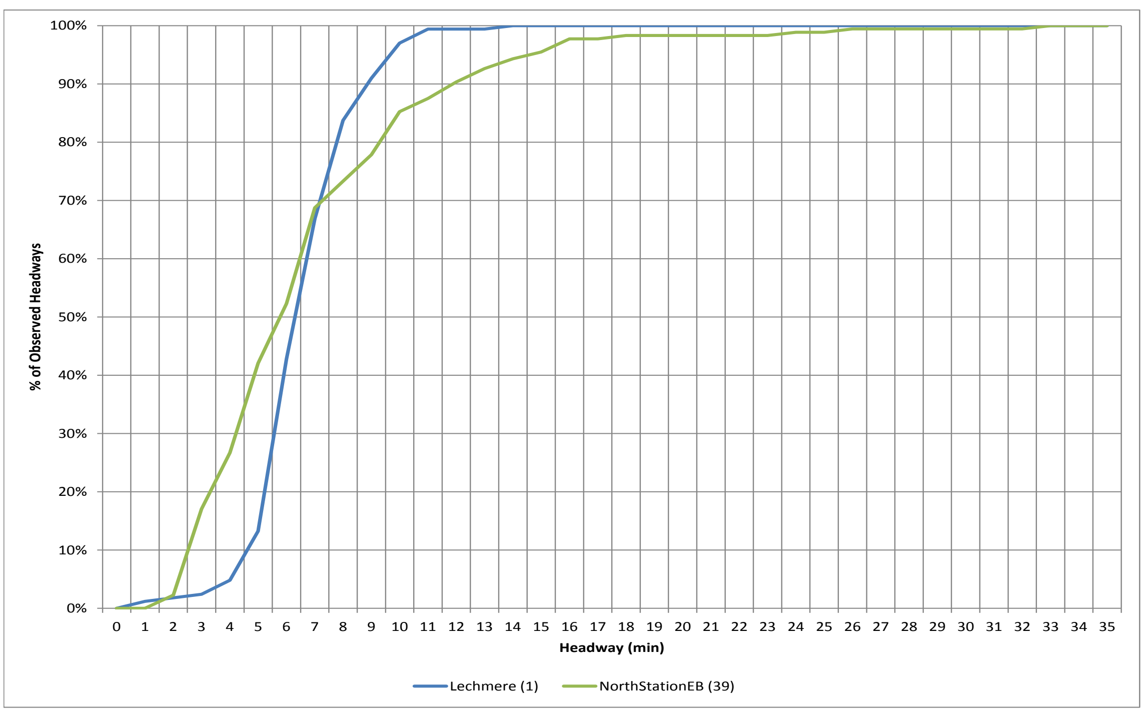

Figure A.21: D Branch Headways, AM Peak (Spring)

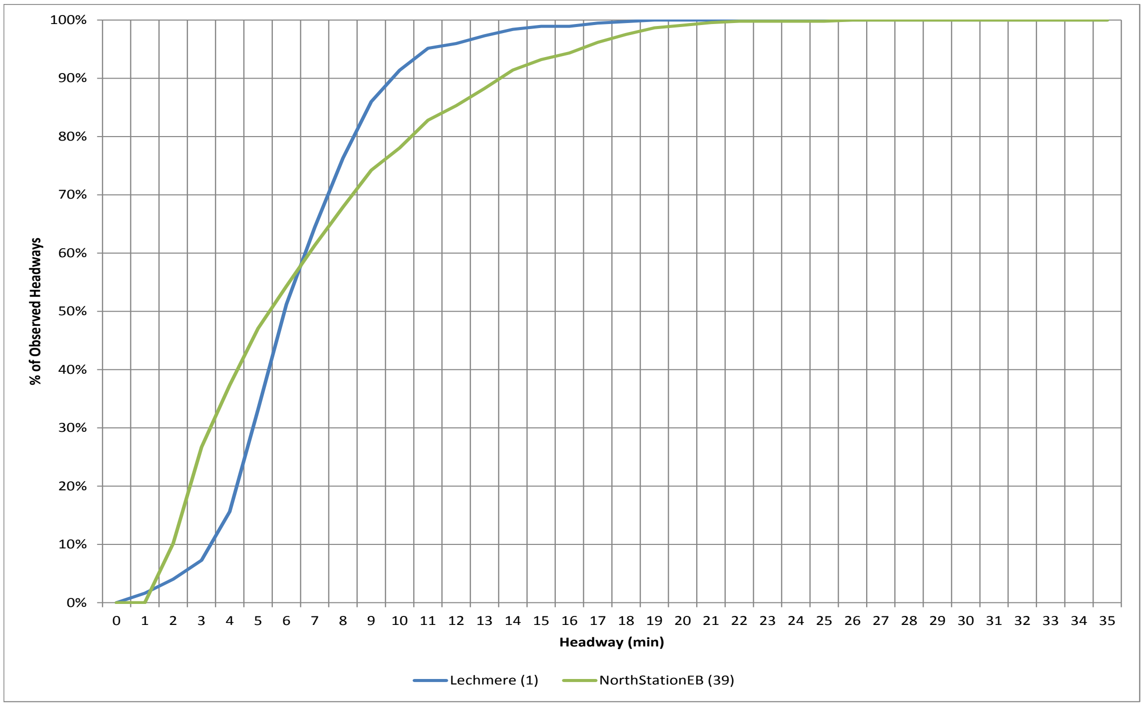

Figure A.22: E Branch Headways, PM Peak (Sept.-Oct. 2010)

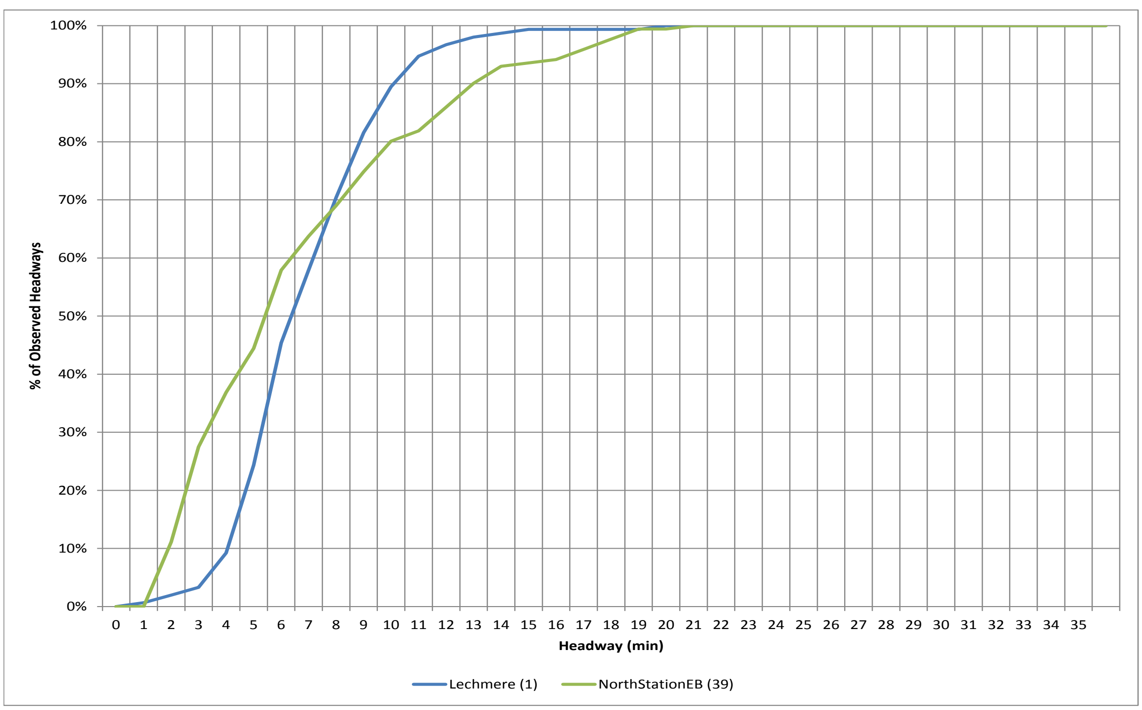

Figure A.23: E Branch Headways, PM Peak (Winter)

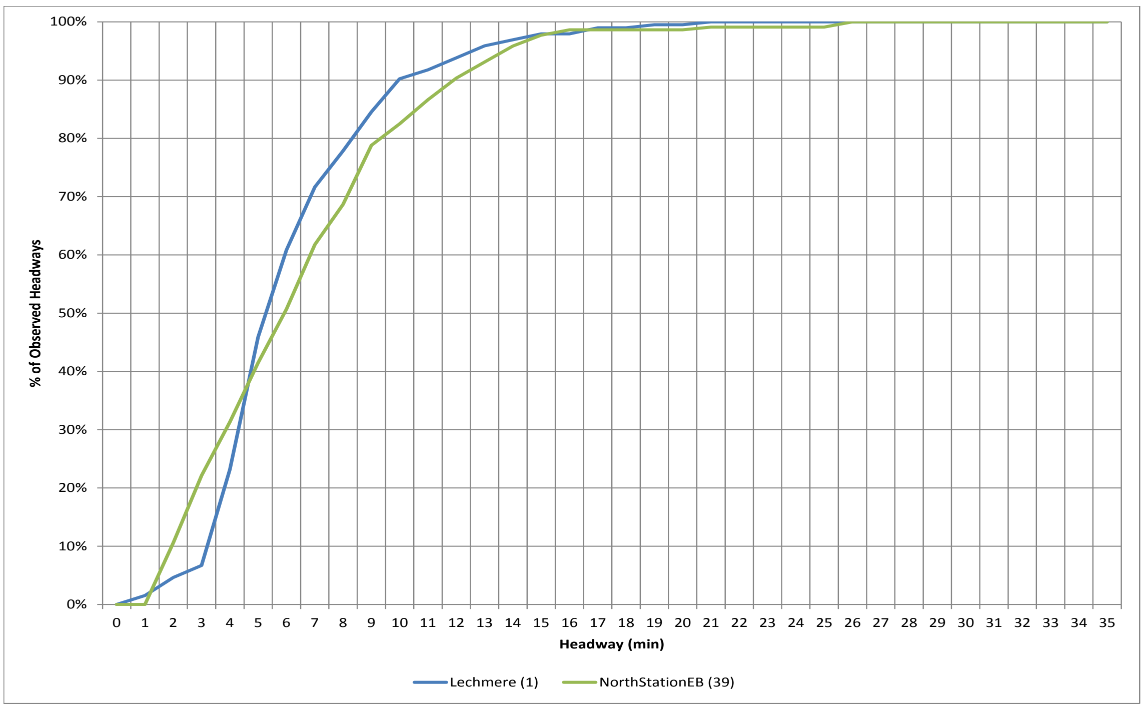

Figure A.24: D Branch Headways, PM Peak (Spring)

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