IMPACT ANALYSIS OF MBTA 2009 KEY BUS ROUTE INITIATIVE PROGRAM

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ABSTRACT

The Massachusetts Bay Transit Agency (MBTA) has the stated service objectives of customer service excellence, accessibility, reliability, and state-of-the-art technology. Over the last few years, the MBTA has been concerned about a possible decline in bus service quality. In response, the MBTA launched the Key Bus Route Initiative (KBRI) program in 2009. Funded entirely by the American Recovery and Reinvestment Act, the program is intended to improve bus service reliability on six key bus routes in the Boston area. The program uses an array of new initiatives to achieve this goal.

In September 2009, our team of four students in the Master of Engineering Program was asked to provide an independent impact analysis of the KBRI program. In response, we worked to analyze KBRI as well as expand the scope of the study to answer the two-part question of *how to best improve bus service performance with limited resources and how to best use existing technology to strategically plan for future performance improvements.* To this end, performance metrics were developed, which focus on customer's perception of both bus service efficiency and reliability. These metrics and the methodology provide a short term tool to analyze KBRI, but also a strategic framework for continuous improvement in overall MBTA bus service.

This report demonstrates that additional resources deployed on KBRI selected routes had considerable positive impacts on bus service performance. As a result of the KBRI initiatives, MBTA customers riding these routes saved a total wait time of 56 hours per day in the AM and PM peak travel periods. In addition to demonstrating how these results were achieved, this report provides further in-depth analysis of MBTA bus service performance. Several cases are shown where performance was improved without adding additional resources. For that reason, we provide general schedule related findings, which are summarized as recommendations for future efficient schedule adjustments on other MBTA routes.

Additionally, our analysis has shown that tremendous potential exists for expanded use of automated data collection systems at the MBTA. By linking several systems, which to this point have not interfaced with one another, we provide to the MBTA a framework for how to use these existing technologies to strategically plan for future performance improvements.

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The four authors would like to thank each other. If we remember anything from MIT, it is that good team work is essential. The four of us came from very diverse backgrounds, but bridged cultural differences to work well together and ended up learning much from one another.

To the 2010 Master of Engineering students, thank you for cheering us up during our many hours of data crunching on our transportation claimed computer work station in the MEng room. Although you often made the MEng room quite lively, we always appreciated your cheerful attitudes and camaraderie. To our program director Eric Adams, thank you for your integration of Transportation into the overall MEng group.

Most importantly, we would like to thank our advisors, Nigel Wilson and John Attanucci, for their dedication to furthering our interest and understanding of transit. We appreciated their push throughout the year right up to the last week, which we feel significantly improved the final version of our thesis.

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LIST OF ABBREVIATIONS

ADC	Automatic Data Collection
AFC	Automated Fare Collection
APC	Automatic Passenger Counting
AVL	Automatic Vehicle Location
CT	Cycle Time
CTPS	Central Transportation Planning Staff
Excess WT	Excess Wait Time
Expected WT	Expected Wait Time
HW	Headway
IVTT	In-Vehicle Travel Time
KBRI	Key Bus Route Initiative
RT	Running Time
SWT	Scheduled Wait Time
TSP	Traffic Signal Priority

1. INTRODUCTION

The Massachusetts Bay Transit Agency (MBTA) is the 5th largest transit agency in the United States, serving approximately 1.3 million customers per day, through an array of services including light rail, heavy rail and bus service. The MBTA operates over 2000 buses across nearly 200 routes within Massachusetts.

Funded entirely by the American Recovery and Reinvestment Act of 2009, the MBTA's *Key Bus Route Initiative* (KBRI) Program was launched with the goal of improving MBTA service performance on six selected key bus routes in the Boston area.

Bus service performance is analyzed in this report as a combination of service efficiency, which includes speed of operations and service frequency, and service reliability, which focuses on the variability of operations. Our analysis will address the question of whether performance has improved under KBRI and whether resources were efficiently deployed. Additionally, this report demonstrates how Automated Data Collection systems can be used to further analyze bus service performance. It will be shown that a strategic implementation and utilization of ADC systems provide a promising opportunity for improving bus service performance.

The report is organized as follows: Chapter 2 will review the KBRI program, discussing details of implementation. Chapter 3 will present our methodology, introducing key performance metrics for use in the analysis of KBRI impacts on bus service performance. In chapter 4, a KBRI route-specific analysis is conducted. Chapters 5 and 6 provide further analysis on Routes 1 and 28, using automated data collection sources to determine traffic segments and intersections where there might be potential for queue-jumping implementation. Lastly, Chapter 7 provides conclusions, including an overall program analysis as well as some general recommendations for cost-effective future changes in MBTA bus service operations.

2. THE MBTA 2009 KEY BUS ROUTE INITIATIVE PROGRAM

This chapter provides an overview of the MBTA Key Bus Route Initiative (KBRI) program. The first section introduces the selected KBRI routes. The second section provides details regarding KBRI implementation and includes expanded discussion on specific KBRI initiatives.

2.1 Selected KBRI Bus Routes

As shown in Table 2-1, the six selected KBRI routes (highlighted in grey) are among the highest ridership routes in the Boston system. If the program is successful, positive impacts of KBRI on service performance are expected to lead to wide-spread improved customer perception of MBTA services, due to the high ridership as well as the geographic coverage of the routes.

Rank	Route	Daily Weekday Boardings
1	Silver Line/Wash St	14709
2	39	14405
3	**1**	**12325**
4	**23**	**11142**
5	**66**	**11088**
6	**28**	**10607**
7	**111**	**8692**
8	57	8665
9	32	7733
10	22	7047
11	**15**	**6951**

Table 2-1: KBRI Route Ridership (Source: MBTA, 2009c)

2.2 KBRI Implementation

The program consists of various initiatives, summarized in Table 2-2, below.

Initiatives	Date of Implementation
Schedule Adjustments	11/07/09
Improved Supervision	Ongoing
Charlie Card Initiative	Ongoing
Roadway Initiatives	05/01/10
Improved Customer Information	11/30/09 to 05/01/10
Improved Amenities	02/15/10 to 05/01/10

Table 2-2: KBRI Implementation (Source: Strangeways, 2010)

The first three of these initiatives - Schedule Adjustments, Improved Supervision, and Charlie Card Initiative - have been implemented and can therefore be analyzed in this report. Schedule adjustments for routes 1, 15, 23, 28 and 66 were implemented on 7 November 2009. Schedule adjustments on route 111 were not implemented in time for this analysis. Improved Supervision and Charlie Card Initiative are ongoing initiatives that are expected to contribute to the overall effectiveness of the MBTA bus system. Roadway Initiatives, Improved Customer Information and Improved Amenities are future initiatives, and therefore no analysis of these initiatives can be undertaken at this time.

2.2.1 Schedule Adjustments

Schedule adjustments were the primary method through which the MBTA attempted to improve bus service performance. Prior to presenting the schedule adjustments, the basic operational variables of running time, recovery time and cycle time are defined here. The scheduled running time of a bus is the scheduled time between the departure of the bus from one terminal and the arrival at the other terminal. The scheduled recovery time is the amount of time scheduled at one terminal between the arrival of the bus and its next departure. The scheduled cycle time is the sum of the running time in both directions and the recovery times at both terminals (Dullea, 2010).

Table 2-3, provided below, summarizes the significant schedule changes affecting the three operational variables of headway (HW), cycle time (CT), and number of buses (#Buses) on the five affected routes. Schedule adjustments were directed at the AM and PM peak periods, when the largest numbers of travelers use the services. As defined by the MBTA, the AM Peak runs from 7:00am to 8:59am and the PM Peak from 4:00pm to 6:29pm.

Route 1	Old HW	New HW	% HW	Old CT	New CT	% CT	Old #Bus	New #Bus	% #Bus
AM Peak	8	8.5	**6%**	80	92	**15%**	10	11	**10%**
PM Peak	7.5	7.5	**0%**	113	113	**0%**	15	15	**0%**
Route 15	**Old HW**	**New HW**	**% HW**	**Old CT**	**New CT**	**% CT**	**Old #Bus**	**New #Bus**	**% #Bus**
AM Peak	6	6	**0%**	49	49	**0%**	9	9	**0%**
PM Peak	9	9	**0%**	63	72	**14%**	7	8	**14%**
Route 23	**Old HW**	**New HW**	**% HW**	**Old CT**	**New CT**	**% CT**	**Old #Bus**	**New #Bus**	**% #Bus**
AM Peak	5	5.5	**10%**	79	80	**1%**	16	15	**-6%**
PM Peak	8	7.5	**-6%**	94	93	**-1%**	13	14	**8%**
Route 28	**Old HW**	**New HW**	**% HW**	**Old CT**	**New CT**	**% CT**	**Old #Bus**	**New #Bus**	**% #Bus**
AM Peak	6.5	6.5	**0%**	95	98	**1%**	14	14	**0%**
PM Peak	10	9	**-10%**	122	112	**-8%**	13	13	**0%**
Route 66	**Old HW**	**New HW**	**% HW**	**Old CT**	**New CT**	**% CT**	**Old #Bus**	**New #Bus**	**% #Bus**
AM Peak	9	8.5	**-6%**	119	122	**3%**	13	14	**8%**
PM Peak	10	9.5	**-5%**	133	126	**-5%**	14	14	**0%**

Table 2-3: Route-Specific Schedule Adjustments (Source: MBTA 2009b/d/e; Dullea, 2010)
Note: Values taken at 8AM for AM Peak and 5PM for PM Peak

2.2.2 Improved Supervision

The MBTA has implemented significant changes in operational bus supervision over the last two decades. In the early 1990's, two "supervisors" at the MBTA's Operations Control Center managed roughly 400 buses each, using only radios and with knowledge of specific bus location limited to infrequent updates from bus operators. Since then, changes in technology have allowed the MBTA to move away from this ineffective manual system to a more automated and efficient one. A state-of-the art operations control system - based on Automatic Vehicle Locator (AVL) technology - has been in place since 2007. Each supervisor has direct oversight and visibility of all buses under his management. This new system provides each supervisor with visibility of up to 200 buses, centrally managing their schedule adherence and headways (Carney, 2010).

The MBTA has continually refined this operating process over the last several years by implementing standard operating procedures, such as the CAD/AVL Operations Control Strategies (MBTA, 2007a), which formalized the use of both preventive and corrective strategies:

> Preventive Strategies: During normal operations, the phenomenon of bus bunching (when two buses arrive at the same stop within seconds of each other) and the related phenomenon of bus gapping (when the headway between two buses is much larger than the scheduled headway) will naturally occur due to external factors such as traffic conditions or operational factors such as poor terminal departure time adherence. When this occurs, MBTA supervisors commonly intervene by holding, expressing, speeding up or slowing down buses to obtain more even headways along the route. Additionally, inspectors at the terminal attempt to ensure that buses are departing at scheduled times, or at times that allow for even headways. Inspectors are in contact with dispatchers at the Operations Control Center who can advise on when to implement preventive actions based on their overall view of the route.
>
> Corrective Strategies: At times, severe congestion or other external factors may necessitate a more drastic course of action. Short turning (when one mid-route stop is chosen as a premature trip terminal) or repositioning of buses may allow the system to return to normal conditions sooner than otherwise would be possible.

While KBRI required a renewed focus on the selected routes 1, 15, 23, 28, 66, and 111, MBTA Operations have always given special attention to these high ridership routes. Therefore, the impacts of the Fall 09 Improved Supervision initiative on bus service performance can be attributed to continuous improvements in existing MBTA operational procedures rather than to any specific changes implemented under KBRI. While these impacts should be considered when assessing the overall effect of KBRI on service performance, for the purposes of this report these effects will be considered second order compared with the effects of the Schedule Adjustments initiative.

2.2.3 Charlie Card Initiative

The Charlie Card is a fare payment medium, which customers can recharge at fare vending machines at certain terminals, in subway stations, or while boarding buses. The Charlie Card allows for easier and faster access to transit systems than older methods of payment such as cash or paper tickets. The MBTA has ongoing initiatives aimed at increasing Charlie Card penetration among its customers, such as student cards as well as a 7-day pass. The first Charlie Card was made available to the general public on December 4, 2006. Since then, penetration as a payment method has increased to nearly 70 percent of all users on KBRI routes, as determined through analysis of Automatic Fare Collection Data. Overall, the MBTA estimates system wide Charlie Card penetration rates for heavy rail and bus services to be approaching 76 percent (Castonguay, 2010).

In summer 2009, the MBTA expanded usage of the Charlie Card to include monthly passes as well as student passes. Impacts of increased Charlie Card penetration should be considered when assessing the overall impacts of KBRI on performance. However, due to the ongoing nature of the Charlie Card initiative, these effects are also considered second order when compared to the effects of the Schedule Adjustment initiative.

3. IMPACT ANALYSIS METHODOLOGY

This chapter presents the methodology applied to analyze the KBRI program. First, in section 3.1, the theory of bus service performance is described, including a discussion of the tradeoffs between service efficiency and service reliability. We also present expectations of the impacts of KBRI Schedule Adjustments on service performance. In section 3.2, the main sources of data for this analysis are introduced as well as the observation periods for which data are analyzed. In section 3.3, we introduce the performance metrics that will be used to analyze impacts of the KBRI program. In section 3.4, we expand the use of performance metrics to include the concept of operational robustness. Lastly, in section 3.5, we provide the framework for conducting a route-level cost-benefit analysis.

3.1 Introduction to Bus Service Performance

When assessing the performance of a service provided to a customer, one should focus on the service attributes the customer is most concerned with. In the case of bus service, these attributes include the wait time at a bus stop and the in-vehicle travel time.

A customer will deem service performance to be high if:

1) The service is efficient; wait time and in-vehicle travel time are reasonable.
2) The service is reliable; wait time and in-vehicle travel time are predictable.

An efficient bus service provides the customer with transportation from origin to destination in a reasonable amount of time. The level of efficiency depends on resources (in the form of buses) to provide a level of service frequency, and also on external factors that contribute to the speed of operations.

A reliable bus service allows a customer to accurately predict his arrival time at his destination. Highly unpredictable travel times would force a customer to budget a large 'buffer' time above the expected travel time for the trip, to ensure that he reaches his destination on time. On the contrary, a very reliable service will allow the customer to allocate less 'buffer' time to his trip (Nakanishi, 1997).

3.1.1 Low and High Frequency Service

In the case of bus service, it is important to distinguish between low-frequency and high-frequency service. The MBTA defines high frequency as a service with headways less than 10 minutes (MBTA, 2007b). For low-frequency service, informed customers tend to time their arrival at a bus stop to catch a specific scheduled trip. Service will be perceived as unreliable if their specific trip is not running as scheduled and they have to wait longer than expected due to poor schedule adherence. Therefore, reliability for low-frequency service is measured in terms of schedule adherence at each stop. During high-frequency service, customers rarely consult schedules and tend to arrive randomly. As a result, they are more concerned with headway regularity than schedule adherence. Service will be perceived as unreliable if headways are very irregular, and customers end up having to wait for a long time (especially if two buses arrive together after a large gap in service). Therefore service reliability for high-frequency routes is measured in terms of headway regularity at each stop. In addition to the variability of waiting time at each stop, reliability also includes the predictability of the second trip attribute, in-vehicle travel time.

KBRI selected routes all provide high-frequency service during peak periods (headways less than 10 minutes). Therefore our analysis focuses on the variability of headways and in-vehicle travel times (or, more generally, running times) rather than schedule adherence at bus stops.

3.1.2 Schedule Adjustments: A Tradeoff Between Operational Efficiency and Reliability

The relationship below (Equation 1) links the number of buses required for service to the scheduled headway and scheduled cycle time. This equation does not include any information about variability of the trip attributes. It nevertheless gives insight into the performance tradeoffs (discussed below) that will appear in developing schedules.

$$Scheduled\ Buses = \frac{Scheduled\ Cycle\ Time}{Scheduled\ Headway} \tag{1.1}$$

To improve service reliability, a bus schedule planner can increase the scheduled cycle time: the bus operator is provided with more time to run the same distance, which minimizes external effects and in turn decreases the variability of the running times and headways. According to Equation (1), the scheduled cycle time may be increased in two ways:

Option 1: Increasing the number of buses, while keeping headways constant. In this case, service reliability is improved without decreasing service frequency.

$$\Delta \#Buses = \frac{\Delta Scheduled\ Cycle\ time}{Scheduled\ Headway} \tag{1.2}$$

Option 2: Increasing scheduled headway, while keeping the number of buses constant. In this case, service reliability is improved at the expense of service frequency (headways increased).

$$\Delta Headway = \frac{\Delta Scheduled\ Cycle\ time}{\#Buses} \tag{1.3}$$

Similarly, to improve service frequency, a bus schedule planner can decrease headways. In accordance with Equation 1, two options are available: a decrease in scheduled cycle time or an increase of the number of buses.

Hence, there is a tradeoff between reliability and operational speed and frequency: the ability to improve one or the other will depend on how the bus schedule planner decides to allocate the additional resources. By introducing several performance metrics, we will analyze the impacts of the schedule adjustments implemented by the MBTA through KBRI on both service efficiency and service reliability.

3.1.3 Impacts of KBRI Schedule Adjustments on Performance

MBTA schedule planners utilized several combinations of schedule adjustments to improve bus service performance under KBRI. Our cause-and-effect theory linking implemented changes to expected impacts is presented below, citing specific examples were KBRI schedule changes resulted in improved performance.

In changes labeled as types 1 to 3, additional buses are provided on the route, while in changes of the types 4 and 5 only the cycle time (or the mix of running time and recovery time) is adjusted to improve service performance.

This list is not exhaustive; however, it presents most cases encountered in the KBRI program where a significant attempt to improve performance was made through changes to the schedules.

<u>Type 1 Change: Additional Resources to Increase Reliability</u>

Cycle time increased (running time increased), number of buses increased, and headways either constant or increased (e.g. Route 1-AM Peak, Route 15- PM Peak).

This type of change targets service reliability, using the additional bus to increase cycle time. This provides the bus operator with slack (more time to run the same distance), which, in case of an unplanned event, can be utilized to offset any disruption in service. We expect the variability of headways and running times to decrease, leading to improved service reliability. A type 1 change can occur with headways remaining constant (service frequency is not affected) or, as in the case of Route 1-AM Peak, with an increase in the headways to provide additional slack (service frequency is decreased). If implemented properly, the adjustments should result in improvements in reliability that will offset the impact of any reduction of service frequency due to increased headways.

<u>Type 2 Change: Additional Resources to Increase Service Efficiency</u>

Cycle time constant, headway decreased, and number of buses increased (e.g. Route 23-PM Peak).

This type of change targets service efficiency, using the additional bus to increase service frequency only. The reduction in headways will have a positive impact on customer scheduled wait time. However, we don't expect any substantial improvements in service reliability, as scheduled cycle time remains unchanged.

<u>Type 3 Change: Additional Resources to Increase both Service Reliability and Service Efficiency</u>

Cycle time increased, headway decreased, and number of buses increased (eg. Route 66-AM Peak).

This type of change targets both service reliability and service efficiency. The additional bus is used to increase cycle time, as well as reduce scheduled headways. For reasons already stated, the increased cycle time has a positive impact on service reliability. On the other hand, service efficiency is increased by reducing the headways. Overall the service performance is expected to improve.

Type 4 Change: Increase in Service Efficiency by Reducing Cycle Time

Cycle time decreased, headway decreased, and number of buses constant (eg. Route 28-PM Peak, Route 66-PM Peak).

This type of change targets service efficiency by using perceived excessive cycle time to increase service frequency. If implemented properly, the decrease in cycle time allows for an increase in service frequency. If implemented when excessive cycle time does not exist, the decrease in cycle time will put the system under schedule constraint. The driver will be less likely to maintain adherence to schedule since he has less time to run the same distance. If this is the case, we expect the variability of actual headways and running times to increase: service reliability deteriorates.

Type 5 Change: Increase in Reliability through Adjustment of the Mix between Running Time and Recovery Time

Cycle time constant with adjustment of the mix between running time and recovery time, headway constant, and number of buses constant (eg. Route 1-PM Peak, Route 15-AM Peak).

This type of change targets service reliability by attempting to adjust the mix of running time and recovery time to alter the behavior of bus operators. Increased scheduled running times allow the drivers to slow speeds along the route. The additional slack provided can be utilized to offset any disruption in service and we expect a reduction in headway and running time variability.

Our analysis will introduce key performance metrics that allow us to compare the expectations provided above to the actual impacts of KBRI on bus service performance. The metrics will be computed by querying and analyzing automated data sources provided by the MBTA.

3.2 Use of Automatic Data Collection Sources

Automatic Data Collection (ADC) systems represent a great opportunity for transit agencies to conduct a variety of statistical analyses which can be used to identify potential improvements in scheduling, planning, operations and performance. However, until recently, limited effort has been made to use these new data sources to evaluate bus service performance.

While ADC systems have been in place at the MBTA since 2007, the MBTA is still in the process of full deployment and refinement of these systems. Not much prior detailed research and analysis of the MBTA's ADC data has been carried out, although some research at MIT has used this data in a bus service reliability analysis. Most notably, Cham used Automatic Vehicle Location (AVL) data to analyze bus service reliability on the Silver Line on Washington Street (Cham, 2006) and Beasley and Hsu also used AVL data to analyze bus service reliability on MBTA routes 1, CT1, CT2, 47, 64, 68, 70/70A, 83 and 85 (Beasley and Hsu, 2009). However, little use has yet been made of Automatic Passenger Counter (APC) data and Automatic Fare Collection (AFC) data in transit operations analysis. These systems can be used to monitor buses, to better understand factors affecting service reliability, to examine possibilities to avoid bus delays or to identify impacts to in-vehicle travel time in the MBTA bus service network.

Our team had the opportunity to be the first to make use of all three ADC sources (AVL, APC, and AFC) to conduct a detailed analysis of MBTA's bus service performance. One major challenge of the project was to link together all these different ADC sources, which are not interconnected in the MBTA's database server network system.

Three primary Automatic Data Collection (ADC) sources are used in this analysis:

- Automatic Vehicle Location (AVL) System
- Automated Fare Collection (AFC) System
- Automatic Passenger Counting (APC) System

Our analysis will compare two distinct observation periods, the first before the KBRI initiatives and the second after implementation. The two observation periods are defined as follows:

- Spring 09: This is the "before initiatives" observation period. The extent of the period varies across ADC sources, but falls within the months of March and April 2009.

- Fall 09: This is the "after initiatives" observation period. The extent of the period varies across ADC sources, but falls within the months of November and December 2009.

Details on each observation period are provided in the following ADC source-specific sections.

3.2.1 Automatic Vehicle Location Data

Automatic Vehicle Locator (AVL) data represents real-time satellite-based global positioning system information of the location of buses in the network. The MBTA has implemented an AVL system for all its bus service operations, so AVL data is available for all KBRI bus routes. The MBTA's AVL system provider is Trapeze ITS and is branded as the TransitMaster product (Barker, 2010).

The AVL observation periods for Spring 09 and Fall 09 are as follows:

Spring 2009	Fall 2009
03/21/09 to 06/19/09	11/16/09 to 12/18/09

Table 3-1: AVL Observation Periods

In the final stages of this project, while analyzing the route segment travel times for Chapters 5 and 6, we came across what appear to be systematic errors in the AVL recordings at the terminals. The inaccuracies in the terminal data vary by route and created by the ways buses operate around the AVL cordons at the terminals. Construction sites and other external factors affecting operations around the terminal may exacerbate the issue. From looking at time-space diagrams and an initial diagnosis these errors do appear to be systematic and also appear to be relatively consistent between time periods allowing us to continue to use them in the rest of our analysis. However, in future analyses we strongly recommend reviewing this issues and addressing it if necessary by excluding the two terminal segments in any AVL based analysis.

3.2.2 Automatic Passenger Count Data

Automated Passenger Count (APC) data represents automatic counts of boarding and alighting passengers at bus stops. The data is generated from a system of a series of sensors placed by the doors that track the number and direction of movements. The MBTA APC data is not available in real time but is uploaded overnight from the internal bus system to the central database server. The MBTA has not yet deployed APC systems in all of its buses. 83 of MBTAs 1000 bus fleet are currently equipped (Barker, 2010). The MBTA's APC system provider is Urban Transportation Associates (UTA). While originally using its own GPS antenna for positioning, it has since been integrated with TransitMaster (AVL System).

APC data was received for routes 23 and 28 for both Spring 09 and Fall 09 observation periods. However, in Fall 09, APC systems were not allocated to buses on a consistent basis, so Fall 09 sample size is too small to compute statistically significant performance metrics and perform a comparison analysis between observation periods.

The APC observation periods for Spring 09 and Fall 09 are as follows:

Spring 2009	Fall 2009
03/21/09 to 04/24/09	10/17/09 to 11/06/09

Table 3-2: APC Observation Periods

3.2.3 Automatic Fare Collection Data

Automatic Fare Collection (AFC) systems record payments by smart cards with unique identification numbers, magnetic strip cards, cash fares, and flash passes. This information is recorded when an individual boards a bus. Some systems with distance or zone based fares also record fare data when a passenger exits the system (mostly with smart cards with unique identification number for an individual, for instance the Suica Card in Tokyo). However, the MBTA bus system has a flat fare, and so fare payments are recorded only when a passenger enters a vehicle. A large proportion of passengers use the Charlie Card, the MBTA's smart card system. The MBTA estimates Charlie Card usage for heavy rail and bus service to be 76%. AFC technology is provided to the MBTA by Scheidt Bachmann (S&B)

AFC data was provided by the MBTA for Spring 09 and Fall 09 observation periods for the selected key routes at the lowest possible aggregation level of individual transactions, by transaction time and fare box.

The AFC observation periods for Spring 09 and Fall 09 are as follows:

Spring 2009	Fall 2009
03/01/09 to 03/31/09	11/28/09 to 12/19/09

Table 3-3: AFC Observation Periods

3.2.4 ADC Data Processing

The ADC data was imported and queried to extract useful information for analysis. The data attributes of each ADC source are explained in Appendix 1. In addition to ADC sources, manual counts from the Central Transportation Planning Staff (CTPS) are used to estimate ridership and load factors.

AFC and APC data are both useful for developing ridership statistics. APC systems are the most accurate since they are designed specifically to count boardings and alightings. AFC transaction data can also be used as a proxy for ridership although it is expected to undercount the actual ridership due a percentage of riders who do not interact with the farebox when boarding (including children, rear door boarders, and fare evaders).

APC is in use on only routes 23 and 28. The APC and AFC data were compared on these two routes where comparable data was available from both systems to estimate a way to best approximate actual ridership from AFC data. The discrepancy between AFC and APC ridership data varied by route and time of day, but in general AFC ridership underestimates APC ridership statistics by 15% to 35% (see Appendix 2 for the detailed analysis). These statistics can be used as guidelines for ridership estimations from AFC data.

3.3 Development of Performance Metrics

In order to assess the impact of KBRI on bus service performance, a set of metrics is defined and will be applied to data from ADC sources over the two observation periods. The metrics were estimated for routes 1, 15, 23, 28 and 66 for both the AM and PM Peak periods. Details regarding the use of extracted data to create these metrics are provided in Appendix 3.

3.3.1 Median Running Time

The metric Median Running Time is a measure that allows us to quantify the impact of schedule changes on customer In-Vehicle Travel Time.

Running time distribution charts display the probability density function of the actual running time of a trip. They provide a basis for comparison between Spring 09 and Fall 09 bus service. The running time distributions are produced by using MBTA provided AVL data. If the distribution moves towards the left (or right) between Spring 09 and Fall 09, it means that the In-Vehicle Travel Time of a customer is likely to get shorter (or longer).

More specifically, the median value of the running time provides a way to quantify the change in running time that a customer is likely to experience due to KBRI. Percentile values (95th) are also provided when relevant as a basis for comparison. The spread of the running time distribution (or the standard deviation) gives an indication of the variability of the running time. The tighter the distribution, the more predictable the running time becomes, and thus the more reliable the service is.

An example of statistical analysis for the inbound direction of Route 1 in the AM Peak is shown below. From Spring 09 to Fall 09, the distribution and median value move to the right, demonstrating a general increase in customer In-Vehicle Travel Time. The width of the distribution remains largely unchanged if not slightly increased. Therefore the variability of the trip attribute running time has not decreased and the service has not become more reliable based solely on the running time analysis.

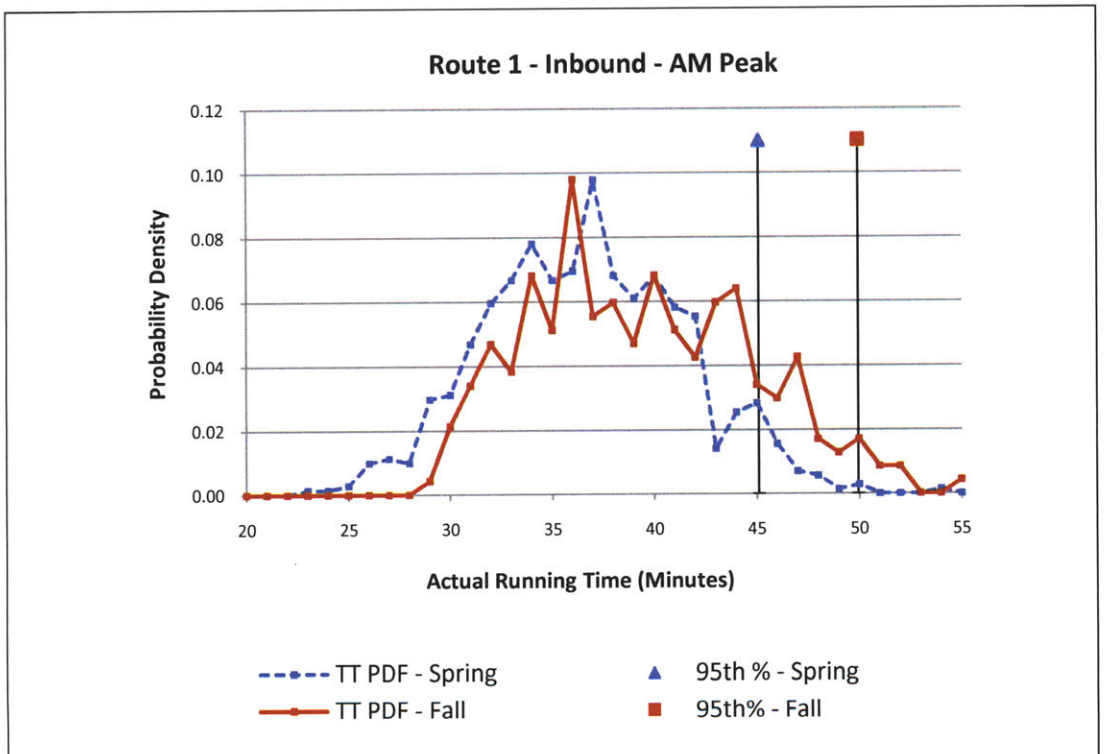

Figure 3-1: Running Time Distributions – Route 1 – AM Peak – Inbound Direction

3.3.2 Expected Wait Time

The metric Expected Wait Time (Expected WT) is a measure of both the service frequency and the reliability of operations. To fully develop and understand the metric Expected Wait Time, we first analyze headway ratios.

The headway ratio distribution is the probability density function of the ratio of actual to scheduled headways based on a statistical analysis of AVL data.

The headway ratio distribution is particularly relevant for high-frequency routes where customers are more concerned with headway variability than schedule adherence. If the distribution becomes tighter (around the value 1), it indicates that a customer is more likely to experience an actual headway close to the scheduled value: the service is perceived as more reliable in terms of waiting times.

The headway ratio distribution is particularly relevant to our analysis since it provides more information about headway variability than alternatives such as time space diagrams. Figures 2 and 3 below show examples of time space diagrams: the scheduled and actual time space diagrams are presented for Route 1-AM Peak, inbound, on the 5th May 2009. It can be seen that, during this particular day and time period, bus bunching and associated gaps in service occurred on several occasions.

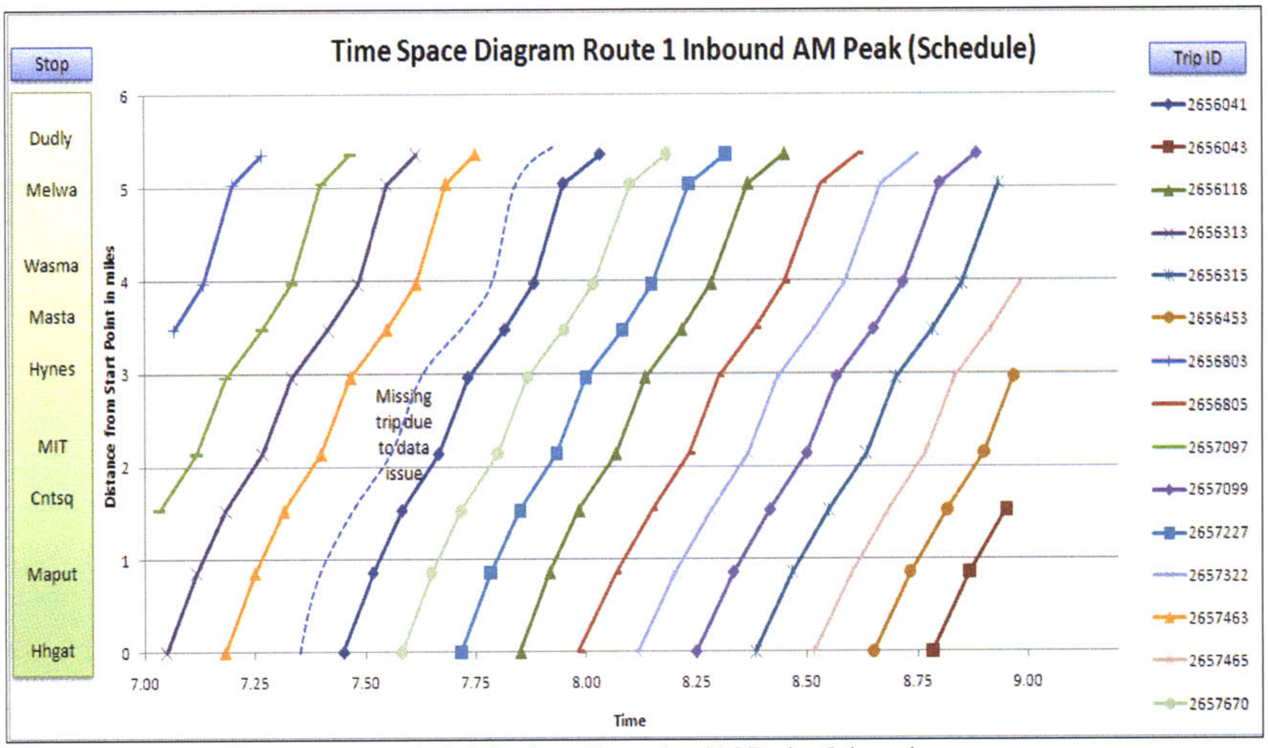

Figure 3-2: Time Space Diagram – Scheduled Trips – Route 1 – AM Peak – Inbound

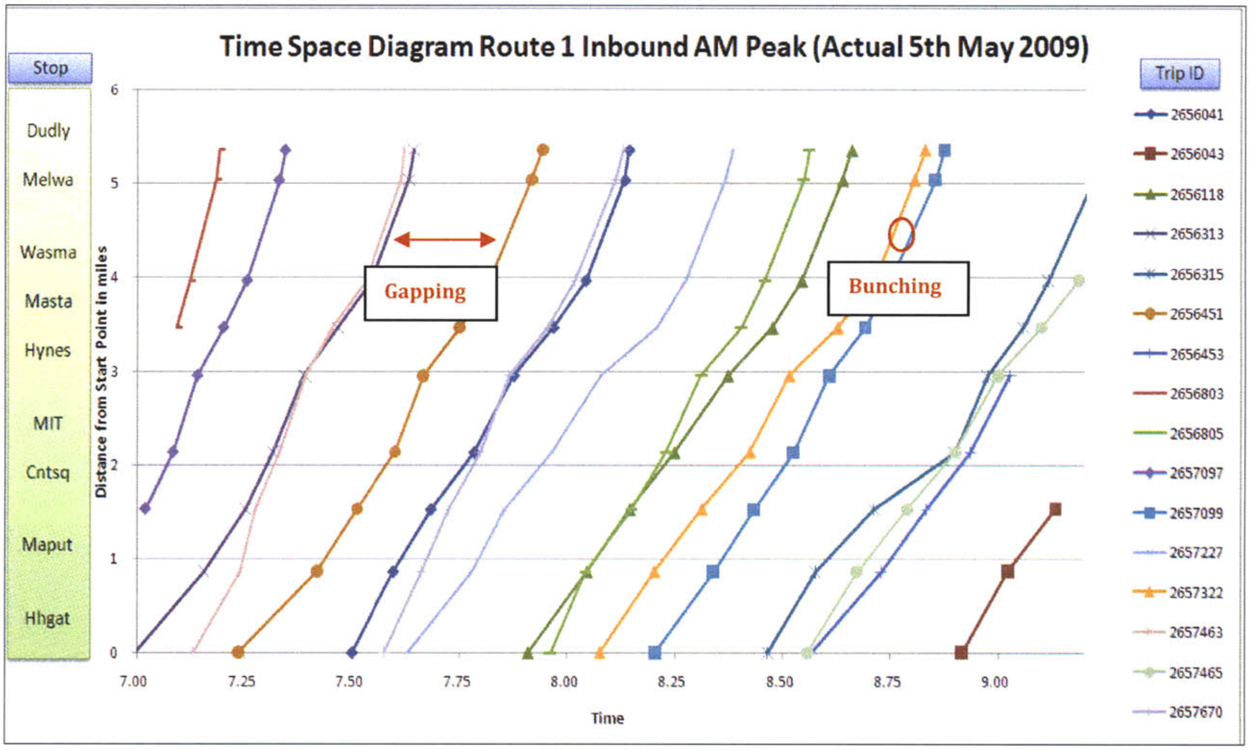

Figure 3-3: Time Space Diagram – Actual Trips – Route 1 – AM Peak – Inound

Time space diagrams are used for a very specific time period at a trip level and provide limited information on headway variability. Aggregating AVL trip-specific data over a longer time period would average out the variability of bus trips, resulting in an actual time space diagram very close to the scheduled diagram. To account for this, headway ratio distributions are used as a basis for comparison over longer time periods and across routes.

An example of the propagation of headway ratios along Route 1-AM Peak is shown in Figure 3-4, below. The distribution is concentrated around the value 1 at the terminal, which means that the actual headway between two buses is likely to be close to the scheduled headway at the terminal. The headway ratio distribution flattens as the buses move along the route: the actual headway becomes less likely to be close to the scheduled value. A 'tail' appears at the edges of the curve as the bus gets closer to the arrival terminal, which means that buses are more and more likely to bunch and gap as they move along the route. The expected wait time experienced by a randomly arriving customer should increase due to increased headway variability.

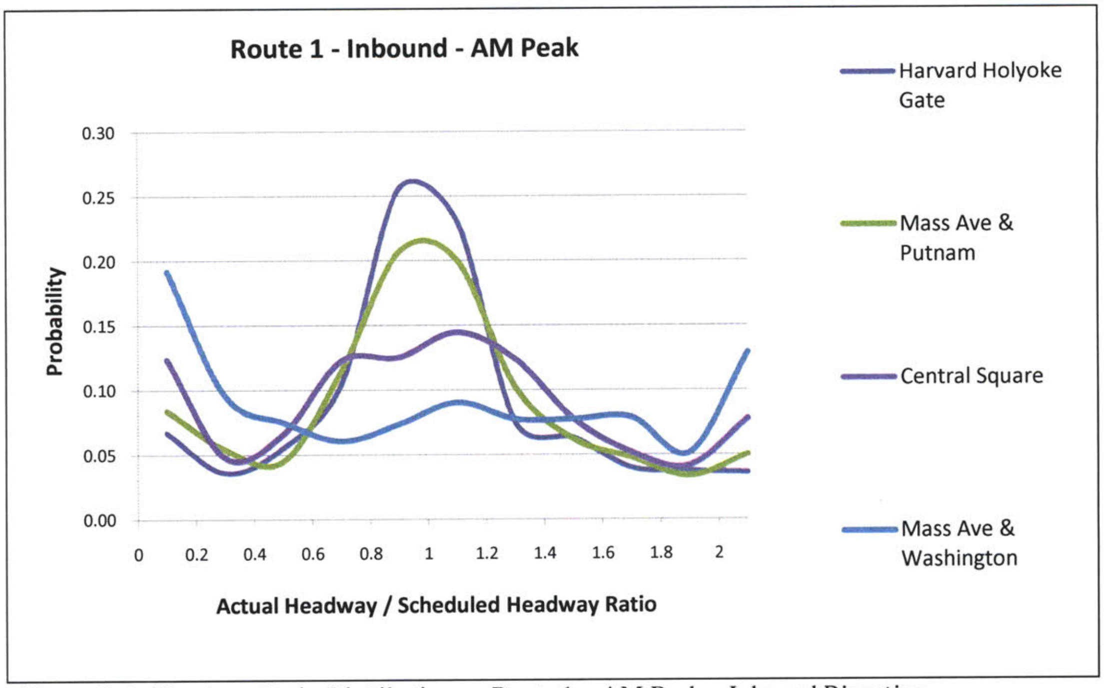

Figure 3-4: Headway Ratio Distributions – Route 1 – AM Peak – Inbound Direction

While headway ratios provide an indication of service reliability, the metric Expected Wait Time quantifies the impact on customer wait time. The Expected Wait Time is the amount of time that a customer will spend waiting for bus service if he arrives randomly at a stop independent of the bus schedule. The relationship which defines expected wait time is:

$$Expected\ Wait\ Time = \frac{Mean\ Headway}{2} + \frac{Variance\ of Headway}{2 * Mean\ Headway} \quad (2)$$

As we can conclude from the formula above, the expected wait time includes both aspects of service frequency and service reliability. Service frequency is addressed through the magnitude of the headways; the smaller the headway, the more frequent the service, the smaller the expected wait time. Service reliability is addressed through the magnitude of the variance of the headway; the more even the service, the smaller the expected wait time.

For purposes of this report, the metric is computed at the median boarding stop along the route, which is the stop where half of all the riders of a trip (on average) have boarded since the bus left the terminal. This gives a good estimate of the expected wait time experienced by a typical customer. The median boarding stop is determined by using the 2007 manual counts by the Central Transportation Planning Staff (CTPS).

A summary of the selected stops for each route is provided below.

Route/Direction	Inbound	Outbound
Route 1	Central Square	Massachusetts Av. at Washington Street
Route 15	Uphams Corner	Dudley
Route 23	Codman Square	Dudley
Route 28	Morton Street	Dudley
Route 66	Union Square	Brigham Circle

Table 3-4 Median Boarding Stops

An example of the application of the expected wait time metric to Route 23 is shown in Figure 3-5, below. In the AM Peak, the headway increased by 10% from 5 to 5.5 minutes between Spring 09 and Fall 09; the subsequent decreased service frequency translates into increased expected wait time. In the PM Peak, the headway decreased by 6% from 8 to 7.5 minutes, which translates into increased service frequency and decreased expected wait time.

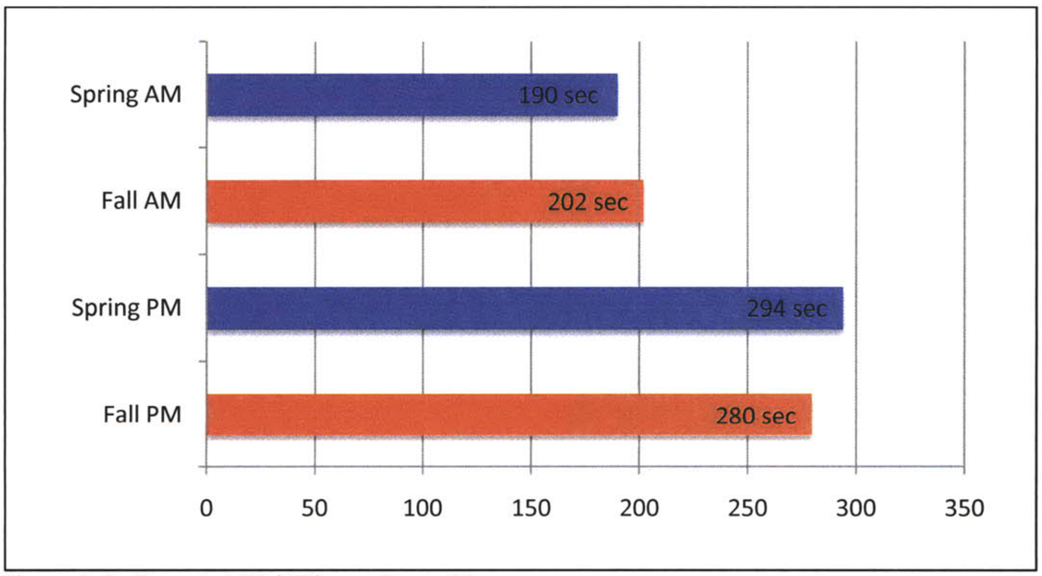

Figure 3-5: Expected Wait Time – Route 23

Excess Wait Time (Excess WT) measures the difference between the actual and the scheduled wait times. The actual wait time is simply the expected wait time defined above. The scheduled wait time (SWT) is the wait time reflected in the schedule, as defined below:

$$Scheduled\ Wait\ Time = \frac{Mean\ Scheduled\ Headway}{2} + \frac{Variance\ of\ Scheduled\ Headway}{2 * Mean\ Scheduled\ Headway} \quad (3)$$

The Excess Wait Time is defined as follows:

$$Excess\ Wait\ Time = Expected\ Wait\ Time - Scheduled\ Wait\ Time \quad (4)$$

This metric captures the "extra" wait time due to operating variability above the waiting time embedded in the schedule. We use it to isolate the impact of KBRI on service reliability from the overall impact on service performance (the latter includes both aspects of reliability and service frequency and is captured by the Expected Wait Time metric defined above). As with the expected wait time, the excess wait time is computed at the median boarding stop along the route.

An example of application of the Excess Wait Time metric to Route 1 is shown below. The largest decrease of excess wait time between Spring 09 and Fall 09 is seen in the AM Peak. This is the result of a sharp decrease in headway variability, which is due to the increased cycle time scheduled in the AM Peak. However the increased reliability comes at the expense of decreased service frequency (headways were increased). The chart shows that excess wait time decreases in the AM Peak, while scheduled wait time increases, with the net effect being an overall reduction in the total expected wait time.

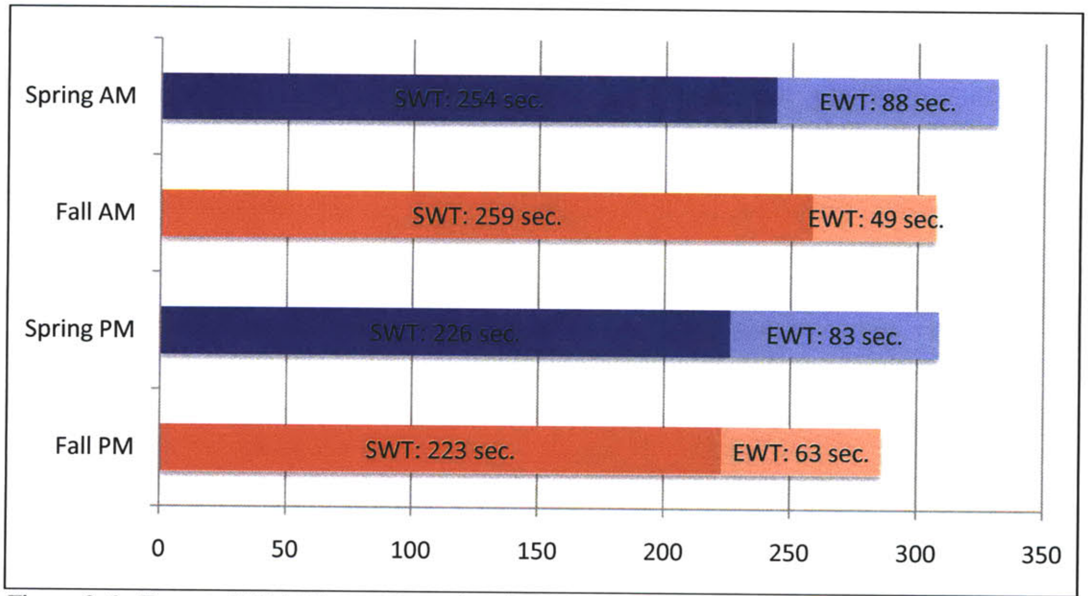

Figure 3-6: Expected Wait Time – Route 1 – AM Peak

3.3.3 Supporting Metric: Terminal Departure Time Adherence

Terminal departure time adherence is the difference between scheduled and actual bus departure times from the terminal. Poor terminal departure time adherence may contribute to poor schedule reliability at stop locations and at the arrival terminal. An example of terminal departure time adherence diagram is provided as Figure 3-7, below. In the figure, a bus is considered 'On time' if departure is within one minute of scheduled time. 'Early' or 'Late' would be departures times outside the two minute schedule window. We can notice a large increase in the proportion of early departures from the inbound terminal (Codman Square) in both peak periods. We will see in the analysis that the increase in actual running times along the route may have led operators to depart earlier to avoid being late at their destination.

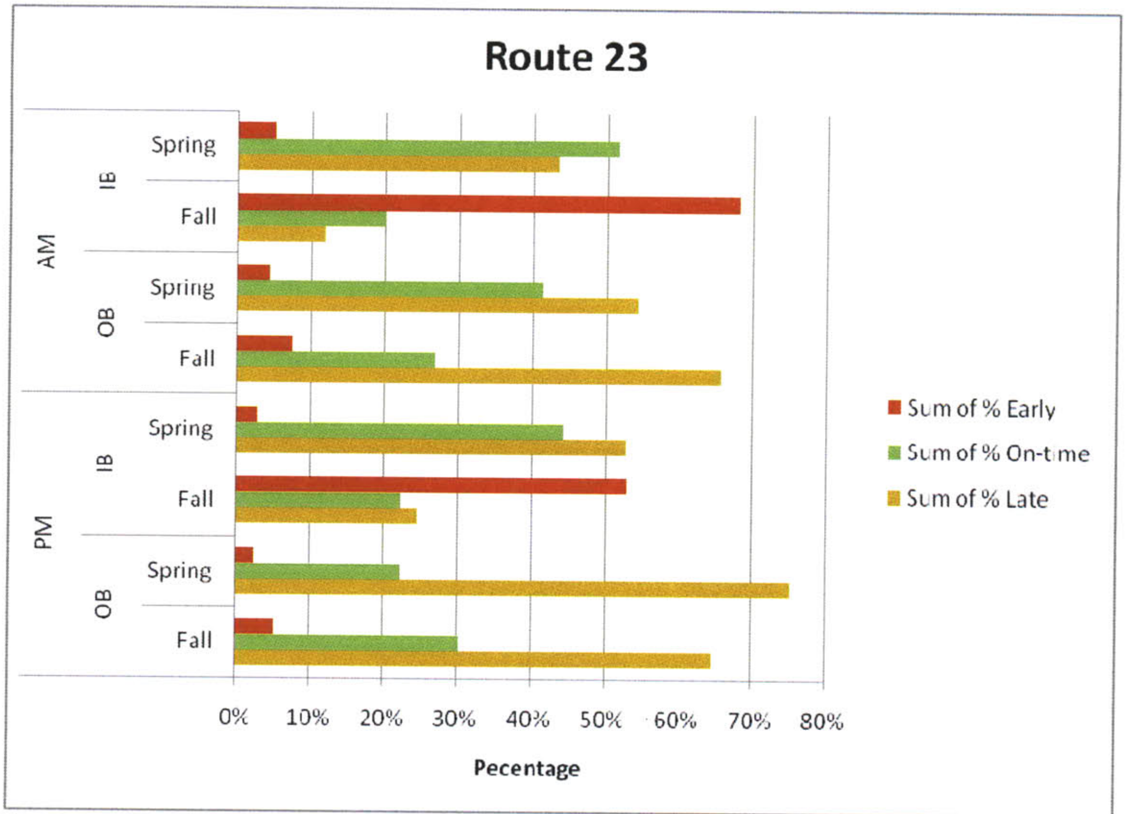

Figure 3-7: Terminal Departure Time Adherence – Route 23

3.4 Operational Robustness

The performance metrics introduced in the preceding sections are used to analyze the impacts of KBRI on bus service performance. The main comparative analysis is conducted on the full Spring 09 and Fall 09 ADC data. However, the initiatives are also expected to make bus service more robust, therefore the corresponding improvements in service performance are expected to be more evident on bad days (days with poor service due to bad weather conditions, traffic delays, collisions and unexpectedly high passenger demand) than on average days.

To analyze the effect of KBRI on robustness of bus operations, a comparative analysis of the 'one-third of all days showing worst performance' is performed. The value of one-third was chosen to provide a sufficient sample size given the shorter three-week Fall 09 observation period and to capture the sensitivity of the performance metrics.

3.5 Cost Benefit Analysis

To fully assess the impacts of KBRI on service performance, it is necessary to evaluate the benefits received from KBRI against the cost of additional resources utilized in the program. Benefits of KBRI are demonstrated through the use of our primary metrics, Expected Wait Time and Mean Running Time. Costs are expressed in terms of dollars deployed for additional buses on KBRI routes. The methodology for how we quantify these values is provided below.

Expected Wait Time Savings
Customer wait time is quantified by our metric Expected Wait Time. For a given time period, the average inbound/outbound Expected Wait Time at the median boarding stop is calculated in Spring 09 and Fall 09. The difference between the two values is multiplied by the average directional ridership values established by the Central Transportation Planning Staff (CTPS, 2007). This number, referred to as 'Wait Time Saved For All Customers', provides the total change in customer wait time for a given route and time period.

In-Vehicle Travel Time Savings
Customer in-vehicle travel time is quantified by our metric Median Running Time. The median running time represents the total in-vehicle travel time of a customer if this customer rides the route from terminal to terminal. For the purpose of our analysis, we make the assumption that an average customer ride 25% of a route. We also make the assumption that changes in running times are evenly distributed along the route, which allows us to apply the running time savings to the average percentage of the route utilized. This value will be referred to in the analysis as 'In-Vehicle Travel Time Saved for All Customers'.

The median running time for Route 1, PM Peak, outbound, decreases by 1.9 minutes. The average customer will experience 25% of this change in running time, which amounts to a savings in in-vehicle travel time of roughly half a minute. With PM Peak outbound ridership established at 1460 passengers, this equates to 11.5 hours of In-Vehicle Travel Time Saved for All Customers.

As mentioned in Chapter 3.3, changes in running times may be attributed to external factors not related to KBRI. Factors such as increased traffic or construction can indeed have a substantial impact on running times. While the cost-benefit analysis includes the changes observed in in-vehicle travel time, it does not consider the causes of these changes. Further studies could discount the estimated impact of external factors on in-vehicle travel time in order to isolate KBRI-related effects. Where appropriate, the cost-benefit analysis will comment on where external factors were known to be present during the observation period.

KBRI Costs
Costs attributed to KBRI include funding needed to change the number of buses used on a route. The cost of adding one bus on a route is estimated by the MBTA as $130.44 per revenue hour of operation (Strangeways, 2010). Adding a bus in the AM Peak, which consists of 2 hours of operations, would result in additional daily cost of $260.88. An additional bus in the PM Peak, which consists of 2.5 hours, would result in additional cost of $326.10.

Overall Cost Benefit Analysis
Having quantified Wait Time Saved For All Customers and In-Vehicle Travel Time Saved for All Customers, we are now able to evaluate the overall effectiveness of the program. A summary of these results will be provided in Chapter 4 for each of the KBRI routes. An example of how these results are displayed is provided here as Table 3-5.

Time Period	Additional Funding	Daily Change in Wait Time for All Customers	Daily Change in In-Vehicle-Travel Time for All Customers
AM Peak	$261	-17.25 hours	12.2 hours
PM Peak	0	-9.0 hours	-12.7 hours

Table 3-5: Sample Cost-Benefit Analysis – Route 1

In assessing the overall success of KBRI at the route level, our analysis will focus more on saved wait time than on saved in-vehicle travel time. This is done for the following reasons:

1. Value of Time – Customers place a higher value on wait time at a bus stop than on time spent traveling on a bus. The time spent on a bus can indeed be used for productive purposes; whereas the time spent waiting at a bus stop is less comfortable and introduces an additional level of uncertainty. Therefore, KBRI changes that affect customer wait time are more effective on improving service performance perception than changes that affect in-vehicle travel time.

2. External Factors – As previously mentioned, several factors influence running times. Many of these are out of the control of schedule planners, such as construction, weather related delays, or additional traffic. AVL data does not allow for the isolation of the effects of these external factors on running times, which means that less significance can be placed on changes in customer in-vehicle travel time due to KBRI.

3. Terminal Effects on AVL Data – Due to the particularities of the AVL system, small changes in operator behavior can have a large effect on running time results. For example, if changes in the running time allow for changed operator behavior near the terminal (eg. the operator remains outside the cordon longer), this will provide a misleading arrival time and yield an overestimated running time. Further studies utilizing AVL data may investigate how to best measure actual running times with consideration to the dynamics at terminals.

4. ROUTE LEVEL KBRI PERFORMANCE ANALYSIS

KBRI key routes are analyzed individually based on the methodology presented in Chapter 3 and according to the following format:

- ***Route Schedule Adjustments and Performance Expectations*** – A summary of implemented initiatives is provided along with their expected impacts on bus service performance.
- ***Performance Results and Analysis*** – Primary metrics – Median Running Time and Expected Wait Time – as well as headway ratios are used to compare bus service performance before and after KBRI initiatives. Cause-and-effect relationships between implemented initiatives and observed impacts are identified where possible. When the primary metrics cannot fully explain the observed impacts, supportive metrics are used, such as the terminal departure time adherence or dwell time analysis (provided in full as Appendix 4).
- ***Cost-Benefit Analysis*** – A cost-benefit analysis is provided, with costs and savings expressed in terms of dollars per hour of customer time saved. Costs include funding needed to change the number of buses used on the route. Benefits are expressed in terms of customer time saved, to include both waiting time and in-vehicle travel time.
- ***Overall Assessment*** – As a conclusion to each route level analysis, the effects of the program will be evaluated and discussed to determine the level of KBRI success. For the various reasons presented previously in Chapter 3.5, the assessment of route success will be based primarily on saved customer wait time. Therefore, a route is classified as either a high, moderate or limited success based on whether customer wait time is saved at a reasonable cost without significant adverse effects to running time.

4.1 Route 1 Performance Analysis

Route 1 is the 3rd highest ridership bus route in the MBTA system, providing service between Cambridge and Boston, carrying 12,325 passengers per weekday (MBTA, 2009c). Inbound service is defined as being from Harvard Square to Dudley Square. The following section provides an analysis of the expected and actual impacts of KBRI on bus service performance.

4.1.1 Route Schedule Adjustments and Performance Expectations

KRBI schedule changes for Route 1 are summarized here in Table 4-1, provided below. Expected impacts of these changes on bus service performance are outlined below, based on the cause-and-effect relationships described in Chapter 3.

- AM Peak: One bus was added to the route and cycle time extended from 80 to 92 minutes. Inbound (to Dudley), running time was increased from 36 to 38 minutes and recovery time at the Dudley terminal was increased from 8 to 9 minutes. Outbound (to Harvard Square), running time was increased from 35 to 36 minutes and recovery time at the Harvard terminal was increased from 1 to 9 minutes.

- PM Peak: Cycle time was held constant at 113 minutes, but the running time and recovery time mix was adjusted. Inbound, running time was increased from 42 to 45 minutes while recovery time at Dudley was decreased from 18 to 15 minutes. Outbound, running time was increased from 38 to 42 minutes while recovery time at the Harvard terminal was decreased from 15 to 11 minutes.

Time Period	Major Route Changes	Expectations (Cause-Effect)
AM Peak	Number of buses increased from 10 to 11 (+10%) Cycle time increased from 80 to 92 minutes (+15%) Headways increased from 8 to 8.5 minutes (+6%)	Resources were added to improve reliability (type 1 change). This should be demonstrated through improved headway adherence, lower excess wait time and improved performance under stress. The increased scheduled wait time due to a slight increase in headways (decreased service frequency) should be offset by the reduced excess wait time as a result of increased service reliability.
PM Peak	Cycle time constant at 113 minutes, with travel time increased from 80 to 87 minutes (+9%), at the expense of recovery time	Running/recovery time mix is adjusted (type 5 change). We expect slightly improved performance due to additional running time and therefore additional slack time provided to bus operators along the route. Scheduled wait time remains unchanged, but excess wait time should decrease, reducing the overall expected wait time.

Table 4-1: Route Changes and Associated Expected Impacts – Route 1

4.1.2 Route Performance Results and Analysis

In this section, the impacts of KBRI on service performance for Route 1 are demonstrated through the application of the primary metrics - Median Running Time and Expected Wait Time - as well as headway ratio distributions to show bus performance at different locations along the route.

a) Median Running Time

Provided below are Route 1 running time distributions showing changes in running times between Spring 09 and Fall 09. Scheduled running times were increased by 3 minutes in the AM Peak and 7 minutes in the PM Peak, while the median running time between the observation periods increased by 1.8 minute in the AM Peak (5.2%) and decreased by 1.1 minute in the PM Peak (-2.5%). In the AM Peak, both the 95th percentile and standard deviation increase, indicating that the running time experienced by a customer is more variable. In the PM Peak, both the 95th percentile and the standard deviation decrease, indicating that the running time is more reliable.

In general, the change in running times between the two observation periods is small and is within the expected range of increase that could be attributed to change in weather conditions between Spring and Fall 09. AVL data does not allow for the isolation of external factors that may be influencing running times, therefore we cannot conclude on the effects of KBRI on running times.

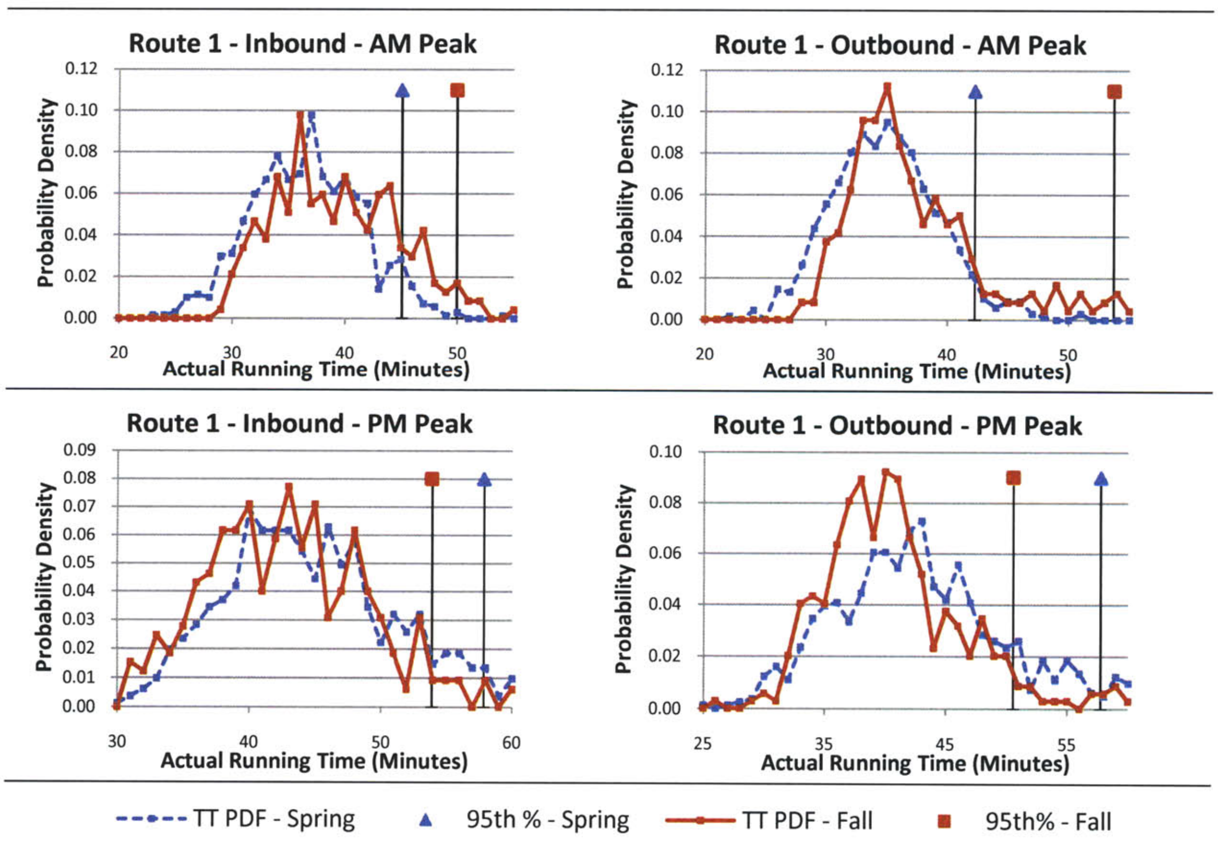

Figure 4-1: Running Time Distributions – Route 1

b) Headway Ratio Distribution

Figure 4-2 displays Route 1 headway ratio distributions showing how headway ratios evolve as the bus moves along the route. Headway ratios for both Spring 09 and Fall 09 are shown side by side for a given direction and time period.

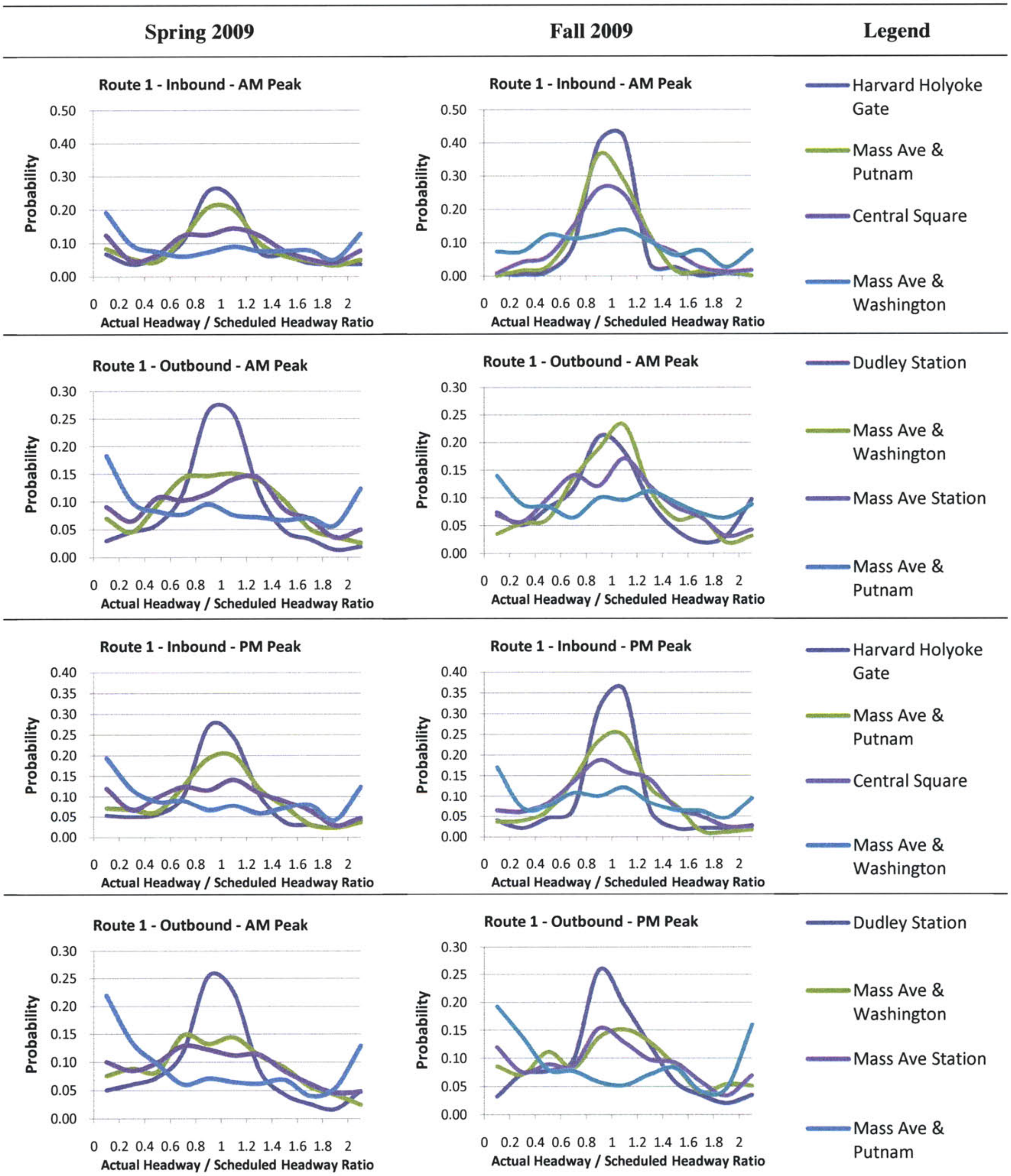

Figure 4-2: Headway Ratio Distributions – Route 1

The probability density function of the headway ratios is generally improved; the curves are more concentrated around a value of one in Fall 09, indicating that the customer is more likely to experience an actual headway close to that which is scheduled. The improvements are significant along the entire route, with the most profound effects seen inbound during AM Peak. Overall, the variability of the headways is decreased, indicating increased reliability of the headways and therefore a potential positive impact on customer wait time. This is made possible by KBRI increased scheduled running times, which provide more slack time to operations.

c) Expected Wait Time

Figure 4-3 displays Route 1 expected customer wait time as experienced at the median boarding stop along the route (Central Square inbound and Massachusetts Avenue at Washington Street outbound).

As discussed in Chapter 3, the total expected customer wait time is the sum of the scheduled wait time and the excess wait time, the former used to show the wait time embedded in the schedule, and the latter capturing the extra wait time due to the variability of operations.

In Fall 09, expected wait times were reduced in both the AM and PM peak periods. In the AM Peak, the expected wait time was reduced despite a decrease in service frequency (increased scheduled wait time). This reduction of 34 seconds results primarily from a reduction in excess wait time (88 to 49 seconds) due to decreased headway variability. In the PM Peak, service frequency remains unchanged, but decreased headway variability results in reduced excess wait time (by 20 seconds). Both of these improvements can be linked to an increase in the scheduled running time, providing operations with more slack time.

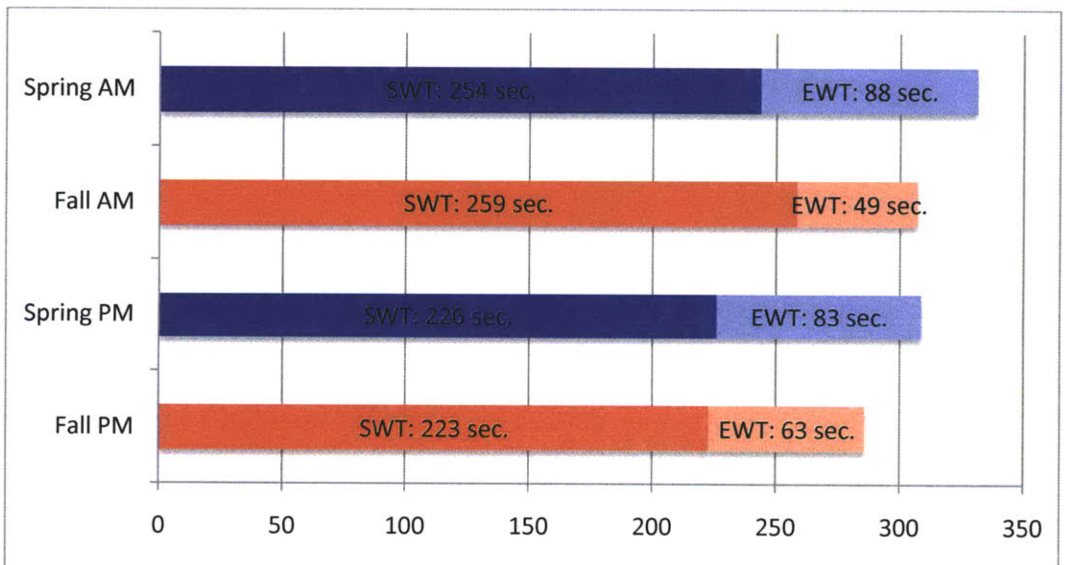

Figure 4-3: Expected Wait Time – Route 1

This increase in performance is further confirmed through an analysis of one-third of all days showing worst performance. As shown below in Figure 4-4, the results are similar to those demonstrated by the full data set, but the decreases in excess wait time is now larger in magnitude, indicating that the operations are responding better under stress.

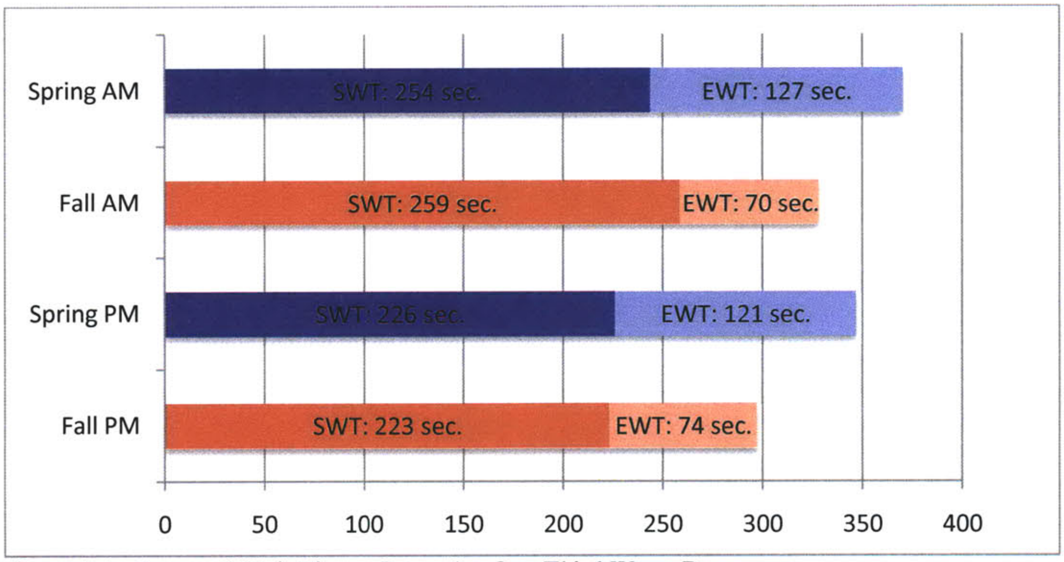

Figure 4-4: Expected Wait Time – Route 1 – One-Third Worst Days

d) Terminal Departure Time Adherence

Figure 4-5 displays departure time adherence at both the Dudley and Harvard terminals. Departures from the Harvard terminal are more often on time in Fall 09. This improved adherence propagates along the route and is consistent with the improvements in headway ratio distribution shown above.

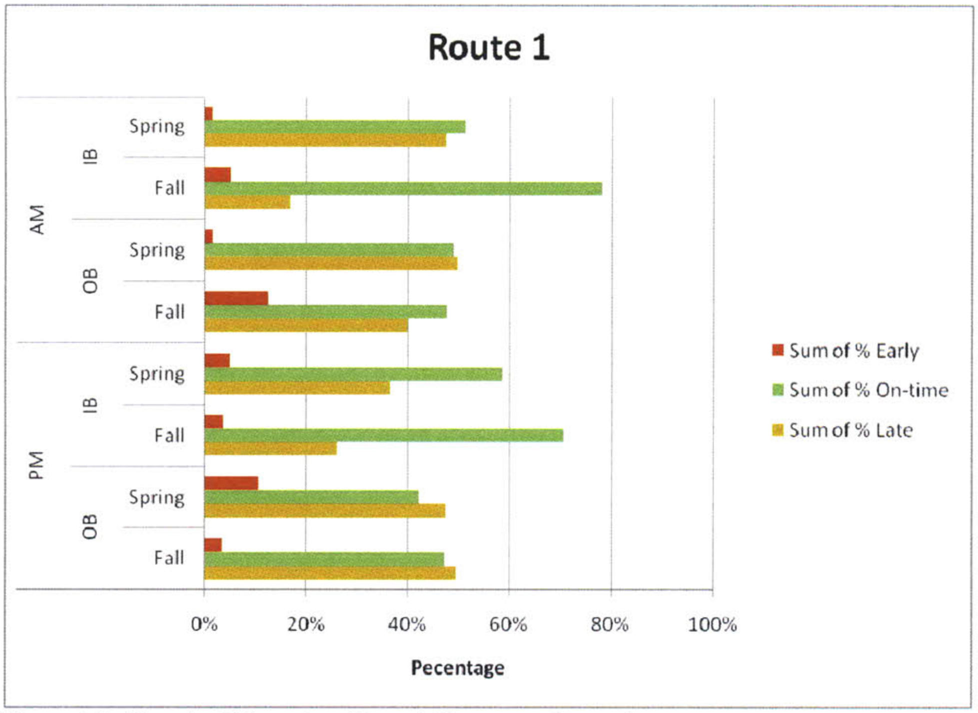

Figure 4-5: Terminal Departure Time Adherence – Route 1

4.1.3 Cost Benefit Analysis

Through KBRI, the MBTA deployed additional resources on Route 1 in the form of one additional bus in the AM Peak, in an effort to improve performance. To assess the effectiveness of these additional resources, a cost benefit analysis is provided below.

Expected waiting time and in-vehicle travel time savings for Route 1, as shown in the previous section, are as follows:

- AM Peak: The average customer experienced 24 seconds less wait time and 28 seconds more in-vehicle travel time.

- PM Peak: The average customer experienced 23 seconds less wait time and 16 seconds less in-vehicle travel time.

Ridership levels for Route 1 (CTPS, 2007), are as follows:

- AM Peak: 1656 riders
- PM Peak: 2988 riders

Using these data and the methodology introduced in Chapter 3, we can estimate costs and benefits to be:

Time Period	Additional Funding	Daily Change in Wait Time for All Customers	Daily Change in In-Vehicle-Travel Time for All Customers
AM Peak	$261	-9.0 hours	12.2 hours
PM Peak	0	-17.3 hours	-12.7 hours

Table 4-2: Cost Benefit Analysis – Route 1

4.1.4 Overall Assessment

Through KBRI, the MBTA was able to save 17.25 hours of customer wait time per day at an average cost of $15.12 per hour in the AM Peak. The downside of the saved wait time is an increase in in-vehicle travel time. In the PM Peak, a simple adjustment to the running time without deploying additional resources had the effect of saving both wait time and in-vehicle travel time in the amount of 17.3 hours and 12.7 hours per day, respectively.

Therefore, we classify KBRI results on Route 1 as a 'High Success'

4.2 Route 15 Performance Analysis

Route 15 is the 11th highest ridership bus route in the MBTA system, providing service between Ruggles Station and Kane Square, carrying 6,951 passengers per average weekday (MBTA, 2009c). Inbound service is defined as being from Kane Square to Ruggles Station. The following section provides an analysis of expected and actual impacts of KBRI on bus service performance.

4.2.1 Route Schedule Adjustments and Performance Expectations

KRBI schedule changes for Route 15 are summarized in Table 4-3, below. Expected impacts of these changes on service performance are outlined below, based on the cause-and-effect relationships described in Chapter 3.

- AM Peak: The cycle time was held constant at 49 minutes, while running time and recovery time mix was adjusted. Inbound (to Ruggles), running time was reduced from 22 to 20 minutes while recover time at the Ruggles terminal was increased from 3 to 5 minutes. Outbound (to Kane Square), running time was reduced from 21 to 20 minutes while recovery time at Kane was increased from 3 to 4 minutes.

- PM Peak: One bus was added to the route and cycle time was extended from 63 to 72 minutes. Inbound, running time was held at 22 minutes while recover time at the Ruggles terminal was increase from 6 to 15 minutes. Outbound, running time was increased from 29 to 30 minutes while recovery time at Kane was reduced from 6 to 5 minutes.

Time Period	Major Route Changes	Expectations (Cause-Effect)
AM Peak	Cycle time remains unchanged at 49 minutes Running time decreased from 43 to 40 minutes (-7%), with recovery time increased from 6 to 9 minutes (+50%)	The mix between running time and recovery time is altered (type 5change). We expect a slight decrease in reliability due to reduced running time. Headway ratio distributions should be more variable. Scheduled wait time remains unchanged, but excess wait time should increase due to the increase in headway variability, increasing overall expected wait time.
PM Peak	Number of buses increased from 7 to 8 (+14%) Cycle time was increased from 63 to 72 minutes (+14%) Recovery time increased, from 12 to 20 minutes (+67%)	Resources were added to improve reliability (type 1 change). We expect improvements in performance due to increased reliability. This should be demonstrated through decreased variability in running time and headways and thus lower expected customer wait time. However, the allocation of the increased cycle time entirely to recovery time may not increase operator flexibility along the route. The positive effects on variability of running times and headways, and thus expected wait time, may therefore be less than expected.

Table 4-3: Route Changes and Associated Expected Impacts – Route 15

4.2.2 Route Performance Results and Analysis

In this section, the impacts of KBRI on service performance for Route 15 are demonstrated through the application of the primary metrics - Median Running Time and Expected Wait Time – as well as headway ratio distributions to show bus performance at different locations along the route.

a) Median Running Time

Figure 4-6 displays Route 15 running time distributions showing changes in running times between Spring 09 and Fall 09 observation periods. Although the scheduled running time was decreased by 3 minutes in the AM Peak, the actual median running time increased by 2.5 minutes (12.9%). The 95th percentile running time also increased. In the PM Peak, the increase in median running time is limited to the inbound direction, where median running time increased by 1.8 minutes (7.5%).

In general, trips are taking longer and running time is more variable. External factors may be contributing to the overall increase in running time. Regardless of the cause, this analysis shows that there may not have been excessive slack in the running time to make schedule adjustments.

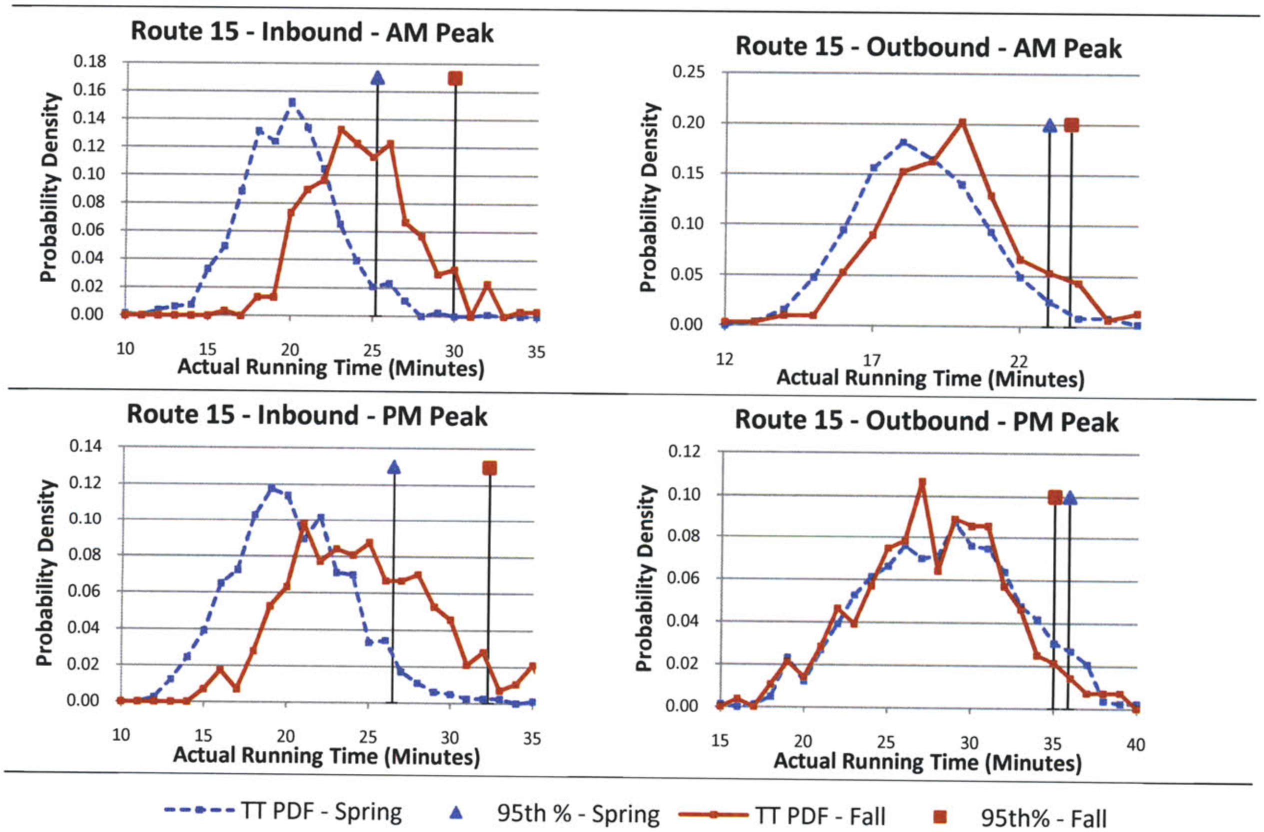

Figure 4-6: Running Time Distributions – Route 15

Several possibilities exist for explaining increased running times along the route. The observed increase in dwell times along the route may provide some insight. Figure 4-7, provided below, displays dwell times at Dudley Station. As shown, dwell times have increased in Fall 09 by an average of one minute in both the inbound and outbound directions. This dwell time increase could be one of the many factors contributing to an overall increase in running times.

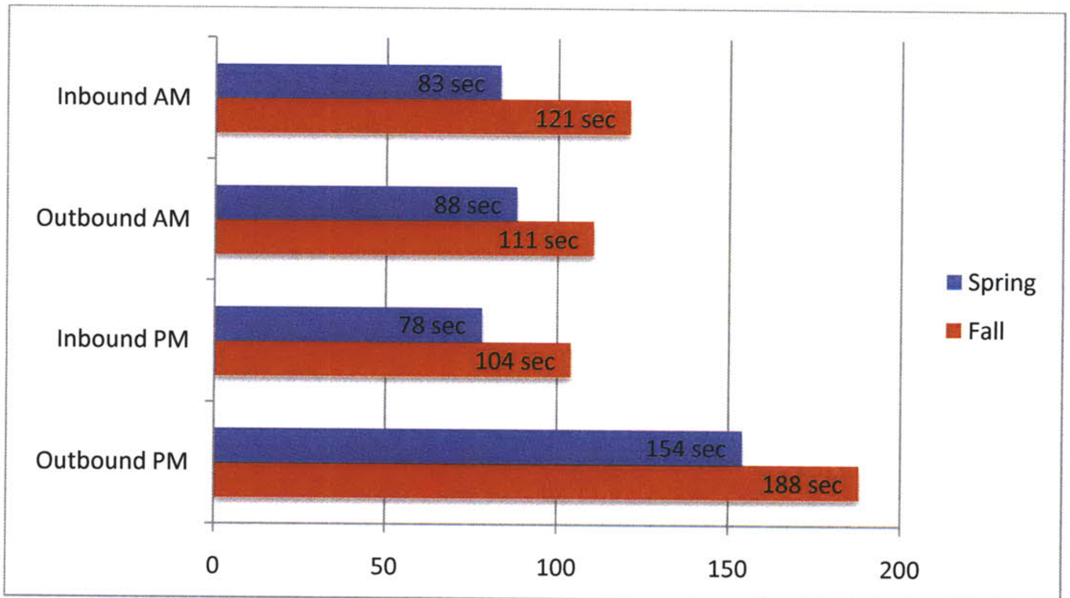

Figure 4-7: Dwell Times at Dudley Station – Route 15

b) Headway Ratio Distribution

Figure 4-8, provided on the following page, displays Route 15 headway ratio distributions showing how headway ratios evolve as the bus moves along the route.

In the AM Peak, headway ratios remain largely unchanged. In the PM Peak, headway ratios have improved in the inbound direction along most of the route from Kane Square to Dudley Square, and in the outbound along the entire route. The additional resources and associated recovery time added to the schedule provided the bus operator with more slack. The subsequent reduction in headway ratio variability should translate into decreased expected customer wait times.

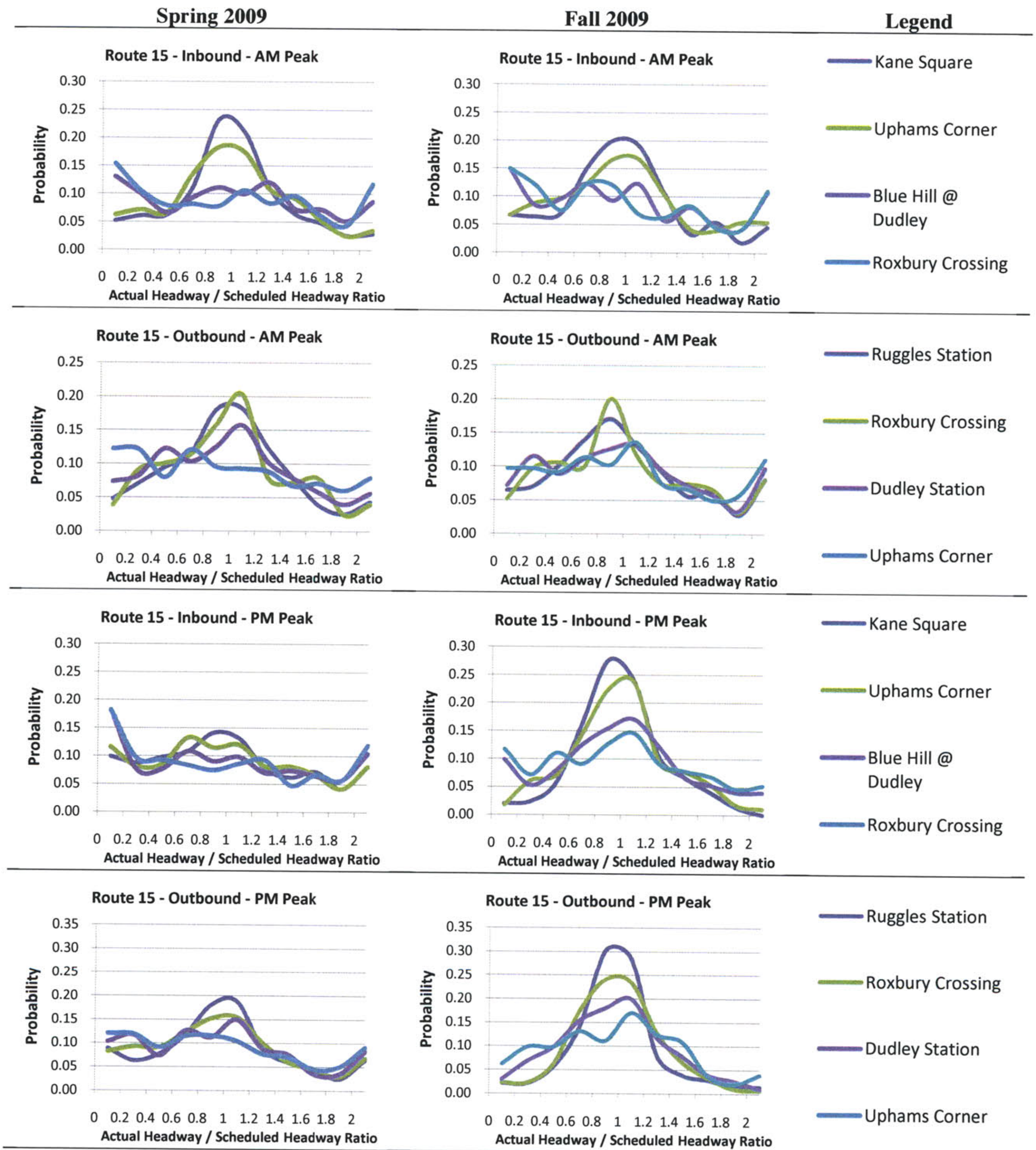

Figure 4-8: Headway Ratio Distributions – Route 15

c) Expected Wait Time

Figure 4-9, provided below, displays Route 15 expected customer wait times as experienced at the median boarding stop along the route (Uphams Corner for inbound direction and Dudley for outbound).

Total expected customer wait time increased slightly in the AM Peak and decreased substantially in the PM Peak. The increase in excess wait time in the AM Peak can be attributed to increased headway variability due to decreased scheduled running times. The decrease in excess wait time in the PM Peak can be attributed to the additional slack time provided to operations through the addition of a bus, and is further confirmed by a decrease in variability of headway ratios, as seen previously.

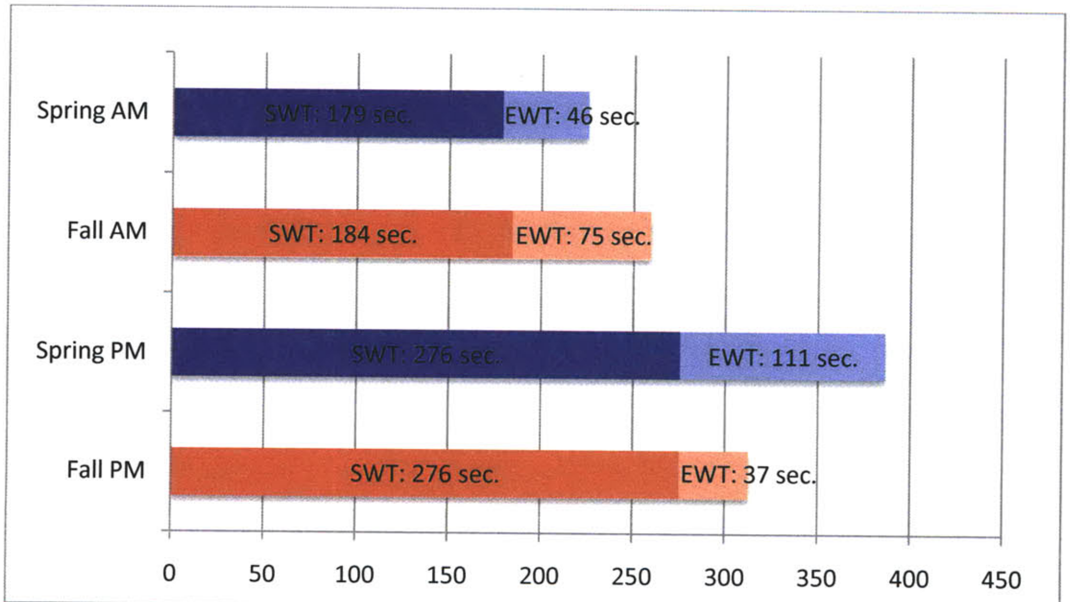

Figure 4-9: Expected Wait Time – Route 15

The results shown through the full data set analysis are further demonstrated through an analysis of the one-third of all days showing worst performance, displayed below as Figure 4-10. The absolute value of the changes is magnified, but the general trend of decreased performance in the AM Peak and increased performance in the PM Peak is again observed.

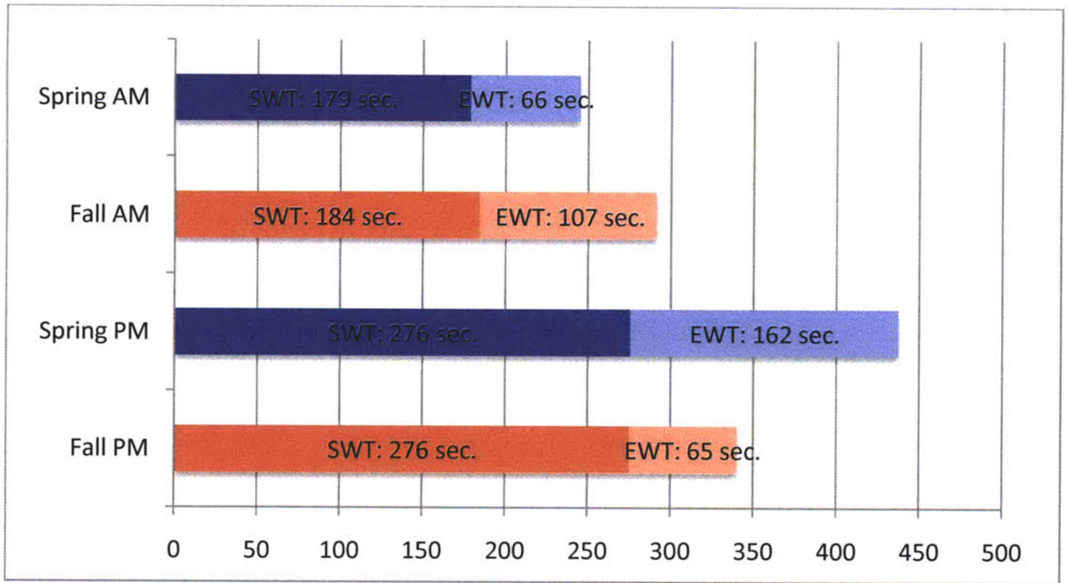

Figure 4-10: Expected Wait Time – Route 15 – One-Third Worst Days

4.2.3 Cost Benefit Analysis

Through KBRI, the MBTA deployed additional resources on Route 15 in the form of one additional bus in the PM Peak in an effort to improve performance. To assess how well these resources were utilized, a cost benefit analysis is provided below.

Expected waiting time savings for Route 15, as shown in the previous section, are as follows:

- AM Peak: The average customer experienced 34 seconds more wait time and 38 seconds more in-vehicle travel time.

- PM Peak: The average customer experienced 97 seconds less wait time and 27 seconds more in-vehicle travel time.

Ridership levels for Route 15 (CTPS, 2007), are as follows:

- AM Peak: 777 riders
- PM Peak: 505 riders

Using these data and weighting ridership levels and wait time savings by direction (inbound and outbound), we can estimate costs and benefits to be:

Time Period	Additional Funding	Daily Change in Wait Time for All Customers	Daily Change in In-Vehicle-Travel Time for All Customers
AM Peak	$0	7.7 hours	13.1 hours
PM Peak	$326	-10.1 hours	2.3 hours

Table 4-4: Cost Benefit Analysis – Route 15

4.2.4 Overall Assessment

KBRI schedule changes saved 10.1 hours of expected customer wait time in the PM Peak at a cost of $32.29 per hour of customer wait time saved. Unfortunately in the AM Peak, performance deteriorated as demonstrated through7.7 hours more wait time and 13.1 hours more in-vehicle travel time.

Due to the missed opportunity in the AM Peak, we classify KBRI results on Route 15 as 'Moderate Success'

4.3 Route 23 Performance Analysis

Route 23 is the 4th highest ridership bus route in the MBTA system, providing service between Ruggles Station and Ashmont Station, carrying 11,142 passengers per average weekday (MBTA, 2009c). Inbound service is defined as being from Ashmont Station to Ruggles Station. The following section provides an analysis of expected and actual impacts of KBRI on service performance.

4.3.1 Route Schedule Adjustments and Performance Expectations

KRBI schedule changes for Route 23 are summarized in Table 4-5, below. Expected impacts of these changes on service performance are outlined below, based on the cause-and-effect relationships described in Chapter 3.

- AM Peak: One bus was removed from the route and headways and cycle time were adjusted accordingly. Headways were increased from 5 to 5.5 minutes and cycle time increased from 79 to 80 minutes. Inbound (to Ruggles), running time was decreased from 34 to 33 minutes and recovery time at the Ruggles terminal was increased from 7 to 9 minutes. Outbound (to Ashmont), running time was increased from 30 to 31 minutes and recovery time at Ashmont was decreased from 8 to 7 minutes.

- PM Peak: One bus was added to the route and headway and cycle time were both decreased. Headways were reduced from 8 to 7.5 minutes and cycle time from 94 to 93 minutes. Inbound, running time was increased from 35 to 36 minutes and recovery time at the Ruggles terminal was decreased from 7 to 5 minutes. Outbound, running time was reduced from 43 to 42 minutes while recovery time at Ashmont was increased from 9 to 10 minutes.

Time Period	Major Route Changes	Expectations (Cause-Effect)
AM Peak	Number of buses decreased from 16 to 15 (-6%) Headways increased from 5 to 5.5 minutes (+10%).	We expect a decrease in performance due to removal of resources. Given that cycle time is unchanged, we do not expect that this removal will have an effect on variability of either running times or headways, and therefore should not have an effect on excess wait times. Expected wait times should increase due solely to decreased service frequency (increased scheduled wait times).
PM Peak	Number of buses increased from 13 to 14 (+8%) Headways decreased from 8 to 7.5 minutes (-6%).	Resources were added to increase service frequency (type 2 change). Given that cycle time is unchanged, we do not expect that this addition will have an effect on variability of either running times or headways. Excess wait times should remain unchanged. Expected wait times should decrease due solely to increased service frequency (decreased scheduled wait times).

Table 4-5: Route Changes and Associated Expected Impacts – Route 23

4.3.2 Route Performance Results and Analysis

In this section, the impacts of KBRI on service performance for Route 23 are demonstrated through the application of the primary metrics - Median Running Time and Expected Wait Time - as well as headway ratio distributions to show bus performance at different locations along the route.

a) Median Running Time

Figure 4-11, provided below, displays Route 23 running time distributions showing changes in running times between Spring 09 and Fall 09 observation periods. Although scheduled running times remained largely unchanged from Spring to Fall 09, actual median running times and 95th percentiles running time increased in the inbound direction in both the AM and PM Peaks (by approximately 8 minutes each). Outbound running times remain largely unchanged.

In general, running times have shifted to the right in Fall 09. However, it is known that construction activities were ongoing during the Fall 09 observation period. Therefore, the effects of KBRI schedule adjustments may not be linked to changes observed in running time distributions.

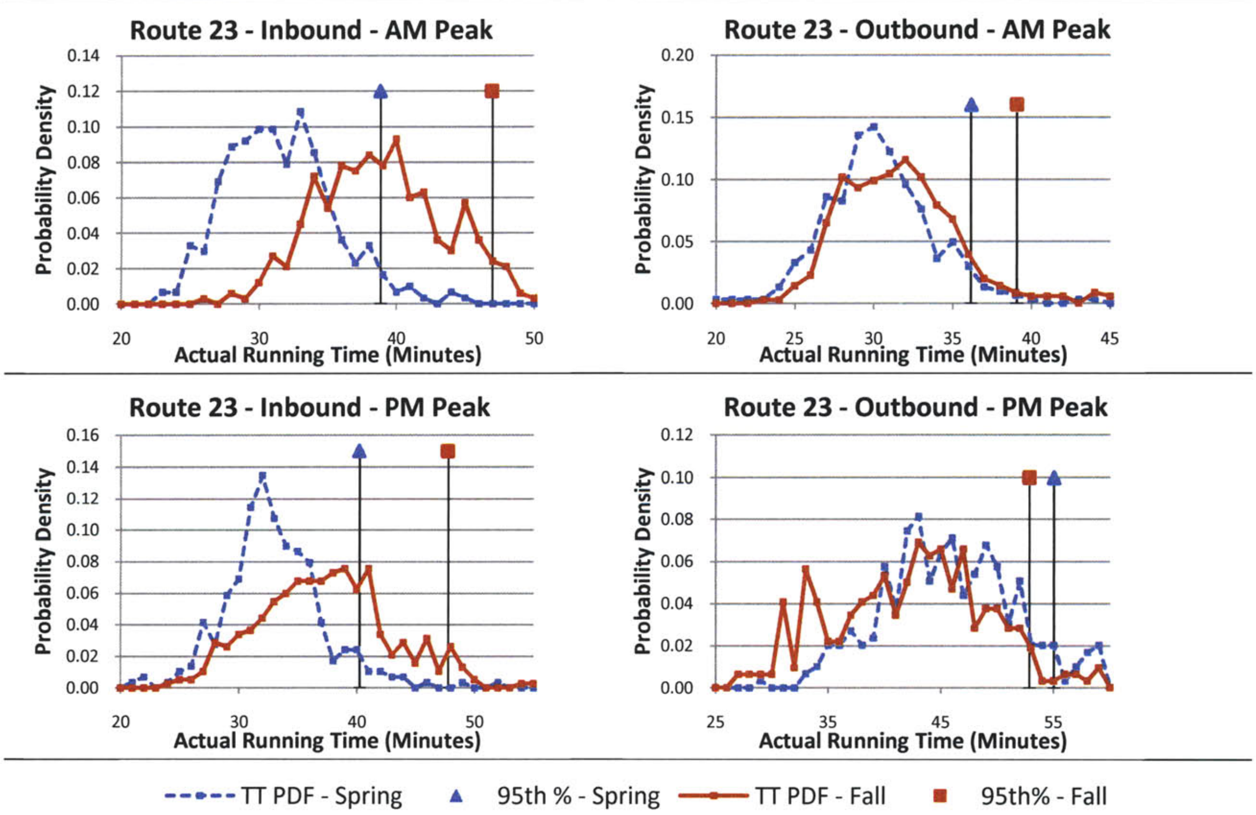

Figure 4-11: Running Time Distributions – Route 23

An analysis of terminal departure time adherence may provide some insight into the cause of this shift in running time distribution. Figure 4-12, below, displays departure time adherence at the route terminals. We can notice a significant increase in the proportion of early departures from the Ashmont terminal (inbound direction) in both the AM and PM Peaks. The increase in actual running times along the route may have led operators to depart earlier on average to avoid being late at their destination.

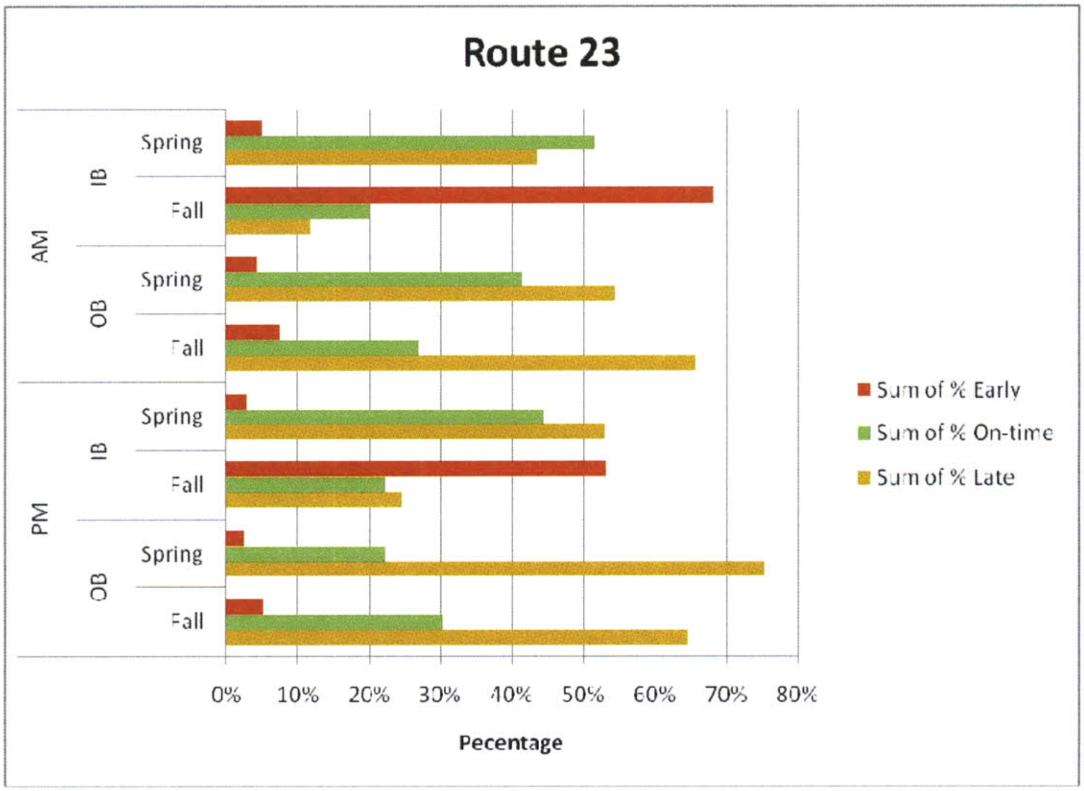

Figure 4-12: Terminal Departure Time Adherence – Route 23

b) Headway Ratio Distribution

Figure 4-13, provided on the following page, display Route 23 headway ratio distributions showing how headway ratios evolve as the bus moves along the route.

The analysis of headway ratio distribution provides mixed results. In the inbound direction in both the AM and PM Peak periods there is a deterioration of headway adherence at the Ashmont terminal. This is likely to be linked to known roadway construction which was underway during Fall 09 at the terminal. However, there are noticeable improvements in the headway distribution at the second observed point, Codman Square, which may be explained by successful corrective supervision strategies. In the outbound direction during the AM Peak period there is a slight deterioration of the headway distribution along the entire route, which may be due to an increase in the proportion of late departures. Headway ratios in the outbound direction during the PM Peak period remain unchanged.

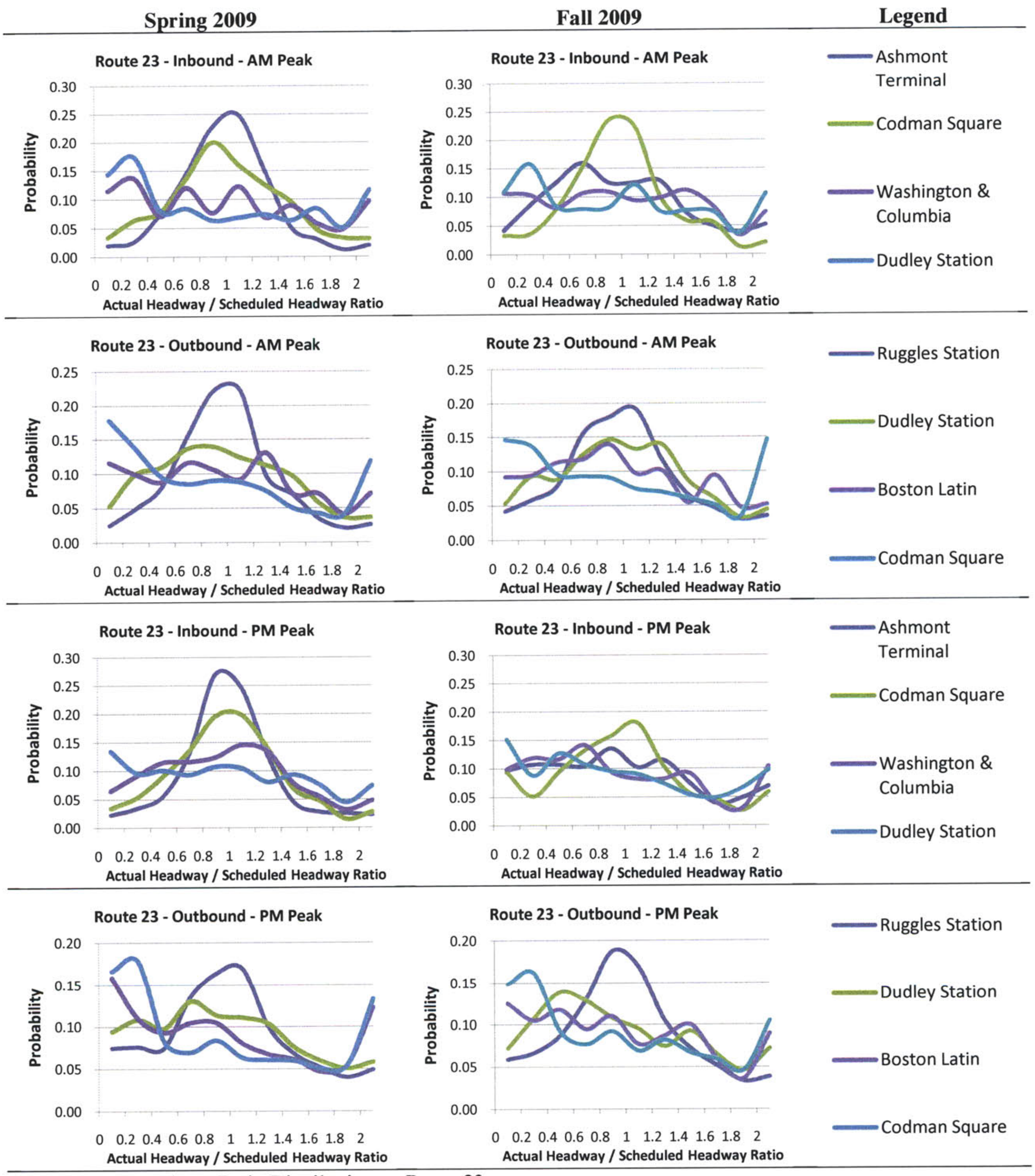

Figure 4-13: Headway Ratio Distributions – Route 23

c) Expected Wait Times

Figure 4-14, provided below, displays Route 23 expected customer wait times as experienced at the median boarding stop along the route (Codman Square for inbound direction and Dudley for outbound).

Given that cycle time was unchanged, we expected that variability of operations would remain unchanged, which is confirmed through an analysis of the expected wait time: expected waiting times increased or decreased due solely to an increase or decrease of scheduled wait times; excess wait time remained unchanged. As expected, the 95th percentile also remained largely unchanged.

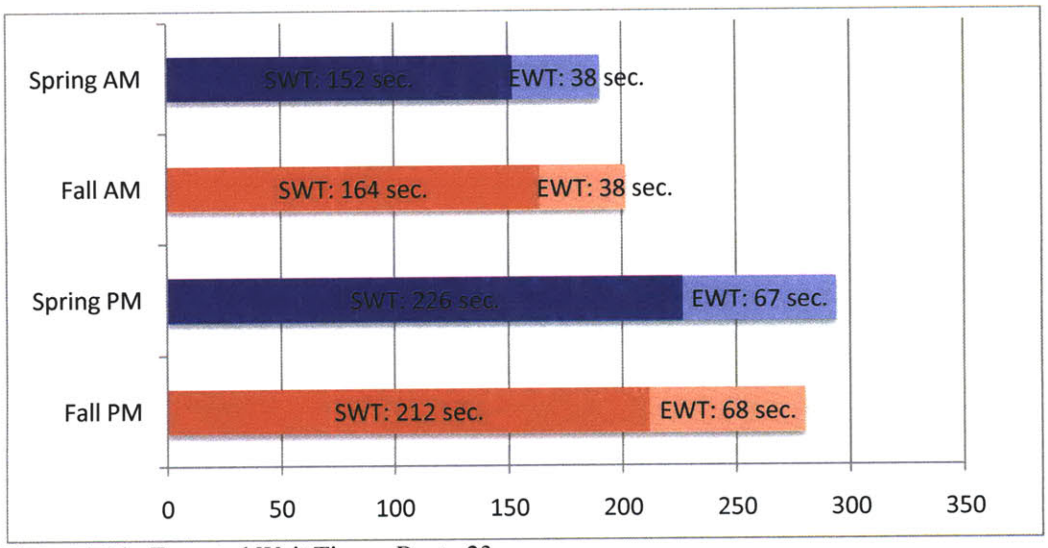

Figure 4-14: Expected Wait Time – Route 23

These results are further demonstrated through an analysis of the one-third of all days showing worst performance, displayed below as Figure 4-15. Excess wait times remain largely unchanged from Spring 09 to Fall 09. The changes in expected wait times are solely due to increased or decreased service frequency.

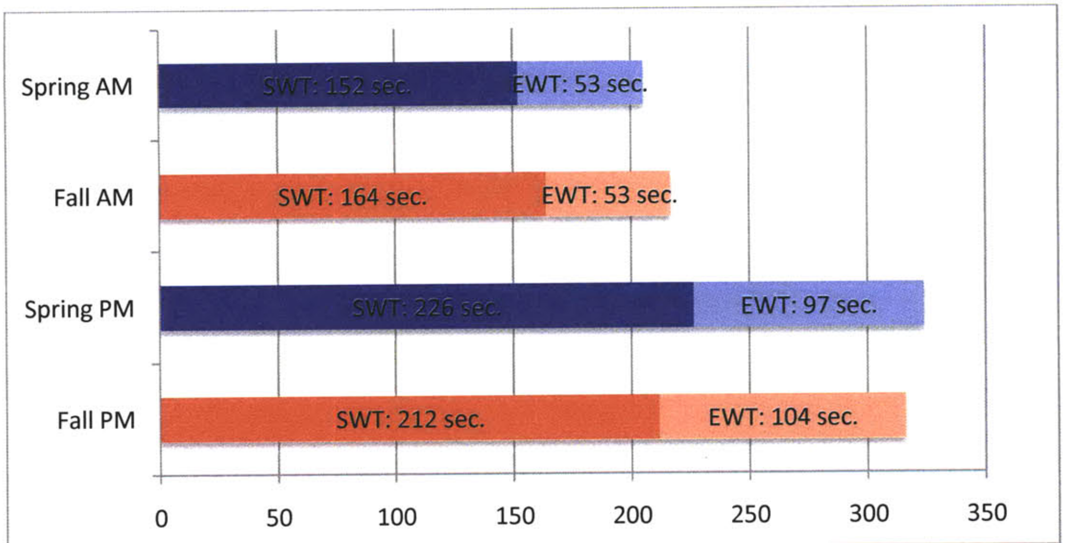

Figure 4-15: Expected Wait Time – Route 23 – One-Third Worst Days

4.3.3 Cost Benefit Analysis

Through KBRI, the MBTA deployed additional resources on Route 23 in the form of one additional bus in the PM Peak period. The MBTA also removed a bus from the route in the AM Peak period. To assess how well these resources were utilized, a cost benefit analysis is provided below.

Expected waiting time savings for Route 23, as shown in the previous section, are as follows:

- AM Peak: The average customer experienced 12 seconds more wait time and 72 seconds more in-vehicle travel time.

- PM Peak: The average customer experienced 13 seconds less wait time and 50 seconds more in-vehicle travel time.

Ridership levels for Route 23 (CTPS, 2007), are as follows:

- AM Peak: 1833 riders
- PM Peak: 2167 riders

Using these data and weighting ridership levels and wait time savings by direction (inbound and outbound), we can estimate costs and benefits to be:

Time Period	Additional Funding	Daily Change in Wait Time for All Customers	Daily Change in In-Vehicle-Travel Time for All Customers
AM Peak	$261	5.5 hours per day	42.5 hours per day
PM Peak	$326	-8.3 hours per day	26.9 hours per day

Table 4-6: Cost Benefit Analysis – Route 23

4.3.4 Overall Assessment

Through KBRI, the MBTA was able to save 8.3 hours of customer wait time per day at an average cost of $32.29 per hour in the PM Peak. In the AM Peak, the removal of a bus resulted in increased customer wait time of 5.5 hours with savings to the MBTA of $47.43 per hour. The net result is a customer savings of 2.8 hours of wait time per day at a cost of $23.29 per hour. The ongoing construction at Ashmont explains the large increase in in-vehicle travel time experienced by customers, therefore it is not considered in the KBRI performance evaluation.

Due to the efficient reallocation of resources and associated wait time savings, we classify KBRI results on Route 15 as a ‘Moderate Success’.

4.4 Route 28 Performance Analysis

Route 28 is the 6th highest ridership bus route in the MBTA system, providing service between Ruggles Station and Mattapan, carrying 10,607 passengers per average weekday (MBTA, 2009c). Inbound service is defined as being from Mattapan to Ruggles Station. The following section provides an analysis of expected and actual impacts of KBRI on bus service performance.

4.4.1 Route Schedule Adjustments and Performance Expectations

KRBI schedule changes for Route 28 are summarized in Table 4-7, provided below. Expected impacts of these changes on service performance are outlined below, based on the cause-and-effect relationships described in Chapter 3.

- AM Peak: Cycle time was increased slightly from 95 to 98 minutes, with running and recovery time mix adjusted. Outbound (to Mattapan), running time was increased from 36 to 38 minutes while recovery time at the Mattapan terminal was increased from 11 to 12 minutes. Inbound (to Ruggles), running time was reduced from 40 to 36 minutes while recovery time at Ruggles was increased from 8 to 12 minutes.

- PM Peak: Cycle time was reduced from 122 to 112 minutes, with running and recovery time mix adjusted. Headways were reduced from 10 to 9.5 minutes. Outbound, running time was reduced from 55 to 51 minutes while recovery time at the Mattapan terminal was increased from 10 to 11 minutes. Inbound, running time remained constant at 38 minutes and recovery time at Ruggles was reduced from 19 to 12 minutes.

Time Period	Major Route Changes	Expectations (Cause-Effect)
AM Peak	No major changes (cycle time was increased from 95 to 98 minutes, +3%)	No major changes were implemented. We may see slight decrease in performance due to the reallocation of cycle time: decreased running time and increased recovery time. More restrictive running time may have negative impacts on the variability of the headway ratios and/or running times. We would see this demonstrated through increased excess customer wait time.
PM Peak	Cycle time was decreased from 122 to 112 minutes (-8%), with running time reduced from 93 to 89 minutes (-4%) Headways reduced from 10 to 9 minutes (-10%).	Cycle time is reduced to increase service frequency (type 4 change). The change - reduced cycle time and headway - indicate that MBTA schedule planners felt the Spring 09 schedule had excessive slack time and therefore could allow for increased service frequency. If sufficient slack time existed, the increase in excess wait time should be limited. If not, we expect a significant increase in excess wait time and headway ratio variability due to decreased running time.

Table 4-7: Route Changes and Associated Expected Impacts – Route 28

4.4.2 Route Performance Results and Analysis

In this section, the impacts of KBRI on service performance for Route 28 are demonstrated through the application of the primary metrics - Median Running Time and Expected Wait Time – as well as headway ratio distributions to show bus performance at different locations along the route.

a) Median Running Time

In the AM Peak, although the scheduled running time was reduced slightly, we see actual median running times and 95th percentile running times increasing. In the PM Peak, the scheduled running time and the scheduled recovery time were reduced, which allowed for an increase in service frequency. Actual median running times remained largely unchanged, increasing by only 1.8%. This may indicate that MBTA schedule planners made good use of excess cycle time to provide this increased service frequency. This will be further confirmed through an analysis of headway variability and expected wait time.

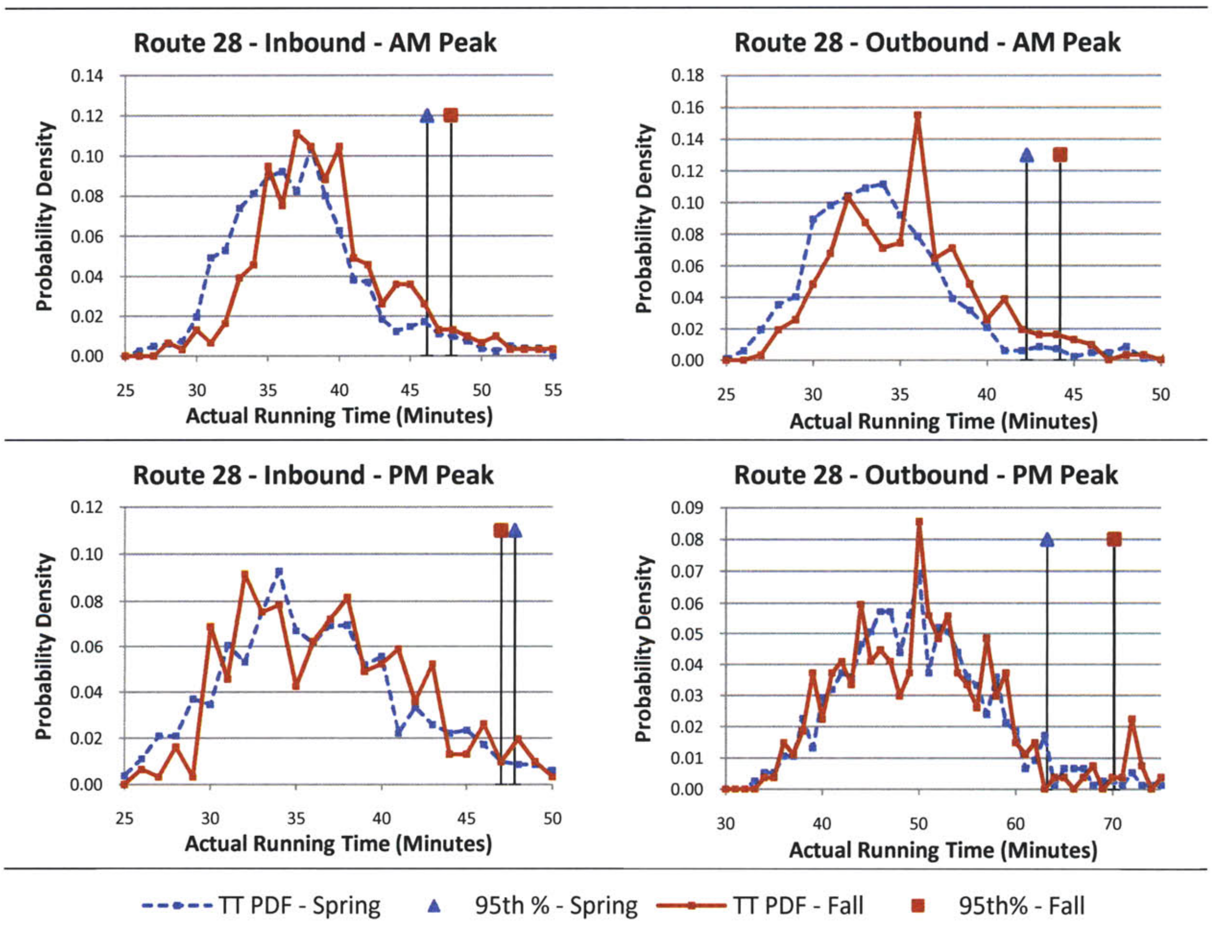

Figure 4-16: Running Time Distributions – Route 28

b) Headway Ratio Distributions

Figure 4-17 displays Route 28 headway ratio distributions showing how headway ratios evolve as the bus moves along the route.

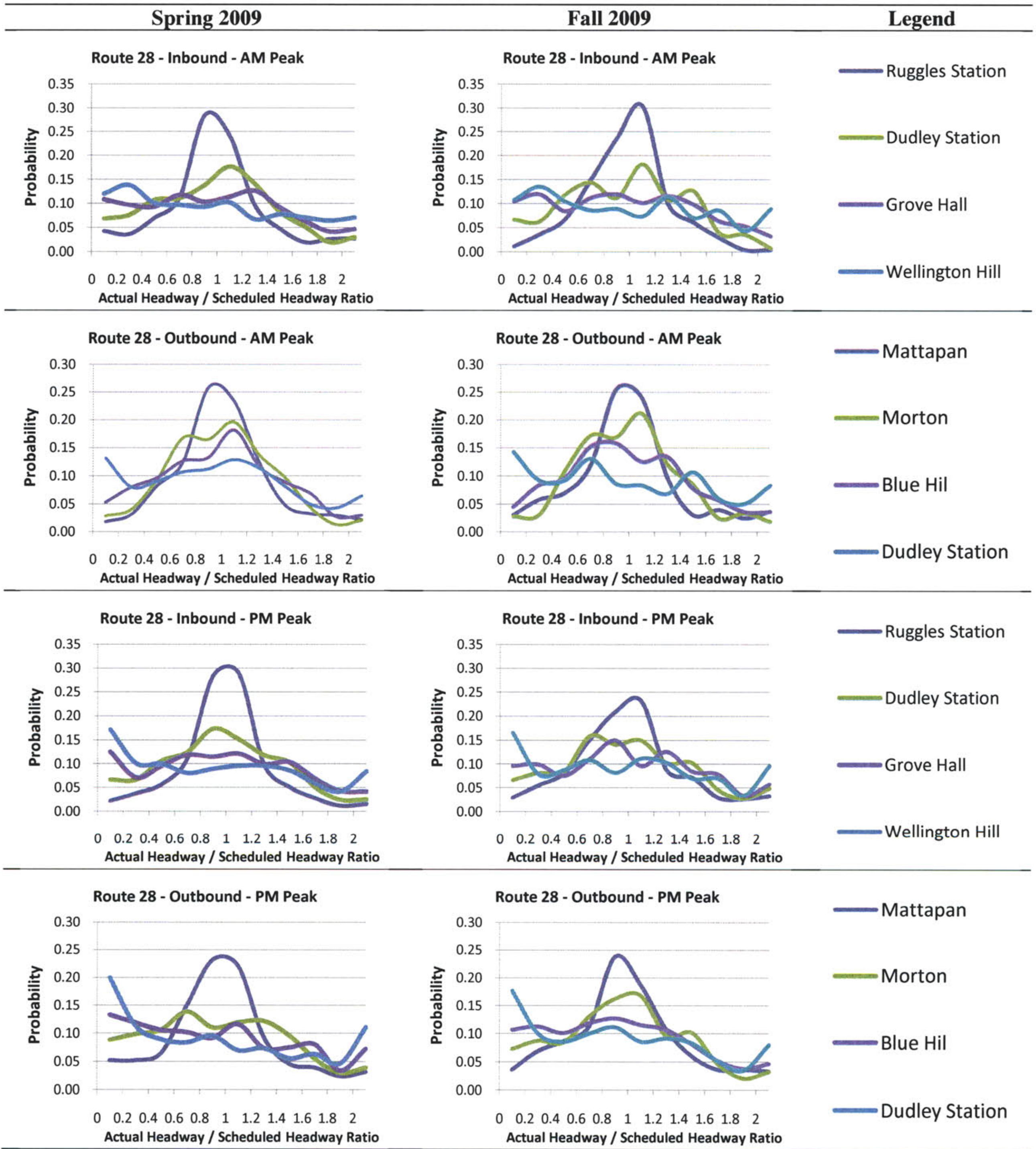

Figure 4-17: Headway Ratio Distributions – Route 28

The analysis shows that headways were largely unaffected by schedule changes along the route. We expected to see increased headway variability in the AM and PM Peaks due to the reduced running times, which is not the case as shown above.

c) Expected Wait Times

Figure 4-18 displays Route 28 expected customer wait times as experienced at the median boarding stop along the route (Morton Street for inbound direction and Dudley for outbound). Expected wait times were largely unaffected in the AM Peak, but were reduced in the PM Peak. In the AM Peak, the slight adjustment to the running time and recovery time mix did not significantly impact operations variability: excess wait time remains unchanged. In the PM Peak, the reduction in cycle time led to an expected savings in scheduled wait time but also a savings in excess wait time. This confirms that schedule planners made good use of the excessive cycle time that was available.

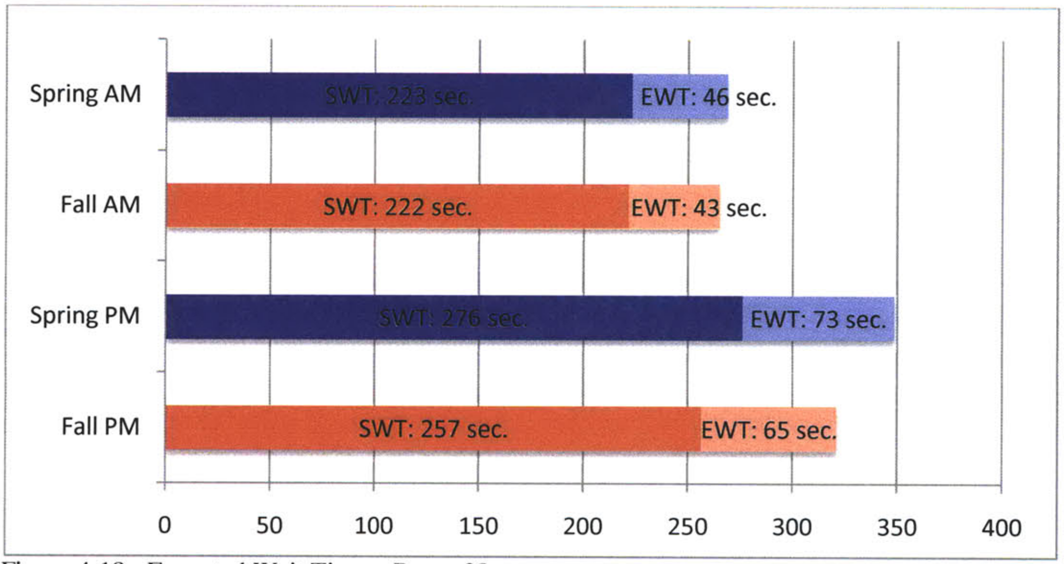

Figure 4-18: Expected Wait Time – Route 28

Although the excessive cycle time was put to good use in the form of increased service frequency as demonstrated above, a further analysis of the expected wait time during the one-third of all days showing worst performance will indicate whether robustness was positively affected by the changes.

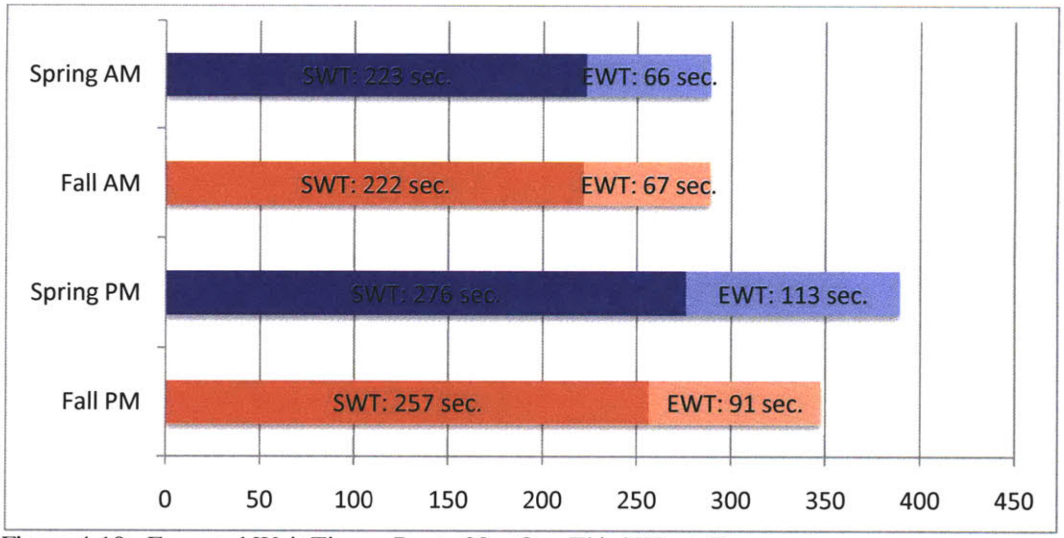

Figure 4-19: Expected Wait Time – Route 28 – One-Third Worst Days

Figure 4-19 shows that operations still maintained enough slack time to allow for continued reductions in excess wait time during these worst days.

4.4.3 Cost Benefit Analysis

Through KBRI, the MBTA did not deploy additional resources on Route 28. A cost-benefit analysis cannot be performed, however for the purpose of the analysis total time savings will still be shown here.

Expected waiting time savings for Route 28, as shown in the previous section, are as follows:

- AM Peak: The average customer experienced 4 seconds less wait time and 27 seconds more in-vehicle travel time.

- PM Peak: The average customer experienced 27 seconds less wait time and 11 seconds more in-vehicle travel time.

Ridership levels for Route 28 (CTPS, 2007), are as follows:

- AM Peak: 1550 riders
- PM Peak: 1858 riders

Using these data and weighting ridership levels and wait time savings by direction (inbound and outbound), we can estimate costs and benefits to be:

Time Period	Additional Funding	Daily Change in Wait Time for All Customers	Daily Change in In-Vehicle-Travel Time for All Customers
AM Peak	$0	-1.9 hours per day	11.6 hours per day
PM Peak	$0	-14.9 hours per day	5.6 hours per day

Table 4-8: Cost Benefit Analysis – Route 28

4.4.4 Overall Assessment

KBRI saved 16.8 hours of expected customer wait time per day, at no cost. This result is due to efficient schedule adjustments primarily in the PM Peak, where excessive cycle time was converted into increased service frequency without adding resources (cycle time and headways were decreased).

As previously mentioned, wait time is commonly valued at twice that of in-vehicle travel time. On this basis, the gains to wait time outweigh the loss in in-vehicle travel time. Therefore, we classify KBRI results on Route 28 as a 'High Success'.

4.5 Route 66 Performance Analysis

Route 66 is the 5th highest ridership bus route in the MBTA system, providing service between Cambridge and Boston, carrying 11,088 passengers per average weekday (MBTA, 2009c). Inbound service is defined as being from Harvard Square to Dudley Square. The following section provides an analysis of actual and expected impacts of KBRI on bus service performance.

4.5.1 Route Schedule Adjustments and Performance Expectations

KRBI schedule changes for Route 66 are summarized in Table 4-9, below. Expected impacts of these changes on service performance are outlined below, based on the cause-and-effect relationships described in Chapter 3.

- AM Peak: One bus was added to the route, allowing for a decrease in headways from 9 to 8.5 minutes and increase in cycle time from 119 to 122. Outbound (to Harvard), running time was reduced from 54 to 52 minutes while recovery time at the Harvard terminal was increased from 4 to 11. Inbound (to Dudley), running time was reduced from 50 to 47 minutes while recovery time at Dudley was increased from 11 to 12.

- PM Peak: Cycle time was reduced from 133 to 126 minutes, with running time and recovery time mix also adjusted. Headways were reduced from 10 to 9.5 minutes. Outbound, running time was increased from 54 to 56 minutes while recovery time at the Harvard terminal was decreased from 13 to 7. Inbound, running time was increased from 49 to 51 minutes while recovery time at Dudley was decreased from 17 to 12.

Time Period	Major Route Changes	Expectations (Cause-Effect)
AM Peak	Number of buses increased from 13 to 14 (+8%) Cycle time increased from 119 to 122 minutes (+3%) with running time decreased from 104 to 99 minutes (-5%) Headways decreased from 9 to 8.5 minutes (-5%).	Resources were added to increase service frequency (type 3 change). The increase in cycle time provides slack time to operations; however the allocation favors recovery time, which, as discussed previously, may not be efficient. Total expected customer wait time should decrease due to a combination of increased service frequency (headways reduced) and this reduction in variability.
PM Peak	Cycle time decreased from 133 to 126 minutes (-5%), with running time increased from 103 to 107 minutes (+4%). Headways reduced from 10 to 9.5 minutes (-5%).	Cycle time is reduced to increase service frequency (type 4 change). The change - reduced cycle time and headway - indicates that MBTA schedule planners felt the Spring 09 schedule had excessive slack time and therefore could allow for increased service frequency. If sufficient slack time existed, the increase in excess wait time should be limited. If not, we expect an increase in excess wait time due to increased headway variability.

Table 4-9: Route Changes and Associated Expected Impacts – Route 66

4.5.2 Route Performance Results and Analysis

In this section, the impacts of KBRI on service performance for Route 66 are demonstrated through the application of the primary metrics - Median Running Time and Expected Wait Time - as well as headway ratio distributions to show bus performance at different locations along the route.

a) Median Running Time

Figure 4-20, provided below, displays Route 66 running time distributions showing no significant changes between Spring 09 and Fall 09 observation periods. In the AM Peak, scheduled running times were reduced, however actual median running times just slightly increased (by 3.2%). In the PM Peak, the scheduled running times were increased; however, actual mean running times remained largely unchanged (increased by 0.3%)

In general, the change in running times between the two observation periods is small and is within the expected range of increase that can be attributed to change in weather conditions between Spring 09 and Fall 09. AVL data does not allow for the isolation of external factors that may be influencing running times, therefore we cannot conclude on the effects of KBRI on running times.

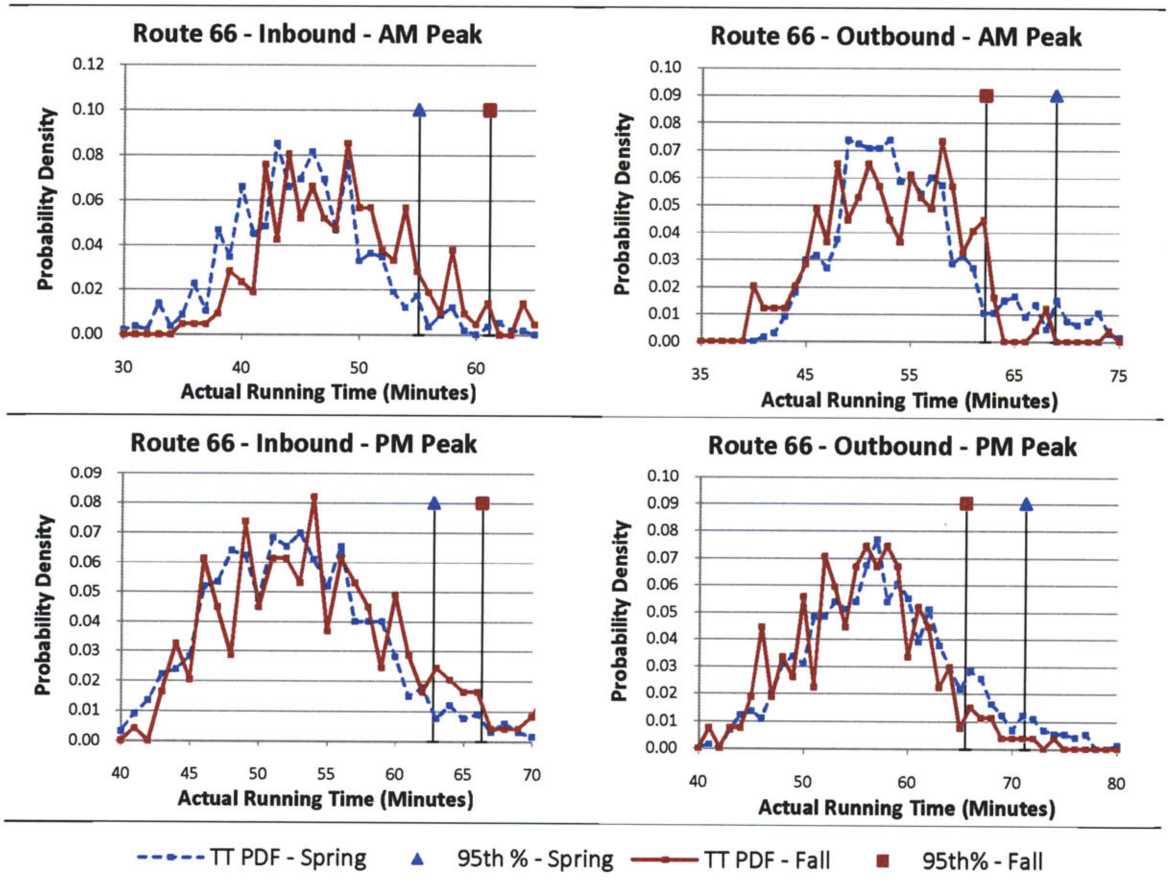

Figure 4-20: Running Time Distributions – Route 66

Figure 4-21, provided below, shows departure time adherence at the terminals for Route 66. We notice an increase in the proportion of late departures from the Harvard terminal during the PM Peak. As expected, the attempt to increase service frequency through reduced cycle time led to scheduled cycle times that are more restrictive. These late departures may have an adverse effect on headway ratios along the entire route.

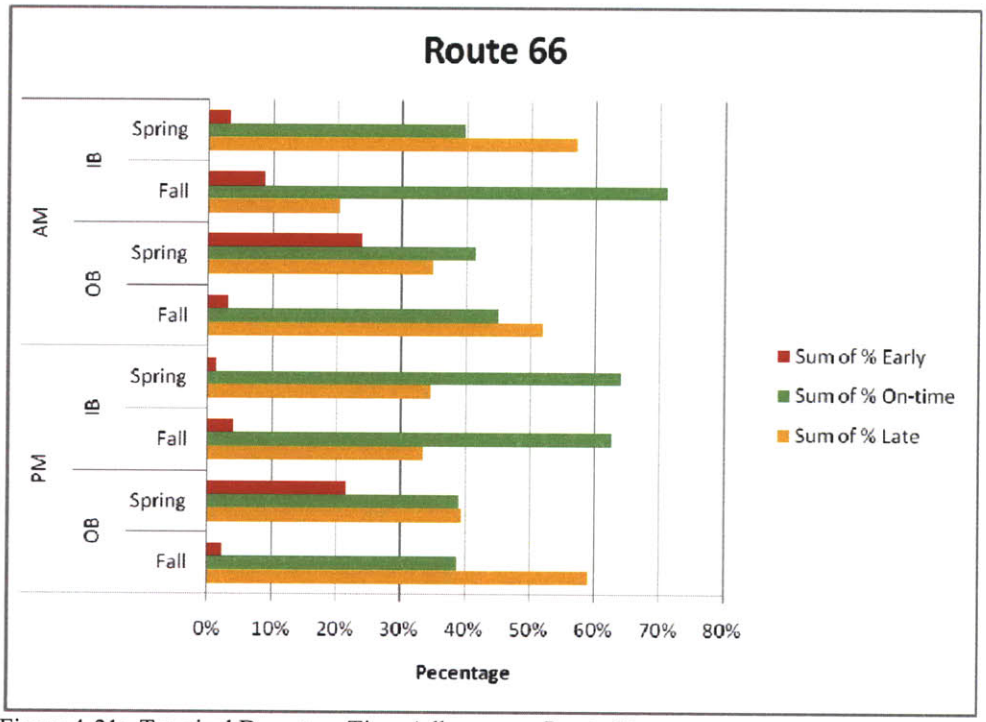

Figure 4-21: Terminal Departure Time Adherence – Route 66

b) Headway Ratio Distributions

Figure 4-22, provided on the following page, displays Route 66 headway ratio distributions showing how headway ratios evolve as the bus moves along the route.

In the AM Peak, headway ratio distributions are improved, mostly in the inbound direction where headway ratios were improved through Brigham Circle (three fourths along the route). This can be attributed to the increased cycle time. A contributing factor, as shown above, is the improvement noted in the terminal departure time adherence.

In the PM Peak, headway ratio distributions deteriorated slightly along the route. This can be attributed to the decrease in cycle time and, more specifically, the sharp reduction in recovery time.

Spring 2009	Fall 2009	Legend

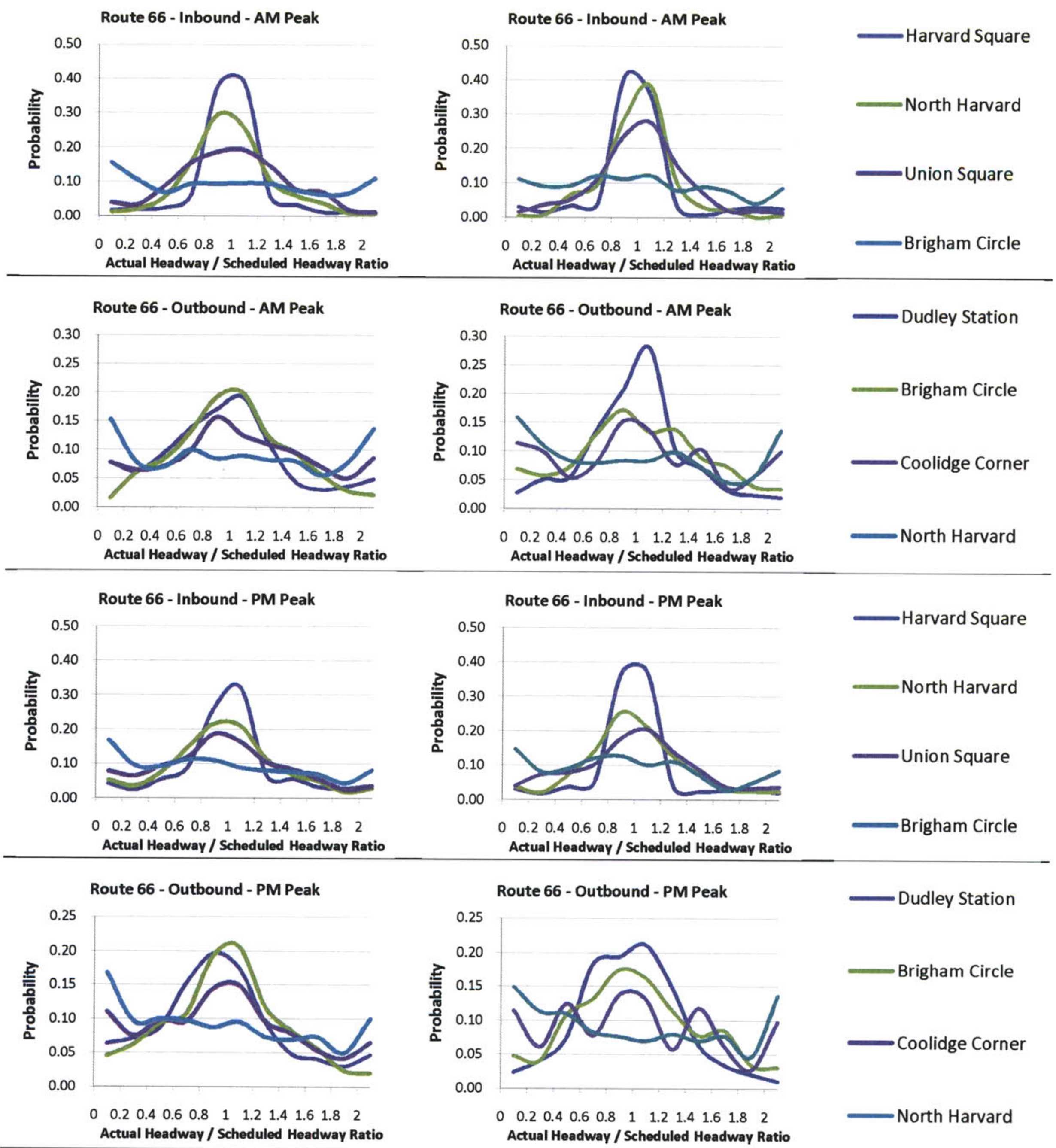

Figure 4-22: Headway Ratio Distributions – Route 66

c) Expected Wait Times

Figure 4-23, provided below, displays Route 66 expected customer wait times as experienced at the median boarding stop along the route (Union Square for inbound direction and Brigham Circle for outbound).

In the AM Peak, the additional bus allowed the MBTA to increase service frequency, which we see below through a reduction in the scheduled wait time. While this goal of increasing service frequency was achieved, the MBTA may have missed an opportunity to improve service reliability. Excess wait time remains largely unchanged; therefore, expected wait time decreases only slightly.

In the PM Peak, the reduction in cycle time without additional resources did not achieve the desired outcome of improving performance. The slight increase in running time had no positive effect on reliability due to the larger decrease in recovery time. Overall, the excess wait time has increased by 8 seconds. The reduction in headway led to a decrease in scheduled wait time, but a larger increase in excess wait time resulted in an overall increase of expected wait time.

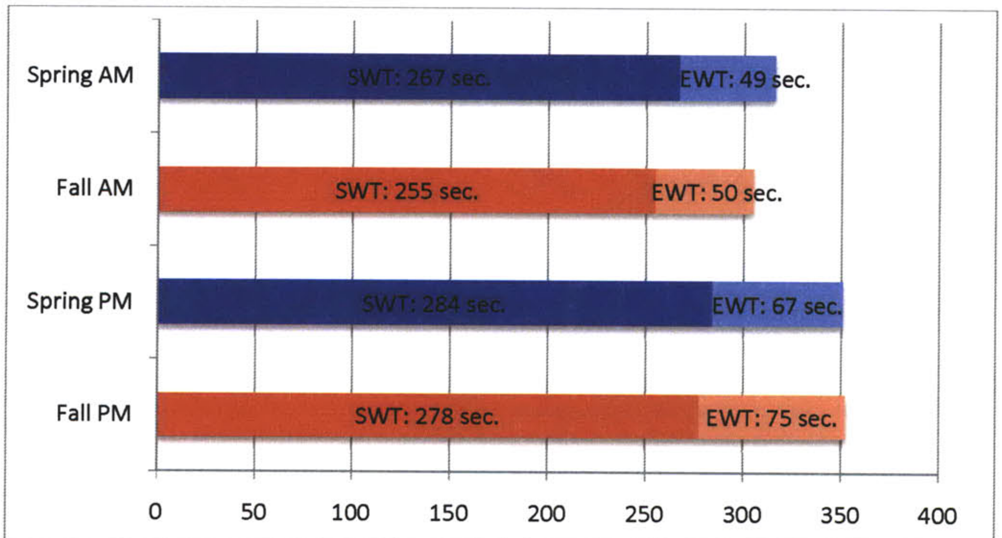

Figure 4-23: Expected Wait Time – Route 66

A further analysis of the expected wait time during the one-third of all days showing worst performance, provided below as Figure 4-24, indicates the same trends, but magnified.

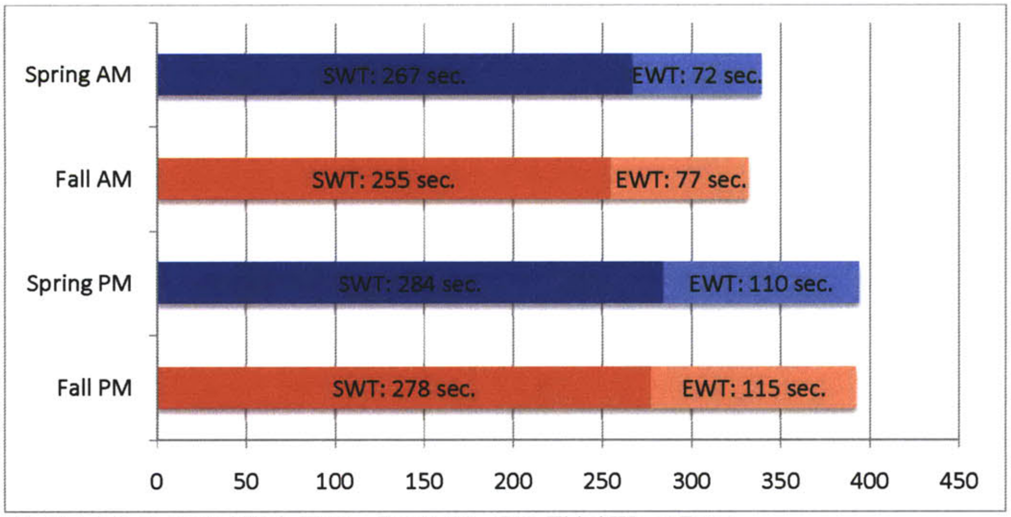

Figure 4-24: Expected Wait Time – Route 66 – One-Third Worst Days

4.5.3 Cost Benefit Analysis

Through KBRI, the MBTA deployed additional resources on Route 66 in the form of one additional bus in the AM Peak in an effort to improve performance. To assess how well these resources were utilized, a cost benefit analysis is provided below.

Expected waiting time savings for Route 66, as shown in the previous section, are as follows:

- AM Peak: The average customer experienced 11 seconds less wait time and 23 seconds more in-vehicle travel time.
- PM Peak: The average customer experienced 2 seconds more wait time and 2 seconds more in-vehicle travel time.

Ridership levels for Route 66 (CTPS, 2007), are as follows:

- AM Peak: 1759 riders
- PM Peak: 2125 riders

Using these data and weighting ridership levels and wait time savings by direction (inbound and outbound), we can estimate costs and benefits to be:

Time Period	Additional Funding	Daily Change in Wait Time for All Customers	Daily Change in In-Vehicle-Travel Time for All Customers
AM Peak	$261	-4.9 hours	14.5 hours
PM Peak	$0	0.5 hour	0.8 hour

Table 4-10: Cost Benefit Analysis – Route 66

4.5.4 Overall Assessment

KBRI saved 4.9 hours of expected customer wait time per day at a cost of $53.24 per hour saved. This result is due to the application of one additional bus to increase service frequency in the AM Peak. However, the success was limited because the additional cycle time resulted in an increased in-vehicle travel time and was not used to improve service reliability (cycle time increased but running time decreased).

Therefore, we classify KBRI results on Route 66 as a 'Moderate Success'.

5. QUEUE JUMPING ANALYSIS - ROUTE 1

Route 1 has been selected for further analysis due to its high ridership and proximity to MIT. Based on AVL analysis and field observations, we provide analysis of potential improvements along the route. Focus is given to segments of the route where highest delays are observed in the AVL data. In these segments, we selected a few traffic intersections where there might be greater potential gains from implementation of queue-jumping lanes.

In January 2010, the Central Transportation Planning Staff released findings regarding delay times along selected bus routes as well as recommendations for future route-specific initiatives (CTPS, 2010a). In particular, CTPS focused on providing Queue-jumping and other forms of Traffic Signal Prioritization (TSP) such as green extensions, red truncations, bus-only signals, and signal coordination. Based on our analysis, this chapter investigates some of the CTPS findings regarding queue-jumping.

Queue-jumping lanes allow a bus to bypass queued vehicles at a red traffic signal and depart first when the signal turns green. They can be even more effective when implemented in conjunction with TSP. Most require elimination of existing traffic or parking lanes although they can also be combined with right-turning traffic. Queue jumping lane benefits are related to the length of the dedicated lane and the length of the queue that is being bypassed. In order to gain noticeable benefits the queues and lanes must be several hundred feet long in order skip entire traffic signal cycles. However, this often requires sacrificing a significant number of parking spaces.

If the queue is short enough to be entirely released during a single green phase the potential savings from implementing a queue jump are calculated as follows.

$$Queue\ Jump\ Savings = Queue\ Travel\ Savings + Red\ Phase\ Dwell\ Time\ Savings \tag{4}$$

$$\begin{aligned} Queue\ Travel\ Savings \\ &= Probability\ of\ Red\ Phase \\ &* Probability\ of\ accessing\ Queue\ Jump\ \ from\ Queue \\ &* Average\ Queue\ Position * Intersection\ Release\ Rate \end{aligned} \tag{4.1}$$

$$\begin{aligned} Red\ Phase\ Dwell\ Time\ Savings \\ &= Probability\ of\ Red\ Phase \\ &* Probability\ of\ accessing\ Queue\ Jump\ \ from\ Queue * Dwell\ Time \\ &* Probability\ (Dwell\ Time < Red\ Wait\ Time) \end{aligned} \tag{4.2}$$

As already mentioned, greater benefits can be gained if the queue is not entirely released during a green phase as the queue jump would allow to save an entire cycle. None of the observed intersections had queues that were not entirely released so there were no time savings from skipping a red phase. Hence, the above formula was used to calculate the time savings for all the following analyses.

Furthermore, CTPS recommended additional forms of Transportation Signal Prioritization (CTPS, 2010a). TSP gives buses priority at traffic signals over private vehicles. Using the current AVL GPS system to locate buses as they approach traffic signals, TSP can then extend green time when it senses a bus approaching, or reduce red time when one joins the queue stopped at a red light. TSP allows buses to move through intersections faster, and more efficiently. TSP can also improve schedule adherence and headways variability by giving priority only to buses that are behind schedule or being closely followed. An analysis of potential TSP implementations would require micro-simulation based on data that was not made available. Thus, TSP was not considered in the scope of this project. However, TSP may provide operational improvements and should be studied further.

Three months of AVL data in Spring 2009 collected at nine different locations allowed for a travel time analysis of each of the corresponding eight route segments. The Spring 2009 data was chosen for this analysis over the Fall 2009 data because the CTPS Key Bus Route Studies were based on data from the same time period (CTPS, 2010a). The list of AVL data collection points and the segment lengths are provided below in Tables 5-2 and 5-3. To analyze schedule adherence along the segments of Route 1, the actual operations were aggregated by trip and compared with the schedule at the nine points on the route. The schedule is designed to accommodate general traffic conditions along the entire route as well as dwell times at each bus stop.

An analysis was conducted to measure the driver's ability to adhere to the schedule as well as to identify the specific segments along the route where schedule deviations most frequently occurred, impacting operational service reliability. First, schedule and actual travel times and speeds were calculated for all the segments. This allowed the slowest and slower than scheduled segments to be identified. Once the slowest segments were identified, the intersections within those segments that were recommended for queue jumping by CTPS were analyzed in more detail. Field observations were made at each potential queue jumping locations measuring the traffic signal timings, the average queue lengths and general traffic conditions. Each selected intersection was observed once during the chosen peak period.

For this analysis only the inbound AM and the outbound PM directions were analyzed. The AM and PM peaks have similar ridership numbers in both directions as shown in Table 5-1, so a different direction was chosen for each period in order to analyze all stops on the route.

Direction	**AM Peak**	**PM Peak**
Inbound	727	1348
Outbound	926	1460

Table 5-1: Average Peak Period Ridership – Route 1

Segment Startpoint	Segment Endpoint	Segment Distance (miles)	Distance from Terminal (miles)
Harvard Holyoke Gate	Mass Ave & Putnam	0.86	0.86
Mass Ave & Putnam	Central Square	0.67	1.53
Central Square	MIT	0.61	2.14
MIT	Mass Ave @ Newbury	0.82	2.96
Mass Ave @ Newbury	Mass Ave Station	0.51	3.47
Mass Ave Station	Massachusetts Ave @ Washington	0.50	3.96
Massachusetts Ave @ Washington	Melnea Cass Blvd @ Washington St	1.07	5.04
Melnea Cass Blvd @ Washington St	Dudley Station	0.32	5.35

Table 5-2: Stop Locations and Distances – Route 1 – Inbound Direction

Segment Startpoint	Segment Endpoint	Segment Distance (miles)	Distance from Terminal (miles)
Dudley Station	Melnea Cass Blvd @ Washington Street	0.32	0.32
Melnea Cass Blvd @ Washington Street	Mass Ave @ Washington Street	1.39	1.07
Mass Ave @ Washington Street	Mass Ave Station	1.89	0.50
Mass Ave Station	Mass Ave @ Newbury	2.40	0.51
Mass Ave @ Newbury	MIT	3.22	0.82
MIT	Central Square	3.83	0.61
Central Square	Mass Ave & Putnam	4.49	0.67
Mass Ave & Putnam	Harvard Gate	5.35	0.86

Table 5-3: Stop Locations and Distances – Route 1 – Outbound Direction

The following sections will identify slow travel segments in the inbound and outbound directions during the AM and PM Peak periods, respectively. This will be followed by identification and analysis of potential queue-jumping locations and conclusions drawn about the effectiveness of queue-jumping strategies at these locations.

5.1 Inbound AM Analysis

First, the scheduled and actual travel times along the eight segments of Route 1 were calculated as shown in Table 5-4. Examining the actual segment speeds shows that there are two areas (three segments shown in Figure 5-1) that operate at noticeably slower average speeds than on the rest of the route. Although on some segments the slow speeds have already been accommodated for in the schedule. The first area consists of the adjacent segments in Cambridge between Massachusetts Avenue & Putnam Street and MIT, which operates at an average speed of 7.1 mph. The second area is between Massachusetts Avenue & Newbury Street and Massachusetts Avenue Station, which operates at an average speed of 6.4 mph. The remaining sections of the route operate at varying speeds ranging from 8 to 11 mph. These identified areas may provide the most potential for improvement by analyzing traffic operations around Central Square and between Massachusetts Avenue & Newbury Street and Massachusetts Avenue Station.

Segment		Segment Travel Time (minutes)		Segment Speed (MPH)	
Startpoint	**Endpoint**	**Scheduled**	**Actual**	**Scheduled**	**Actual**
Harvard Holyoke Gate	Mass Ave & Putnam	4.5	7.0	11.4	7.3
Mass Ave & Putnam	Central Square	4.2	5.2	9.5	7.6
Central Square	MIT	5.0	5.4	7.3	6.7
MIT	Mass Ave @ Newbury	4.0	4.8	12.3	10.2
Mass Ave @ Newbury	Mass Ave Station	4.6	4.8	6.6	6.4
Mass Ave Station	Massachusetts Ave @ Washington	4.0	3.8	7.5	7.9
Massachusetts Ave @ Washington	Melnea Cass Blvd @ Washington St	4.6	5.7	14.0	11.2

Segment		Segment Travel Time (minutes)		Segment Speed (MPH)	
Startpoint	**Endpoint**	**Scheduled**	**Actual**	**Scheduled**	**Actual**
Melnea Cass Blvd @ Washington St	Dudley Station	4.6	1.1	4.1	17.4

Table 5-4: Segment Travel Times and Speeds – Route 1 – Inbound Direction

The following Figure 5-1 shows the three identified slow segments, along with intersections that were identified as potential locations for queue-jumping.

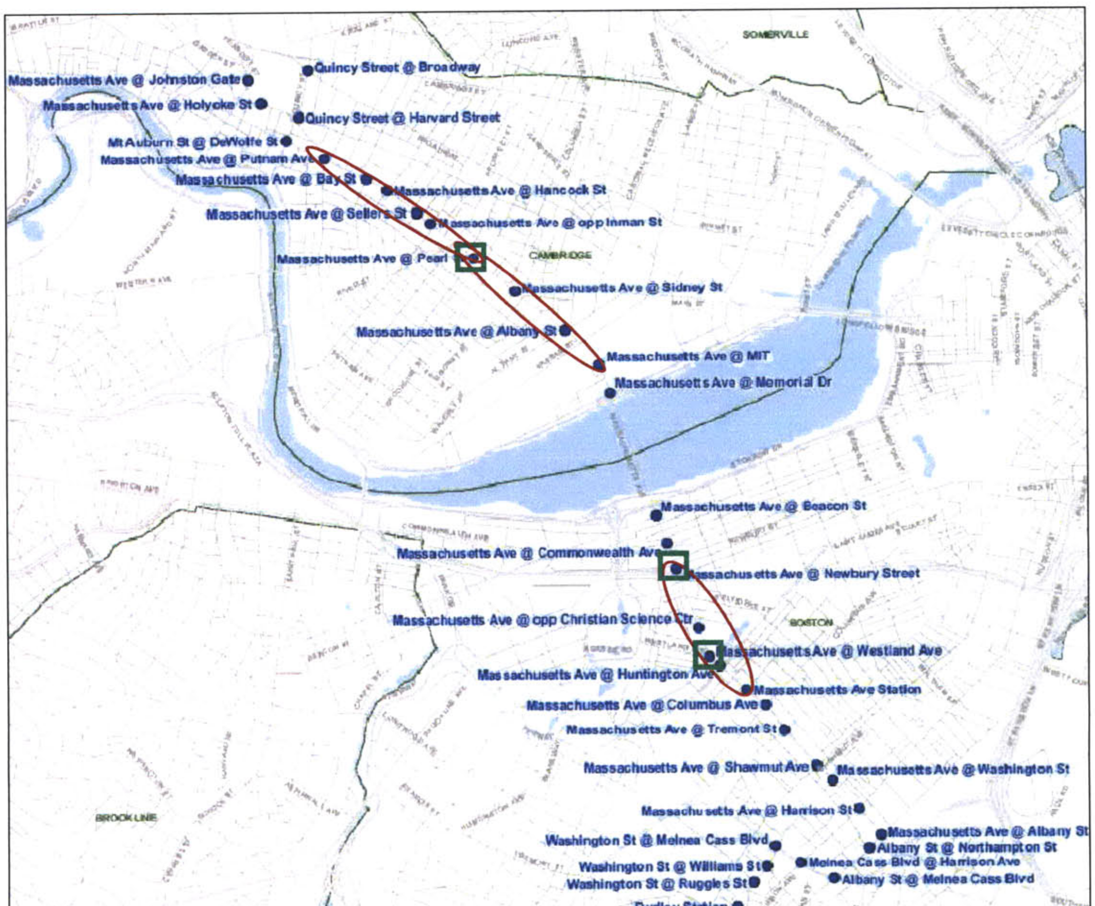

Figure 5-1: Stop Location Map – Route 1 – Inbound Direction

The Time-Space diagram in Figure 5-2 along with Table 5-5 below clearly demonstrate the route's operations and deviations from schedule. Due to location of AVL cordon sensors at the terminals, the initial and final segment travel times and speeds may be inaccurate. Therefore these segments were not analyzed further in this section of the report. Aside from data inaccuracies at these two terminal points, on average the route operates behind schedule with multiple segments showing delays in the range of 0.8 to 1.2 minutes. Aggregating the actual travel times of all the non-terminal segments shows that the average actual travel time exceeds the scheduled travel time by 3.4 minutes between the second and penultimate stops. This indicates that the current traffic operations have not been fully accounted for in the route's schedule. Schedule adjustments and traffic operation strategies should therefore be considered to correct these deviations.

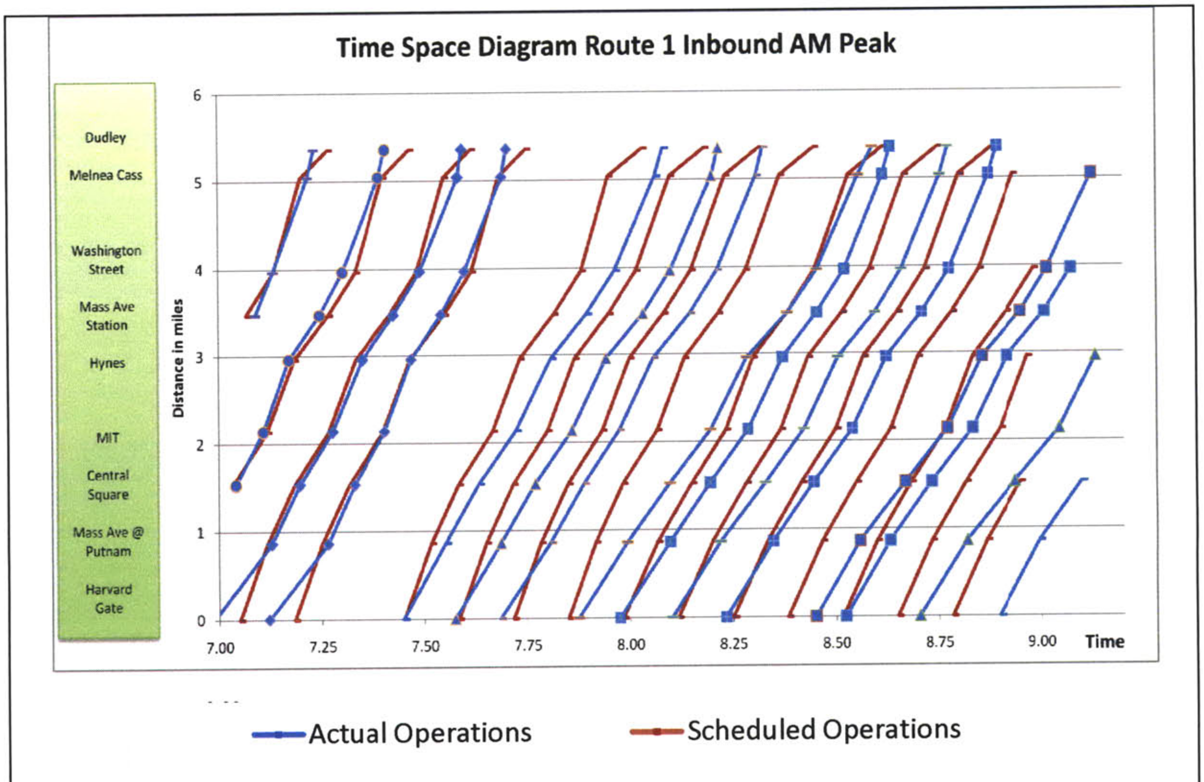

Figure 5-2: Time-Space Diagram Plot – Route 1 – AM Peak - Inbound Direction

Segment Startpoint	Segment Endpoint	Actual Travel Time – Scheduled Travel Time (minutes)
Harvard Holyoke Gate	Mass Ave & Putnam	2.5
Mass Ave & Putnam	Central Square	1.0
Central Square	MIT	0.4
MIT	Mass Ave @ Newbury	0.8
Mass Ave @ Newbury	Mass Ave Station	0.2
Mass Ave Station	Massachusetts Ave @ Washington	-0.2
Massachusetts Ave @ Washington	Melnea Cass Blvd @ Washington St	1.2
Melnea Cass Blvd @ Washington St	Dudley Station	-3.5

Table 5-5: Schedule Deviation – Route 1 – AM Peak – Inbound Direction

In order to identify potential locations for queue jump lanes the three slowest segments previously noted were analyzed in detail. In the following subsection the major boarding stops and adjacent intersections within these three segments were observed and analyzed based on the CTPS Key Bus Route Study (CPTS, 2010a).

5.1.1 Massachusetts Avenue & Prospect Street

The CTPS Key Bus Routes Study made no recommendations for improvements to bus stops in Cambridge. Field observations revealed that there might be an opportunity to implement a shared bus and right-turn only lane in the far right eastbound lane of Massachusetts Avenue as it approaches Prospect Street. The observed queue size from a limited sample of observations varied from 6-12 vehicles leading to an estimated savings of 5-10 seconds based on observed queue sizes, intersection operations and traffic signal timings as explained in the methodology at the beginning of this chapter (Equation 4). However, if the bottleneck at the intersection of Essex Street creates a queue stretching back to Prospect Street the benefits could be significantly greater. A receiving lane on the far side of Prospect Street could also be considered to increase the benefits. The near-side queue jump lane would require conversion of a 130' right-turn only lane and a longer lane would require lengthening the crosswalk and eliminating parking spaces. The receiving lane on the far-side of the intersection would require eliminating the sidewalk bulb out on the southern corner of the intersection in order to allow continuous flow to the stop at Pearl Street.

Figure 5-3: Massachusetts Avenue at Pearl Street Map

5.1.2 Massachusetts Avenue & Newbury Street

The CTPS Key Bus Routes Study had the following recommendations for the Massachusetts Avenue at Boylston Street stop:

"The signal at Newbury Street could use red truncation and green extension to prioritize buses through the intersection without stopping. The stop at Newbury Street could be clearly marked as a bus-only area. The current stop is missing the rear "T" sign than indicates a no-parking/tow-zone area. The bus-only area could also potentially be extended to cover the entire right-hand lane between Newbury Street and Boylston Street. A dedicated bus-only light could then be installed at the intersection with Boylston Street to allow buses to jump the queue and merge into the right-hand travel lane ahead of general traffic." (CTPS, 2010a)

Observations from the field revealed average queue sizes between 10 and 15 vehicles on the nearside of the Newbury intersection with Massachusetts Avenue. The time savings were estimated to be 8-12 seconds per bus using the above-mentioned methodology (see Equation 4). Extending the queue jump lane for the entire block between Newbury Street and Commonwealth Ave would create a 210' lane and require elimination of 13 parking spaces.

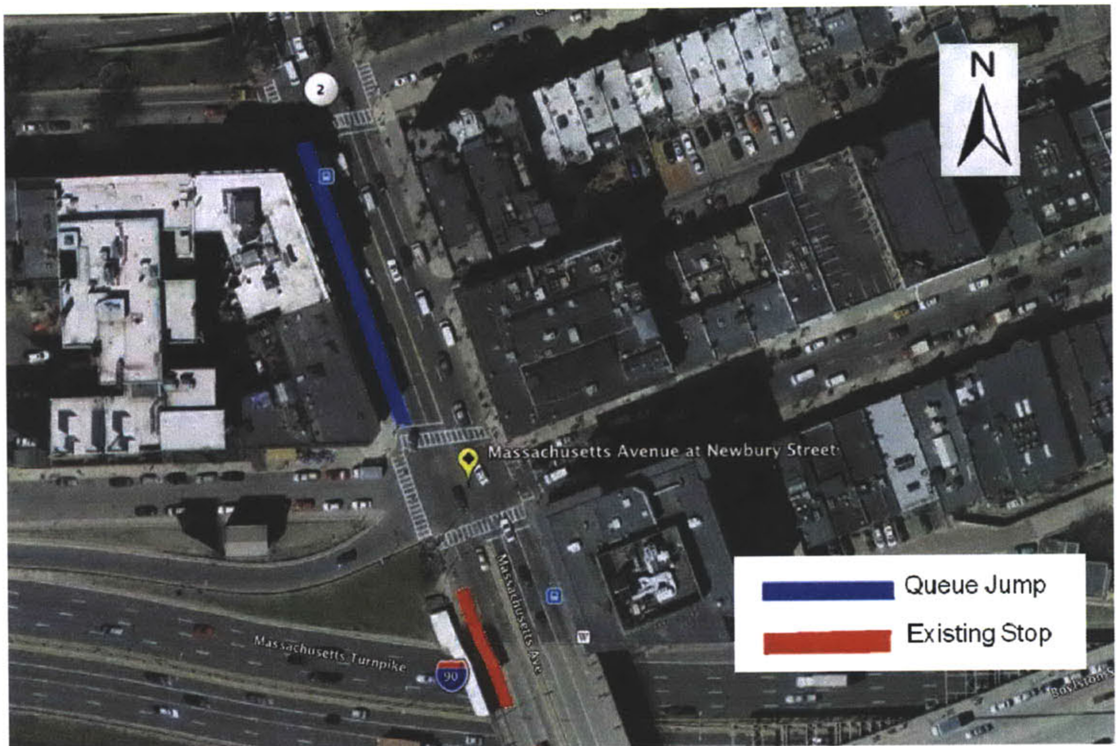

Figure 5-4: Massachusetts Avenue at Newbury Street Map

5.1.3 Massachusetts Avenue & Huntington Street

The CTPS Key Bus Routes Study had the following recommendations for the Massachusetts Avenue at Huntington Avenue stop:

"The existing stop location for Huntington Avenue is on a curb extension. As a result, stopped buses reduce the Massachusetts Avenue southbound road capacity to one lane. It is therefore recommended that the stop be moved south of the curb extension and replace the parking lane to the intersection with St. Botolph Street, at which a queue jump could be inserted.

The subsequent stop at the Massachusetts Avenue Station would lie only 0.077 miles from the relocated Huntington Avenue stop; however, both stops provide connections to rapid transit lines. Therefore, it is recommended that both stops remain." (CTPS, 2010a)

Field observations at the intersections of Massachusetts Avenue at Huntington Avenue and Massachusetts Avenue at St. Botolphs Street revealed maximum queue sizes of up to 5 vehicles on the nearside of the St. Botolphs Street intersection with Massachusetts Avenue. Based on these queue sizes, intersection operations and traffic signal timings, the time savings were estimated to be 4 seconds per bus. The proposed queue would be 80' long and require elimination of 5 parking spaces. Another queue jump was analyzed on the preceding block of Massachusetts Avenue in front of the Boston Symphony Orchestra. This queue jump had a higher potential savings of 5-7 seconds but may conflict with arrivals to the Symphony Orchestra.

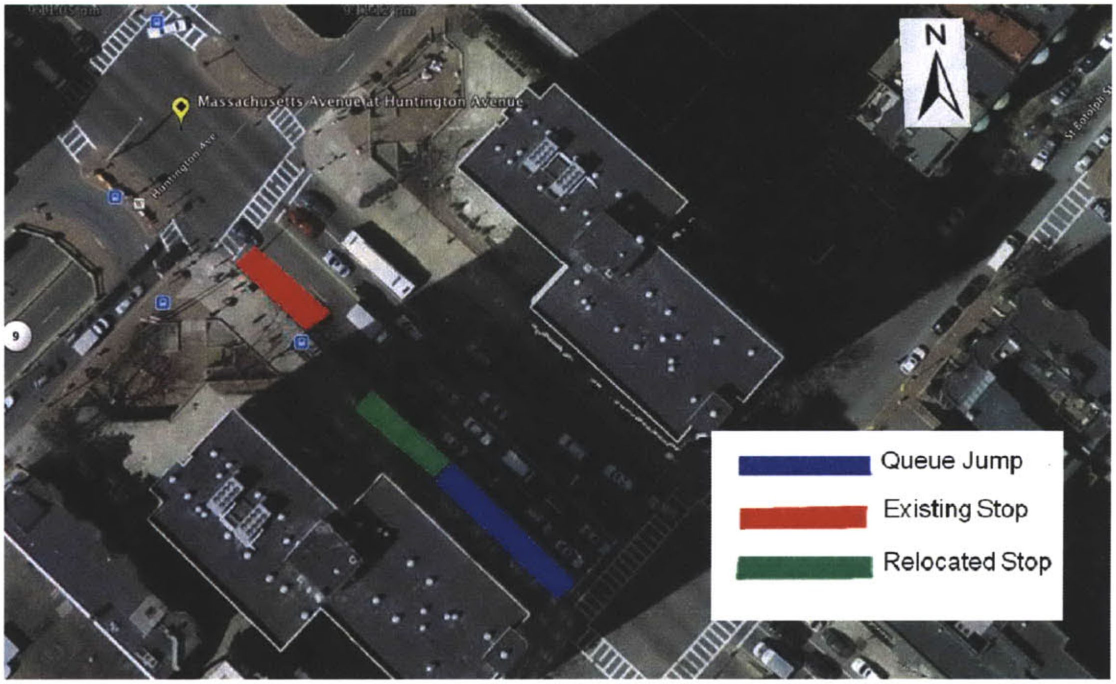

Figure 5-5: Massachusetts Avenue at Huntington Avenue Map

5.2 Outbound PM Analysis

First the scheduled and actual travel times along the eight outbound segments of Route 1were calculated as shown in Table 5-6. Examining the actual segment speeds shows that there are two areas (three segments), shown in Figure 5-6 with noticeably slower average speeds than the rest of the route, including two of the same segments noted in the analysis of the Inbound AM Peak. On all three of these slower segments the speeds have not been accounted for in the schedule as they all operate at slower than scheduled speeds. The first area includes the two adjacent segments between Massachusetts Avenue & Washington Street and Massachusetts Avenue & Newbury Street, which operate at average speeds of 5.5 mph. The second area is the segment from MIT to Central Square which operates at an average speed of 5.3 mph. The remaining sections of the route operate at significantly higher speeds ranging from 8 to 10 mph. These identified areas may provide the most potential for improvement by analyzing traffic operations around Massachusetts Avenue Station and Central Square.

Segment Startpoint	Segment Endpoint	Scheduled Segment Travel Time (minutes)	Actual Segment Travel Time (minutes)	Scheduled Segment Speed (MPH)	Actual Segment Speed (MPH)
Dudley Station	Melnea Cass Blvd @ Washington Street	4.0	8.8	4.8	2.2
Melnea Cass Blvd @ Washington Street	Mass Ave @ Washington Street	3.8	7.8	16.9	8.3
Mass Ave @ Washington Street	Mass Ave Station	4.8	5.3	6.3	5.6
Mass Ave Station	Mass Ave @ Newbury	5.0	6.7	6.1	4.5
Mass Ave @ Newbury	MIT	4.8	5.1	10.4	9.6
MIT	Central Square	4.8	6.9	7.7	5.3
Central Square	Mass Ave & Putnam	5.0	4.4	8.0	9.2
Mass Ave & Putnam	Harvard Gate	4.8	2.0	10.9	26.4

Table 5-6: Segment Travel Times and Speeds – Route 1 – Outbound Direction

The following Figure 5-6 shows the three identified slow segments, along with intersections that were identified as potential locations for queue-jumping.

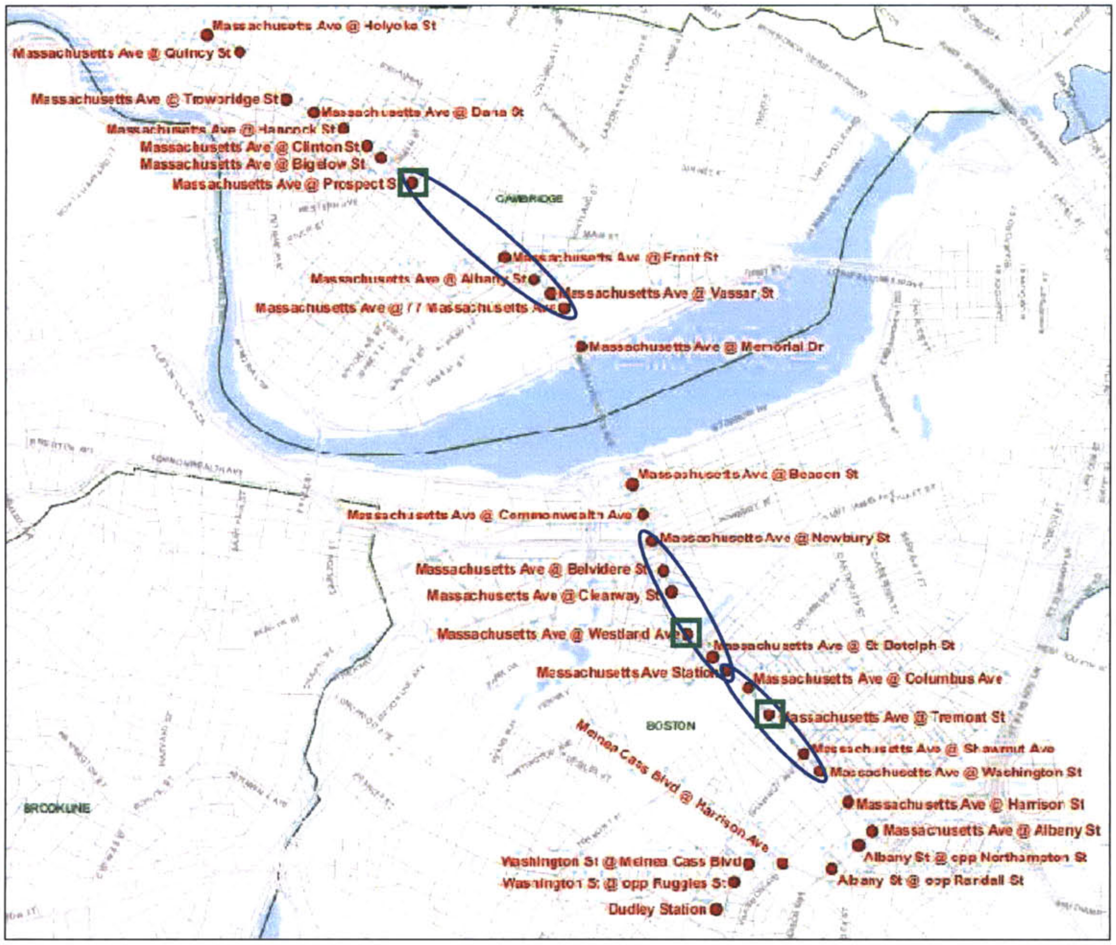

Figure 5-6: Segments Showing Highest Delay – Route 1 – Outbound Direction

The Time-Space diagram in Figure 5-7 along with Table 5-7 below clearly demonstrate the route's operations and deviations from schedule. Due to location of AVL cordon sensors at the terminals the initial and final segment travel times and speeds are inaccurate. Aside from data inaccuracies at these two points, on average the route operations deviate significantly from the schedule with multiple segments showing significant average delays in excess of 1.5 minutes. Aggregating the actual travel times of all the non-terminal segments shows that the actual travel time exceeds the scheduled travel time by 8.3 minutes on average, indicating that the current traffic operations are poorly accounted for in the route's schedule and that extending the running time or implementing traffic improvement strategies are necessary for improving Route 1 PM Peak operations.

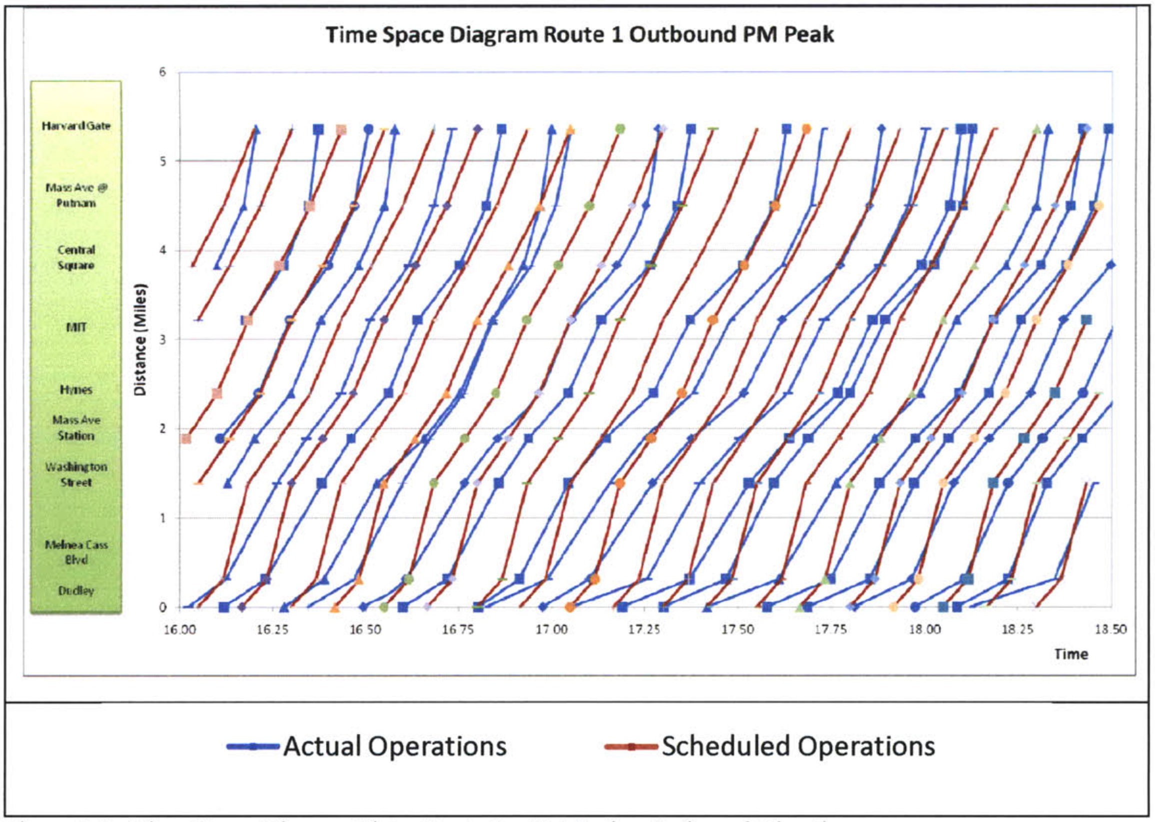

Figure 5-7: Time-Space Diagram Plot – Route 1 – PM Peak – Outbound Direction

Segment Startpoint	Segment Endpoint	Actual Travel Time – Scheduled Travel Time (minutes)
Dudley Station	Melnea Cass Blvd @ Washington Street	4.8
Melnea Cass Blvd @ Washington Street	Mass Ave @ Washington Street	4.0
Mass Ave @ Washington Street	Mass Ave Station	0.6
Mass Ave Station	Mass Ave @ Newbury	1.7
Mass Ave @ Newbury	MIT	0.4
MIT	Central Square	2.2
Central Square	Mass Ave & Putnam	-0.6
Mass Ave & Putnam	Harvard Gate	-2.8

Table 5-7: Schedule Deviation – Route 1 – PM Peak – Outbound Direction

In order to identify potential locations for queue jump lanes the three slowest outbound PM Peak segments previously noted were analyzed in detail. In the following subsection the major boarding stops and adjacent intersections within these three segments were observed and analyzed.

5.2.1 Massachusetts Avenue & Prospect Street

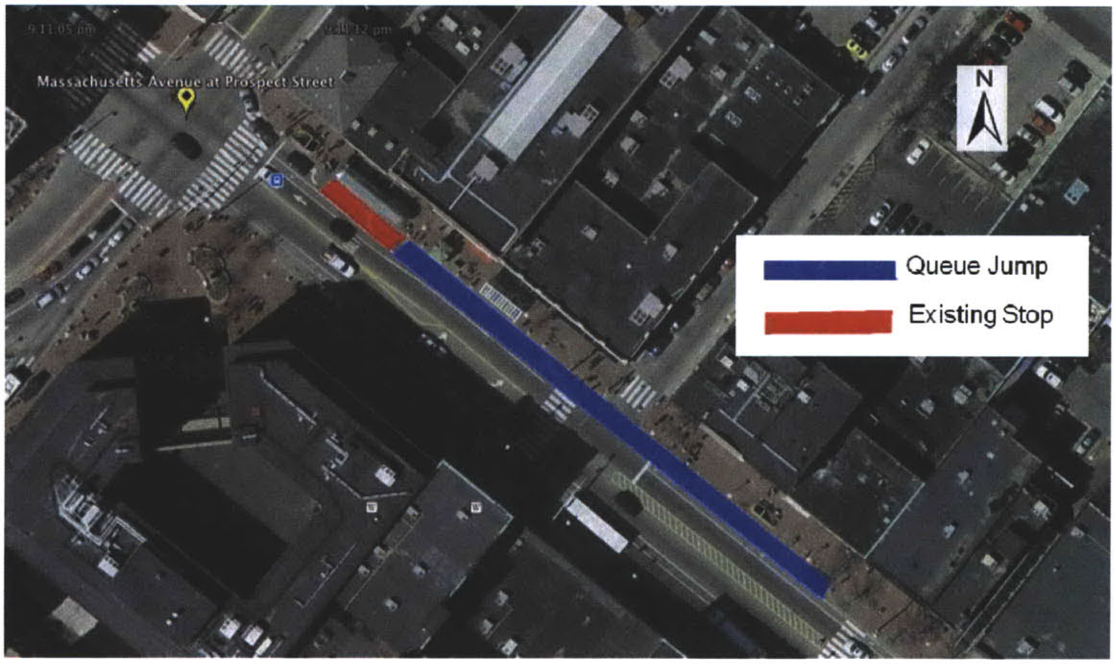

Figure 5-8: Massachusetts Avenue at Prospect Street Map

The CTPS Key Bus Routes Study had no recommendations for bus stops located in Cambridge. Field observations of the intersection of Massachusetts Avenue at Prospect Street revealed that there might be an opportunity to implement a shared bus and right-turn lane, possibly stretching back to the intersection of Pearl Street. A single through traffic lane makes this section of Massachusetts Avenue very congested. Average queue sizes range from 8 to 12 vehicles, often stretching beyond Essex Street. These operations may significantly benefit from a queue jump lane as relieving the bottleneck may allow buses to skip entire cycles while approaching the bus stop. Based on intersection signal timings and queue lengths, the estimated average savings under normal traffic conditions are 10 seconds. However, alleviating the bottlenecked conditions for buses could significantly increase the potential benefits. Extending the queue jump lane past Essex Street would require elimination of the five space taxi stand east of Essex Street. It would also require eliminating the bulb out on the north corner of the intersection.

5.2.2 Massachusetts Avenue & Westland Avenue

The CTPS Key Bus Routes Study had the following recommendations for the Massachusetts Avenue at Westland Avenue stop:

"The existing stop at Westland Street is set up for a queue jump. Painting the lane to indicate that it is a bus-only area would prevent vehicles from pulling into that lane and blocking buses from reaching the bus stop. Since Massachusetts Avenue north of Westland Avenue has two receiving lanes, it would not appear that the bus lane would need a dedicated light. However, given the layout of the intersection, vehicles in the middle travel lane of Massachusetts Avenue south of Westland Avenue often switch into the right-hand lane as they cross the intersection. Therefore, a dedicated light for buses could reduce the opportunity for conflicts between private vehicles and buses." (CTPS, 2010a)

Field observations support the CTPS recommendations that eliminating car access from the third, far-right lane would be a beneficial and simple to implement solution. It is currently used as a queue jumping lane when not full of general traffic. However, if filled with cars, the car access provides no benefit, and if the middle lane is queued beyond the entrance to the lane then it cannot be accessed. There is a subway station preventing any extension of the lane. The average queue size does not exceed 6 vehicles and there is a proportionally long green phase, therefore average potential savings are estimated at up to 3 seconds. This does not require sacrificing any parking spaces as it is currently a right-turn only lane.

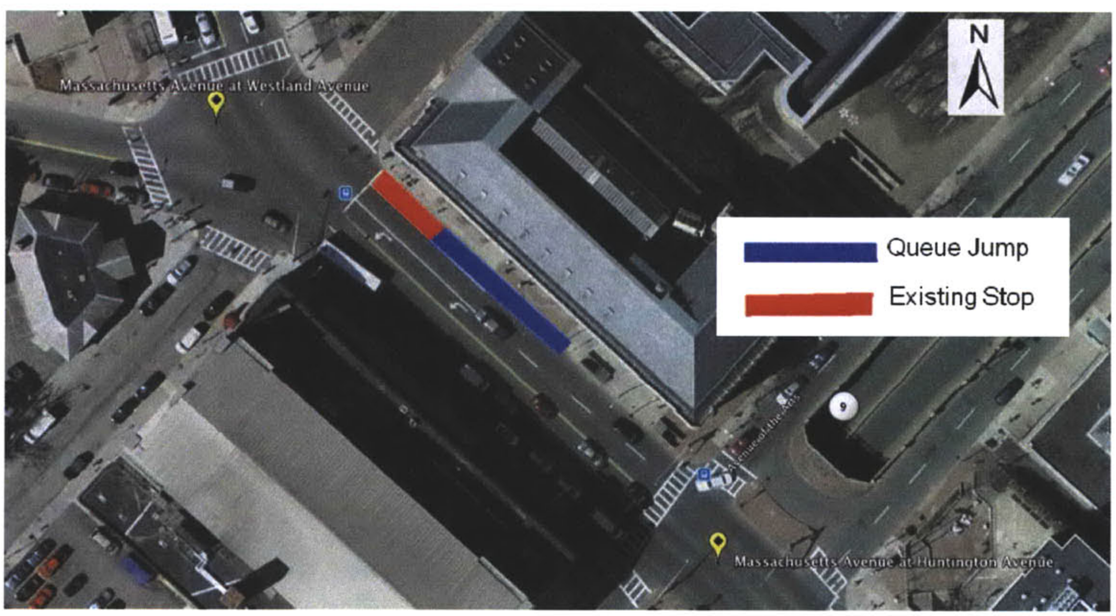

Figure 5-9: Massachusetts Avenue at Westland Avenue Map

5.2.3 Massachusetts Avenue & Tremont Street

The CTPS Key Bus Routes Study had the following recommendations for the Massachusetts Avenue at Tremont Street stop:

"Similar to the inbound direction where the stop at Shawmut Avenue is currently located on the far side of the intersection, it is recommended that the stop be moved to the near side and a queue jump be established. This would result in a stop spacing of 0.177 miles to the subsequent stop at Tremont Street, which is also recommended for queue-jump treatment. As in the inbound direction, the width of Tremont Street is currently insufficient to allow buses to merge back into the right-hand travel lane before the intersection ends. Sufficient space in the near-term for buses to pull in and out this stop and to merge back into general traffic could be ensured by eliminating a few parking spots." (CTPS, 2010a)

Field observations support the CTPS recommendation that the effect of moderate levels of traffic on bus operations could be alleviated by moving the stop location to the near-side and implementing a queue jump lane. If the far right lane were converted to a queue jump, buses would be able to access the lane from the intersection with Chester Square meaning there would be the potential to bypass up to 10 vehicles. The average queue size ranges from 10 to 15 vehicles, which, combined with cycle times, leads to an estimated savings of 14-16 seconds. This would require the elimination of 11 parking spaces on Massachusetts Avenue.

Figure 5-10: Massachusetts Avenue at Tremont Street Map

5.3 Conclusions on Queue Jump Potential

Overall the analysis of these identified queue jump locations showed varying average potential time savings of 5 to 15 seconds. Greater savings may be found from longer queue-jump lanes that allow buses to skip entire cycles when the queue is longer than the number of vehicles that can be released in a single green phase. Our field observations did not witness any instances of the entire queue not being released during a single green phase. In addition, there are significant costs to implementation of queue-jumping in terms of parking space elimination and private vehicle traffic disturbance, even from implementing the shorter lanes suggested in the CTPS Key Bus Routes Studies. Our analysis showed some increased benefits from relocating the stop to the near-side of the intersection at queue-jump locations but this would prevent sharing the lane with right-turning traffic. It is recommended to explore traffic signal improvements and traffic signal prioritization prior to implementation of queue-jumping at any of these locations, as the financial and political costs are likely greater than less than significant bus travel time savings.

6. QUEUE JUMPING ANALYSIS - ROUTE 28

Route 28 has been selected for further analysis due to its high ridership and availability of APC data. Using APC and AVL data, as well as field observations, we developed recommendations on potential improvements along the route. Focus is given to segments of the route where highest delays are observed through AVL data. In these segments, we conducted a comparative analysis of APC and AVL data to select a few traffic intersections where there might be potential gains from implementation of queue-jumping lanes.

In January 2010, the Central Transportation Planning Staff released findings regarding delay times along selected bus routes as well as recommendations for future initiatives (CTPS, 2010b). In particular, CTPS focused on providing queue-jumping and other forms of Traffic Signal Prioritization (TSP) such as green extensions, red truncations, bus-only signals, and signal coordination. Based on our analysis, this chapter investigates some of the CTPS findings regarding queue-jumping.

Queue-jumping lanes allow a bus to bypass queued vehicles at a red traffic signal and depart first when the signal turns green. They can be even more effective when implemented in conjunction with TSP. Most require elimination of existing traffic or parking lanes although they can also be combined with right-turning traffic. Queue jumping lane benefits are related to the length of the dedicated lane and the length of the queue that is being bypassed. In order to gain noticeable benefits the queues and lanes must be several hundred feet long in order skip entire traffic signal cycles. However, this often requires sacrificing a significant number of parking spaces.

If the queue is short enough to be entirely released during a single green phase the potential savings from implementing a queue jump are calculated as follows.

$$Queue\ Jump\ Savings = Queue\ Travel\ Savings + Red\ Phase\ Dwell\ Time\ Savings \quad (5)$$

$$\begin{aligned} Queue\ Travel\ Savings & \\ &= Probability\ of\ Red\ Phase \\ &* Probability\ of\ accessing\ Queue\ Jump\ \ from\ Queue \\ &* Average\ Queue\ Position * Intersection\ Release\ Rate \end{aligned} \quad (5.1)$$

$$\begin{aligned} Red\ Phase\ Dwell\ Time\ Savings & \\ &= Probability\ of\ Red\ Phase \\ &* Probability\ of\ accessing\ Queue\ Jump\ \ from\ Queue * Dwell\ Time \\ &* Probability\ (Dwell\ Time < Red\ Wait\ Time) \end{aligned} \quad (5.2)$$

As mentioned above, greater benefits can be gained if the queue is not entirely released during a green phase as the queue jump would allow the potential to save an entire cycle. None of the observed intersections had queue that were not entirely released so there were no time savings from skipping a red phase. Hence, the above formula was used to calculate the time savings for all the following analyses.

Furthermore, CTPS (2010b) also recommended different forms of TSP, which gives buses priority at traffic signals over private vehicles. Using the current AVL GPS system to locate buses as they approach traffic signals, TSP can then extend green time when it senses a bus approaching, or reduce red time when one joins the queue stopped at a red light. TSP allows buses to move through intersections faster, and more efficiently. TSP can also improve schedule adherence and headways variability by giving priority only to buses that are behind schedule or being closely followed. Analysis of potential TSP implementation would require micro-simulation based on data that was not made available so TSP was not considered in the scope of this project. However, TSP may provide operational improvements and should be studied further.

Three months of AVL data from Spring 2009 collected at 11 different locations allowed for a travel time analysis of each of the corresponding 10 route segments. The Spring 2009 data was chosen for this analysis over the Fall 2009 data because the CTPS Key Bus Route Studies (CTPS, 2010b) were based on data from the same time period. The list of AVL data collection points and the segment lengths are provided below in Table 6-1 and 6-2. To analyze schedule adherence along the segments of route 28 the actual operations were aggregated by trip and compared to the schedule at the 11 AVL collection points along the route. The schedule is designed to accommodate general traffic conditions along the route as well as dwell times at each bus stop. An analysis was conducted to measure the drivers' ability to adhere to the schedule as well as to identify the specific segments along the route where schedule deviations were most likely to occur and impact operational service reliability.

Segment Startpoint	Segment Endpoint	Segment Distance (miles)	Distance from Terminal (miles)
Mattapan Station	Wellington Hill	1.02	1.02
Wellington Hill	Morton Street	0.41	1.42
Morton Street	Blue Hill Avenue	0.75	2.17
Blue Hill Avenue	Franklin Park	0.61	2.78
Franklin Park	Grove Hall	0.53	3.31
Grove Hall	Warren Street @ Boston Latin Academy	0.41	3.73
Warren Street @ Boston Latin Academy	Warren Street @ Walnut Ave	0.68	4.41
Warren Street @ Walnut Ave	Dudley Station	0.29	4.69
Dudley Station	Roxbury Station	0.58	5.27
Roxbury Station	Ruggles Station	0.56	5.84

Table 6-1: Stop Locations and Distances – Route 28 – Inbound Direction

Segment Startpoint	Segment Endpoint	Segment Distance (miles)	Distance from Terminal (miles)
Ruggles Station	Roxbury Station	0.56	0.56
Roxbury Station	Dudley Station	0.58	1.14
Dudley Station	Warren Street @ Walnut Ave	0.29	1.43
Warren Street @ Walnut Ave	Warren Street @ Boston Latin Academy	0.68	2.11
Warren Street @ Boston Latin Academy	Grove Hall	0.41	2.52
Grove Hall	Franklin Park	0.53	3.06
Franklin Park	Blue Hill Avenue	0.61	3.67
Blue Hill Avenue	Morton Street	0.75	4.41
Morton Street	Wellington Hill	0.41	4.82
Wellington Hill	Mattapan Station	1.02	5.84

Table 6-2: Stop Locations and Distances – Route 28 – Inbound Direction

For this analysis only the peak direction was analyzed during each peak period. Importance was placed on analyzing the operations of the inbound AM and the outbound PM directions due to the potential for greater passenger time savings. From the Spring APC data it was shown that the average load factors in the peak directions were more than double the average rate in the opposite direction. As shown in Table 6-3 in the AM Peak the average load factor in the inbound direction is 19.7 passengers compared to 9.1 in the outbound direction. As would be expected the PM Peak shows the opposite trend with the outbound average load factor of 29.4 more than double the inbound average load factor of 14.2.

Direction	AM Peak (Avg. Load Factor)	PM Peak (Avg. Load Factor)
Inbound	19.7	14.2
Outbound	9.1	29.4

Table 6-3: Average Peak Load Factors – Route 28

The following sections will identify slow travel segments in the inbound and outbound directions during the AM and PM Peak periods, respectively. This will be followed by identification and analysis of potential queue-jumping locations and conclusions drawn about the effectiveness of queue-jumping strategies at these locations.

6.1 Inbound AM Analysis

The scheduled and actual travel times and operational speeds along the 10 segments of Route 28 were calculated as shown in Table 6-4. Examining the actual segment speeds shows that there are two areas (three segments), shown in Figure 6-4, that operate at noticeably slower average speeds than on the rest of the route, although on some segments the slow speeds have already been accommodated for in the schedule. The first is the segment around the commercial district approaching the Grove Hall stop which operates at an average speed of 7.8 mph.

The second area consists of the two adjacent segments that approach and depart from Dudley Station with speeds averaging 8.1 mph. The remaining sections of the route operate at speeds over 30% faster at average speeds approaching 11 mph. These identified areas may provide the most potential for improvement by analyzing traffic operations around the Grove Hall district and by analyzing bus and general traffic operations in and around Dudley Terminal.

Segment Startpoint	Segment Endpoint	Scheduled Segment Travel Time (minutes)	Actual Segment Travel Time (minutes)	Scheduled Segment Speed (MPH)	Actual Segment Speed (MPH)
Mattapan Station	Wellington Hill	3.7	11.2	16.6	5.5
Wellington Hill	Morton Street	2.0	2.6	12.2	9.5
Morton Street	Blue Hill Avenue	4.7	4.1	9.5	10.8
Blue Hill Avenue	Franklin Park	3.0	3.2	12.2	11.3
Franklin Park	Grove Hall	3.7	4.1	8.6	7.8
Grove Hall	Warren Street @ Boston Latin Academy	2.5	2.5	9.9	9.8
Warren Street @ Boston Latin Academy	Warren Street @ Walnut Ave	4.2	3.2	9.7	12.7
Warren Street @ Walnut Ave	Dudley Station	1.4	2.1	12.1	8.2
Dudley Station	Roxbury Station	4.6	4.3	7.6	8.0

Segment Startpoint	Segment Endpoint	Scheduled Segment Travel Time (minutes)	Actual Segment Travel Time (minutes)	Scheduled Segment Speed (MPH)	Actual Segment Speed (MPH)
Roxbury Station	Ruggles Station	9.6	3.2	3.5	10.5

Table 6-4: Segment Travel Times and Speeds – Route 28 – Inbound Direction

The time-space diagram plot in Figure 6-1 along with Table 6-5 below clearly demonstrate the route's operations and deviations from schedule. Due to location of AVL cordon sensors at the terminals the initial and final segment travel times and speeds are inaccurate. Thus, the first and ultimate travel segments were not analyzed in this section. Aside from data inaccuracies at these two points, the route operates on average close to schedule with no segments showing significant average delays in excess of 1.0 minute. Aggregating the actual travel times of all the non-terminal segments shows that on average the actual travel time only exceeds the scheduled travel time by 0.1 minute, indicating that the current traffic operations have been fully accounted for in the route's schedule.

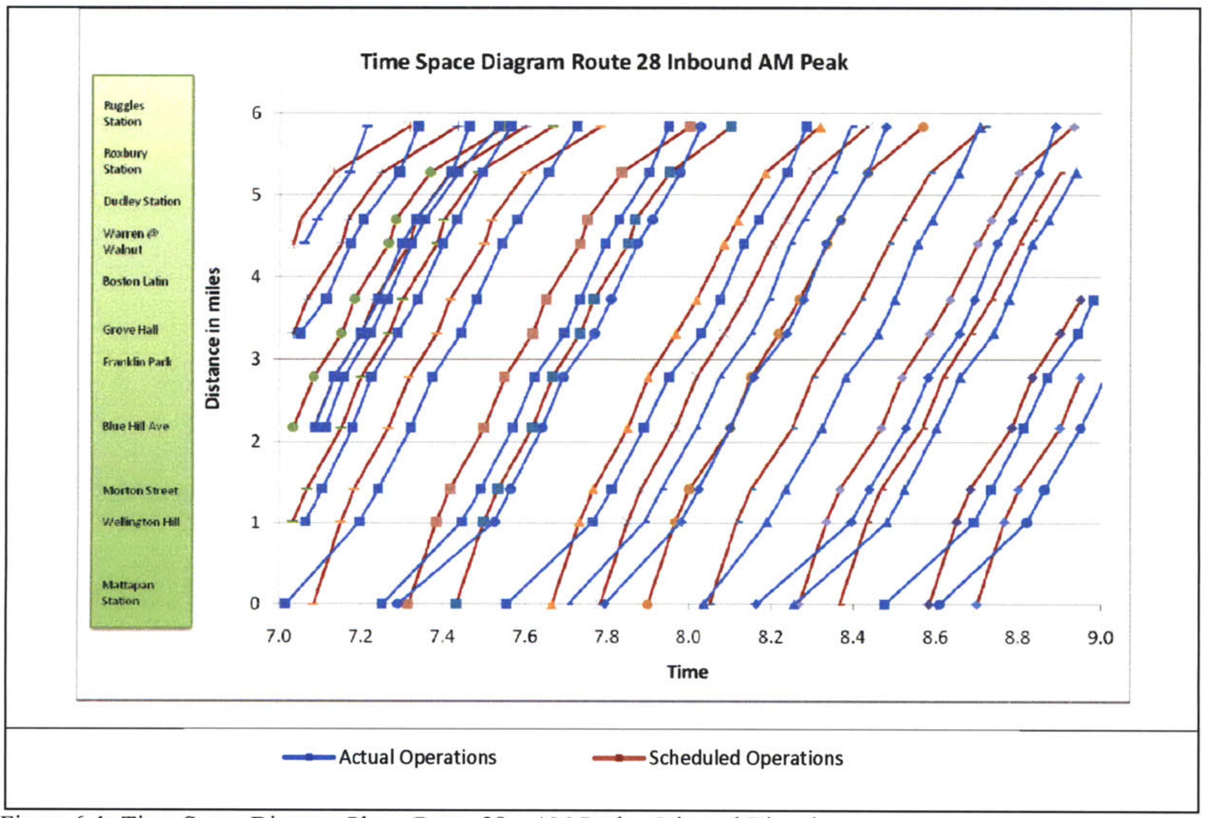

Figure 6-1: Time-Space Diagram Plot – Route 28 – AM Peak – Inbound Direction

Segment Startpoint	Segment Endpoint	Actual Travel Time – Scheduled Travel Time (minutes)
Mattapan Station	Wellington Hill	7.5
Wellington Hill	Morton Street	0.6
Morton Street	Blue Hill Avenue	-0.6
Blue Hill Avenue	Franklin Park	0.2
Franklin Park	Grove Hall	0.4
Grove Hall	Warren Street @ Boston Latin Academy	0.0
Warren Street @ Boston Latin Academy	Warren Street @ Walnut Ave	-1.0
Warren Street @ Walnut Ave	Dudley Station	0.7
Dudley Station	Roxbury Station	-0.2
Roxbury Station	Ruggles Station	-6.4

Table 6-5: Schedule Deviation – Route 28 – AM Peak – Inbound Direction

Both of these systems generate data that may be used to approximate dwell times although in different manners and with different levels of accuracy. In order to identify specific locations with the greatest potential for improvement in operations, dwell time metrics were generated and compared from both the AVL and APC sources. Figure 6-2 depicts the framework for linking attributes of both data sources.

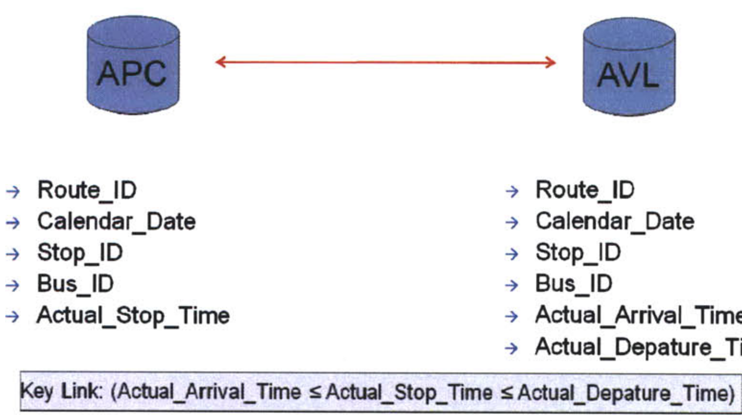

Figure 6-2: Framework for Linking AVL and APC Data

The APC system generates dwell time based on door operations at bus stops and is therefore a relatively accurate source of dwell time data. In contrast the AVL data provides a much less accurate proxy for dwell time estimation as it encompasses all operations inside of a 400' diameter cordon around each bus stop. The AVL dwell time is calculated from the time entering the bus stop cordon to the time leaving the cordon. This means that the estimated dwell time based on AVL data includes both the actual dwell time at the stop and all traffic operations within the 400' cordon around the stop. By subtracting the more accurate APC dwell time from the AVL generated dwell time, it is possible to isolate the traffic operations component of the AVL dwell time analysis and estimate the amount of time it takes to travel across each individual bus stop cordon (Figure 6-3).

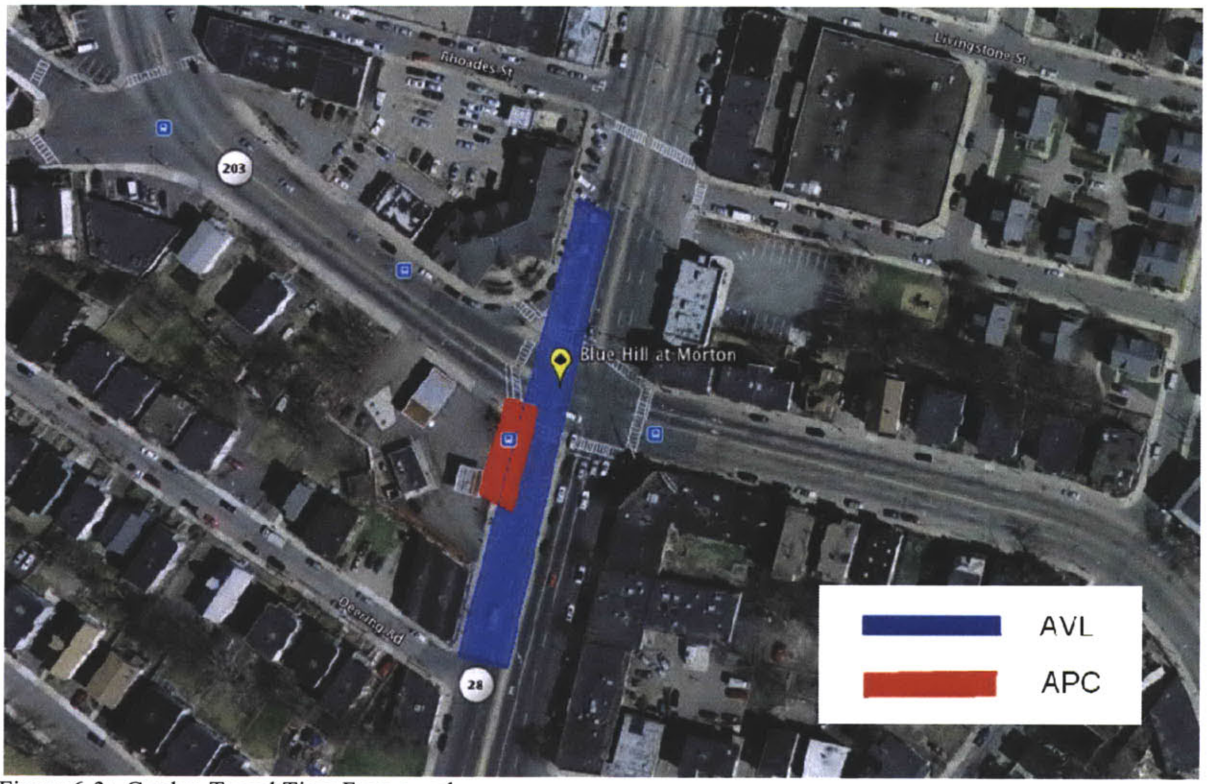

Figure 6-3: Cordon Travel Time Framework

The cordon travel time values calculated by subtracting the APC dwell time from the AVL proxy dwell time can be seen in Figure 6-5. This is one step that can be taken to identify potential locations to implement traffic improvement strategies such as traffic signal prioritization and queue jumping. Examining this cordon operations data shows that the values generated at the terminals are inaccurate as the cordon times generated from the AVL data include the bus recovery time in addition to the dwell time and the operations time. Aside from the inaccurate values at the terminals the average cordon travel times varied by stop and time period with values generally ranging from 25 seconds to 70 seconds.

The following Figure 6-4 shows the three identified slow segments, along with intersections that were identified as potential locations for queue-jumping.

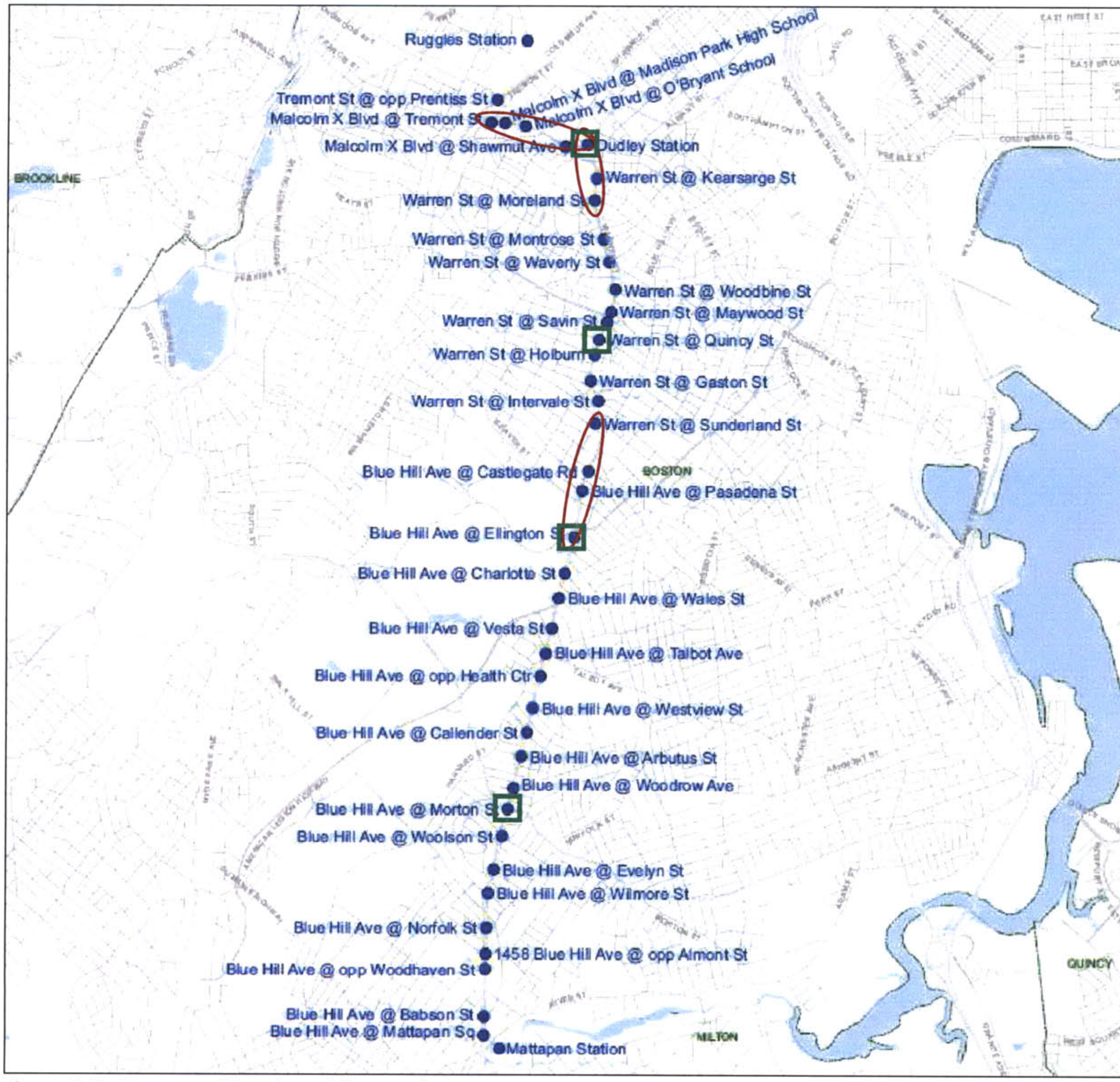

Figure 6-4: Segments Showing Highest Delay – Route 28 – Inbound Direction

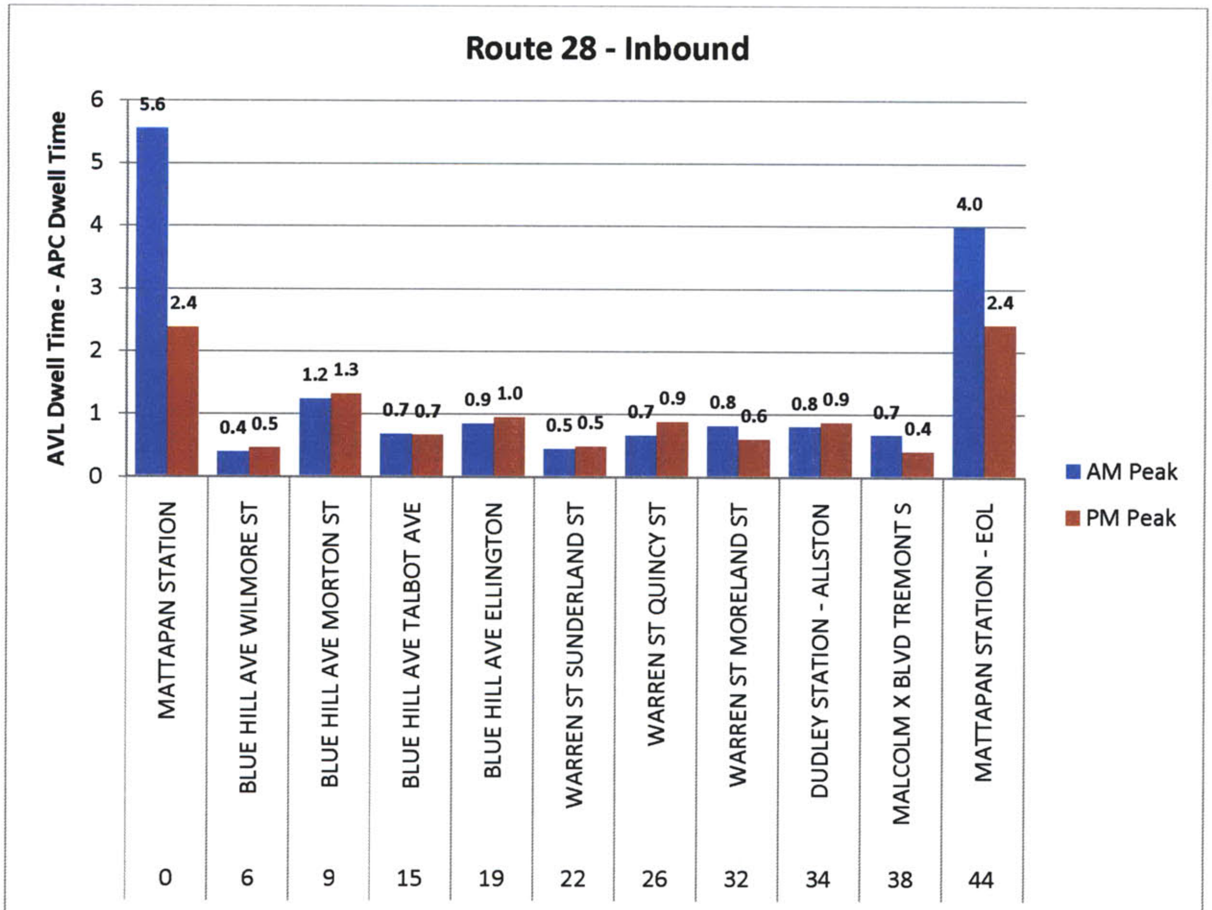

Figure 6-5: AVL Cordon Travel Times – Route 28 – Inbound Direction

The average cordon travel time value is useful but it is more important to gauge the probability of relatively high cordon travel time as opposed to the average value as the higher travel time operations will benefit the most from implementation of queue jumping at the intersection. In addition there is a limit to the potential benefit for each bus because the bus will only be able to skip the length of the queue, limiting the potential benefit when the traffic queue is longer than the queue jumping lane. In order to do this analysis, the probability of a cordon travel time exceeding a threshold of 1 minute, which approximates the intersection cycle time, was decided to be a more useful metric of identifying the potential gain from implementation of traffic improvement strategies at each intersection. Figure 6-6 shows the probabilities of the cordon travel exceeding one minute at each of the analyzed intersections.

The CTPS Key Bus Route Study of Route 28 recommends investigating the potential benefits of implementing queue jumping at 15 of the 30 analyzed inbound stops. Our analysis of 9 non-terminal stops consists of three out of the 15 identified for potential queue jumping implementation. These three intersections are Blue Hill Avenue at Morton Street, Blue Hill Avenue at Ellington Ave, and Warren Street at Quincy Street. Analyzing the probability of the cordon travel time exceeding the one minute threshold demonstrates that the intersection of Blue Hill Ave at Morton Street is the best potential candidate of the analyzed intersections, as it exceeds this threshold more than 70% of the time. The two other intersections identified by CTPS as potential queue jump sites had less than 30% probabilities of exceeding the 1 minute cordon travel time, which makes them less than ideal candidates for implementation. Although the CTPS study specifically does not analyze operations at Dudley Station this analysis shows that cordon travel times at that station exceed the one minute threshold approximately 45% of the time and support the identified need to further study the terminal's operations.

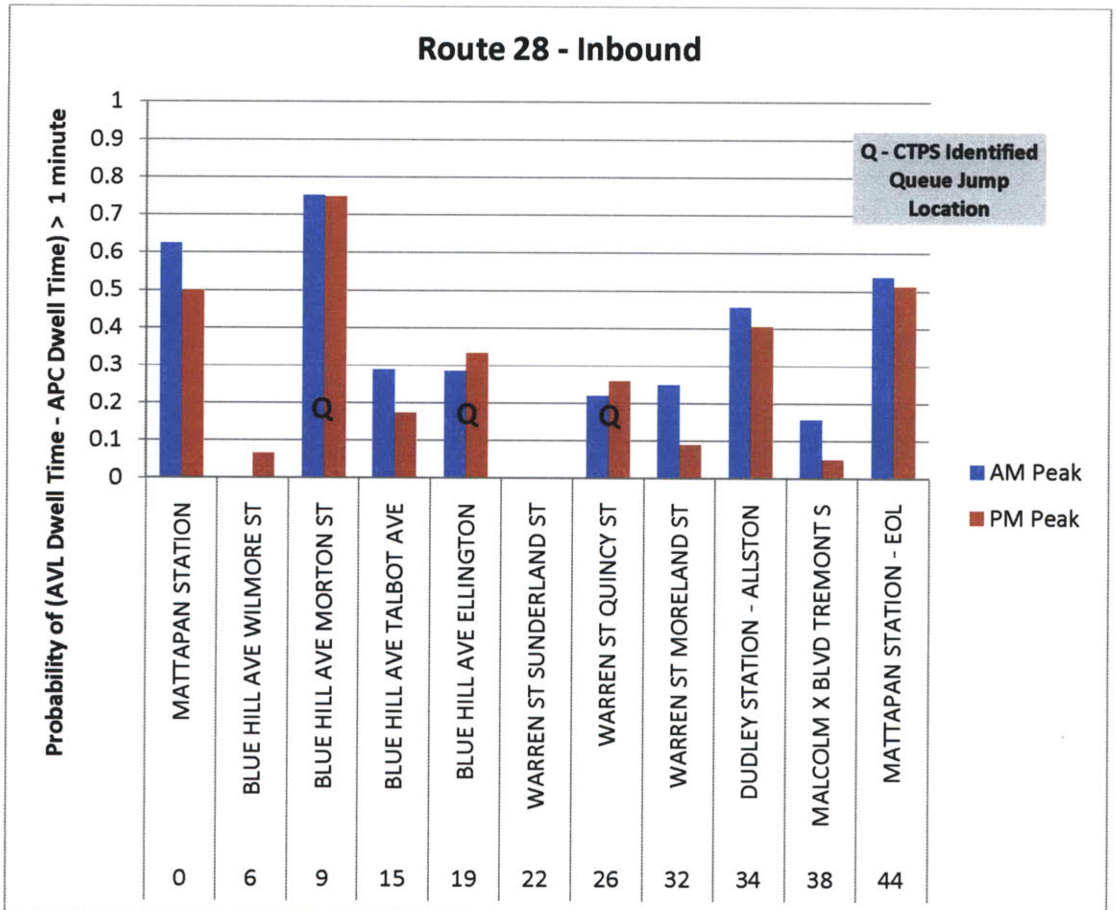

Figure 6-6: Excess Cordon Travel Time Probabilities – Route 28 – Inbound Direction

The distributions of cordon travel times for each of the three intersections in this analysis identified by CTPS as potential queue jump locations are provided below in Figures 6.7, 6.9, and 6.11. Additionally, the distribution of cordon travel times for Dudley Station, presented in Figure 6.13, shows that terminal traffic improvements may significantly reduce travel time. The following subsection analyzes potential bus intersections for queue-jumping in more detail.

6.1.1 Blue Hill Avenue at Morton Street

Blue Hill Avenue at Morton Street was shown to be the best potential candidate for queue jumping as the cordon travel time exceeded the one minute threshold more than 75% of the time and exceeded 90 seconds 45% of the time (as shown in Figure 6.7, Delta being the difference between AVL and APC dwell times, which is the cordon travel time). This means that a high proportion of buses would benefit from implementation of a queue jumping lane.

The CTPS Key Bus Routes Study had the following recommendations for the Blue Hill Avenue at Morton Street stop:

"The current location of the next stop at Morton Street is at the far-side of the intersection with Blue Hill Avenue. It is recommended that a queue jump be inserted at this location. This would require moving the stop to the near-side of the intersection and eliminating parking approximately 100-200 feet back from the intersection, depending on the size of the queue that forms." (CTPS, 2010b)

Initial field observations showed that the queue extending from Morton Street varies but regularly exceeds 12 vehicles meaning that a high proportion of buses would benefit from implementing a queue jump lane on the near side of Blue Hill Avenue. Calculations based on these observations and assuming a 200' queue jump lane showed average potential time savings of 14-18 seconds per bus, depending on the length of the queue jump lane. This would require elimination of 12 parking spaces.

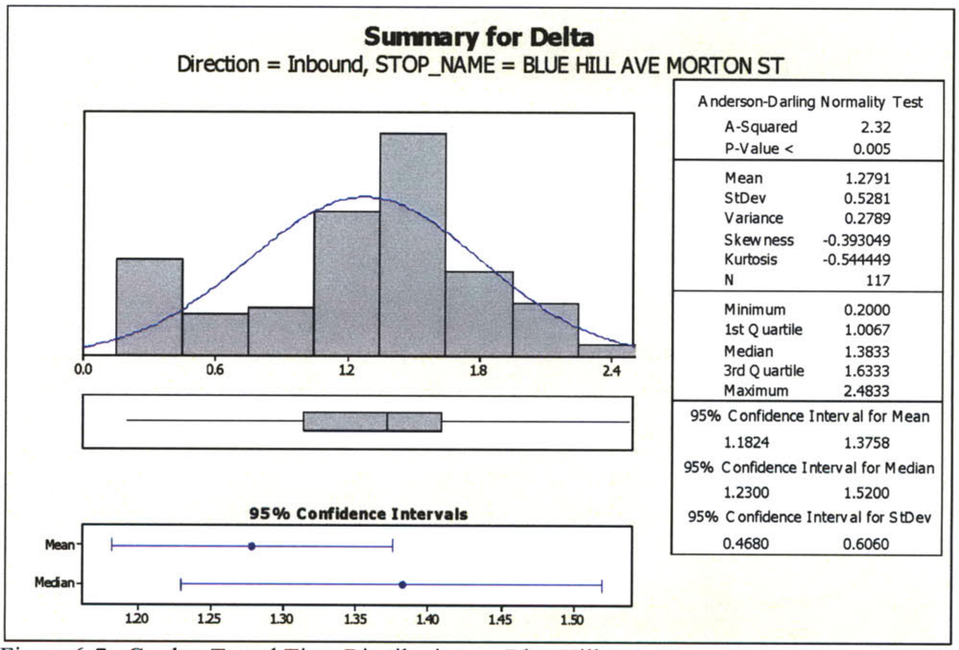

Figure 6-7: Cordon Travel Time Distribution on Blue Hill Avenue at Morton Street – AM Peak – Inbound

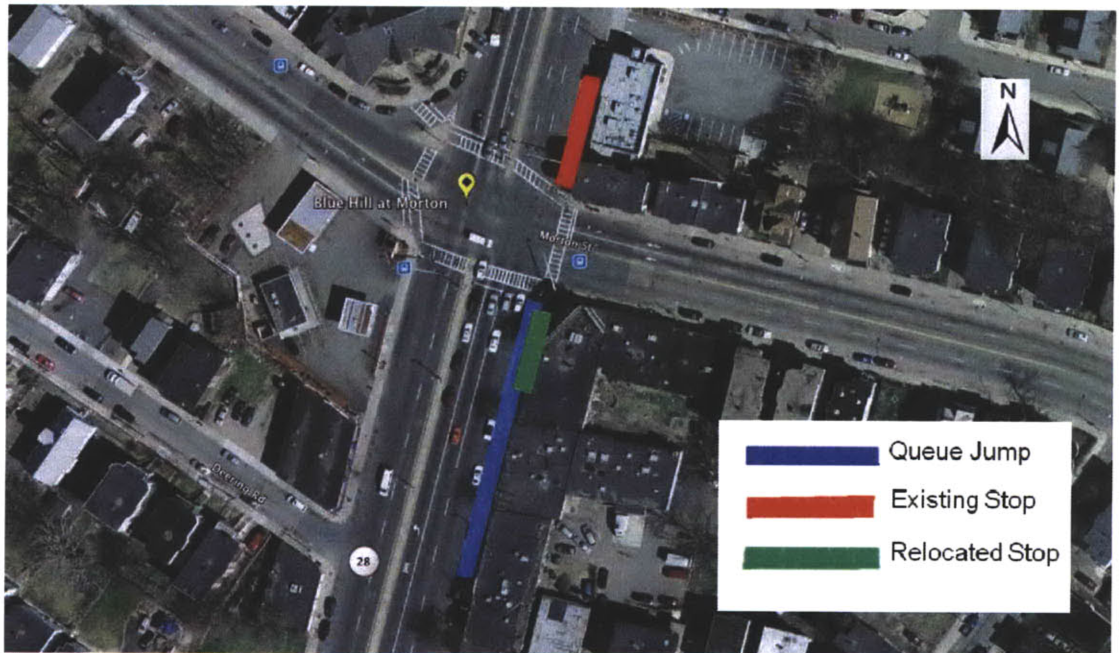

Figure 6-8: Blue Hill Avenue at Morton Street Aerial View

6.1.2 Blue Hill Avenue at Ellington Street

The intersection of Blue Hill Avenue and Ellington Street would only see relatively minor benefits from implementation of a queue jumping lane as only 29% of the cordon travel times exceed the one minute threshold and only 7% exceed the 90 second threshold (as shown in Figure 6-9, Delta being the difference between AVL and APC dwell times, which is the cordon travel time).

The CTPS Key Bus Routes Study had the following recommendations for the Blue Hill Avenue at Ellington Street stop:

"The subsequent stop at Ellington Street is recommended for relocation to the nearside of Glenway Street. Since Blue Hill Avenue expands to four travel lanes north of McLellan Street, a queue jump could replace the right-hand lane between McLellan Street and Glenway Street. The resulting distance between the stops at American Legion Highway and the relocated stop at Glenway Street would be approximately 0.254 miles. TSP treatment through red truncation and green extension is also recommended for the following signalized intersection at Columbia Road.

With the proposed relocation of the stop at Ellington Street to Glenway Street, it is also recommended that the stop at Pasadena Road be moved south to the near-side of Seaver Street. The queue-jump lane could replace either parking or the right-hand travel lane starting approximately at the beginning of the left-turn lane for Seaver Street. The resulting distance between the stops at Glenway Street and Seaver Street would be approximately 0.238 miles." (CTPS, 2010b)

Initial field observations showed that the queue extending from Ellington Street varies but regularly exceeds 10 vehicles meaning that a high proportion of buses would benefit from implementing a queue jump lane on the near side of Blue Hill Avenue. Calculations based on these observations showed average potential time savings of 10-15 seconds per bus depending on the length of the queue jump lane. Implementation of this queue jump requires the elimination of 8 parking spaces.

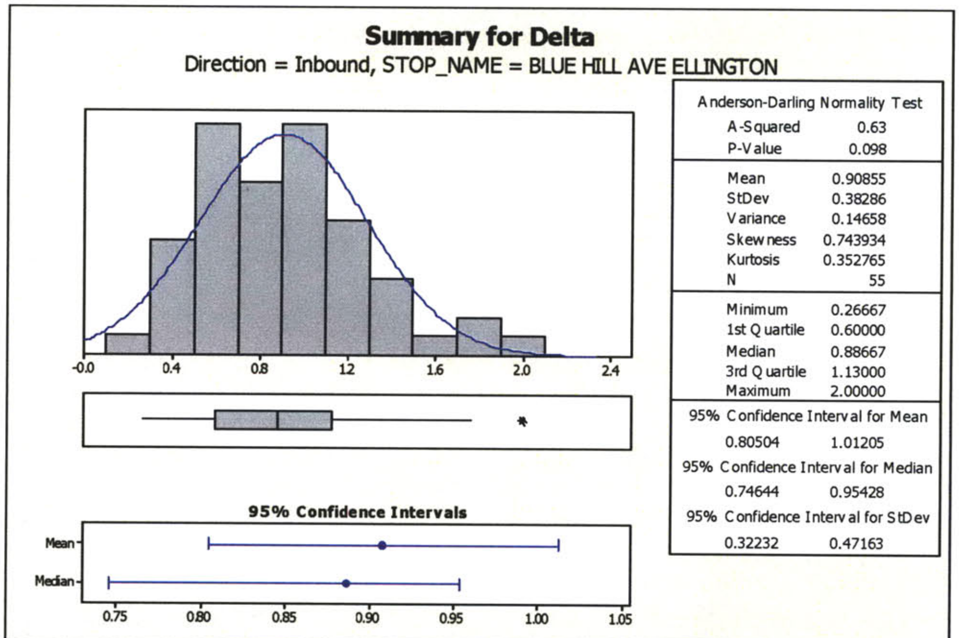

Figure 6-9: Cordon Travel Time Distribution on Blue Hill Avenue at Ellington – AM Peak – Inbound

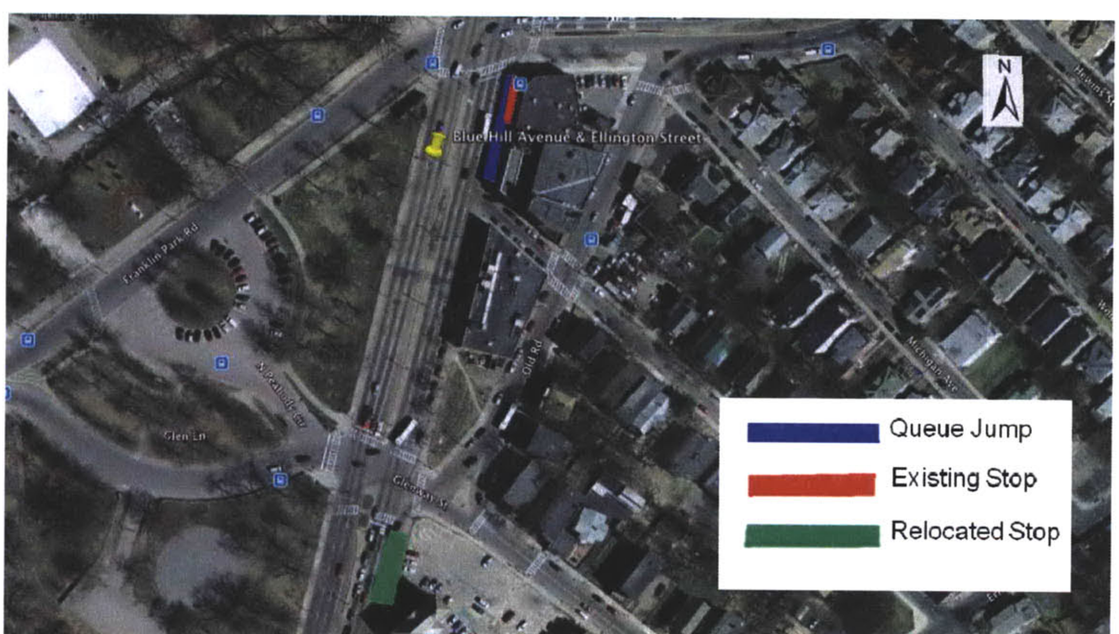

Figure 6-10: Blue Hill Avenue at Ellington Street Aerial View

6.1.3 Warren Street at Quincy Street

The intersection of Warren Street at Quincy Street would see even fewer benefits from implementation of a queue jumping lane as only 22% of the cordon travel times exceed the one minute threshold and less than 1% exceed the 90 second threshold (as shown in Figure 6-11, Delta being the difference between AVL and APC dwell times, which is the cordon travel time).

The CTPS Key Bus Routes Study had a general recommendation for implementation of a queue jump lane for the Warren Street at Quincy Street stop. Initial field observations showed that the queue extending from Morton Street varies but regularly exceeds 8 vehicles meaning that a high proportion of buses would benefit from implementing a queue jump lane on the near side of Blue Hill Avenue. Calculations based on these observations showed average potential time savings of 8 to 12 seconds per bus depending on the length of the queue jump lane.

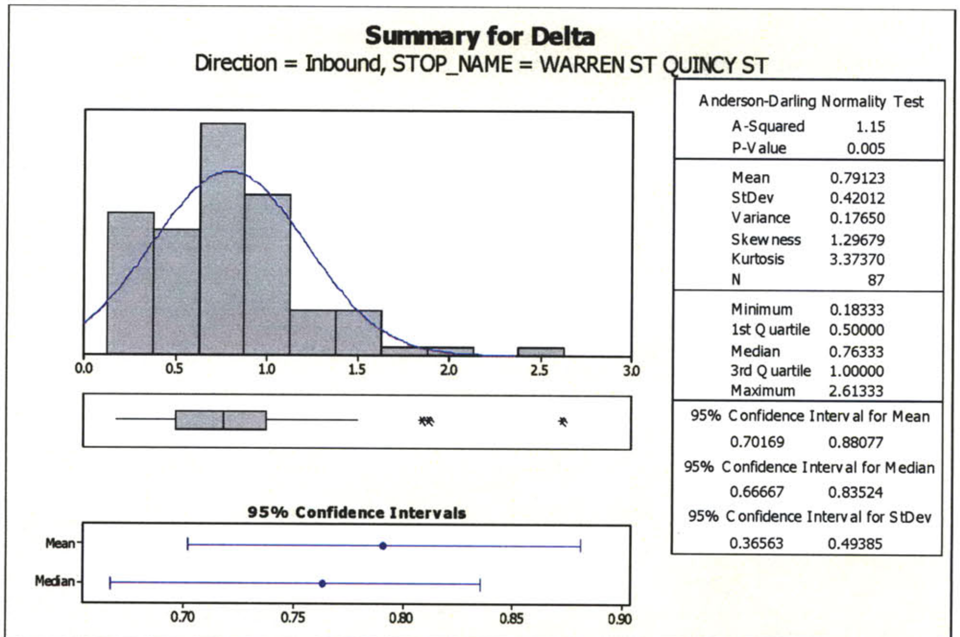

Figure 6-11: Cordon Travel Time Distribution on Warren Street at Quincy Street – AM Peak – Inbound

Figure 6-12: Warren Street at Quincy Street Aerial View

6.1.4 Dudley Station

Analyzing the cordon travel times surrounding Dudley Station show that there is potential be gained from improved terminal operations as 45% of the cordon travel times exceed the one minute threshold and 15% exceed the 90 second threshold (as shown in Figure 6-13, Delta being the difference between AVL and APC dwell times, which is the cordon travel time). A detailed study of the operations at the terminal is recommended as there appears to be significant potential improvement upon current operations. However, an analysis of the terminal operations is beyond the scope of this study.

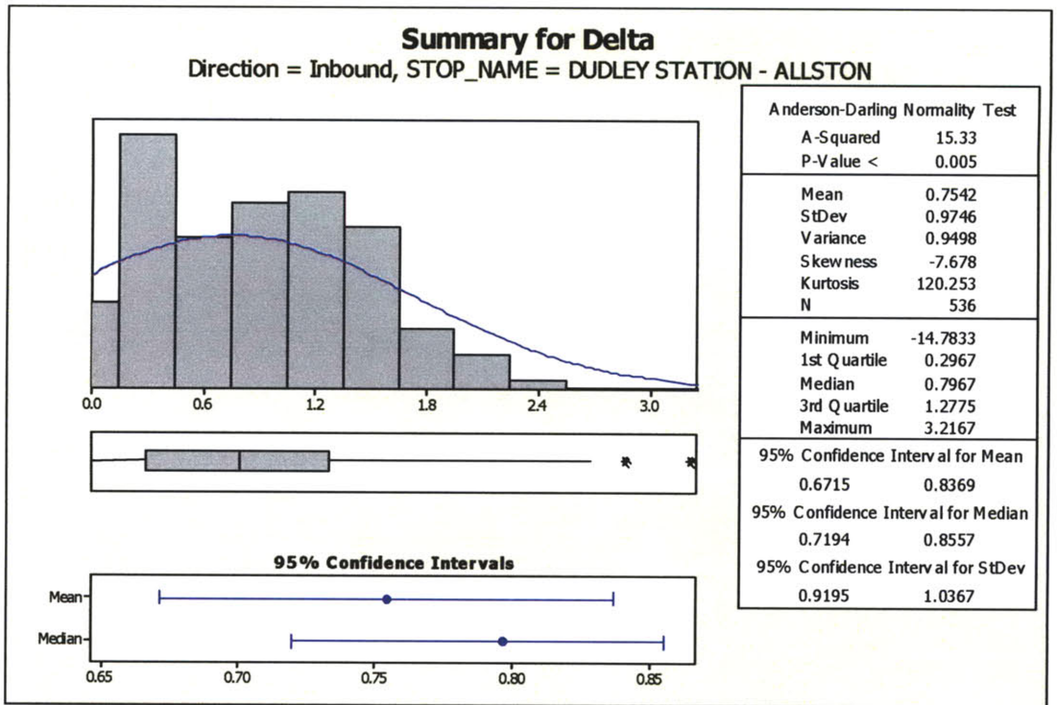

Figure 6-13: Cordon Travel Time Distribution at Dudley Station – AM Peak – Inbound

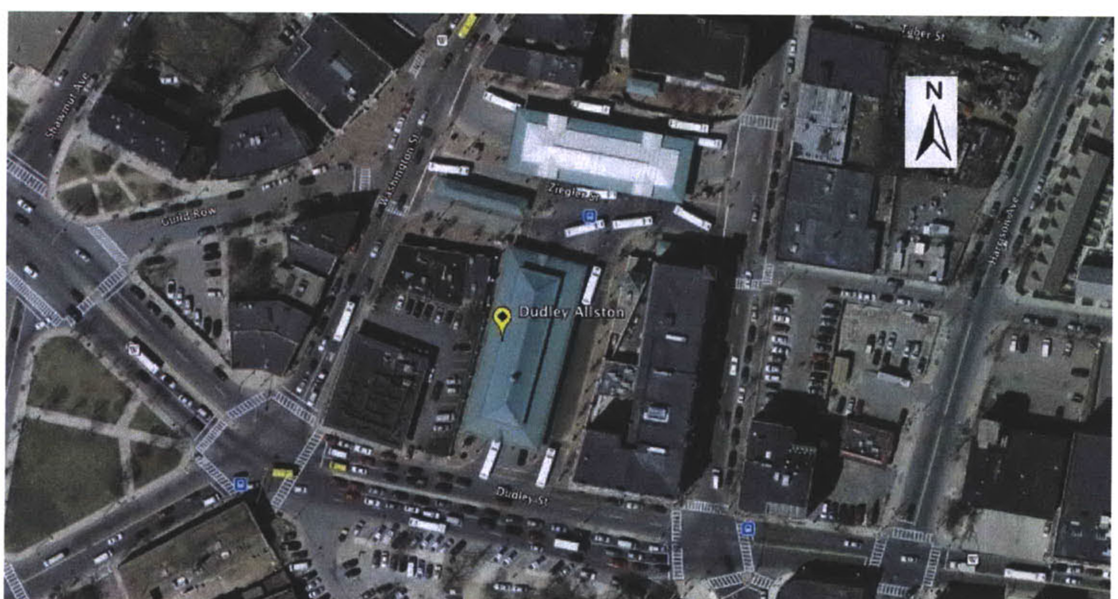

Figure 6-14: Dudley Station Aerial View

6.2 Outbound PM Analysis

Table 6-6 shows the scheduled and actual travel times along the 10 outbound segments of Route 28 and the corresponding average operational speeds. Examining the actual segment speeds shows that there are three areas (five segments), shown in Figure 6-15, that operate at noticeably slower average speeds than on the rest of the route, including the same segments noted in the analysis of the Inbound AM Peak. Also, as with the Inbound AM Peak, on some slower segments the lower speeds have already been accommodated for in the schedule.

The first area includes the segments around the commercial district approaching and leaving the Grove Hall stop which operate at average speeds of 7.8 mph and 5.8 mph, respectively. The second area is the segment from Blue Hill Avenue to Morton Street which operates at an average speed of 7.6 mph. The third area consists of the segments that approach and depart from Dudley Station with speeds averaging 8.0 mph and 3.6 mph, respectively. The remaining sections of the route operate at significantly faster speeds ranging from 9.3 mph to over 15 mph. These identified areas may provide the most potential for improvement by analyzing traffic operations around the Grove Hall district, the segment between Blue Hill Avenue and Morton Street.

Segment Startpoint	Segment Endpoint	Scheduled Segment Travel Time (min)	Actual Segment Travel Time (min)	Scheduled Segment Speed (MPH)	Actual Segment Speed (MPH)
Ruggles Station	Roxbury Station	4.0	14.1	8.4	2.4
Roxbury Station	Dudley Station	3.4	4.4	10.3	8.0
Dudley Station	Warren Street @ Walnut Ave	5.0	4.7	3.4	3.6
Warren Street @ Walnut Ave	Warren Street @ BLA	4.4	4.4	9.4	9.3
Warren Street @ BLA	Grove Hall	4.0	3.2	6.2	7.8
Grove Hall	Franklin Park	4.7	5.5	6.8	5.8
Franklin Park	Blue Hill Avenue	3.5	3.2	10.4	11.4
Blue Hill Avenue	Morton Street	5.0	5.9	9.0	7.6
Morton Street	Wellington Hill	2.0	1.6	12.2	15.1

Segment Startpoint	Segment Endpoint	Scheduled Segment Travel Time (min)	Actual Segment Travel Time (min)	Scheduled Segment Speed (MPH)	Actual Segment Speed (MPH)
Wellington Hill	Mattapan Station	14.5	10.0	4.2	6.1

Table 6-6: Segment Travel Times and Speeds – Route 28 – Outbound Direction

The following figure shows the three identified slow segments, along with intersections that were identified as potential locations for queue-jumping.

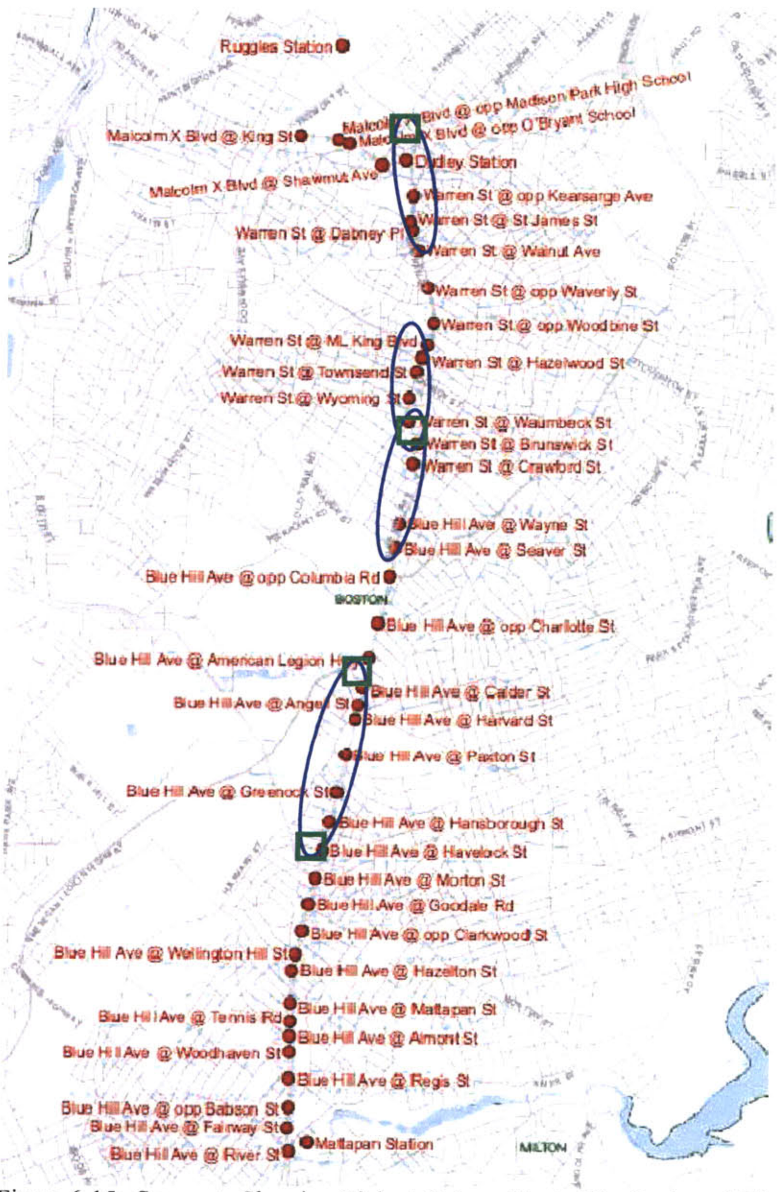

Figure 6-15: Segments Showing Highest Delay – Route 28 – Outbound Direction

The Time-Space diagram in Figure 6-16 along with Table 6-7 below clearly demonstrate the route's operations and deviations from schedule. Due to location of AVL cordon sensors at the terminals the initial and final segment travel times and speeds are inaccurate. Thus, the first and ultimate travel segments were not analyzed in this section. Aside from data inaccuracies at these two points, the route operates on average close to schedule with no segments showing significant average delays in excess of 1.0 minute. Aggregating the actual travel times of all the non-terminal segments shows that the average actual travel time exceeds the scheduled travel time by 0.9 minute indicating that the current traffic operations have not been fully accounted for in the route's schedule and that extending the running time for one of the delayed segments by 1.0 minute may improve operational service reliability.

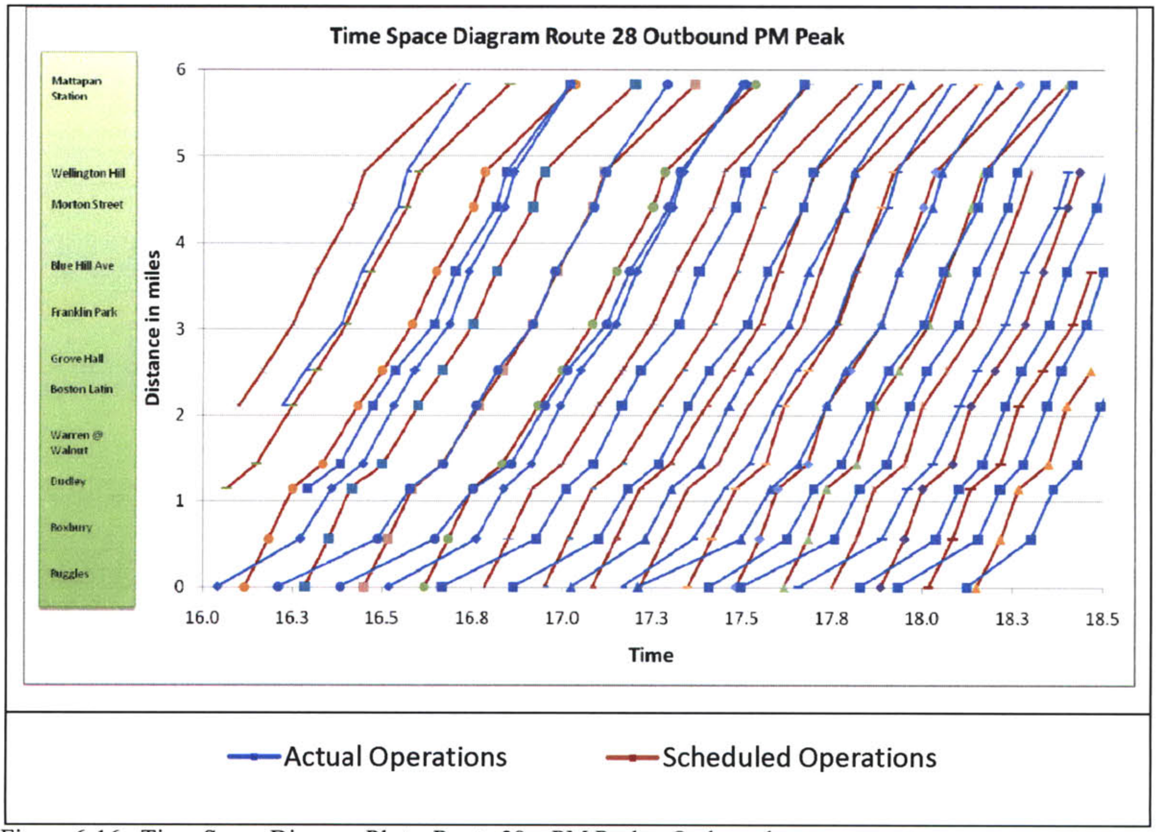

Figure 6-16: Time-Space Diagram Plot – Route 28 – PM Peak – Outbound

Segment Startpoint	Segment Endpoint	Actual Travel Time – Scheduled Travel Time (minutes)
Ruggles Station	Roxbury Station	10.1
Roxbury Station	Dudley Station	1.0
Dudley Station	Warren Street @ Walnut Ave	-0.3
Warren Street @ Walnut Ave	Warren Street @ Boston Latin Academy	0.0
Warren Street @ Boston Latin Academy	Grove Hall	-0.8
Grove Hall	Franklin Park	0.8
Franklin Park	Blue Hill Avenue	-0.3
Blue Hill Avenue	Morton Street	0.9
Morton Street	Wellington Hill	-0.4
Wellington Hill	Mattapan Station	-4.5

Table 6-7: Schedule Deviation – Route 28 – PM Peak – Outbound Direction

The same methodology was used to generate the cordon travel times from the APC and AVL data as was used and previously explained for Route 28 Inbound. The Route 28 Outbound PM cordon travel time values calculated by subtracting the APC dwell time from the AVL proxy dwell time can be seen in Figure 6-17. This is one step that can be taken to identify potential locations to implement traffic improvement strategies such as traffic signal prioritization and queue jumping. Examining this cordon operations data shows that the values generated at the terminals are inaccurate as the cordon times generated from the AVL data include the bus recovery time in addition to the dwell time and the operations time. Aside from the inaccurate values at the terminals, the average cordon travel times varied greatly by stop and time period with values generally ranging from 15 seconds to 100 seconds.

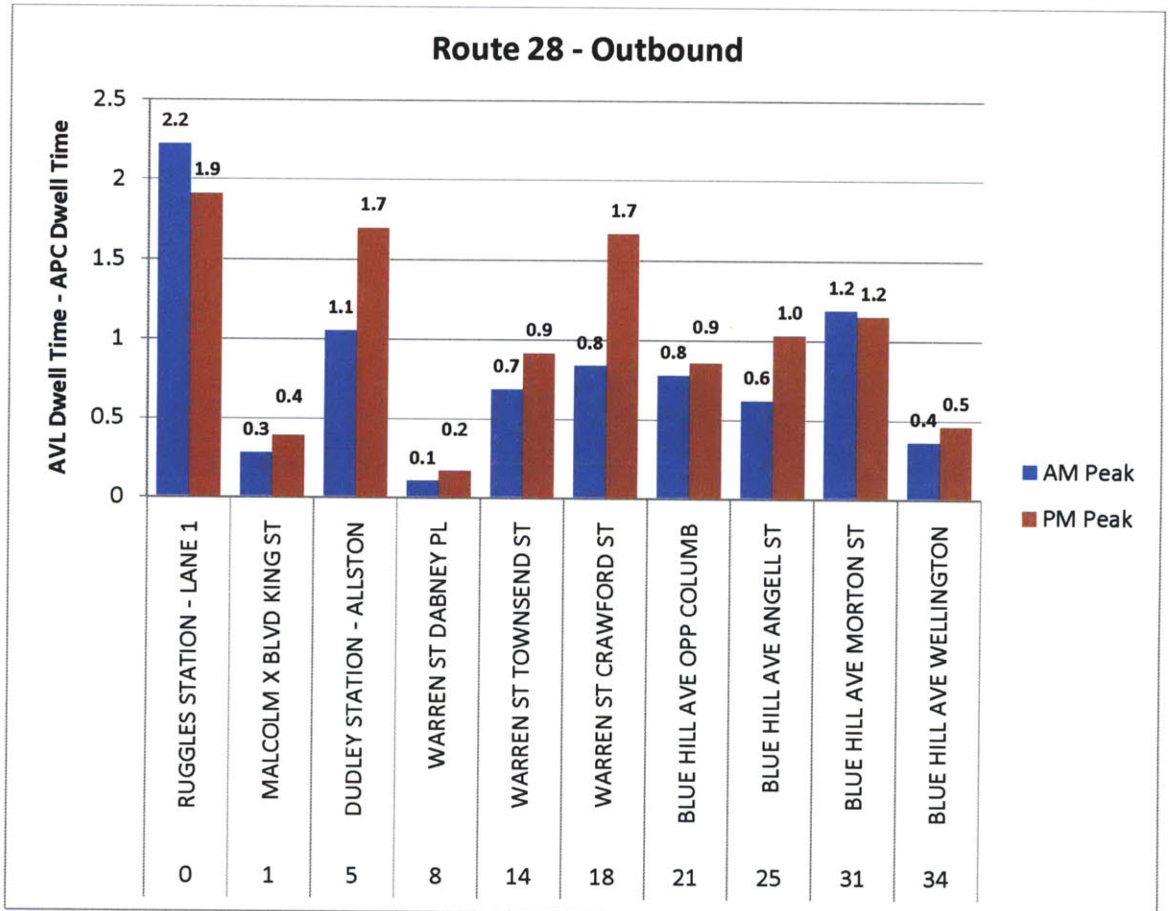

Figure 6-17: AVL Cordon Travel Times – Route 28 – Outbound Direction

As explained in the analysis of Route 28 Inbound AM, the average cordon travel time value is useful but it is more important to gauge the probability of a relatively high cordon travel time as opposed to the average value. The higher travel time operations above a specified threshold will improve the most from implementation of queue jumping at an intersection. In addition there is a limit to the potential benefit for each bus because the bus will only be able to skip the length of the queue, limiting the potential benefit when the traffic queue is longer than the queue jumping lane. In order to do this analysis, the probability of a cordon travel time exceeding a threshold of 1 minute, which approximates the intersection cycle time, was decided to be a more useful metric to identify potential gains from implementation of traffic improvement strategies at each intersection. Figure 6-18 shows the probabilities of the cordon travel time exceeding one minute at each of the analyzed intersections.

The CTPS Key Bus Route Study of Route 28 recommends investigating the potential benefits of implementing queue jumping at 11 of the 30 analyzed outbound stops. Our analysis of nine non-terminal stops consists of only one of the 11 identified for potential queue jumping implementation. This intersection is Blue Hill Avenue at Angell Street. Analyzing the probability of the cordon travel time exceeding the one-minute threshold demonstrates that the intersection of Blue Hill Avenue at Angell Street is a potential candidate of the analyzed intersections as it exceeds this one-minute threshold 50% of the time.

In addition to the intersections identified by the CTPS study as potential queue jumping locations there are three locations that exceeded the one minute threshold more than 65% of the time in the PM peak, which indicates that they may be potential candidates for other traffic improvement strategies. These three intersections are Warren Street at Crawford Street, Blue Hill Avenue at Morton Street and Dudley Station.

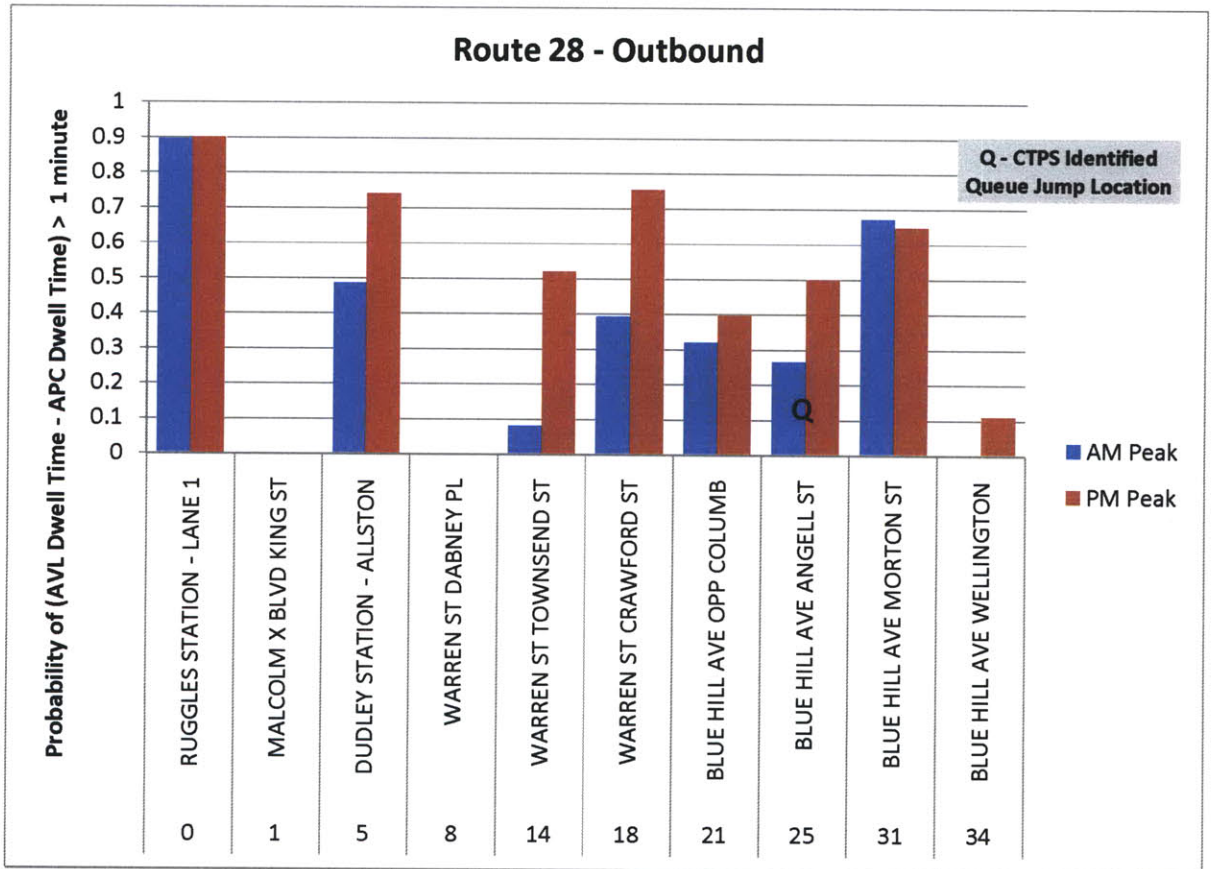

Figure 6-18: Excess Cordon Travel Time Probabilities – Route 28 – Outbound Direction

The distributions of cordon travel times for each of the three intersections in this analysis identified by CTPS as potential queue jump locations are provided below in Figures 6-19, 6-23, and 6-25. Additionally, the distribution of cordon travel time for Dudley Station, presented in Figure 6-21, shows that terminal traffic improvements may significantly reduce travel time. The following subsection analyses potential bus stop intersections for queue-jumping in more detail.

6.2.1 Blue Hill Avenue at Angell Street

Blue Hill Avenue at Angell Street was the only intersection in this analysis that was identified by the CTPS study as a potential candidate for queue jumping. The cordon travel time analysis supported CTPS' recommendation for further study of this intersection as the probability of exceeding the one minute threshold was 50% and the probability of exceeding 90 seconds was 17% (as shown in Figure 6-18, Delta being the difference between AVL and APC dwell times, which is the cordon travel time). This means that at least half of the buses would receive close to the maximum potential benefit from implementation of a queue jumping lane.

The CTPS Key Bus Routes Study had the following recommendations for the Blue Hill Avenue at Angell Street stop:

"The subsequent stop at Angell Street currently lies at the near-side of the intersection. It is recommended that this stop be relocated to the far-side of the intersection and the right-hand travel lane be converted into a queue-jump lane. As there is no right-turn at this intersection, the stop line for the queue-jump lane could be eliminated, and buses could proceed through the intersection upon serving the stop or yielding to left-turning traffic from Harvard Street and Talbot Avenue. With the recommended relocation of the stop at Angell Street to the far-side of that intersection, the following stop at the far-side of Harvard Street would lie only 0.071 miles away. These locations would provide a stop on both sides of a busy intersection. The signal at Harvard Street could be coordinated with the signal at Talbot Avenue." (CTPS, 2010b)

Field observations of the bus stop operations revealed that there are two components of delay at the stop that could be mitigated by implementation of queue jumping lanes. The first component is the delay to reenter traffic and wait for eight vehicles to be released from the intersection. The second component is the delayed approach to the bus stop, which the bus may wait to access if the queue from the Harvard Street intersection exceeds 10 vehicles. Creating a queue jump lane between Angell Street and Harvard Street would only eliminate two parking spaces and would allow buses to bypass eight vehicles and to reentry more easily into general traffic.

A limited number of observations showed a queue length extending from Harvard Street ranging from 6 to 23 vehicles. This means that a large proportion of approaching buses would benefit from an additional queue jump lane extending further upstream along Blue Hill Ave as it would allow for quicker entry and avoid waiting in traffic to access the stop. Calculations based on the field observations showed average potential savings of 6-8 seconds per bus. Implementation of this queue jump requires the elimination of 6 parking spaces.

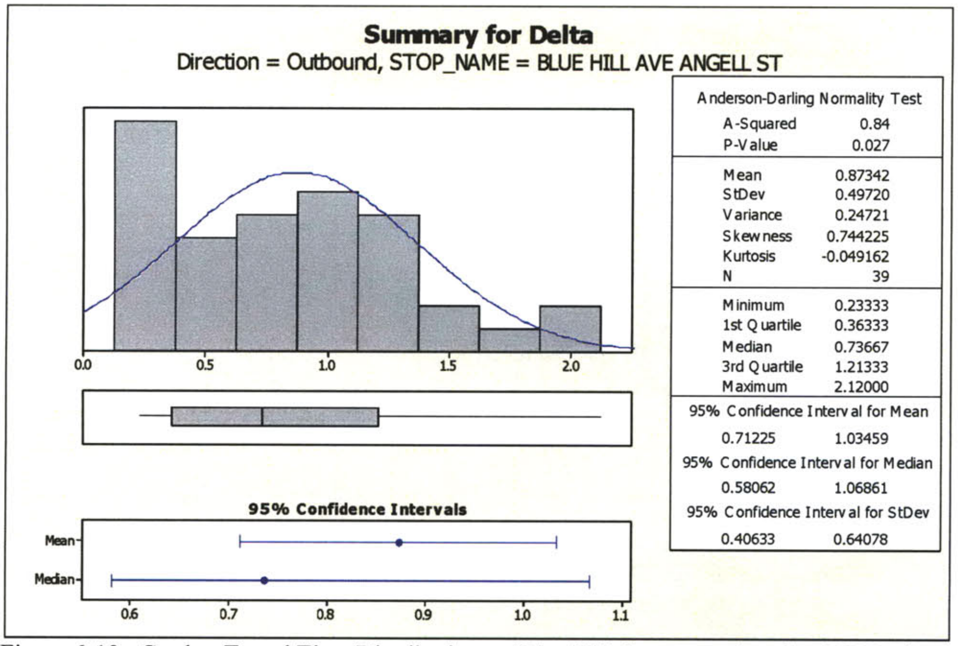

Figure 6-19: Cordon Travel Time Distribution on Blue Hill Avenue at Angell – PM Peak – Outbound

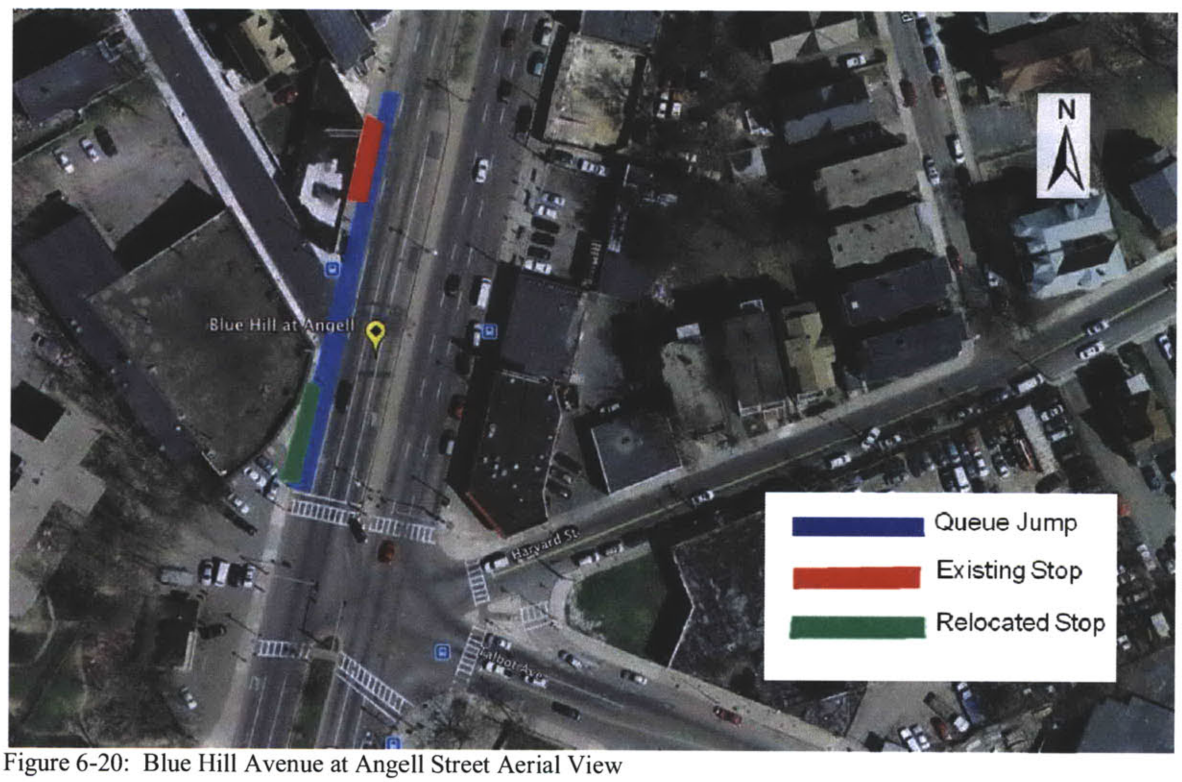

Figure 6-20: Blue Hill Avenue at Angell Street Aerial View

6.2.2 Dudley Station

Analyzing the cordon travel times surrounding Dudley Station shows again that there is potential be gained from improved terminal operations as 74% of the cordon travel times exceed the one minute threshold, 47% exceed the 90 second threshold, and 24% exceed two minute threshold (as shown in Figure 6-21, Delta being the difference between AVL and APC dwell times, which is the cordon travel time). A detailed analysis of the operations around Dudley station is beyond the scope of this project, however this data shows the need and potential to be gained from improving operations around the terminal. Field observations also supported the data analysis showing major delays in the vicinity of Dudley Station. Strategies such as dedicated lanes in the adjacent street should be considered.

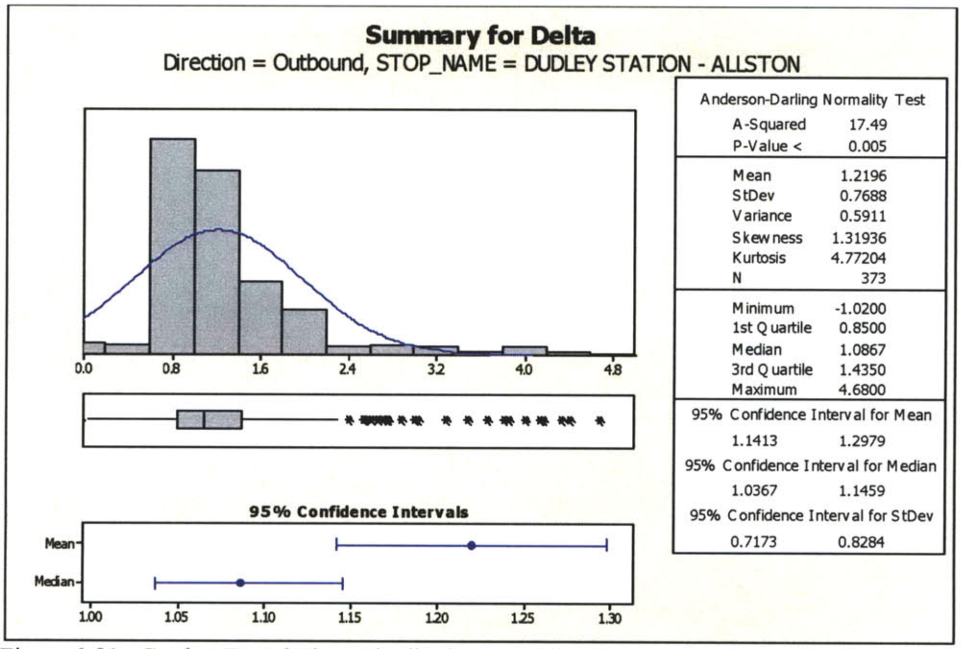

Figure 6-21: Cordon Travel Time Distribution at Dudley Station – PM Peak – Outbound

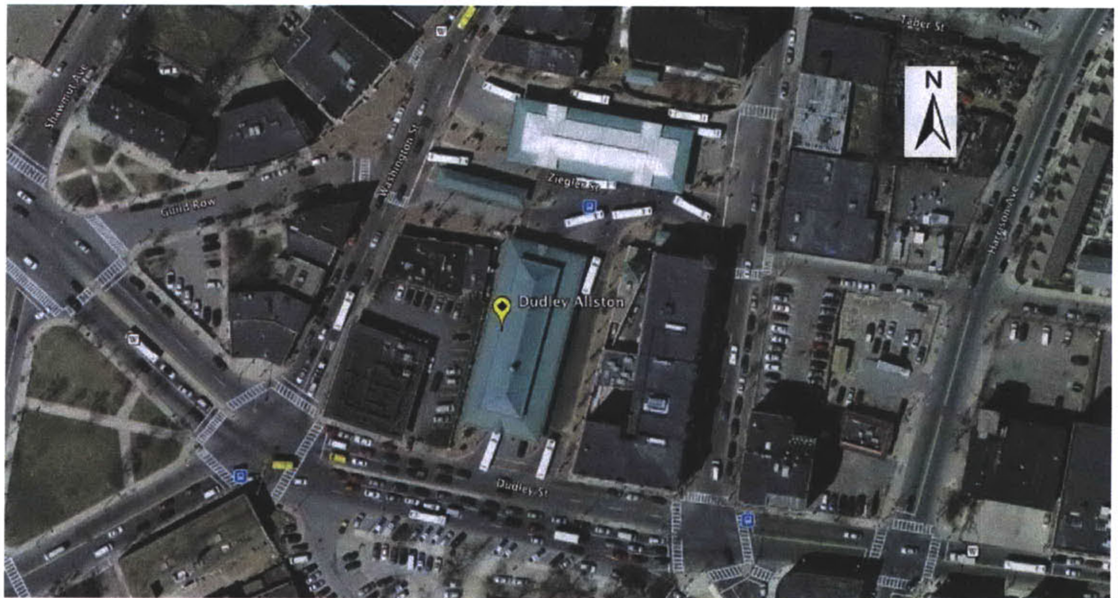

Figure 6-22: Dudley Station Aerial View

6.2.3 Warren Street at Crawford Street

The intersection of Warren Street and Crawford Street, which was not identified in the CTPS study as a potential queue jumping location, was shown to have significant potential for traffic operation improvements. In the PM peak 76% of the cordon travel times exceed the one minute threshold, 55% exceed the 90 second threshold and 31% exceed the 2 minute threshold (as shown in Figure 6-23, Delta being the difference between AVL and APC dwell times, which is the cordon travel time).

Initial field observations showed that one possible strategy would be to convert the right-turn only lane departing from the bus stop at Crawford into a bus-only lane approaching the Blue Hill Avenue intersection. Observations showed that the queue from Blue Hill Avenue regularly extends beyond the Crawford Street bus stop meaning that a dedicated lane would allow for a high proportion of buses to avoid delays from waiting for 12 vehicles to be released. Initial calculations based on signal timings and queue lengths estimated that average time savings from implementation of this lane would be 15 seconds. Implementation of the queue-jump lane would not require elimination of parking spaces.

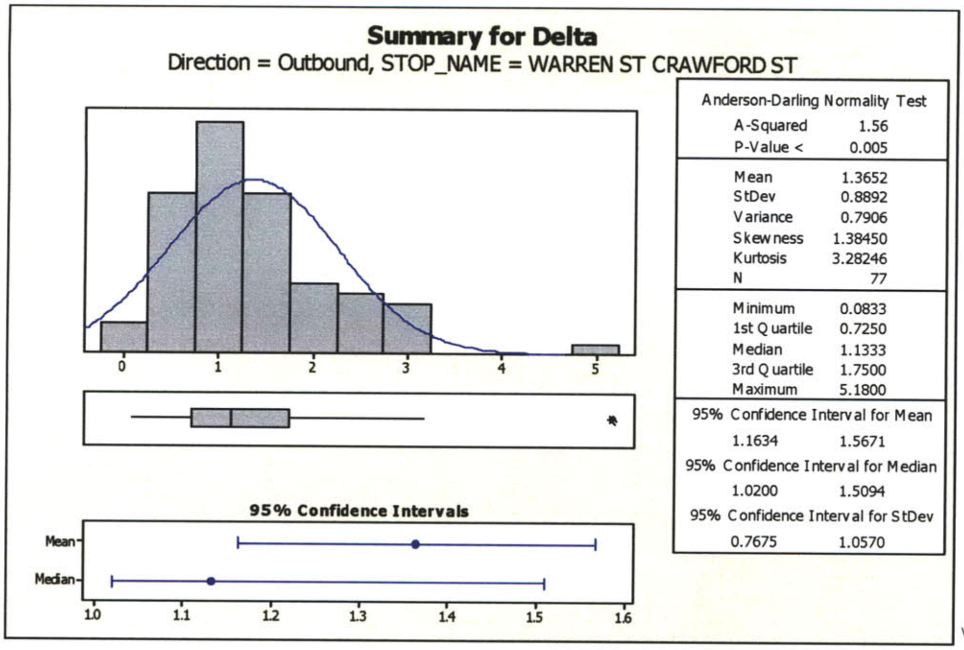

Figure 6-23: Cordon Travel Time Distribution on Warren Street at Crawford St. – PM Peak – Outbound

Figure 6-24: Warren Street at Crawford Street Aerial View

6.2.4 Blue Hill Avenue at Morton Street

The intersection of Blue Hill Avenue at Morton was also not specifically identified in the CTPS study as a potential queue jumping location but similarly shown to have potential for traffic operation improvements. In the PM peak 65% of the cordon travel times exceed the one minute threshold, 33% exceed the 90 second threshold and only 5% exceed the two minute threshold (as shown in Figure 6-25, Delta being the difference between AVL and APC dwell times, which is the cordon travel time).

Field observations of this intersection revealed that a potential strategy would be to consider removing the angled parking on the near side of Blue Hill Avenue adjacent to the police station and implementing a dedicated bus lane between Rhoades Street and Morton Street. Estimated average potential savings of implementing this strategy would be 12 seconds. The implementation would require elimination of 11 angled parking spaces in front of the police station or reorientation of the spaces to accommodate an additional lane of traffic.

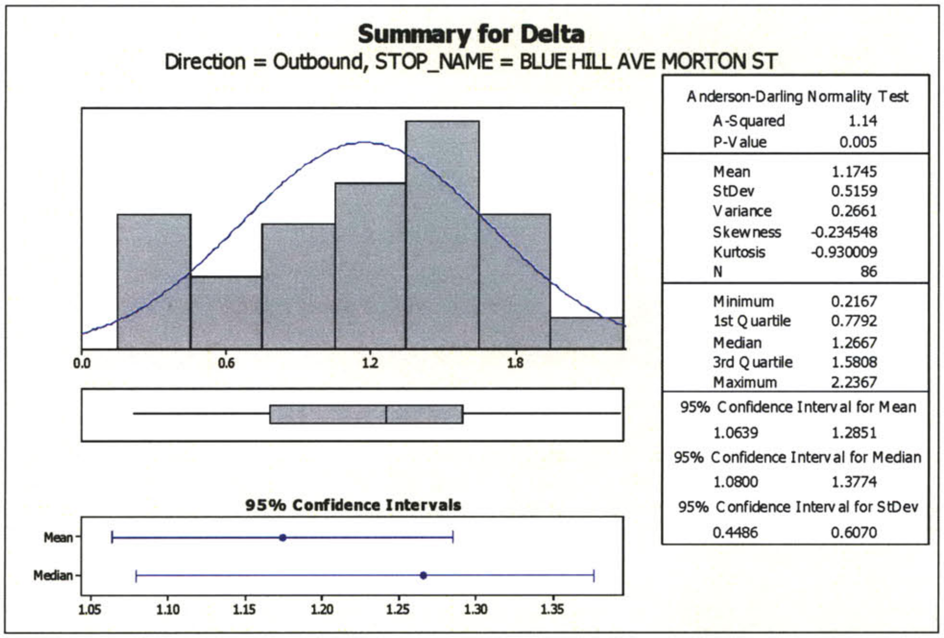

Figure 6-25: Cordon Travel Time Distribution on Blue Hill Avenue at Morton Street – PM Peak – Outbound

Figure 6-26: Blue Hill Avenue at Morton Street Aerial View

6.3 Conclusions on Queue Jump Potential

Overall the analysis of these identified queue jump locations on Route 28 showed varying average potential time savings of 5 to 20 seconds. Greater savings may be found from longer queue-jump lanes that allow buses to skip entire cycles when the queue is longer than the number of vehicles that can be released in a single green phase. During our field observations we rarely witnessed instances of the entire queue not being released during a single green phase. In addition, there are significant costs to implementation of queue-jumping in terms of parking spaces elimination and private vehicle traffic disturbance, even from implementing the shorter lanes suggested in the CTPS Key Bus Routes Studies.

Our analysis showed some increased benefits from relocating the stop to the near-side of the intersection at queue-jump locations but this would prevent sharing the lane with right-turning traffic. It is recommended to explore traffic signal improvements and traffic signal prioritization prior to implementation of queue-jumping at any of these locations, as the costs in terms of construction and political confrontation out weight the minor benefits from bus running time reduction.

7. GENERAL CONCLUSIONS

Our report concludes by providing a summarized analysis of the overall KBRI program, as well as general recommendations for future schedule adjustments on other MBTA bus routes and for effective further use of the existing ADC systems.

7.1 Overall Assessment of KBRI

A customer assesses performance of a bus service based on his or her trip attributes, two of which are related to bus service scheduling and are affected by KBRI changes - expected wait time and in-vehicle travel time. In chapter 4, a route-level assessment was provided where each route was classified based on the KBRI impacts on these two attributes. In assessing the overall success of KBRI at the route level, our analysis focused primarily on saved wait time rather than in-vehicle travel time. As explained in detail in Chapter 3.5, this was done for the following reasons:

1. Value of Time – Customers place a higher value on wait time at a bus stop than on time spent traveling on a bus.
2. External Factors – AVL data does not allow for the isolation of KBRI effects on in-vehicle travel time from other external factors.
3. Terminal Effects on AVL Data – Small changes in operator behavior at terminals can have a large effect on running time results.

As demonstrated in Table 7-1, KBRI provided mixed results, but had an overall beneficial effect on service performance. When resources were added, KBRI was shown to reduce customers' expected wait time by 28.2 hours per day during the AM and PM peak time periods. This was achieved at a cost of $41.60 per hour of customer wait time saved. However, wait time savings were also seen in most cases where buses were not added. Thus the overall benefits of KBRI should not only be attributed to the additional resources, but also to appropriate schedule changes and an overall attitude and culture towards improving bus service reliability.

Route	Time Period	Additional Funding	Change in Wait Time	Change in In-Vehicle-Travel Time	Route-Level Assessment
1	AM Peak	$261	-4.9 hours	14.5 hours	High Success
	PM Peak	$0	0.5 hours	0.8 hour	
15	AM Peak	$0	7.7 hours	13.1 hours	Moderate Success
	PM Peak	$326	-10.1 hours	2.3 hours	
23	AM Peak	$-261	5.5 hours	42.5 hours	Moderate Success
	PM Peak	$326	-8.3 hours	26.9 hours	

Route	Time Period	Additional Funding	Change in Wait Time	Change in In-Vehicle-Travel Time	Route-Level Assessment
28	AM Peak	$0	-1.9 hours	11.6 hours	High Success
	PM Peak	$0	-14.9 hours	5.6 hours	
66	AM Peak	$261	-4.9 hours	14.5 hours	Moderate Success
	PM Peak	$0	0.5 hours	0.8 hour	

Table 7-1: Summary of KBRI Impacts to Bus Service Performance

Section 7.2 will further outline how future schedule adjustments can be efficiently conducted on other MBTA routes.

7.2 General Recommendations for Schedule Adjustments

The analysis of the impacts of KBRI on bus service performance along the selected bus routes allows us to draw some general conclusions, listed below.

1. Consider the Tradeoff between Service Efficiency and Service Reliability

To influence bus service performance, schedule planners can address service efficiency and/or service reliability. The two are inter-related in that changes to one will likely have effects on the other.

When buses were added (Routes 1-AM, 15-PM, 23-PM, 66-AM), customer wait time savings were realized in all cases, albeit at different levels. Route 1-AM Peak experienced a large degree of savings, with customers saving 34 seconds of expected wait time per trip. The additional bus was used to improve reliability by increasing the overall cycle time. Route 23-PM Peak also experienced large savings, with customers saving 13 seconds of expected wait time per trip. The additional bus was used to increase service frequency without affecting reliability.

However, schedule adjustments that target reliability or service frequency alone - such as those presented above - may also have adverse effects. On Route 66-PM Peak, schedule planners increased service frequency at the expense of reliability, and despite the decrease in scheduled wait time, the overall expected wait time increased (the excess wait time increased at larger magnitude than the decrease in scheduled wait time).

The resulting conclusion is that the schedule planner should consider both aspects of performance - service efficiency and service reliability - when making schedule changes.

2. Consider Increasing Service Reliability before Service Efficiency

As mentioned above, schedule planners can use additional resources to increase either service efficiency and/or service reliability. Our report demonstrates that a larger decrease of expected wait time was possible when reliability, rather than efficiency, was targeted.

On Routes 1-AM and 15-PM, the additional bus is used to improve reliability. The cycle time is increased, which leads to a substantial decrease of excess wait time: customers are saved 34 seconds (10%) and 74 seconds (19%) of expected wait time per trip, on the two routes respectively.

On Routes 23-PM and 66-AM, the additional bus is used to increase service frequency only. This leads to reduced scheduled wait times: customers are saved 14 seconds (5%) and 11 seconds (3.5%) of expected wait time per trip, respectively on the two routes.

Although the above-presented results are route specific, we can draw the general rule of thumb that targeting service reliability can lead to larger gains in Expected Wait Time than service efficiency.

3. Consider Running Time and Recovery Time Mix

As expected, when buses were added (Routes 1-AM, 15-PM, 23-PM, 66-AM), customer wait time savings were realized in all cases. Unfortunately, resources are limited, and a bus cannot always be added to improve performance.

Results from our analysis show that along routes where cycle time was held constant with no change in the number of buses, performance was increased through a beneficial adjustment of the mix of running time and recovery time. An example is Route 1-PM, where an increase in running time (cycle time constant) led to an average savings of 23 seconds of wait time/trip. On the other hand, performance deteriorated along Route 15-AM, where recovery time was increased at the expense of running time. For this route, customers waited on average an additional 34 seconds per trip. One explanation for this observation may be the following: additional running time provides bus operators with slack time to mitigate external factors and slowing speed along the route is something which operators can control. This in turn decreases the variability of both the running times and headways, reducing the excess wait time that customers experience. On the contrary, a tighter schedule (decreased running time to allow for increased recovery time) is likely to be unrealistic; bus operators will try to speed up, actual running times may decrease slightly, but the variability of operations will most likely increase.

However, slower operating speeds may result in longer in-vehicle travel times. As explained previously, customers prefer wait time savings approximately 2:1 over in-vehicle travel time savings. Wait time savings therefore have more of an impact on a customer's perception of bus service performance.

The resulting conclusion is that service reliability can be best improved by decreasing recovery time to allow for increased running time (with cycle time remaining constant).

4. Buses May be Added or Removed without Effect on Reliability (with Constant Cycle Time)

As resources are limited, it may be advantageous to reallocate buses from one route to another, or between time periods. As demonstrated by several cases within our report (23-AM, 23-PM, 66-AM), the addition or subtraction of a single bus was used to increase or decrease service frequency along the route without adjusting cycle time. While this resulted in increased (or decreased) performance in the form of reduced (or increased) customer scheduled waiting times, the effect to excess waiting times was little to none. Along Route 23-PM Peak, a bus was added, which allowed for an increase in service frequency with no effect on reliability (excess wait time unchanged). Along Route 23-AM Peak, a bus was removed without impacting reliability.

Therefore, as a general conclusion, buses may be removed from a route operating at less than capacity with minimal effects on service reliability, as long as cycle time remains constant.

5. Consider the Utilization of Excessive Cycle Time

When total scheduled cycle time exceeds the running time necessary to run the route, MBTA schedule planners can use the extra cycle time to increase service frequency without deterioration of reliability of operations. However, this must be done with caution.

Along Route 28-PM, the reduction of cycle time was used to reduce headways without adding a bus. Customers expected wait time decreased without affecting reliability of operations (excess wait time constant). This was made possible due to excessive amount of cycle time prior to the schedule change. Along Route 66-PM, a similar schedule adjustment was made, however customers expected wait time increased due to a large decrease in service reliability (excess wait time increased). This is a result of an overestimation of the excessive amount of cycle time prior to the schedule changes.

Therefore, as a general conclusion, excessive cycle time can be converted into increased service frequency; however, this must be approached with caution to avoid negative side effects to reliability.

7.3 General Recommendations for Automatic Data Collection (ADC) Usage

The in-depth analysis using data from ADC systems on Routes 1 and 28 demonstrates how effective these systems can be to analyze bus service performance. The following recommendations are provided so that the MBTA can take full advantage of the integration of these systems.

1. Potential from Connecting ADC Systems

Our analysis of data collected from the three ADC systems revealed that there are opportunities for deriving additional insights from linking the databases (see Figure 7-1).

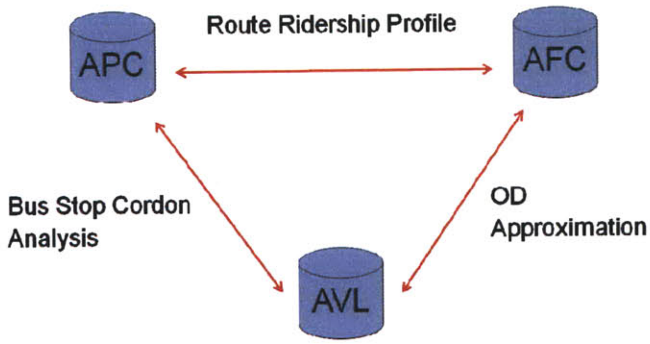

Figure 7-1: Linking ADC Databases

Linking the APC and AFC databases (see Appendix 2) allowed us to compare ridership estimates derived from the two data sources. AFC transaction data systematically undercounts the more accurate APC boarding data. However, APC systems are currently only installed on 83 buses while AFC systems are installed system wide. Comparing the ridership profiles from these two different systems, it may be possible to make more accurate estimates about ridership levels and load factors by calibrating the AFC data with route-specific APC ridership and load factor profiles.

A second illustrative opportunity comes from linking the APC and AVL systems as explained in Chapter 6. Linking these two systems allows for isolation of the traffic operation time within the bus stop AVL cordon from the APC recorded dwell time. This identification of operational times and speeds around the bus stops and intersections can assist in identifying locations that may benefit from operational improvements such as queue-jumping or traffic signal prioritization.

A third example comes from linking the AVL and AFC databases, which allows for inference of Charlie card users' alighting locations. This in turn allows for the development of transit rider OD data which may be utilized to gain a better understanding of how passengers use the bus network.

These are three selected examples used to illustrate the potential benefits of linking these separate databases.

2. Strategic Management of Data

Three separate firms currently provide the three ADC systems as noted in Chapter 3.3. In the process of analyzing AVL, APC, and AFC data we frequently experienced challenges interfacing the data due to inconsistent and incompatible structures and formats between the three sources. It is recommended that a strategic approach be taken to create standards for an integrated database with respect to formats and IDs and to identify additional attributes that may allow for easier and improved interfacing between data sources.

3. Consistent Utilization of Technology

These ADC systems are only beneficial when properly utilized to strategically collect data. In our analysis, we came across APC data from Fall 2009 where the APC equipped buses had not been consistently deployed on Routes 23 and 28 as intended. This led to scattered APC data collection across the bus network with sample sizes that were too small to conduct the desired analysis.

4. Active Usage of ADC Data

Once the ADC systems are integrated and utilized to consistently collect data, the MBTA can take full advantage of the data for service planning, control and management, as well as for performance measurement and monitoring. These systems indeed provide a wealth of data and the analysis of this data should be a priority within any high-performing organization.

In addition to the analysis of this data for planning and management purposes, portions of the data can be used to improve real-time operations. For instance, given that these key bus routes are high-frequency routes, adherence to headways is more important than adherence to the schedule. However, the bus operators are currently equipped with monitors that only provide schedule adherence information. Providing the operators with information about the location of the preceding bus would be more useful in maintaining headways and improving operational service reliability.

Lastly, streaming portions of this data to the public can greatly improve riders' experience with the MBTA. For instance, live monitoring of bus locations allows riders to better plan their trips by reducing their 'buffer' time. Their experienced wait times are then reduced, which improves customer perception of the service.

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APPENDICES

Appendix 1: Automated Data Collection (ADC) Systems

Appendix 2: Comparison of Ridership Estimation Using AFC and APC

Appendix 3: MIT Data Mining Approach

Appendix 4: Route Summaries

Appendix 1 : Automated Data Collection (ADC) Systems

The appendix explains the different ADC sources in more detail focusing on the different data attributes provided.

1. Automatic Vehicle Location (AVL) Data

AVL Data represents real-time satellite-based global positioning system (GPS) information of the location of buses in the network. The AVL provided data can support the following data attributes for the location of a bus at a specific point time. The MBTA has implemented an AVL system for all its bus service operations so AVL data is available for all key bus routes.

Data attribute	Description
Crossing_ID	Distinct data record of a scheduled bus trip crossing a specific point time location, a unique Crossing_ID (numeric value as unique identifier) is generated for each arrival and departure of a distinct bus at a major bus stop
Calendar_date	Date of the data record (mm/dd/yyyy 12:00:00 AM)
Service_type	Service type of the data record (e.g. "MUWTWeekday-011" for Weekday service)
Route ID	Route identifier (e.g. "28" for route 28)
Direction	String value to indicate inbound or outbound direction
Variation	Combined with route identifier to indicate the traveled route variation (e.g. "151" for route 15 variation 1)
Vehicle	Value to indicate vehicle number of data record (e.g. "824" for vehicle 824 according to MBTA bus numbering)
Run	Value to indicate a run which are two successive trips on a route (inbound and outbound)
Stop_number	Value associated with a specific bus stop
Time_point_name	String value associated with a specific point time (e.g. mostly bus stop)
Trip_id	Value associated with scheduled trip (unique per week)
Scheduled_time	Scheduled time at time point (value corresponding to time in seconds to past midnight of day of service, trips which past midnight are same day service)
Actual_arrival_time	Actual time entering a specific radius (approximately 175ft) around a bus stop (value corresponding to time in seconds to past midnight of day of service, trips which past midnight are same day service)
Actual_departure_time	Actual time leaving a specific radius (approximately 250ft) ftaround a bus stop (value corresponding to time in seconds to past midnight of day of service, trips

Data attribute	Description
	which past midnight are same day service)
Adherence	Difference between values "Scheduled_time" and "Actual_departure_time"
Scheduled_headway	Scheduled headway as a comparison of the scheduled times between two successive vehicles at a specific time
Actual_headway	Scheduled headway as a comparison of the actual departure times between two successive vehicles at a specific time point
Point_type	String value indicating if "Startpoint", "Midpoint" or "Endpoint"
Passes_standard	String value indicating if time point record satisfies MBTA service delivery policy (e.g. "Too late" for bus which are too late at time point)

Table A1-1: Data attributes of MBTA AVL data (source: own representation)

2. Automatic Passenger Count (APC) Data

APC Data represents automatic counts of boarding and alighting passengers at bus stops. The data is generated from a system of a series of sensors placed by the doors that track the number and direction of movements. The MBTA APC data is not available in real time but is uploaded overnight from the internal bus system to the central database server.

The MBTA has not yet fully deployed Automatic Passenger Count Systems in all of its buses. To be more precise, just a small number of the MBTA buses are equipped with an APC system. APC data was received only for routes 23 and 28 for both the spring and fall time period. However, the APC equipped buses were not used consistently in the fall time period so there was not adequate data to compute statistically significant performance metrics and perform a comparison analysis between time periods.

Table 2 presents a sample data record from the APC system randomly chosen from a sample APC data set for route 28. The data record shows the smallest possible aggregation level of boarding's and alighting of passengers at a specific bus stop (here: MALCOLM X BLVD O BRYANT on route 28). The example was chosen to provide a better understanding of the data attributes.

Data attribute	Value	Selected description
LOAD_NUM	416	Value to indicate vehicle number of data record (e.g. "824" for vehicle 824 according to MBTA bus numbering)
STOP_SEQ_ID	36	Stop Sequence ID
STOP_ID	11149	See AVL data attribute
STOP_NAME	MALCOLM	See AVL data attribute
ACT_STOP_TIME	13:25.0	Actual Stop Time
PSGR_ON	3	Passengers boarding
PSGR_OFF	12	Passengers alighting
PSGR_LOAD	14	Total passenger on-board
PSGR_LD_CHG		Passenger Load Change
TRIP_DATE	03-23-09 00:00.0	See AVL data attribute
ROUTE	28	See AVL data attribute
PATTERN	0	
BLOCK	2205	
LATITUDE	42.33075	Geographical information
LONGITUDE	-71.08843	Geographical information
ACT_TRIP_RUN_MILES	26.7	Actual trip distance since trip start
TRIP	1732	See AVL data attribute
DOOR_CYCLES	2	
GPS_ERROR_FT	25	
DAY_OF_WK	1	Day of the week
DIRECTION	1	Inbound (value 1), Outbound (value 2)
ACT_MILES_SINCE_LAST_STOP	0.12	Actual distance since last bus stop
ACT_MINS_SINCE_LAST_STOP	0.4	Actual time since last bus stop
PSGR_MILES	2.69	Average travel distance by passenger

Data attribute	Value	Selected description
PSGR_HOURS	0.141	Average travel time by passenger
BUS	737	See AVL data attribute
DBNN	903	
DWELL_DOOR_MINS	NULL	
LINE	28	
TRIP_ID	NULL	See AVL data attribute
SCH_TIME	00:00.0	See AVL data attribute
SCH_RUN_MINS	99.9	
ACT_RUN_MINS	99.9	
TRIP_MILES_ODOM	0	
TRIP_MILES_GPS	26.7	
DEVIATION_MINS	99	
DWELL_TOT_MINS	0.37	Total dwell time
MS_FILE	MBT0903B	
QC_ODOM	1	
QC_GPS	0	
QC_COUNTS	9	
QC_ASSIGNMENT	100	
SA_PERCENT_GOOD	NULL	
SCHOOL	NULL	
SERVICE	NULL	
SOURCE_REC_TYPE	D	
PREV_BUS_SCH_TIME	NULL	
NEXT_BUS_SCH_TIME	NULL	
NUM_WC_RECS	0	

Data attribute	Value	Selected description
NUM_SP1_RECS	0	
NUM_SP2_RECS	0	
VERSION	6.55	

Table A1-2: Sample APC data record by bus stop aggregation level (source: Barker, 2010)

Higher aggregation levels are available as well, for instance by trip specific stop, segment, or block. However, our analysis focused on data aggregated by boardings and alighting at specific bus stops for specific trips (smallest possible aggregation level) to provide a meaningful link to the AVL data at the same aggregation level. The APC data attributes above in bold and italics are most important for our analysis.

3. Automatic Fare Collection (AFC) Data

Automatic Fare Collection (AFC) systems record payments by smart cards with unique identification numbers, magnetic strip cards, cash fares, and flash passes recorded by the operator. This information is recorded when an individual person boards a bus. However, more advanced systems with distance based fares also record fare data when a passenger exits the system (mostly with smart cards with unique identification number for an individual person, for instance Suica Card in Tokyo). However, the MBTA bus service system is designed to record fare payments only when passengers board. A high proportion of passengers use the Charlie Card, the MBTA's smart card system.

We received AFC data for the spring and fall periods for all defined routes at the lowest possible aggregation level of individual transactions at a certain time at a certain farebox in a bus.

Data attribute	Value	Description
Deviceid	753	Fare box ID equivalent to the bus ID
CREADATE	3/2/09 9:36 AM	Date and time of transaction
ROUTE	23	Route
Amount	1	
TicketDesc	SV Adult (SC)	Fare type
TICKETSERIALNO	403101887	Ticket serial number
DESCRIPTION	Smart Card Mifare 1k	Media type (here: Charlie Card)
MOVEMENT	Validation	Validation or Upgrade
RemainingAmount	330	Remaining value in ($$¢¢) format
Sign	0	
TransactionAmount	125	Transaction value in ($$¢¢) format
TransactionSign	1	
UsedValue	1	
AutoExtension	0	

Table A1-3: Sample of recorded fare transaction from AFC data source (source: Castonguay, 2010)

Appendix 2 : Comparison of ridership estimation using AFC and APC systems

This appendix gives insights into the discrepancy between AFC and APC data in estimating ridership numbers. The comparison analysis was carried out on Routes 23 and 28, the two Key Bus Routes in this study for which both data sources were available. The time period of boarding data comparison was limited to the seven weekdays between the 21st 31st of March due to the limited availability of data. However, the sample size for matching trip boarding data was still sufficiently high to make statistically significant conclusions (N = 305 and N = 279 for Route 23 and Route 28, respectively). The assumption was made that while not all trips were included in the AFC data extract provided by the MBTA, all the trips that were included contained a complete set of transactions. Figure A2-1 provides a framework which was used to link attributes of both data sources.

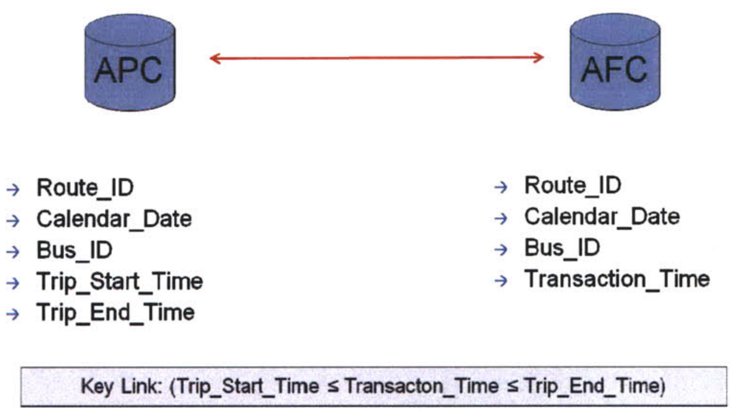


Figure A2-1: Framework for Linking APC and AFC Data

In order to analyze the discrepancy between boarding data of AFC and APC, two approaches were taken. First, the absolute difference between AFC and APC boardings was analyzed. Second, the relative difference in form of a ratio AFC/APC was evaluated. Finally the results were put together by analyzing the impact the number of boardings had on the discrepancy between ridership estimation of AFC to APC.

Route 23 AFC & APC Ridership Comparison

1. Delta AFC – APC

The initial analysis compared the differences between the ridership counts from the AFC and APC data sources as shown in Figure A2-1. The general trend shows the AFC data undercounting the APC data which appears to be a log-normal distribution of the difference. This indicates that the undercounting is probably not random but systematic.

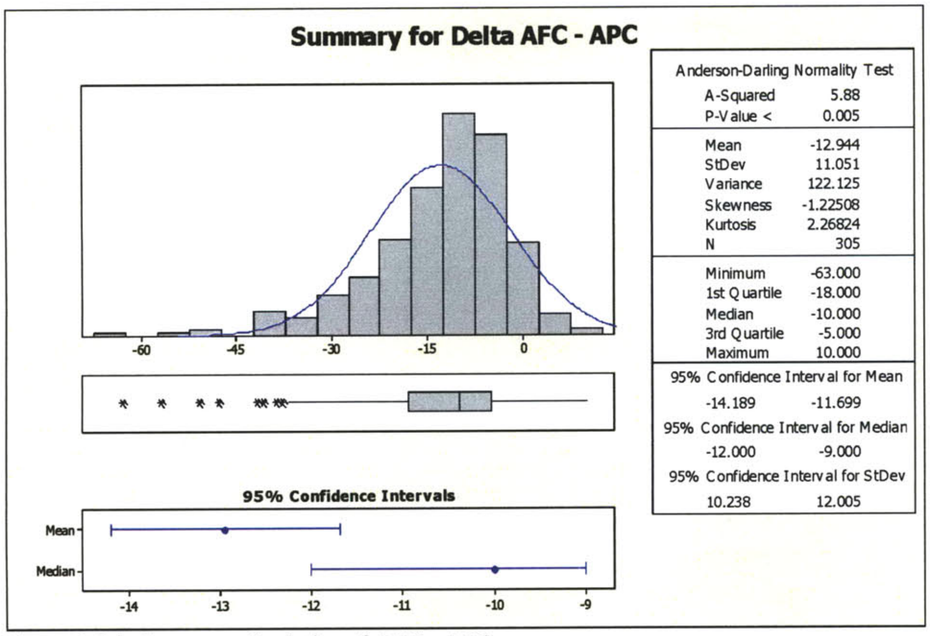


Figure A2-1: Summary Statistics of AFC - APC

The differences were also analyzed based on the MBTA's six schedule time periods as shown in Figures A2-2 and A2-3. This segmentation of the time periods showed the most significant undercounting during the Early AM time period, followed by the Midday School and then the AM and PM peak periods. This led to the hypothesis that unregistered boardings by school children had the most significant impact on undercounting by the AFC. The second most significant impact appeared to be peak period traffic operations leading to commuters being waved onto to buses in order to maintain schedule adherence.

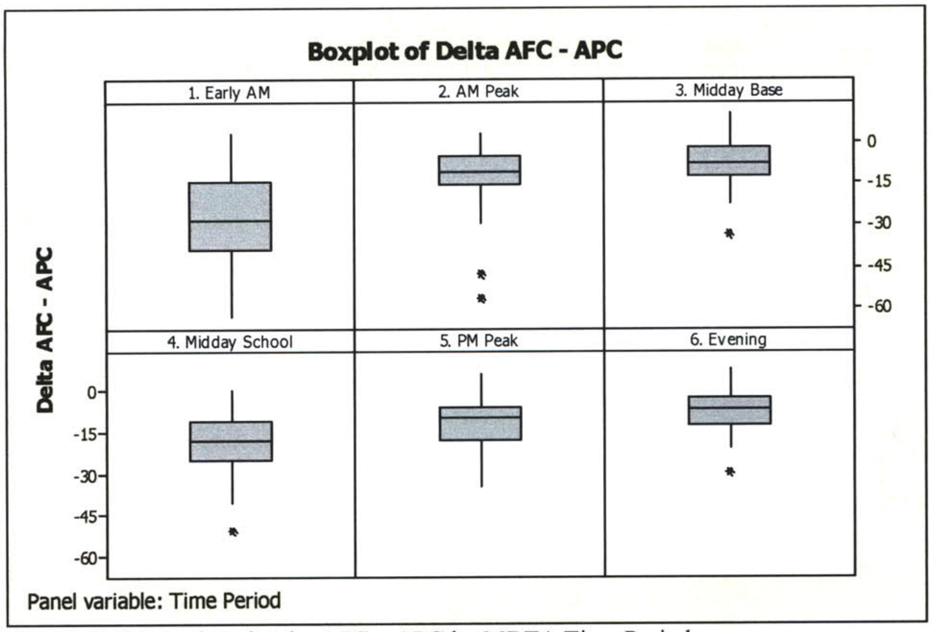


Figure A2-2: Boxplot of Delta AFC – APC by MBTA Time Period

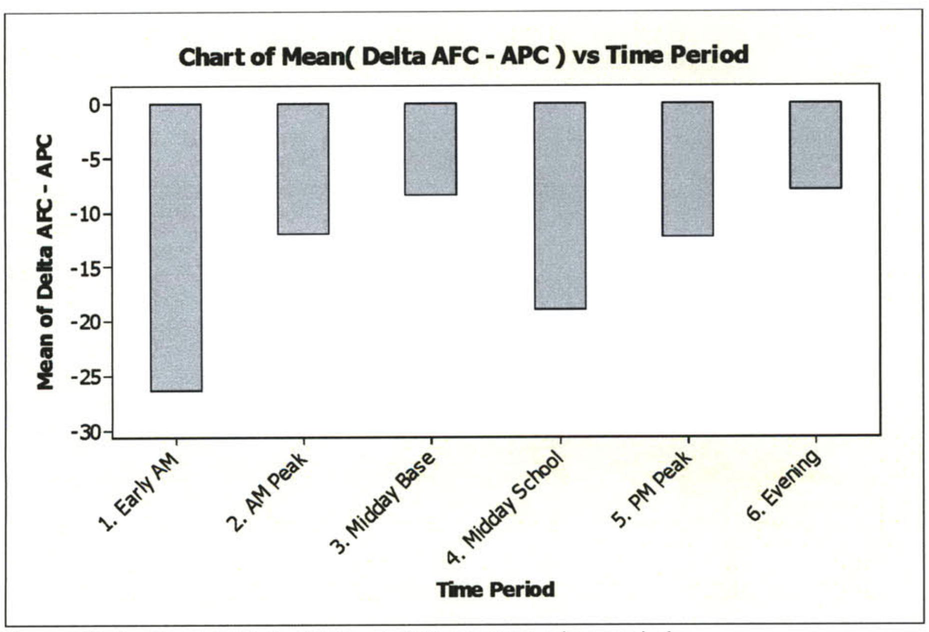


Figure A2-3: Absolute Delta AFC – APC by MBTA Time Period

Next the number of boardings per trip were aggregated by hour for AFC and APC and then compared throughout the day. Figure A2-4 shows that the highest boardings per trip occur during the midday period between the peaks when there are lower frequencies suggesting high passenger loads during this time period.

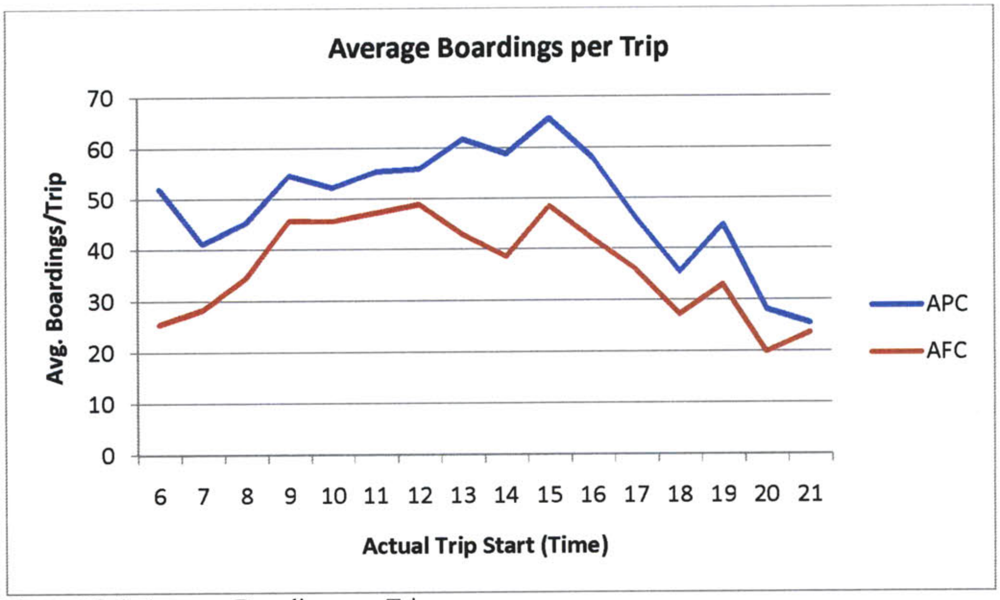


Figure A2-4: Average Boardings per Trip

2. Ratio AFC/APC

A comparison of the ratios of ridership counts from the AFC and APC data sources throughout the day was used as a second analysis as shown in Figure A2-5. The general trend still shows the AFC data undercounting the APC data although the distribution of ratios appears to be a normal distribution. This still indicates that the undercounting is probably not random but systematic.

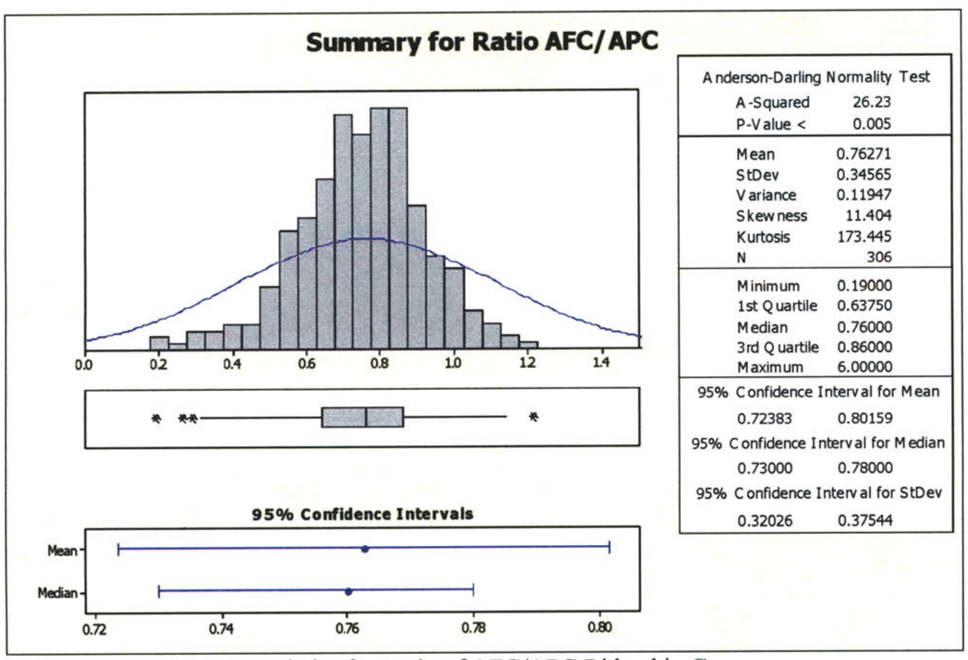


Figure A2-5: Summary Statistics for Ratio of AFC/APC Ridership Counts

The ratios were also analyzed based on the MBTA's six schedule time periods as shown in Figures A2-6 and A2-7. This segmentation of the time periods showed the most significant percentage of undercounting during the Early AM time period, followed by the Midday School and then the AM and PM peak periods. This further supports the previously noted hypothesis that unregistered boardings by school children had the most significant impact on undercounting by the AFC.

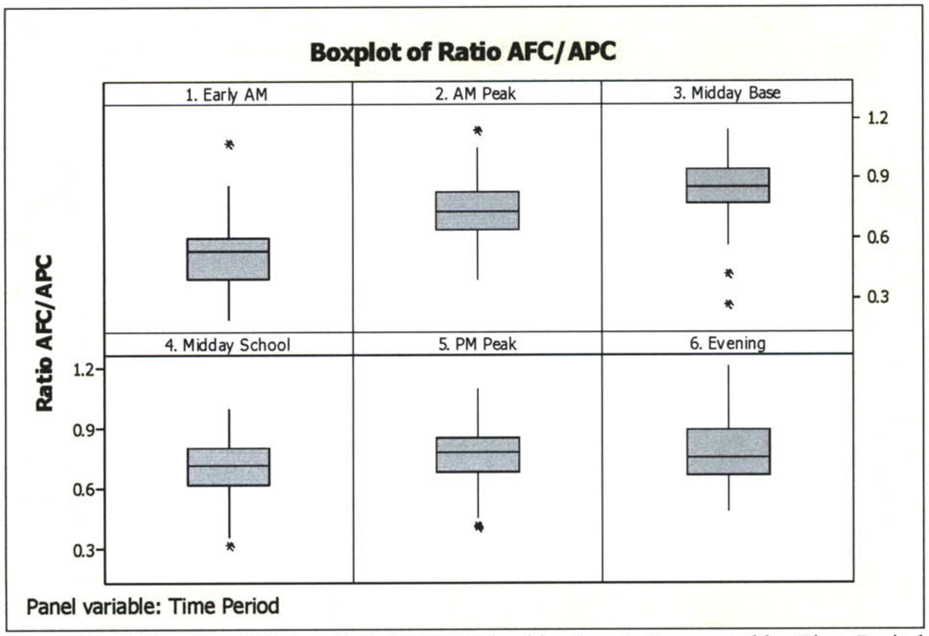


Figure A2-6: Boxplot of Ratio of AFC/APC Ridership Counts Segmented by Time Period

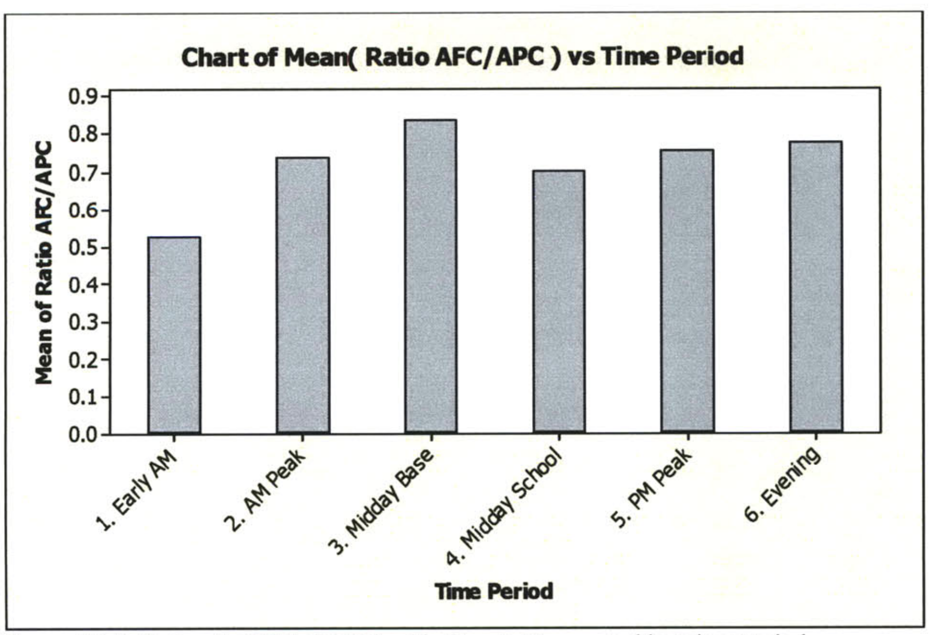


Figure A2-7: Ratio of AFC/APC Ridership Counts Segmented by Time Period

Next the ratio of AFC vs. APC boardings per trip were aggregated by hour and then compared throughout the day. Figure A2-8 shows that the highest percentage of AFC recorded transactions per trip occurred on trips starting between 9am and 1pm, a period of the day when there are lower service frequencies.

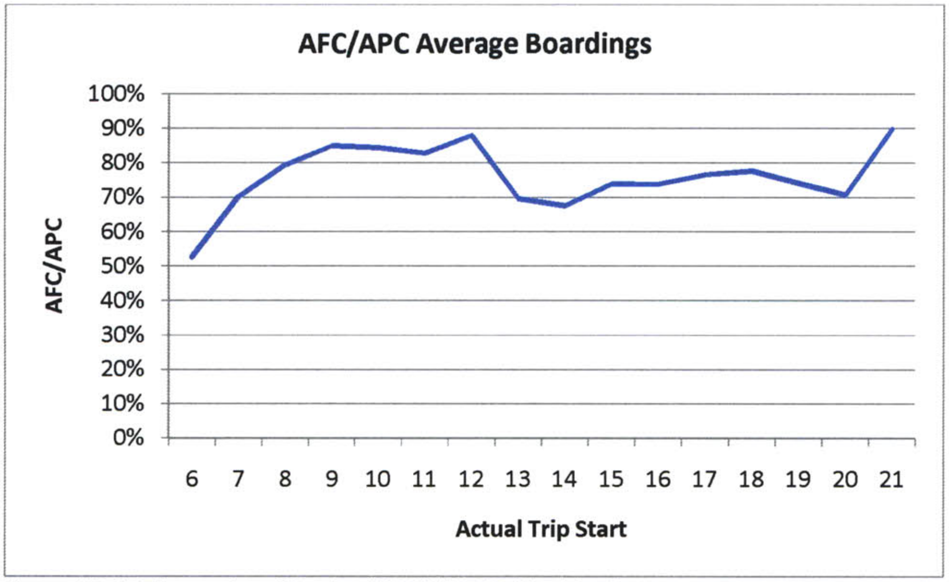


Figure A2-8: Time series of Ratio of AFC/APC Ridership Counts

3. Regression

A linear regression was run regressing the ratio of AFC/APC boardings on the level of APC boardings. The regression model had very poor explanatory power with an R^2 of 0.014 but came up with statistically significant estimates of the coefficients for the constant and level of APC Boardings with a negative but small value for β_APC of -.0011. This means that a marginal increase of 10 passengers would be expected to reduce the AFC/APC ratio by 1.1%. The poor R^2 value may indicate that there are not consistent policies being followed by MBTA operators in regards to unregistered boardings.

Regression Analysis: Ratio AFC/APC versus APC Boardings

```
The regression equation is
Ratio AFC/APC = 0.799 - 0.00108 APC Boardings


Predictor            Coef     SE Coef      T      P
Constant          0.79886     0.02709  29.49  0.000
APC Boardings  -0.0010811   0.0005125  -2.11  0.036


S = 0.170329   R-Sq = 1.4%   R-Sq(adj) = 1.1%
```

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	0.12910	0.12910	4.45	0.036
Residual Error	303	8.79064	0.02901		
Total	304	8.91974			

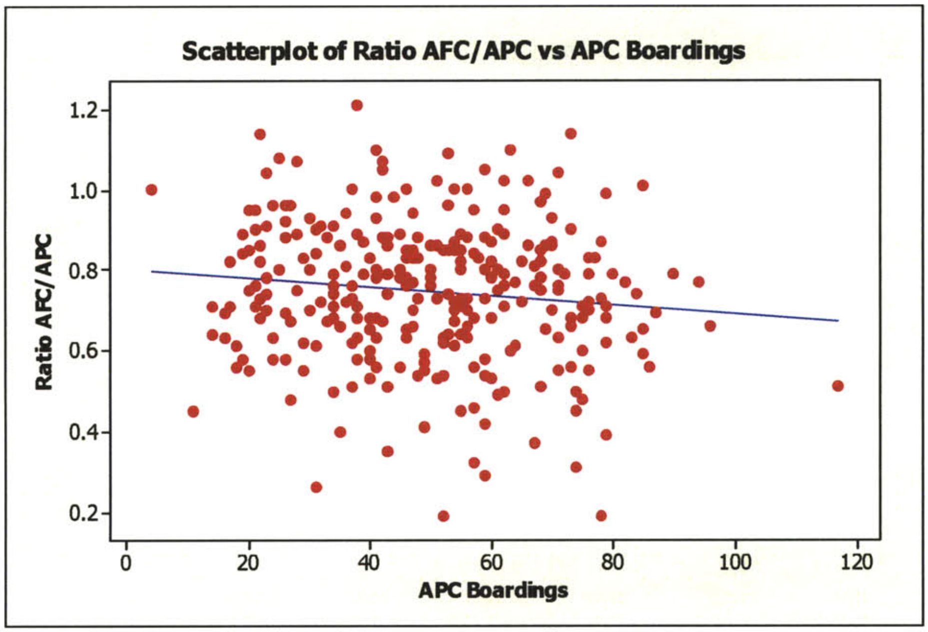


Figure A2-9: Scatterplot of AFC/APC vs. APC Boardings

Individual regressions were run on the segmented data to identify if there were more distinct trends in specific periods. The Early AM period of trips starting between 6am and 7am showed the strongest trend of a decreasing AFC/APC ratio with increasing APC ridership levels. As mentioned previously, this may be due to a combination of high levels of commuter and school children boarding and being waved on to busier buses at times of high traffic. Linear regression models on the remaining time specific segmented data had very poor explanatory power further suggesting that there is no consistent policy being followed by MBTA operators with respect to unregistered boardings.

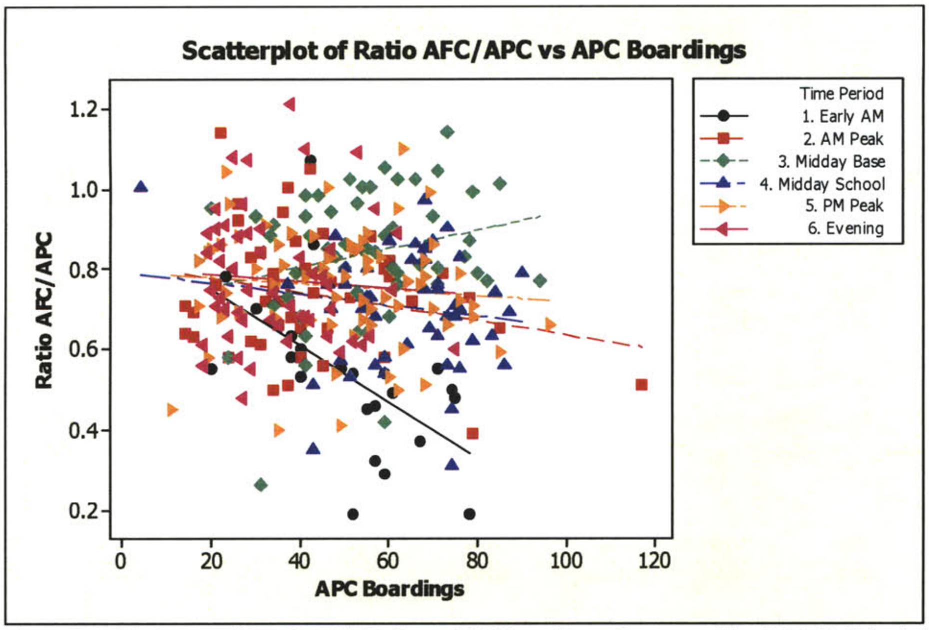


Figure A2-10: Scatterplot of AFC/APC vs. APC Boardings Segmented by MBTA Schedule Time Periods

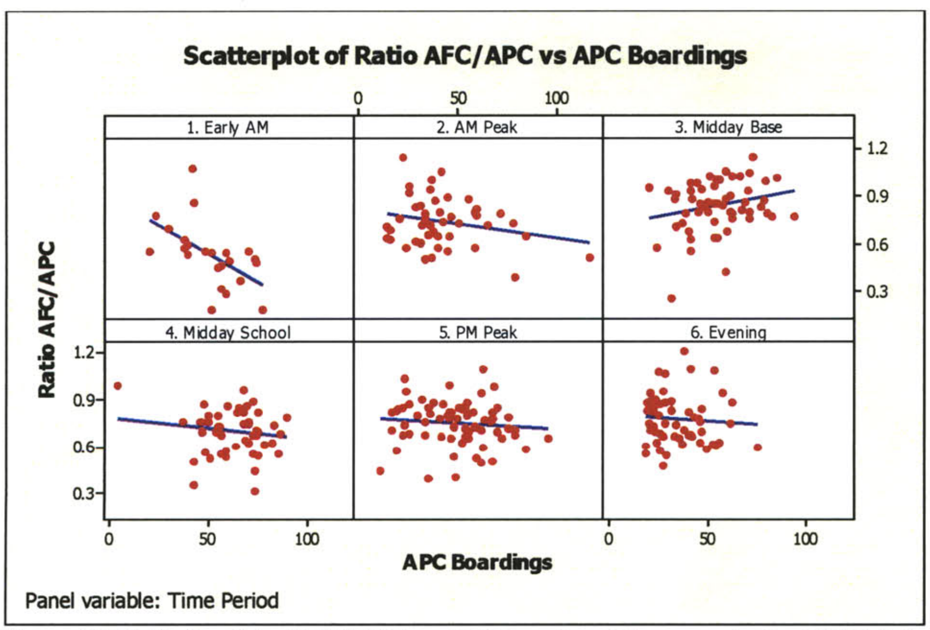


Figure A2-11: Scatterplot of AFC/APC vs. APC Boardings Disaggregated by MBTA Schedule Time Periods

Route 28 AFC & APC Ridership Comparison

1. Delta AFC – APC

As with Route 23 the initial analysis compared the differences between the ridership counts from the AFC and APC data sources as shown in Figure A2-12. The general trend for route 28 also shows the AFC data undercounting the APC data in what appears to be a log-normal distribution of the difference. Similarly to Route 23, this indicates that the undercounting is probably not random but systematic.

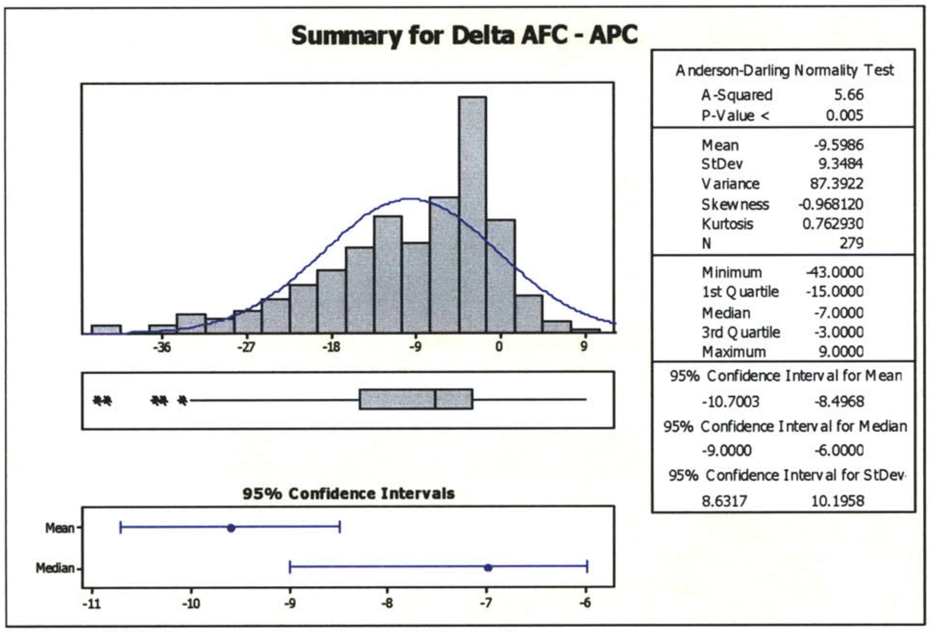


Figure A2-12: Summary Statistics of AFC - APC

The differences were also analyzed based on the MBTA's six schedule time periods as shown in Figures A2-13 and A2-14. This segmentation of the time periods showed the most significant undercounting during the Early AM time period, followed by the Midday School and then AM and PM peak periods. Once again this led to the hypothesis that unregistered boardings by school children had the most significant impact on undercounting by the AFC.

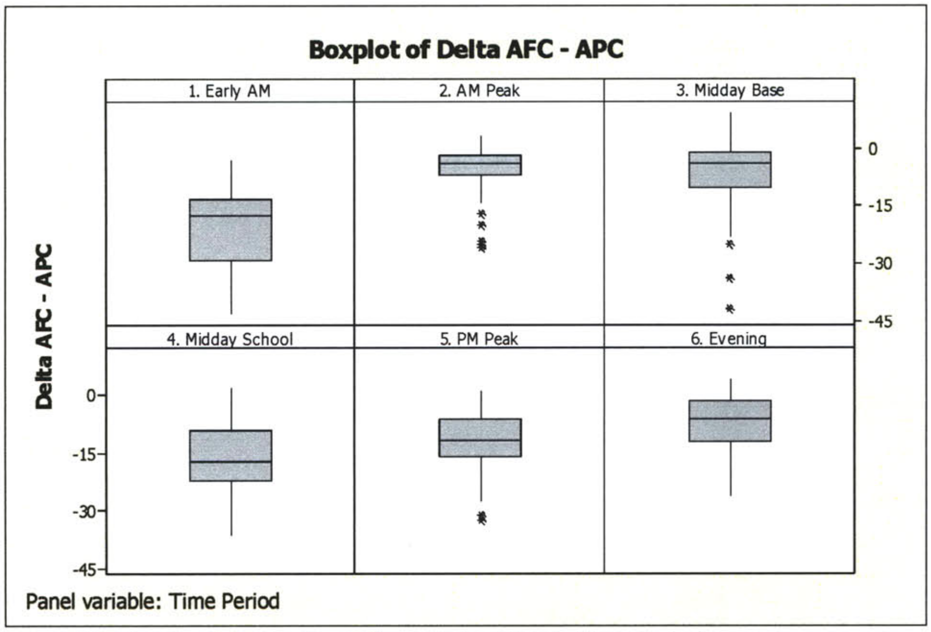


Figure A2-13: Boxplot of Delta AFC – APC by MBTA Time Period

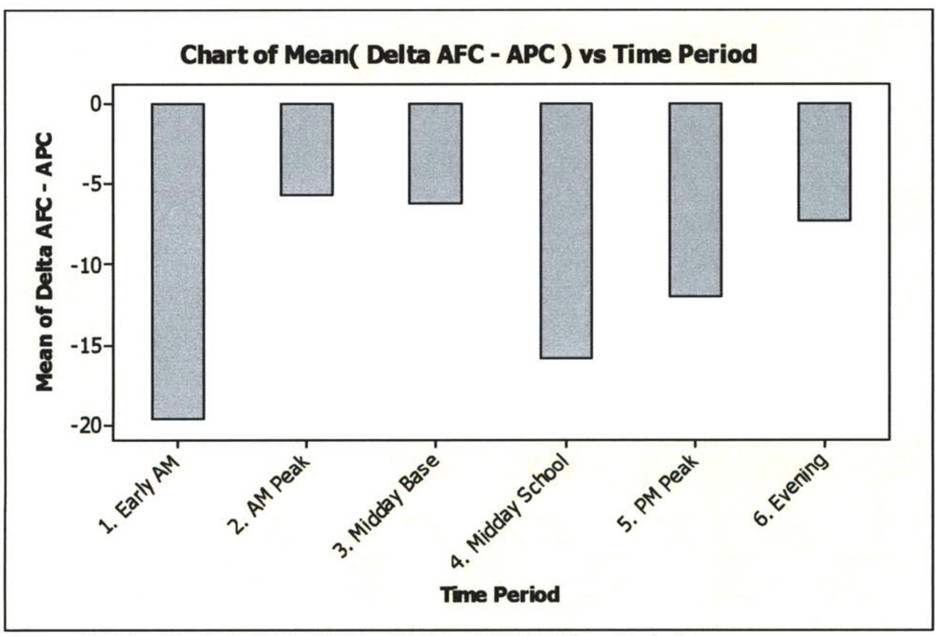


Figure A2-14: Absolute Delta AFC – APC by MBTA Time Period

Next the number of boardings per trip were aggregated by hour for AFC and APC and then compared throughout the day. Figure A2-15 shows that the highest boardings per trip occur during the midday period from 12 noon to 2pm when there are lower service frequencies.

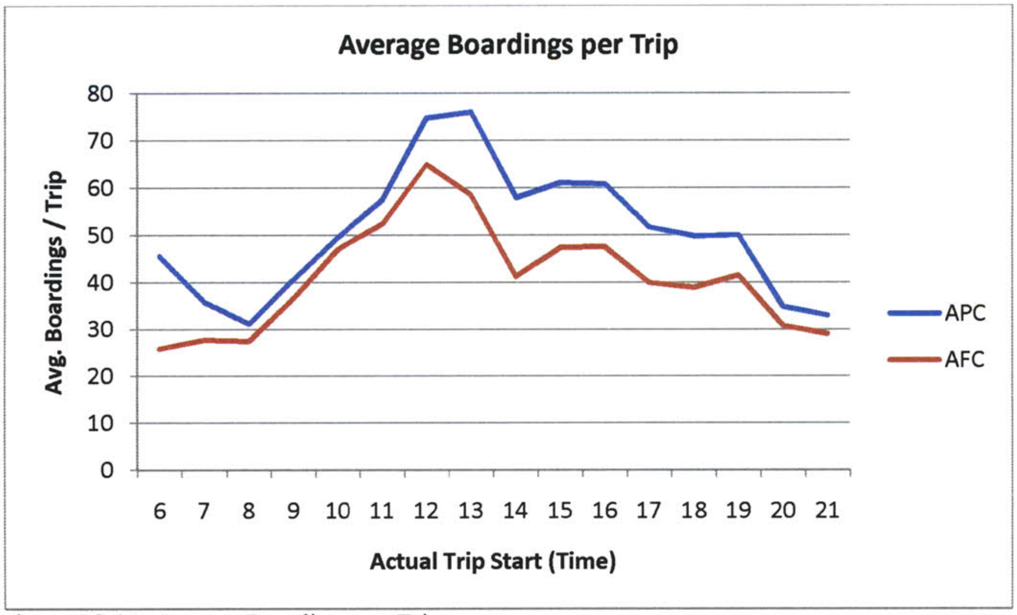


Figure A2-15: Average Boardings per Trip

2. Ratio AFC/APC

A comparison of the ratios of ridership counts from the AFC and APC data sources throughout the day was used as a second analysis as shown in Figure A2-16. The general trend still shows the AFC data undercounting the APC data although the distribution of ratios appears to be a normal distribution. This still indicates that the undercounting is probably not random but systematic.

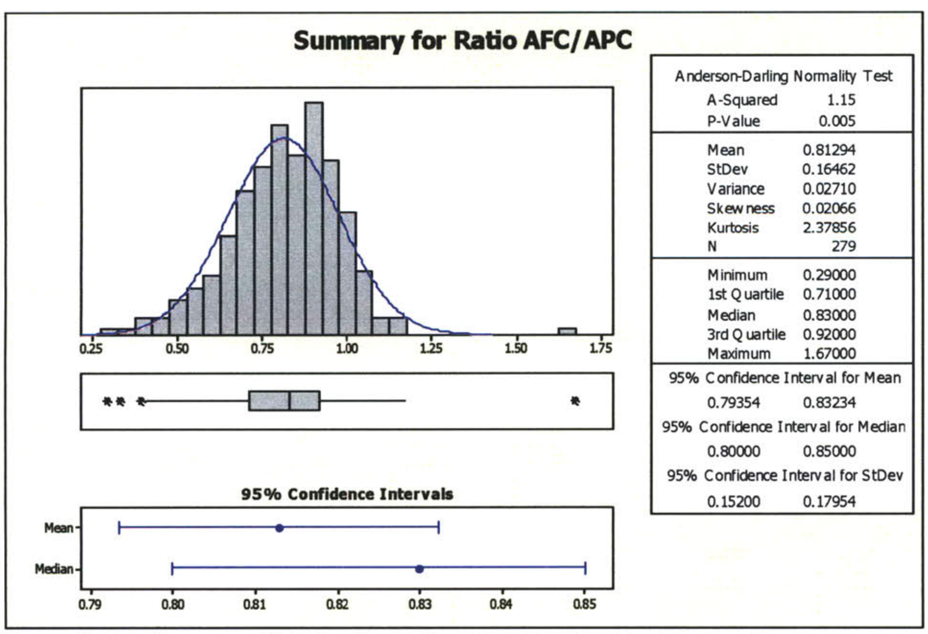


Figure A2-16: Summary Statistics for Ratio of AFC/APC Ridership Counts

The ratios were also analyzed based on the MBTA's six schedule time periods as shown in Figures A2-17 and A2-18. This segmentation of the time periods showed the most significant percentage of undercounting during the Early AM time period, followed by the Midday School and then the AM and PM peak periods. This further supports the previously noted hypothesis that unregistered boardings by school children had the most significant impact on undercounting by the AFC.

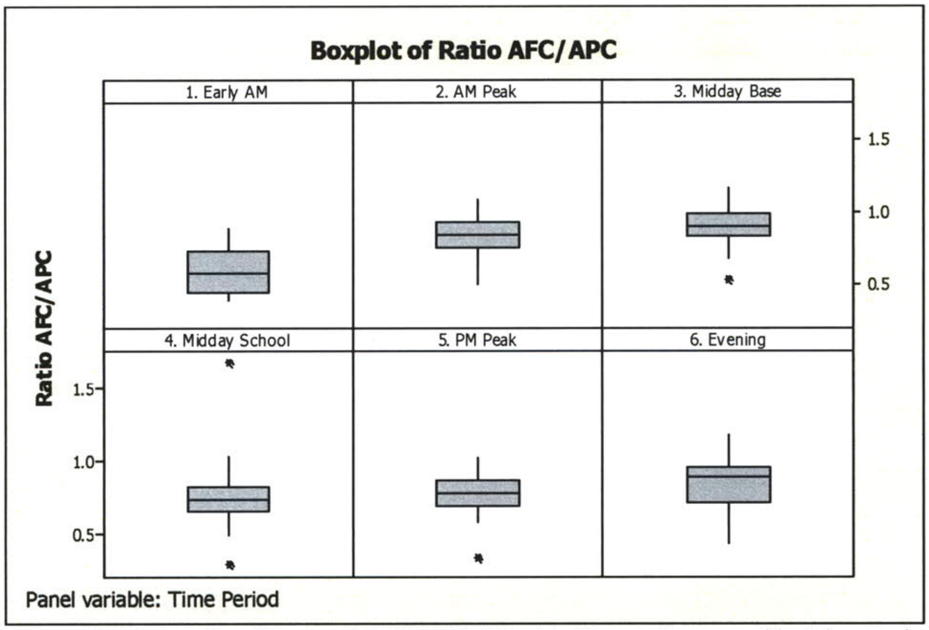


Figure A2-17: Boxplot of Ratio of AFC/APC Ridership Counts Segmented by Time Period

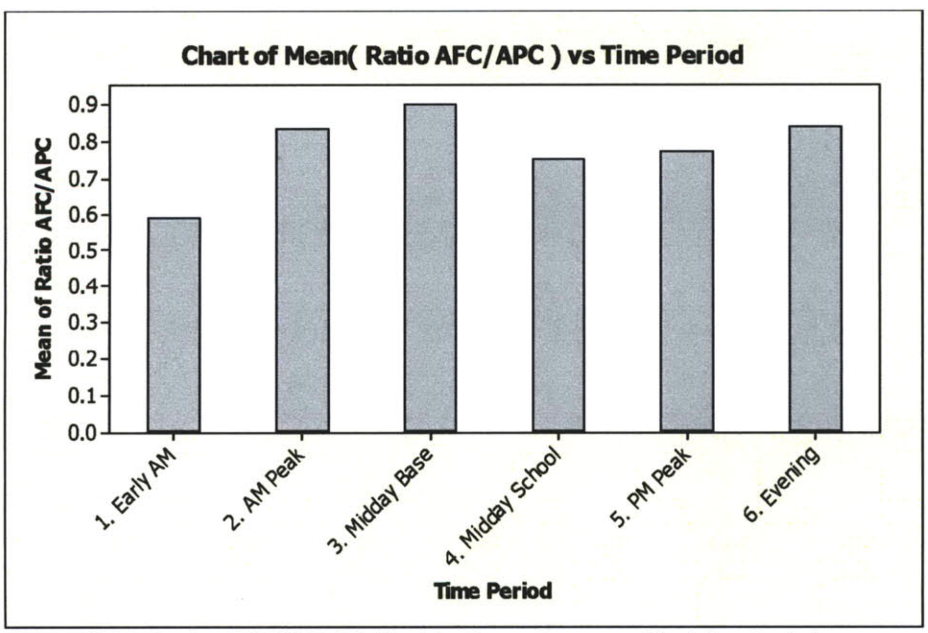


Figure A2-18: Ratio of AFC/APC Ridership Counts Segmented by Time Period

Next the ratio of AFC vs. APC boardings per trip were aggregated by hour and then compared throughout the day. Figure A2-19 shows that the highest percentage of AFC recorded transactions per trip occurred on trips starting between 8am and 1pm, a period of the day containing the end of the AM peak but primarily the late morning and midday when there are lower service frequencies.

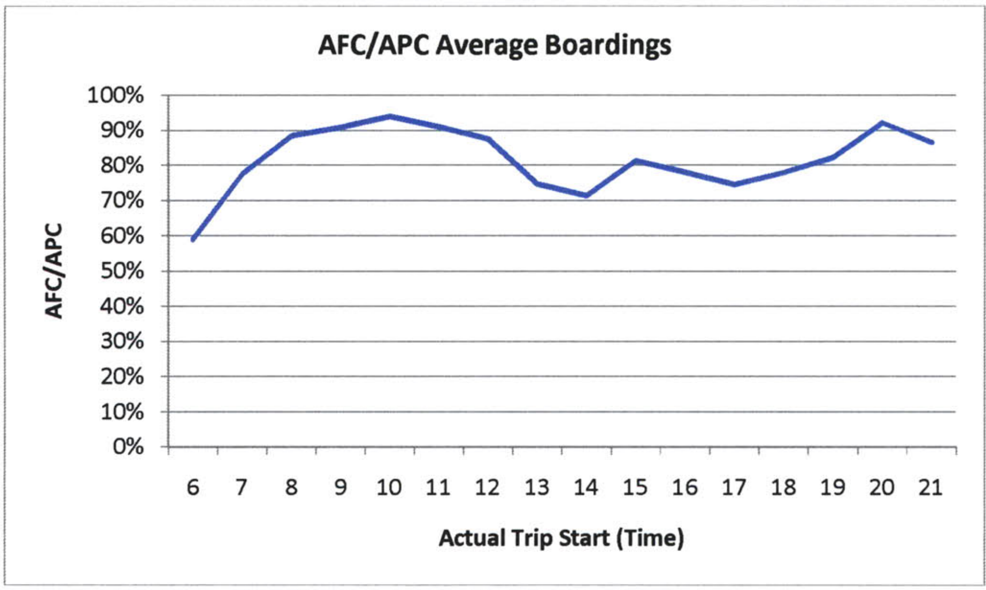


Figure A2-19: Time series of Ratio of AFC/APC Ridership Counts

3. Regression

A linear regression was run regressing the ratio of AFC/APC boardings on the level of APC boardings. The regression model had no explanatory power with an R^2 of 0.001 and came up with a statistically insignificant estimate of the coefficient for level of APC Boardings. The poor R^2 value may further indicate that there are not consistent policies being followed by MBTA operators in regards to unregistered boardings.

Regression Analysis: Ratio AFC/APC versus APC Boardings

```
The regression equation is
Ratio AFC/APC = 0.822 - 0.000247 APC Boardings


Predictor              Coef    SE Coef      T      P
Constant            0.82217    0.02288  35.93  0.000
APC Boardings    -0.0002466  0.0004176  -0.59  0.555


S = 0.156821   R-Sq = 0.1%   R-Sq(adj) = 0.0%
```

```
Analysis of Variance

Source          DF       SS       MS     F      P
Regression       1  0.00857  0.00857  0.35  0.555
Residual Error 276  6.78762  0.02459
Total          277  6.79619
```

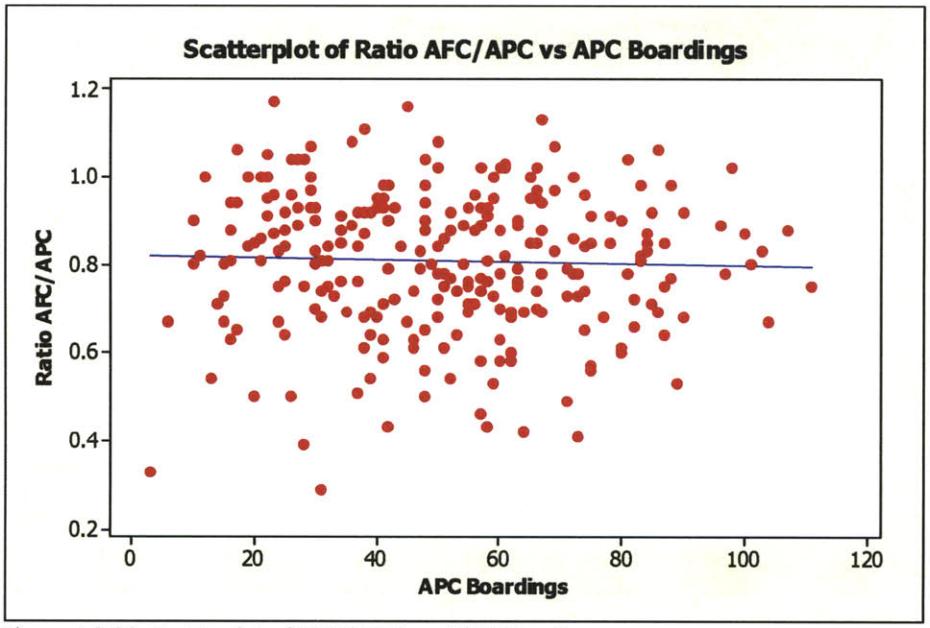


Figure A2-20: Scatterplot of AFC/APC vs. APC Boardings

Individual regressions were run on the segmented data to if there were more distinct trends in specific periods. As with Route 23 the Early AM period of trips starting between 6am and 7am showed the strongest trend of a decreasing AFC/APC ratio with increasing APC ridership levels. As mentioned previously this may be due to a combination of high levels of commuter and school children boarding and being waved on to busier buses at times of high traffic. Linear regression models on the remaining time specific segmented data had very poor explanatory power further suggesting that there is no consistent policy being followed by MBTA operators with respect to unregistered boardings.

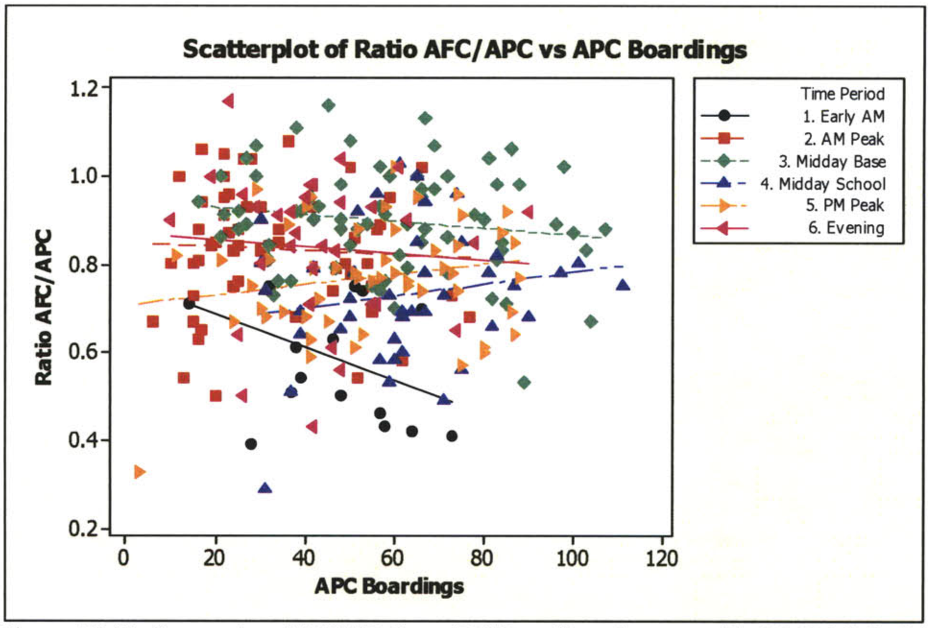


Figure A2-21: Scatterplot of AFC/APC vs. APC Boardings Segmented by MBTA Schedule Time Periods

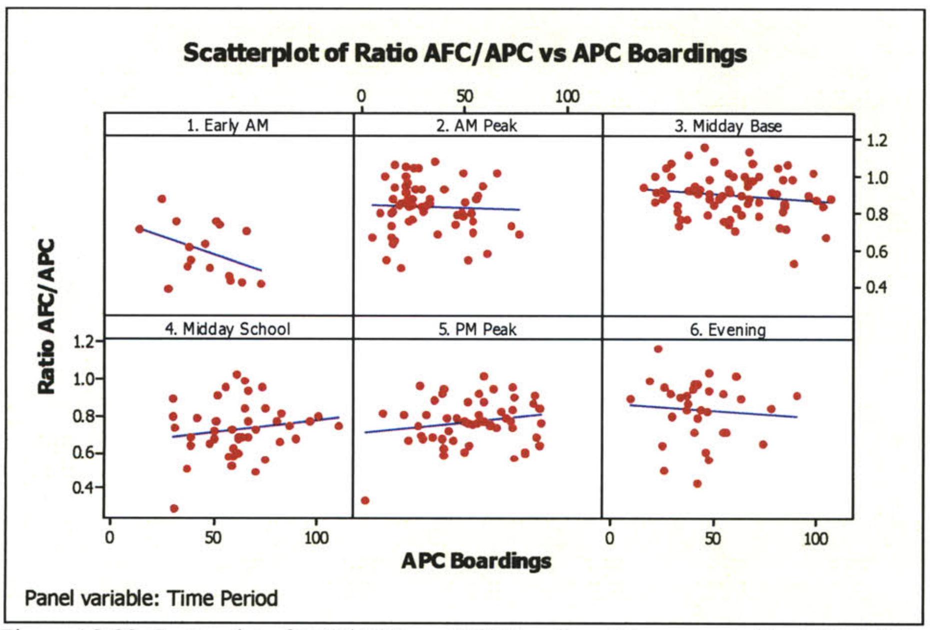


Figure A2-22: Scatterplot of AFC/APC vs. APC Boardings Disaggregated by MBTA Schedule Time Periods

Appendix 3 : MIT Data Mining Approach

1. IT infrastructure

It was found useful to set up an appropriate IT structure for the project and the organization of our team. A free file hosting service (sharepoint) was used which uses cloud computing to store and share all of the project data and files. The file hosting service operated by Dropbox, Inc. was found to be most appropriate for our project needs in terms of functionality, storage space and price.

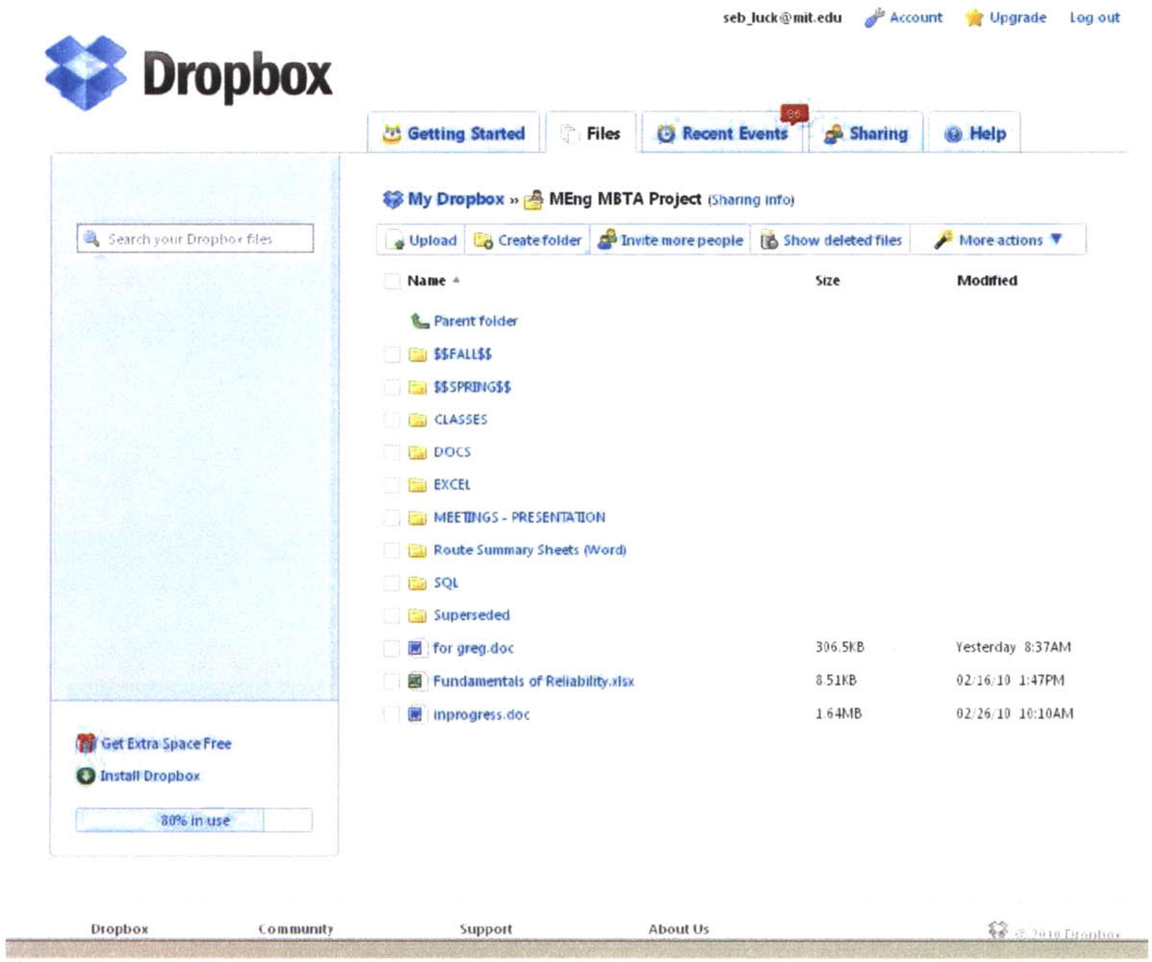


Figure A3-1: Dropbox to manage MEng MBTA Project

A network drive was also set up on the CEE-Net with a large storage capacity to backup MBTA raw data, manipulated and aggregated data files, and superseded data analysis. Updates in the Dropbox were continuously synchronized with the network backup drive to prevent unforeseen data loses.

2. SQL as Data Aggregation Tool

An initial decision had to be made as to which database software package to use between Microsoft Access and SQL Server. The majority of the data from the MBTA was received in .CSV or .MDF (SQL) format. In addition to the ease of importing SQL was chosen because of better performance, scalability, network capability and its better overview of data and queries.

Once imported, SQL was used to clean the databases of all incomplete and possibly problematic data. This consisted of erasing all rows that missing values for any of the critical attributes. Rows of data containing extreme Travel Time or HW values that were obviously due to data errors rather than just being outliers were also deleted.

We erased approximately 5-10% of the travel time data and approximately 20% of the HW data which requires the data for consecutive trips.

Once each database had been cleaned, it was transformed, aggregated and filtered as necessary for export to Excel. Standardized queries were developed in order to generate the same sets of data outputs for different routes, peak periods and seasons of data.

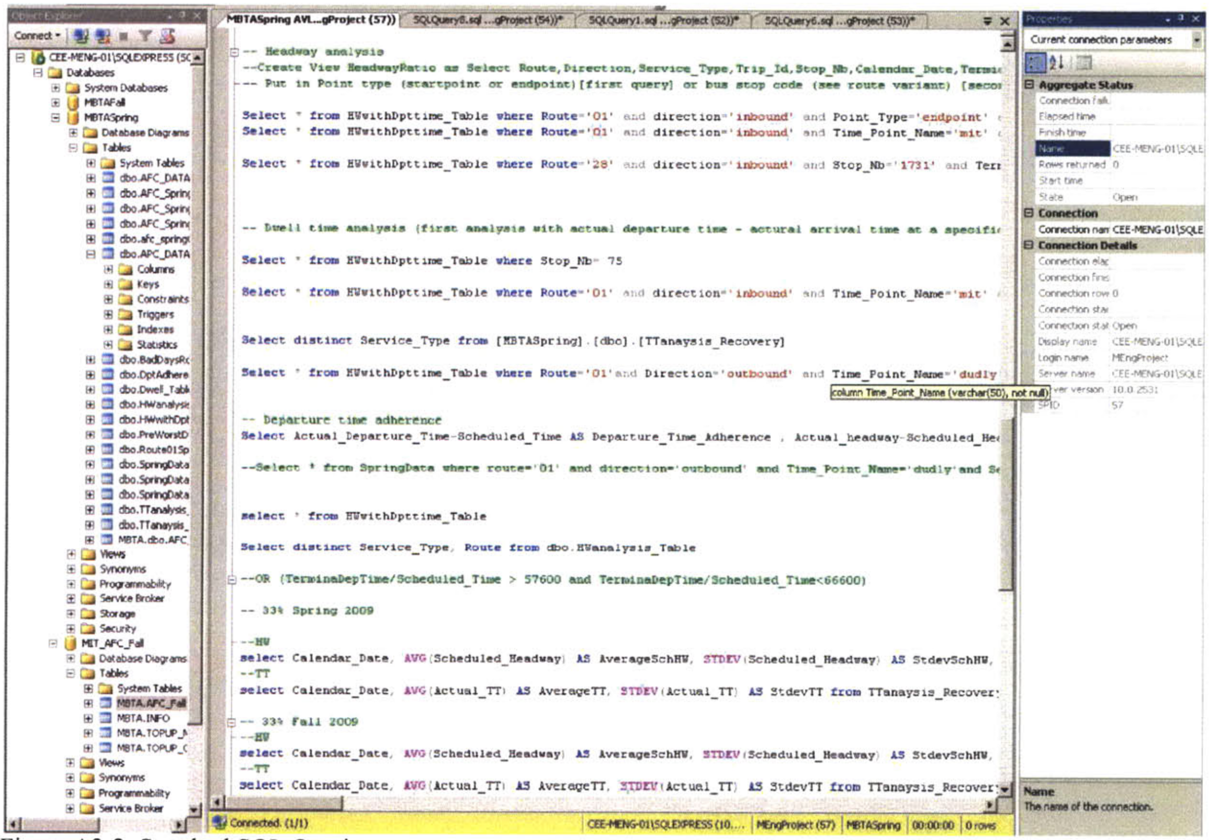


Figure A3-2: Standard SQL Queries

3. Excel Templates and VBA Code to Calculate Performance Metrics.

Once the data was transformed, aggregated, and filtered into appropriate subsets, it was exported to Excel due to better flexibility in calculating relevant performance metrics and creating graphs. Microsoft Excel was used to perform several steps of statistical analyses to develop our standardized performance metrics.

These Excel worksheets were set up as templates with the intended ease of mass production for multiple routes, peak periods, directions, and data subsets.

Although not all were critical to our analysis, templates were created for calculating the following

- AVL: TT Analysis, HW Analysis, Dwell Time Analysis, Terminal Departure Adherence,
- APC: Ridership, Load Factor, Dwell Time,
- AFC: Ridership, Fare Media Penetration.

Below an example of an Excel template for TT Analysis is shown.

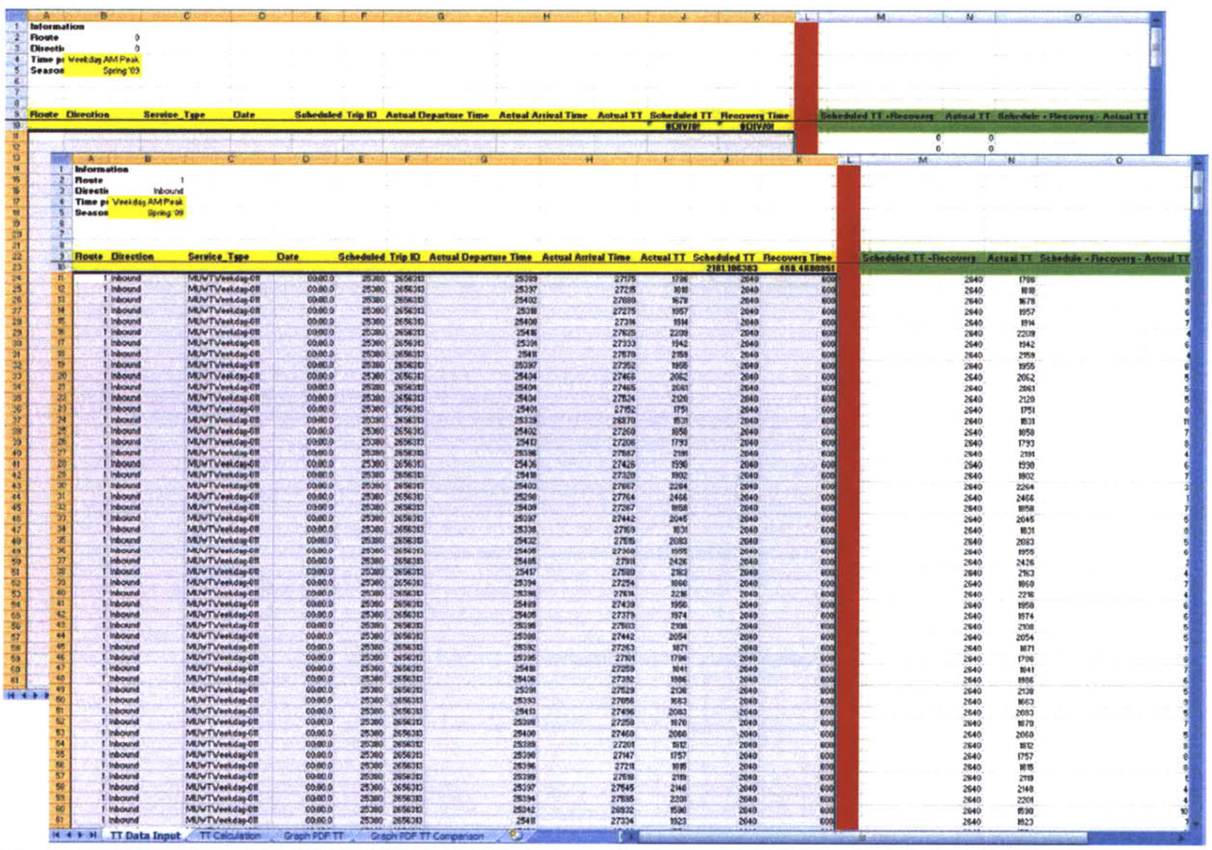


Figure A3-3: Excel Template for TT Analysis

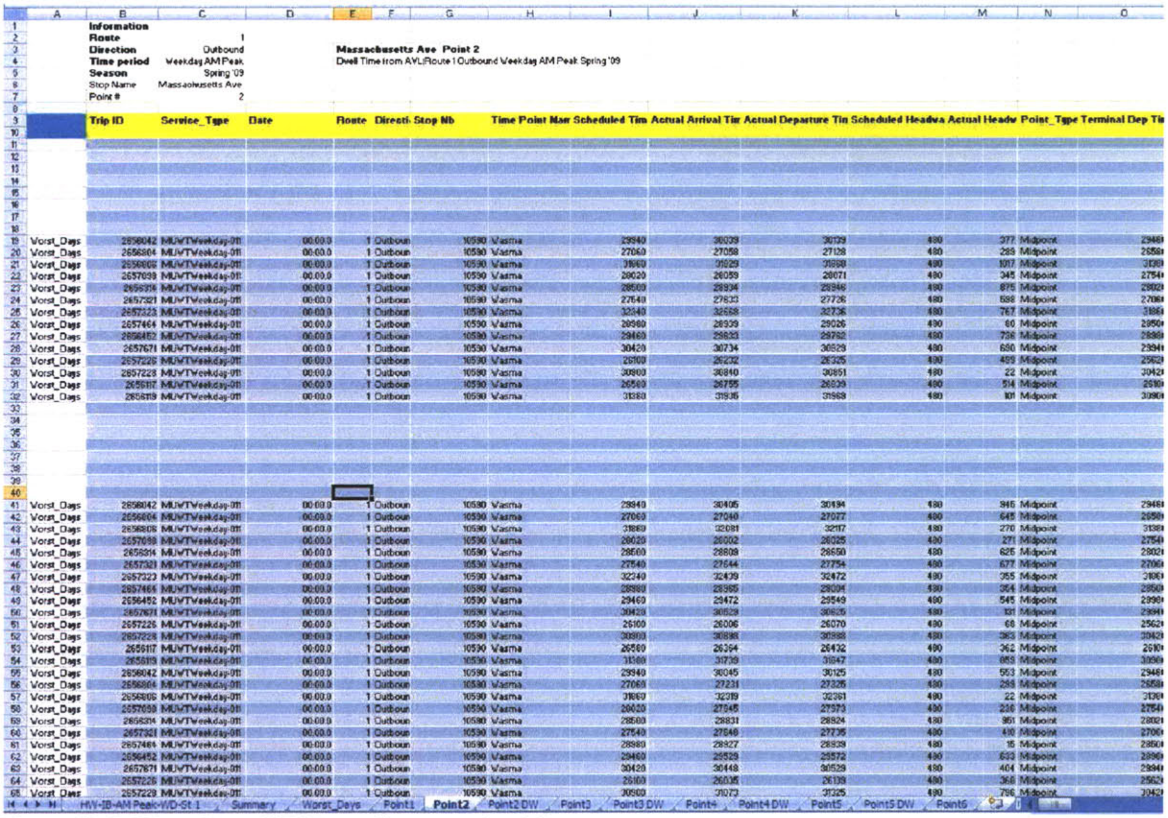
The statistics and charts generated from these processes were used as the basis of the analysis conducted of the effectiveness of the Key Routes Initiatives.

In order to evaluate the robustness of the system's reliability, a subset of the worst performing periods was analyzed. Due to the Fall sample size of only 15 weekdays the worst five, or 33%, were chosen as our poor performing sample. The worst days for each peak period were determined by ranking them based on Expected Waiting Time (EWT) and average Trip Running Time (RT). The values were weighted giving 2/3 importance to the EWT and 1/3 to RT. The chart below shows the ranking for Route 1, OB, AM in the Spring.

	B	D	F	G	I	K	L	M	N	O	P
1	1										
2	Outbound							Min	0.003	0.016	
3	AM								0.087	4.410	4.497
4	Spring							Weight	2.000	1.000	3.000
5								Max-Min	0.037	0.004	
6		Avg Sch HW	Avg Act HW	SD Act HW	Average	Act Wait Tim	Sch Wait Tin	EWT	Ranking EWT	Ranking TT	Weighted Total
7	Wednesday, June 03, 2009	480.00	473.00	435.73	2266.00	437.20	240.00	197.20	0.040	0.018	0.938
8	Tuesday, May 12, 2009	480.00	596.00	278.68	2386.00	363.15	240.00	123.15	0.025	0.019	0.757
9	Wednesday, April 01, 2009	480.00	464.00	391.01	2178.00	396.75	240.00	156.75	0.032	0.018	0.723
10	Thursday, April 09, 2009	480.00	495.00	375.78	2140.00	390.14	240.00	150.14	0.030	0.017	0.670
11	Monday, April 13, 2009	480.00	526.00	387.97	2037.00	406.08	240.00	166.08	0.034	0.016	0.651
12	Tuesday, June 16, 2009	480.00	502.00	359.83	2104.00	379.96	240.00	139.96	0.028	0.017	0.606
13	Friday, May 01, 2009	480.00	476.00	362.23	2072.00	375.83	240.00	135.83	0.028	0.017	0.566
14	Friday, May 08, 2009	480.00	504.00	357.06	2045.00	378.48	240.00	138.48	0.028	0.017	0.555
15	Thursday, March 26, 2009	480.00	499.00	350.32	2073.00	372.47	240.00	132.47	0.027	0.017	0.555
16	Thursday, June 04, 2009	480.00	526.00	310.04	2158.00	354.37	240.00	114.37	0.023	0.017	0.552
17	Tuesday, April 14, 2009	480.00	472.00	341.76	2110.00	359.73	240.00	119.73	0.024	0.017	0.536
18	Tuesday, April 28, 2009	480.00	520.00	305.81	2118.00	349.93	240.00	109.93	0.022	0.017	0.506
19	Friday, June 19, 2009	480.00	493.00	341.49	2020.00	364.77	240.00	124.77	0.025	0.016	0.486
20	Monday, March 30, 2009	480.00	451.00	340.85	2065.00	354.30	240.00	114.30	0.023	0.017	0.482
21	Monday, April 06, 2009	480.00	488.00	318.98	2087.00	348.25	240.00	108.25	0.022	0.017	0.476
22	Thursday, April 02, 2009	480.00	485.00	264.54	2247.00	314.65	240.00	74.65	0.015	0.018	0.474
23	Monday, June 08, 2009	480.00	483.00	352.07	1964.00	369.81	240.00	129.81	0.026	0.016	0.462
24	Friday, June 05, 2009	480.00	479.00	306.84	2116.00	337.78	240.00	97.78	0.020	0.017	0.460
25	Thursday, April 16, 2009	480.00	475.00	328.94	2025.00	351.40	240.00	111.40	0.023	0.016	0.441
26	Friday, May 15, 2009	480.00	466.00	315.57	2061.00	339.85	240.00	99.85	0.020	0.017	0.426
27	Wednesday, April 08, 2009	480.00	512.00	290.01	2051.00	338.13	240.00	98.13	0.020	0.017	0.412
28	Tuesday, April 07, 2009	480.00	465.00	279.11	2148.00	316.26	240.00	76.26	0.015	0.017	0.405
29	Monday, April 27, 2009	480.00	529.00	258.61	2078.00	327.71	240.00	87.71	0.018	0.017	0.394
30	Wednesday, May 27, 2009	480.00	487.00	293.78	2056.00	332.11	240.00	92.11	0.019	0.017	0.393
31	Monday, June 15, 2009	480.00	474.00	305.87	2038.00	335.69	240.00	95.69	0.019	0.017	0.393
32	Tuesday, March 24, 2009	480.00	498.00	261.30	2126.00	317.55	240.00	77.55	0.016	0.017	0.393
33	Tuesday, May 05, 2009	480.00	493.00	295.78	2031.00	335.23	240.00	95.23	0.019	0.016	0.386
34	Wednesday, May 20, 2009	480.00	490.00	253.74	2139.00	310.70	240.00	70.70	0.014	0.017	0.377
35	Wednesday, May 13, 2009	480.00	460.00	303.24	2033.00	329.95	240.00	89.95	0.018	0.016	0.368
36	Thursday, June 18, 2009	480.00	440.00	281.40	2129.00	309.99	240.00	69.99	0.014	0.017	0.367
37	Friday, March 27, 2009	480.00	506.00	228.53	2154.00	304.61	240.00	64.61	0.013	0.017	0.366
38	Friday, April 03, 2009	480.00	493.00	263.42	2089.00	316.88	240.00	76.88	0.016	0.017	0.362

Figure A3-4: 33% Ranking Template

The worst days identified in the previous process were used to reanalyze the performance metrics in order to evaluate the effects of the Key Routes Initiatives on the system's robustness. The worst days for each peak period were loaded in to the original TT and HW Analysis files containing the full datasets. A VBA macro was scripted to then clean the data of all days not included in the list of the 33% worst days. Figure A3-5 shows the cleaning process in Microsoft Excel.



FigureA3-5: Worst Days HW Data after executing Macro

Below is the VBA code which was used to clean the full HW data set of all days except the 33% worst days. The VBA code had to be adjusted to the different Excel templates.

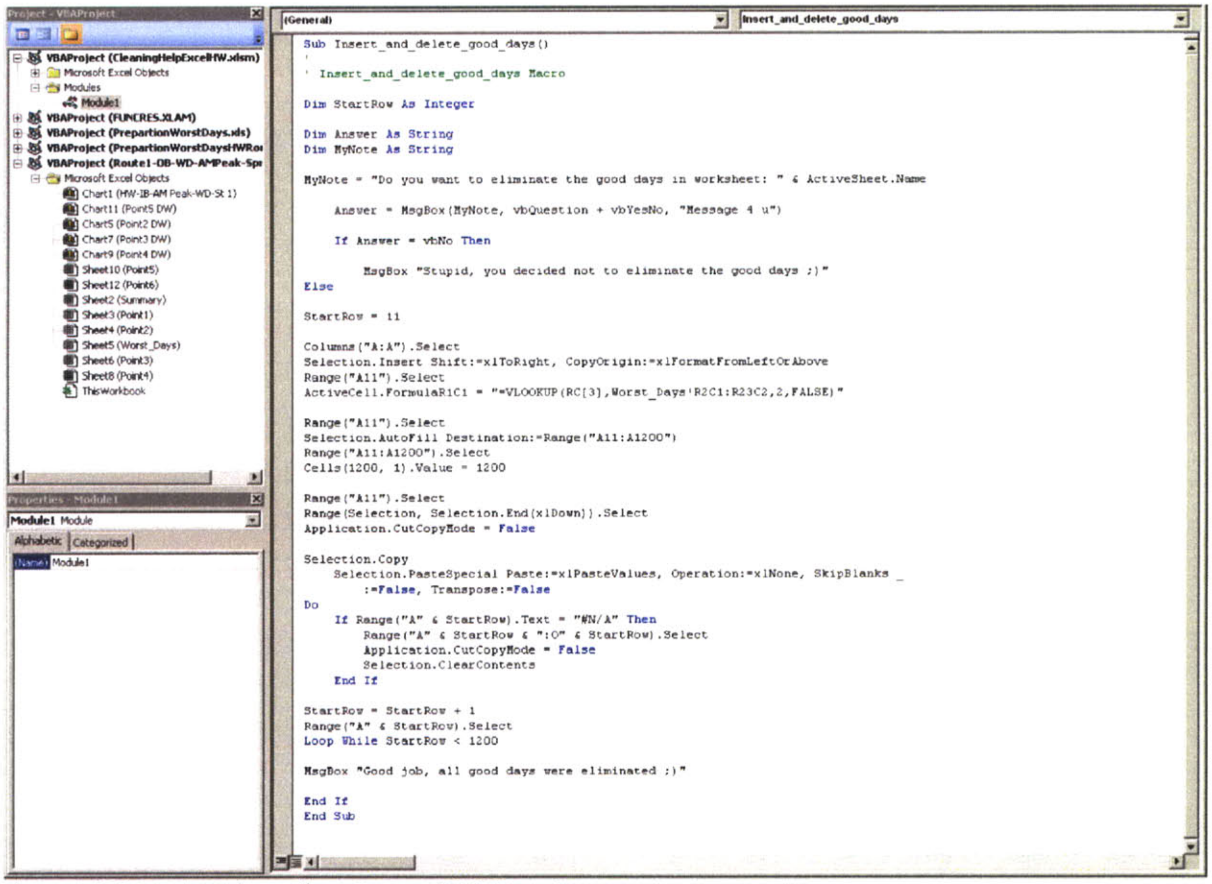


Figure A3-6: VBA Code to Clean Data to 33% Worst Days

Performance metric results of the individual templates were then compiled in a route performance summary template showing the differences in performance between time periods, peak times, and directions. These aggregated performance metrics formed the basis for the TAP impact analysis. Below the route performance summary template is shown.

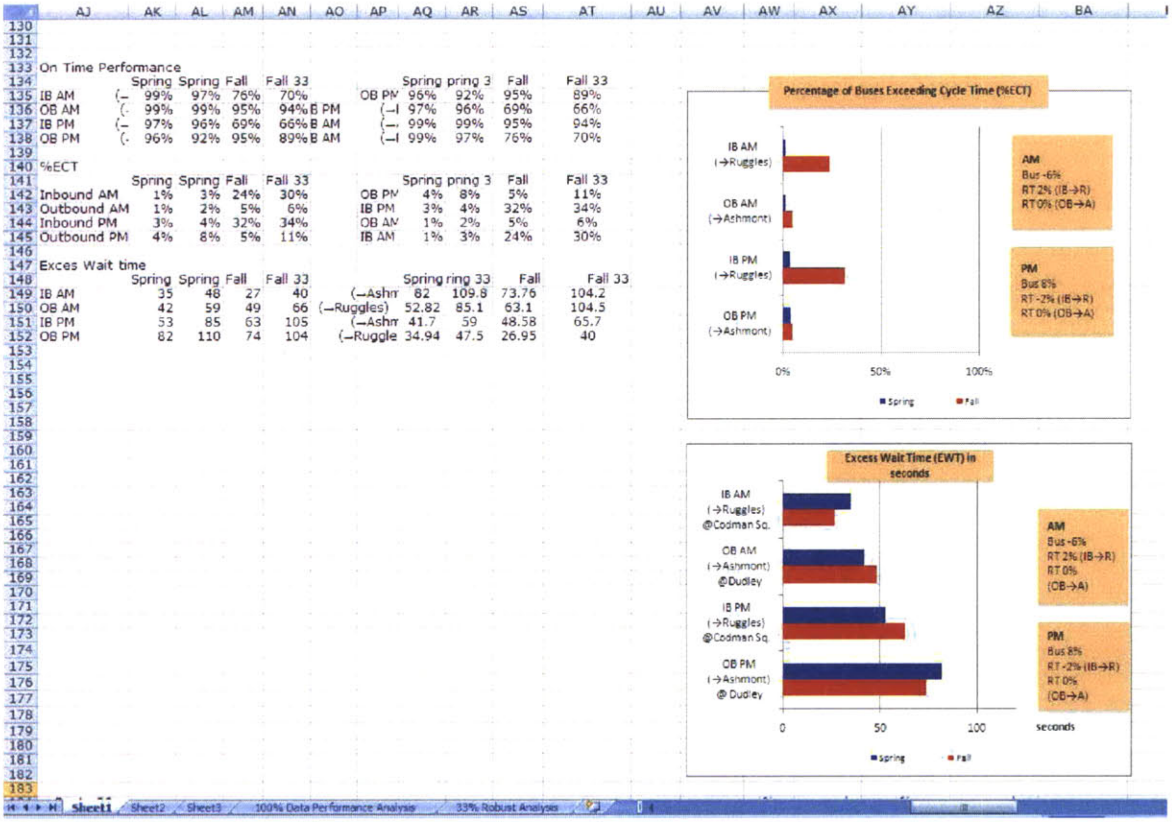


Figure A3-7: Route Performance Summary Template

Appendix 4 - Route 1 Summary

1. Summary

Route 1 is the 3rd highest ridership route in the greater Boston area, providing bus service from Cambridge into downtown Boston with ridership levels measured at 12,325 for 2007. Inbound service runs from Harvard Square to Dudley, with outbound providing return service.

Route 1 runs along Massachusetts Avenue, from Harvard, past Massachusetts Institute of Technology, over the Charles River via the Harvard Bridge into Boston, past Berklee College of Music to Boston Medical Center, then southwest to Dudley via Albany Street and Melnea Cass Boulevard. Limited stop service over most of the route is provided by the CT1.

Stops include Massachusetts Ave & Holyoke St, Mt Auburn St & Putnam Ave, Massachusetts Ave & Pearl St, 84 Massachusetts Ave, Massachusetts Ave & Newbury St, Massachusetts Ave & Massachusetts Ave St Massachusetts Ave & Washington St Washington St & Melnea Cass Blvd Dudley Station.

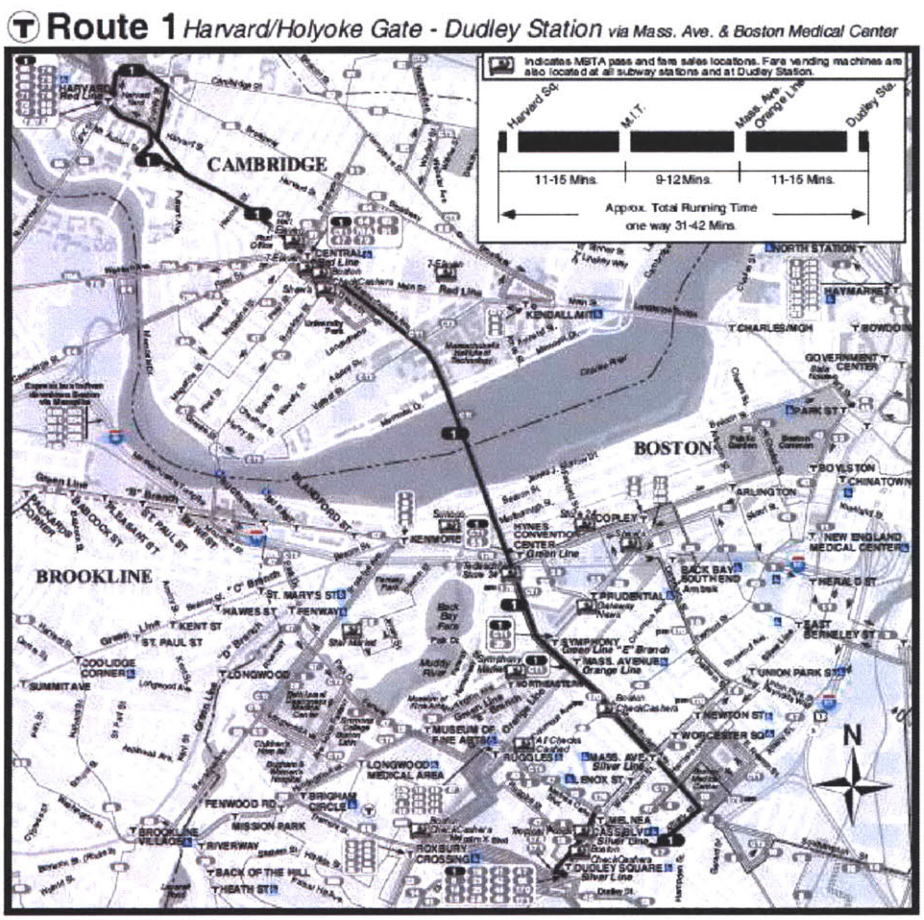


Figure A4-1: Route 1 Map

2. KBRI Schedule Adjustments for Route 1

Below is a summary of schedule changes initiated on 7 November 2009 for this route:

- AM Peak: One bus was added to the route and cycle time extended from 80 to 92 minutes. Inbound to Dudley, running time was increased from 36 to 38 minutes and recovery time at the Dudley terminal was increased from 8 to 9 minutes. Outbound to Harvard Square, running time was increased from 35 to 36 minutes and recovery time at the Harvard terminal was increased from 1 to 9 minutes.

- PM Peak: Cycle time was held constant at 113 minutes, but the running time and recovery time mix was adjusted. Inbound to Dudley, running time was increased from 42 to 45 minutes while recovery time at the Dudley terminal was decreased from 18 to 15 minutes. Outbound to Harvard Square, running time was increased from 38 to 42 minutes while recovery time at the Harvard terminal was decreased from 15 to 11 minutes.

3. Performance Metrics

a. Running Time Distribution

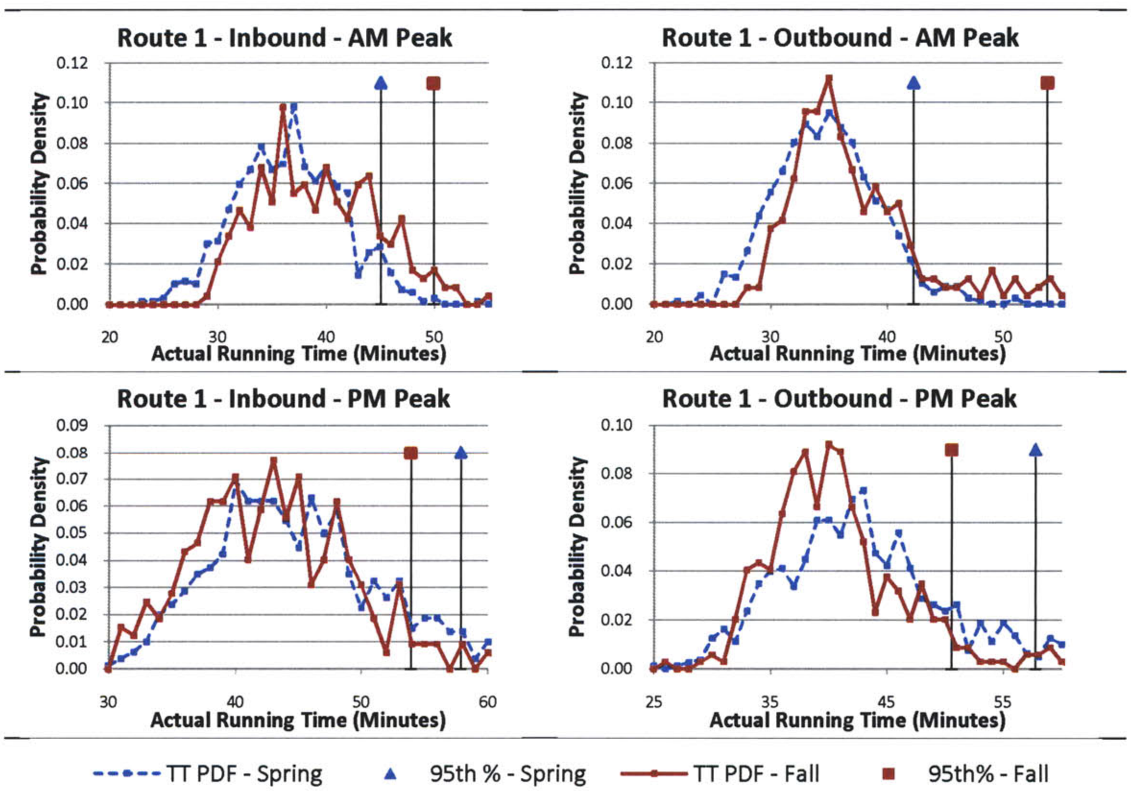


Figure A4-2: Running Time Distributions – Route 1

b. Expected Wait Time

Expected Wait-Time as experienced at the median boarding stop along the route (Central Square for inbound direction and Massachusetts Avenue at Washington Street for outbound).

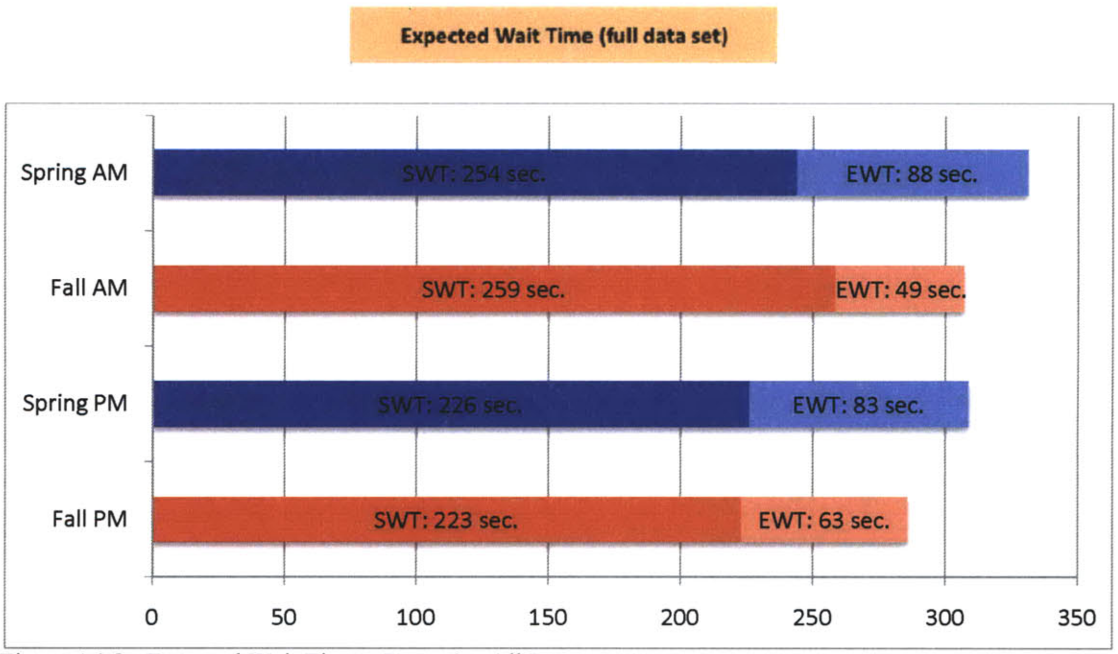


Figure A4-3: Expected Wait Time – Route 1 – All Days

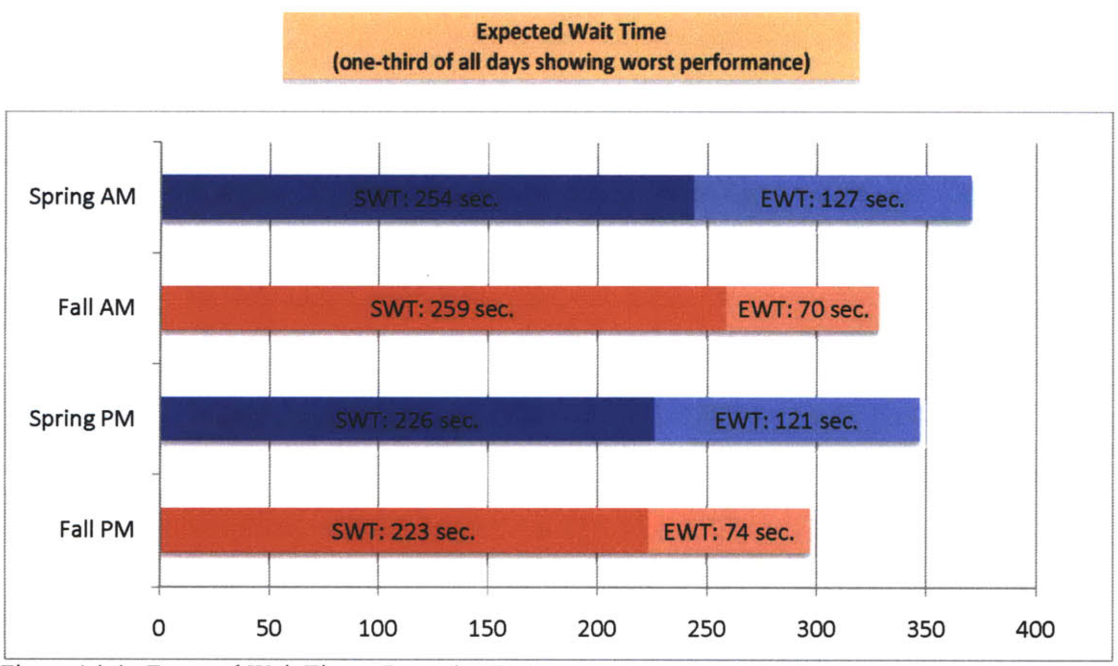


Figure A4-4: Expected Wait Time – Route 1 – Worst Days

c. Terminal Departure Time Adherence

Terminal Departure Adherence, Route 1

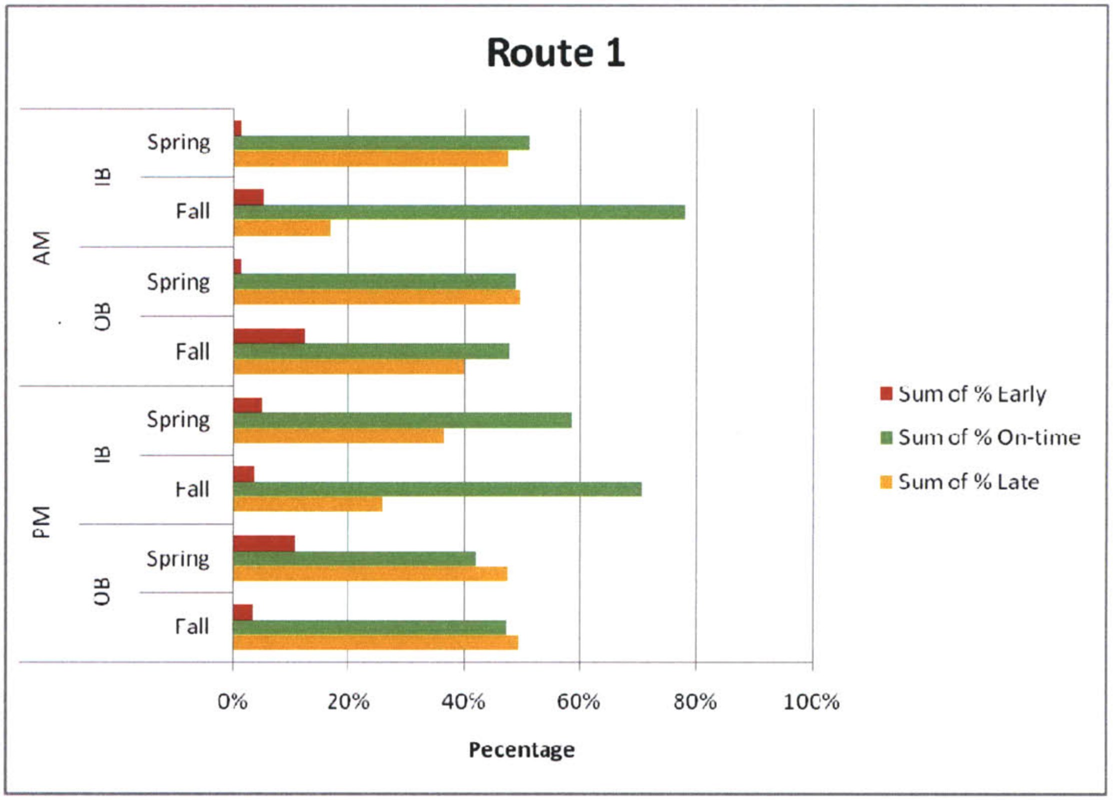
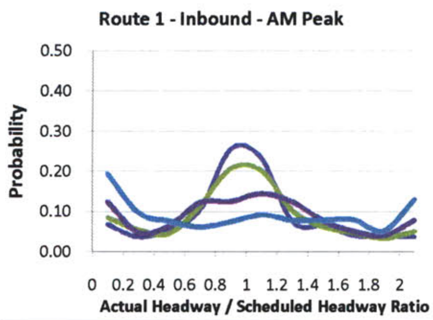
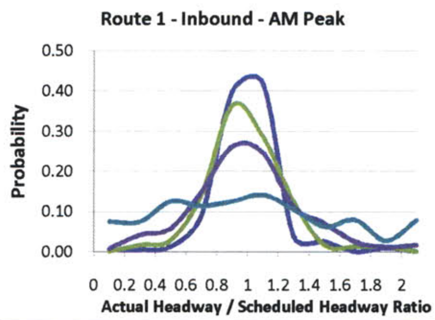


Figure A4-5: Terminal Departure Time Adherence – Route 1

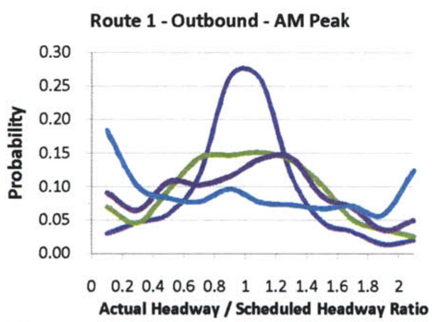
d. Headway Ratios

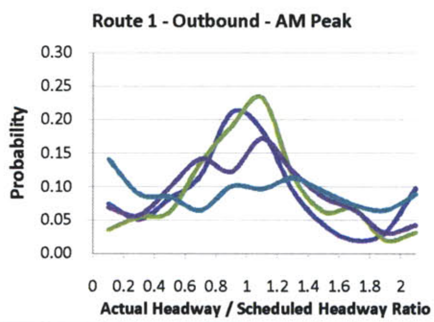
Spring 2009 | **Fall 2009** | **Legend**



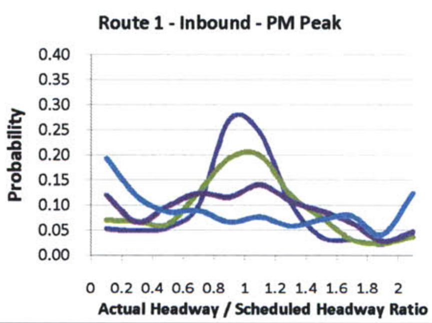


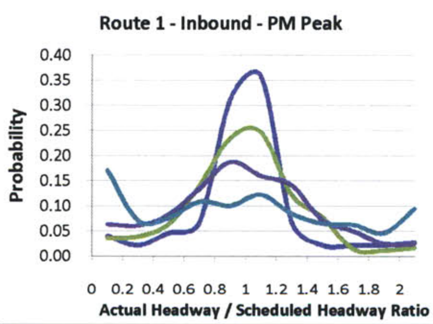
Harvard Holyoke Gate
Mass Ave & Putnam
Central Square
Mass Ave Station



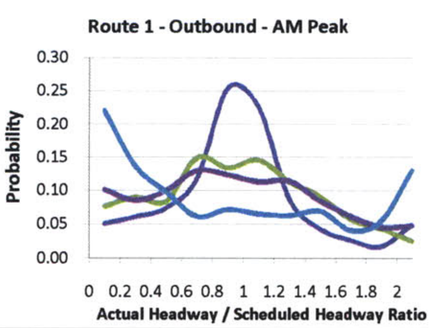


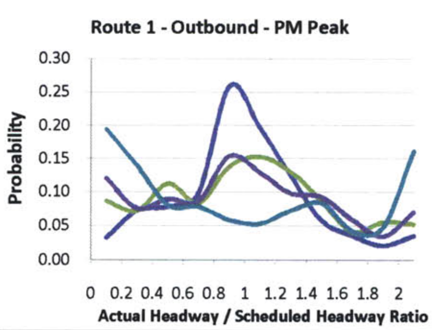
Dudley Station
Mass Ave Station
Mass Ave Station
Mass Ave & Putnam





Harvard Holyoke Gate
Mass Ave & Putnam
Central Square
Mass Ave Station





Dudley Station
Mass Ave Station
Mass Ave Station
Mass Ave & Putnam

Figure A4-6: Headway Ratio Distributions – Route 1

e. Dwell Time (measured at the median boarding stop: here Central Square in both inbound and outbound directions)

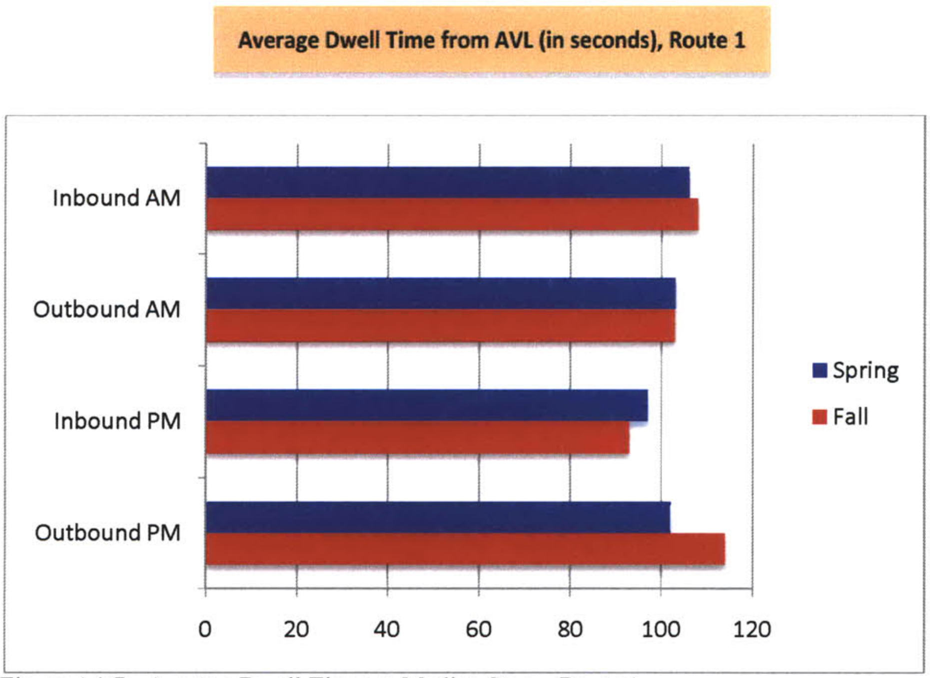


Figure A4-7: Average Dwell Times at Median Stop – Route 1

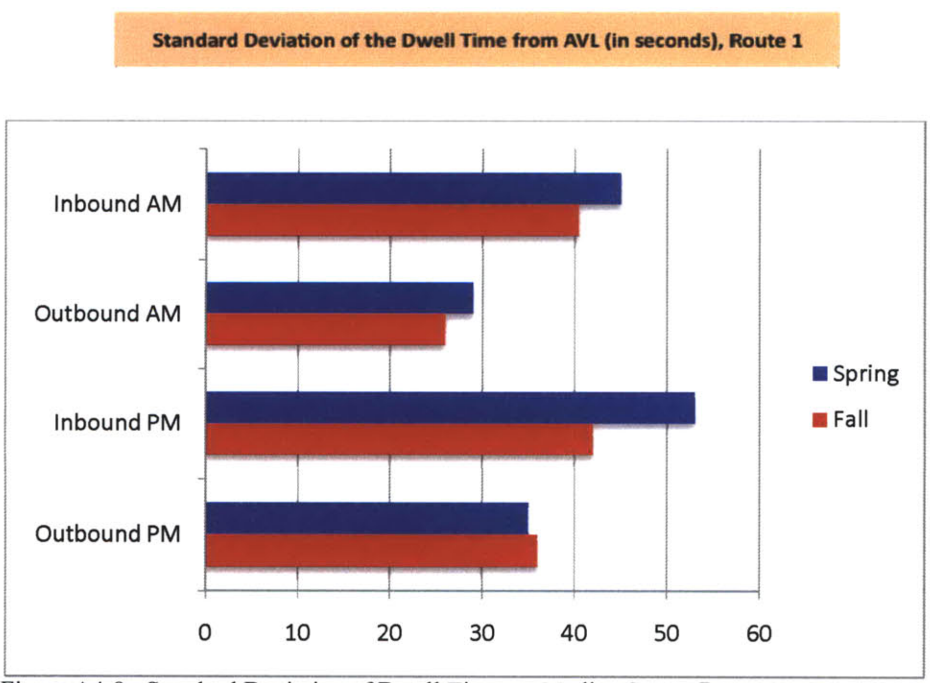


Figure A4-8: Standard Deviation of Dwell Times at Median Stop – Route 1

<u>**Appendix 4 - Route 15 Summary**</u>

<u>1. Summary</u>

Route 15 is the 11th highest ridership route in the greater Boston area, providing bus service within Boston from Ruggles to Kane Square with ridership levels measured at 6,951 for 2007. Inbound service runs from Ruggles to Kane Square, with outbound providing return service.

Route 15 runs from Kane Square, several blocks west of Savin Hill, west on Hancock Street and Dudley Street past Uphams Corner to Dudley, continuing west on Malcolm X Boulevard to Roxbury Crossing and north on Tremont Street to Ruggles. The 15 also runs from Ruggles all the way to Fields Corner after a certain time.

Stops include Shmont Station Geneva Ave Opp Vinson St, Fields Corner Station & Red Line Bowdoin St & Geneva Ave St Peters Sq & Church Hancock St & Bowdoin St Columbia Rd & Hancock St Dudley St & Magazine St Dudley Station Malcolm X Blvd & Tremont St Ruggles Sta.

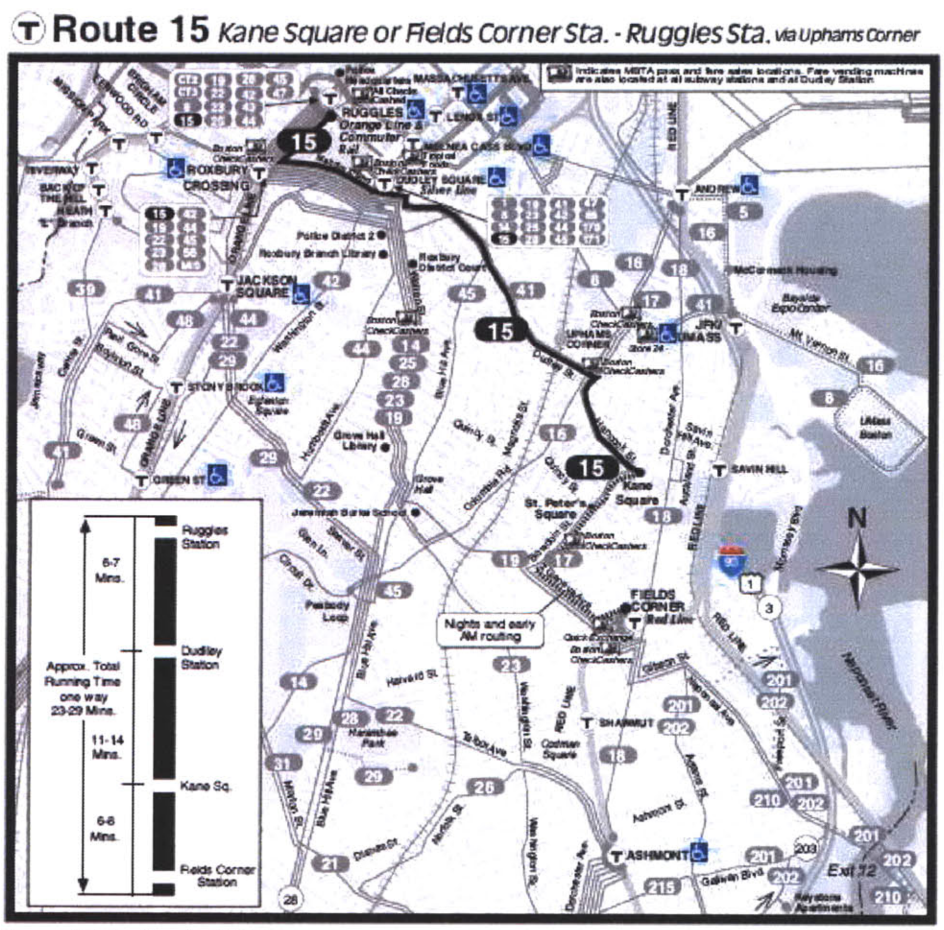


Figure A4-9: Route 15 Map

2. KBRI Schedule Adjustments for this Route

Below is a summary of schedule changes initiated on 7 November 2009 for this route:

- AM Peak: The cycle time was held constant at 49 minutes, while running time and recovery time mix was adjusted. Inbound to Ruggles, running time was reduced from 22 to 20 minutes while recover time at the Ruggles terminal was increased from 3 to 5 minutes. Outbound to Kane Square, running time was reduced from 21 to 20 minutes while recovery time at the Kane Square terminal was increased from 3 to 4 minutes.

- PM Peak: One bus was added to the route and cycle time was extended from 63 to 72 minutes. Inbound to Ruggles, running time was held at 22 minutes while recover time at the Ruggles terminal was increase from 6 to 15 minutes. Outbound to Kane Square, running time was increased from 29 to 30 minutes while recovery time at the Kane terminal was reduced from 6 to 5 minutes.

3. Performance Metrics

a. Running Time Distributions

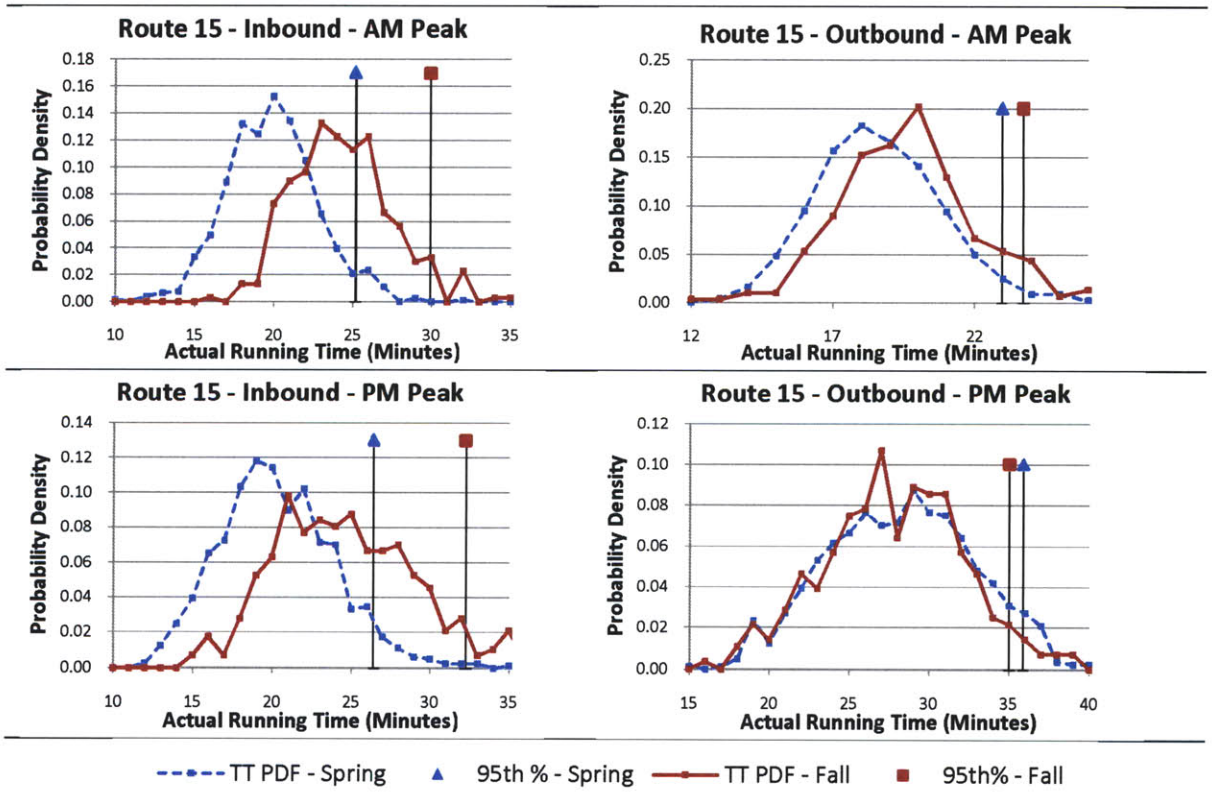


Figure A4-10: Running Time Distributions – Route 15

b. Expected Wait-Time (measured at the median boarding stop, here: Uphams Corner for inbound direction and Dudley for outbound).

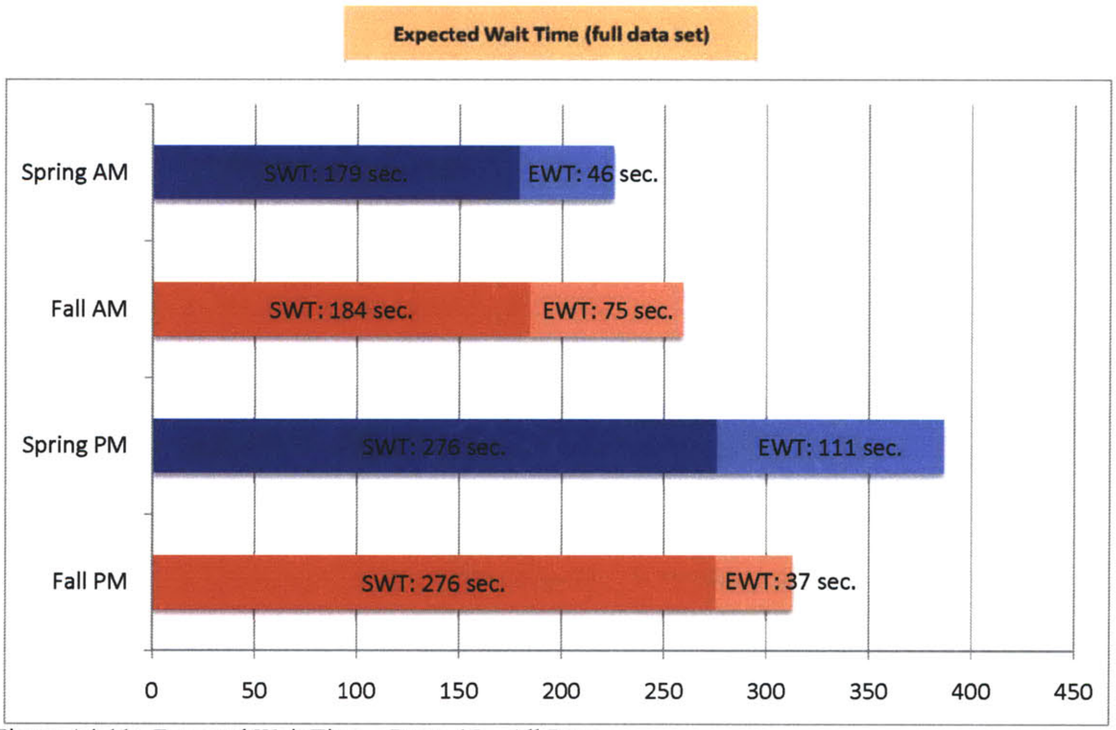


Figure A4-11: Expected Wait Time – Route 15 – All Days

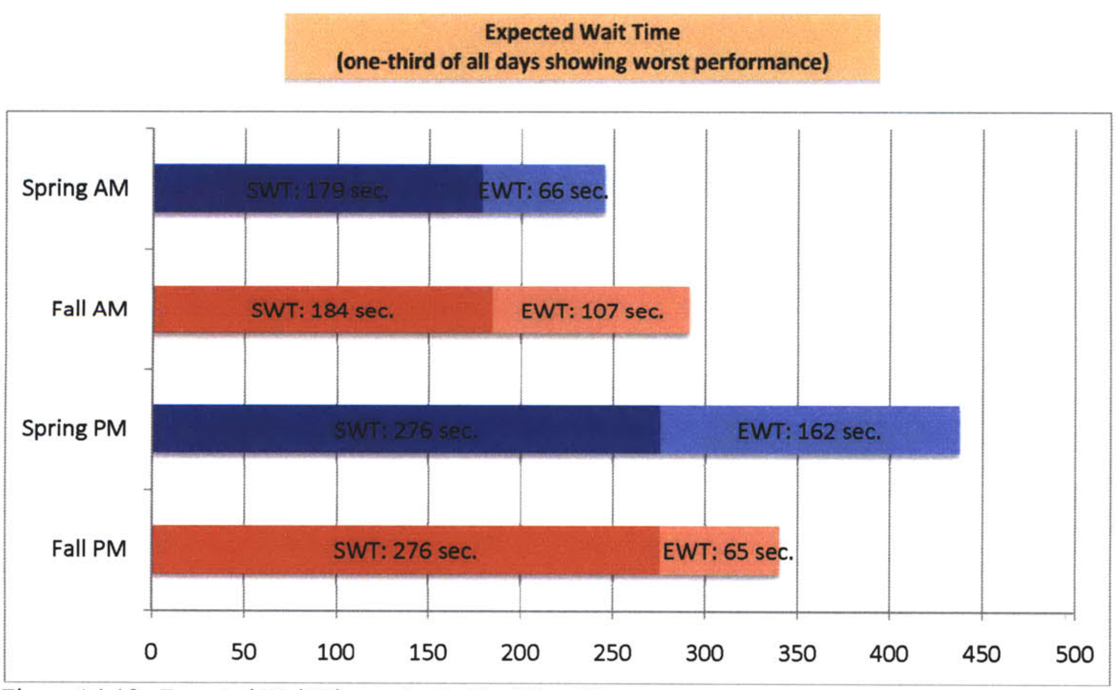


Figure A4-12: Expected Wait Time – Route 15 – Worst Days

c. Terminal Departure Adherence

Terminal Departure Adherence, Route 15

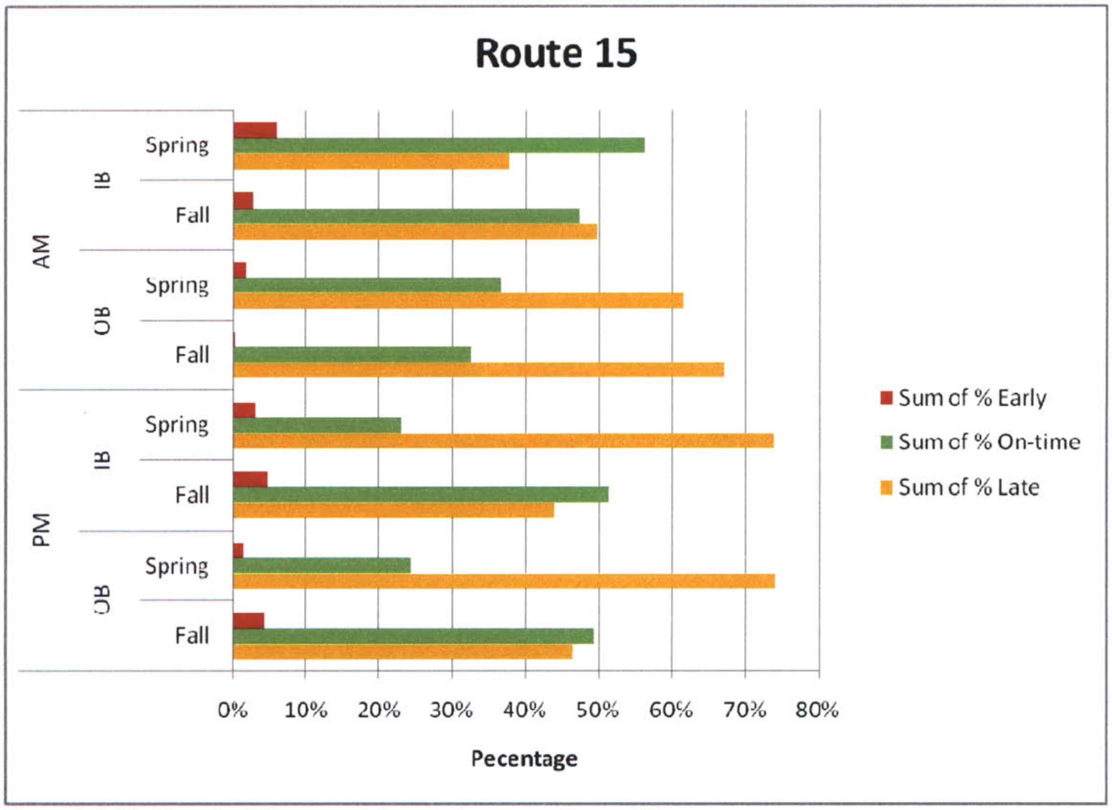


Figure A4-13: Terminal Departure Time Adherence – Route 15

d. Headway Ratios

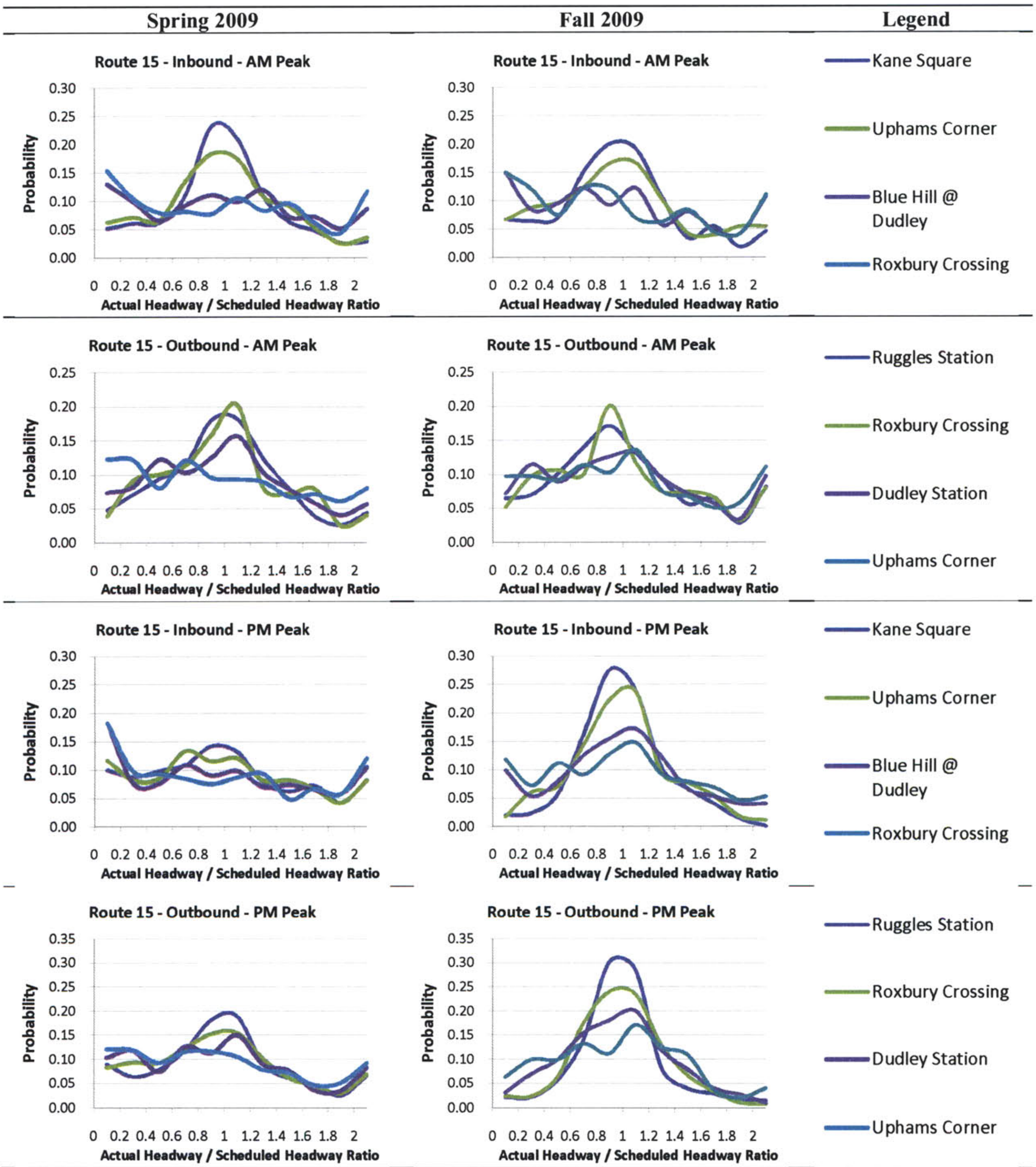


Figure A4-14: Headway Ratio Distributions – Route 15

e. Dwell Time (measured at the median boarding stop, here: Dudley station, in both inbound and outbound directions)

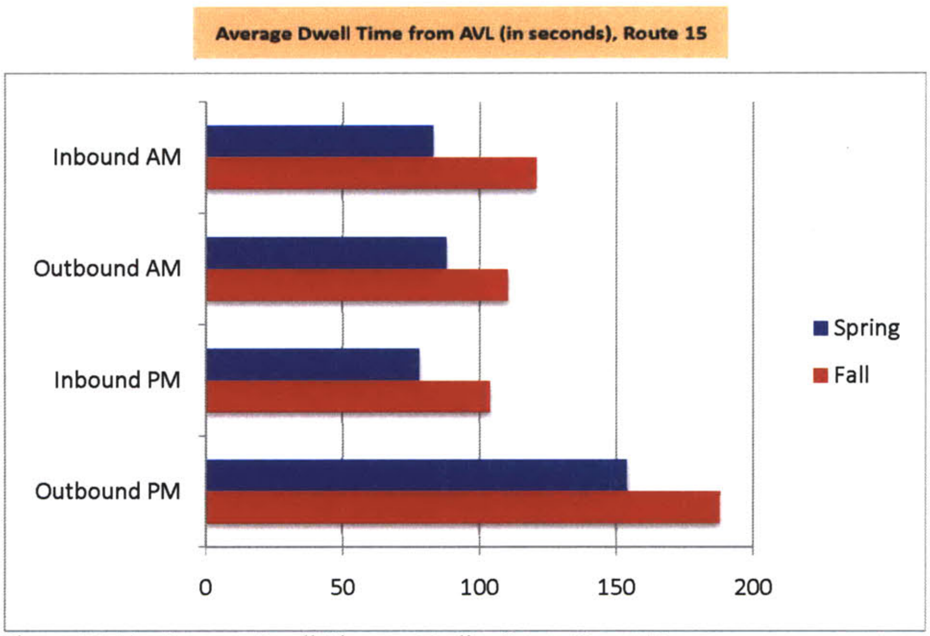


Figure A4-15: Average Dwell Times at Median Stop – Route 15

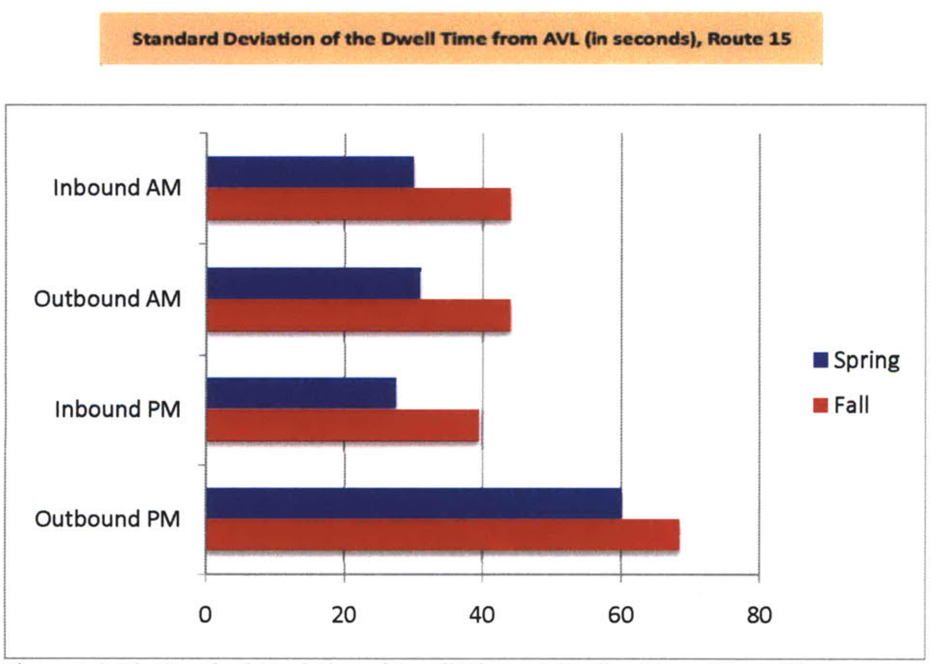


Figure A4-16: Standard Deviation of Dwell Times at Median Stop – Route 15

<u>**Appendix 4 - Route 23 Summary**</u>

<u>1. Summary</u>

Route 23 is the 4th highest ridership route in the greater Boston area, providing bus service within Boston from Ruggles to Ashmont with ridership levels measured at 11,142 for 2007. Inbound service runs from Ashmont to Ruggles, with outbound providing return service.

Route 23 starts out of Ashmont on Talbot Avenue (Boston), turns north on Washington Street, following that onto Warren Street to Dudley. From Dudley the 23 heads west on Malcolm X Boulevard to Roxbury Crossing and north on Tremont Street to Ruggles.

Stops include Ashmont Station, Talbot Ave & Centre St, Washington St & Bowdoin St, Washington St & Columbia Rd, Warren St & Sunderland St, Warren St & Quincy St, Warren St & Moreland St, Dudley Station, Malcolm X Blvd & Tremont St, Ruggles Sta.

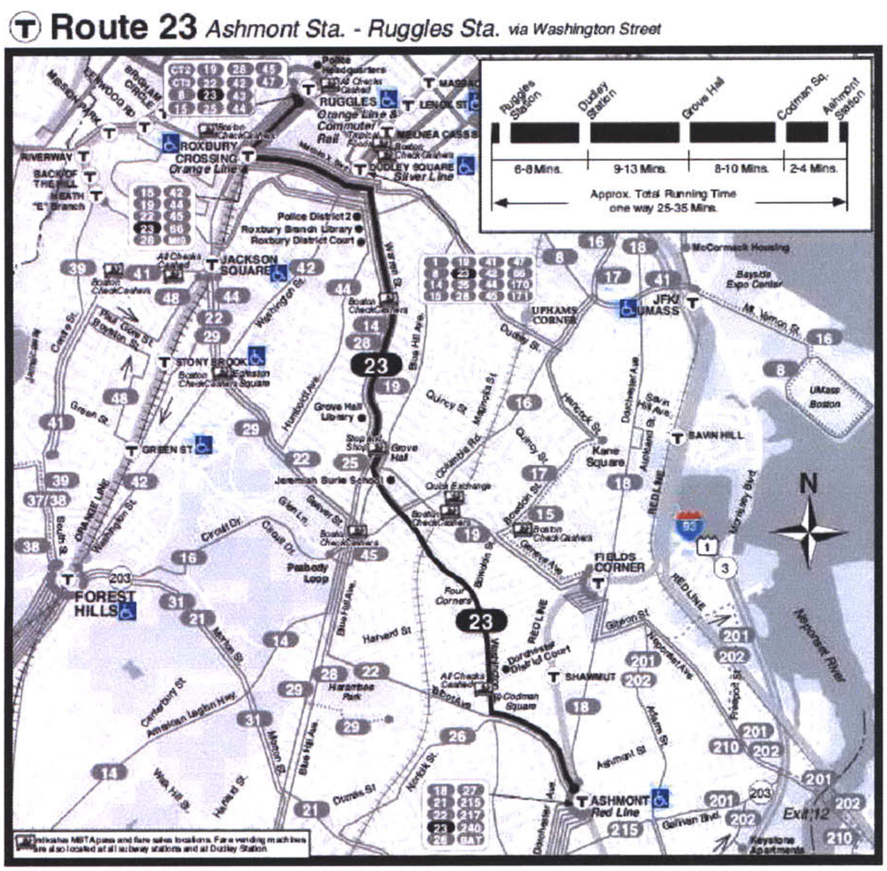


Figure A4-17: Route 23 Map

2. KBRI Schedule Adjustments for Route 23

Below is a summary of schedule changes initiated on 7 November 2009 for this route:

- AM Peak: One bus was removed from the route and headways and cycle time were adjusted accordingly. Headways were increased from 5 to 5.5 minutes and cycle time increased from 79 to 80 minutes. Inbound to Ruggles, running time was decreased from 34 to 33 minutes and recovery time at the Ruggles terminal was increased from 7 to 9 minutes. Outbound to Ashmont, running time was increased from 30 to 31 minutes and recovery time at the Ashmont terminal was decreased from 8 to 7 minutes.

- PM Peak: One bus was added to the route and headway and cycle time were both decreased. Headways were reduced from 8 to 7.5 minutes and cycle time from 94 to 93 minutes. Inbound to Ruggles, running time was increased from 35 to 36 minutes and recovery time at the Ruggles terminal was decreased from 7 to 5 minutes. Outbound to Ashmont, running time was reduced from 43 to 42 minutes while recovery time at the Ashmont terminal was increased from 9 to 10 minutes.

3. Performance Metrics

a. Running Time Distribution

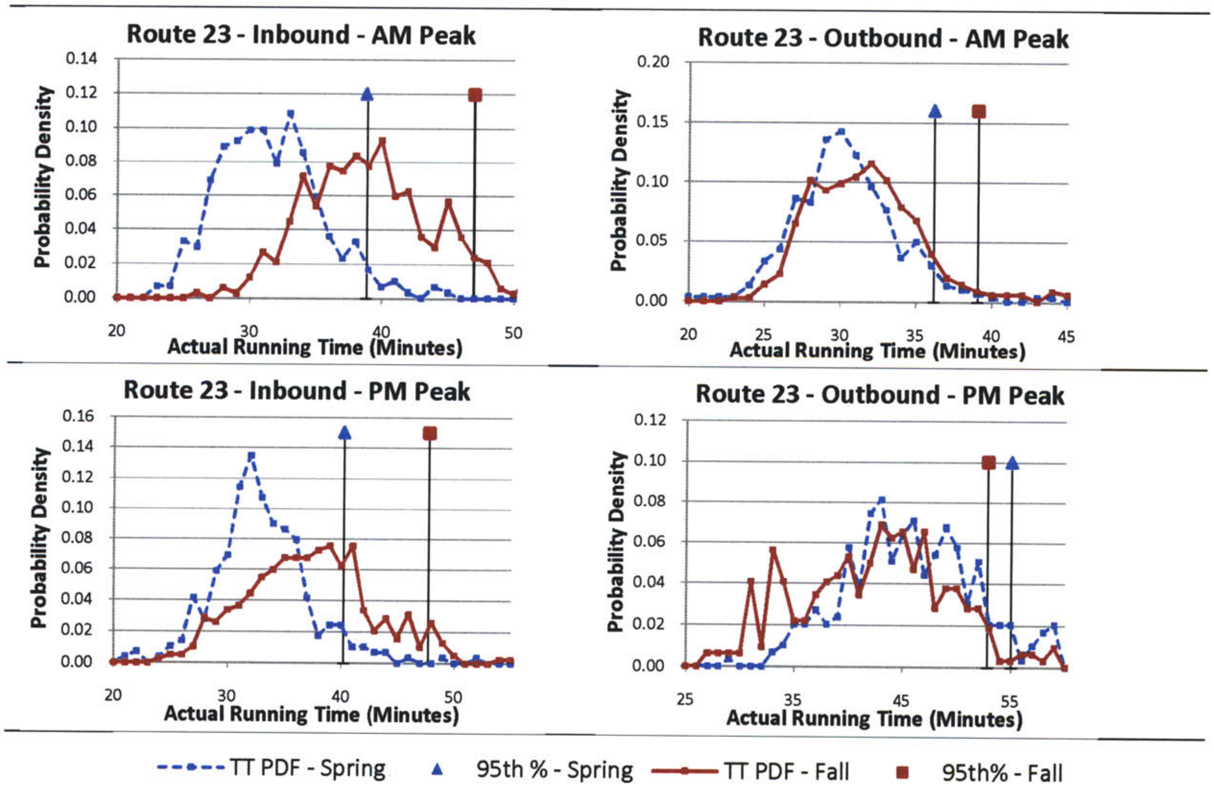


Figure A4-18: Running Time Distributions – Route

b. Expected Wait Time, as experienced at the median boarding stop along the route (Codman Square for inbound direction and Dudley for outbound).

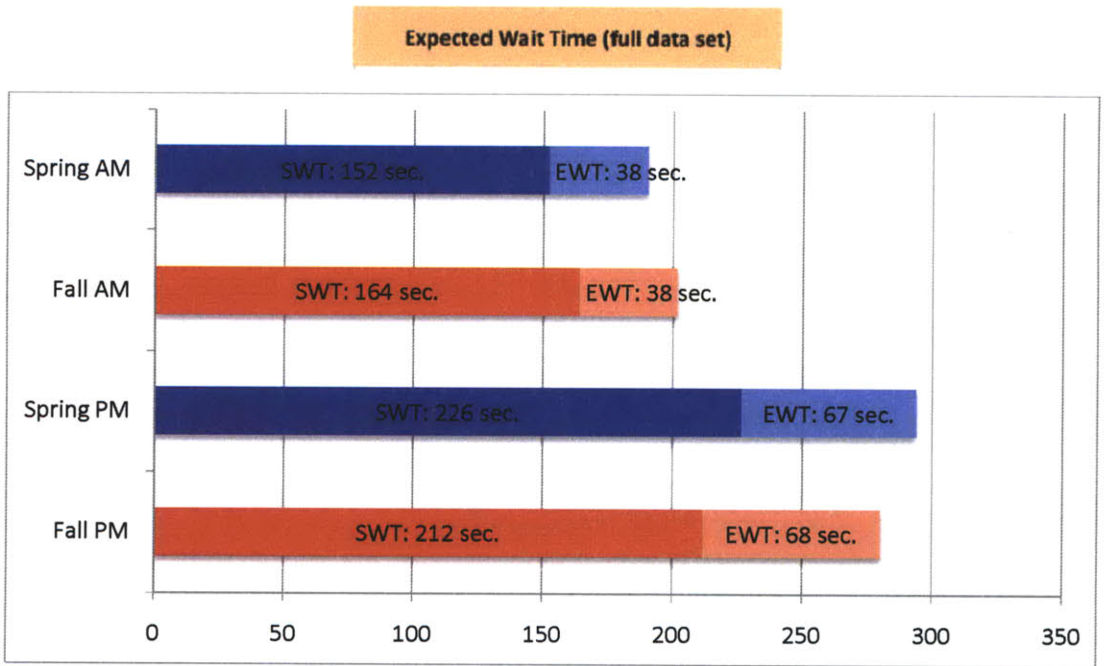


Figure A4-19: Expected Wait Time – Route 23 – All Days

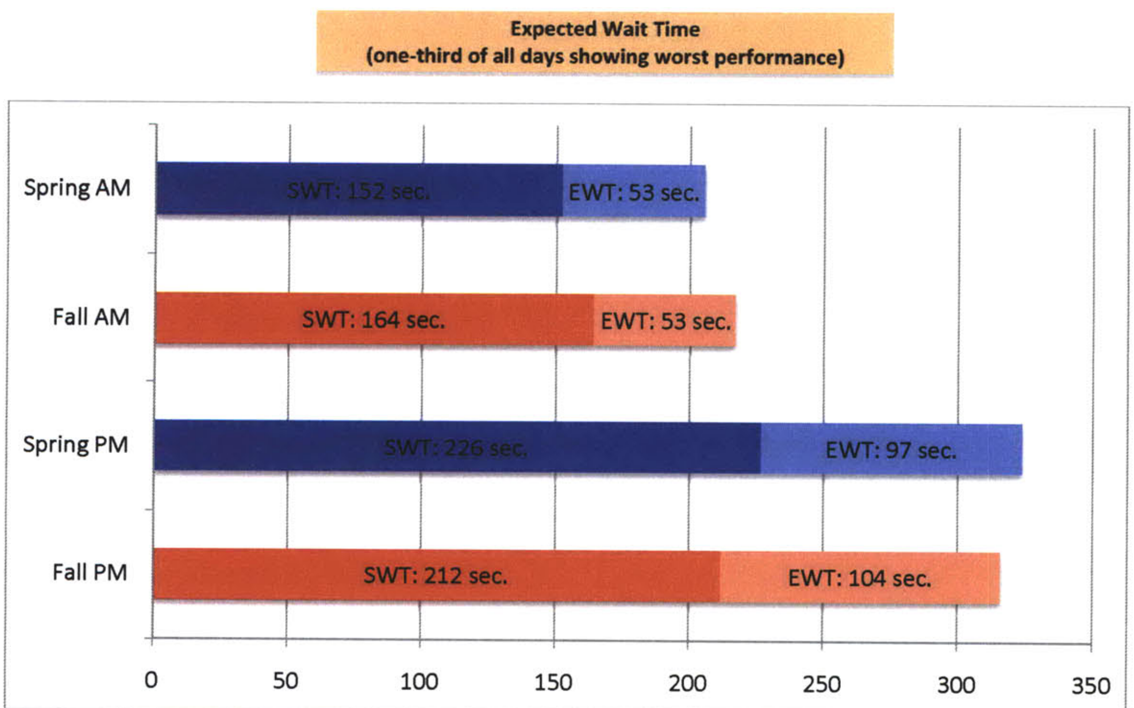


Figure A4-20: Expected Wait Time – Route 23 – Worst Days

c. Terminal Departure Adherence

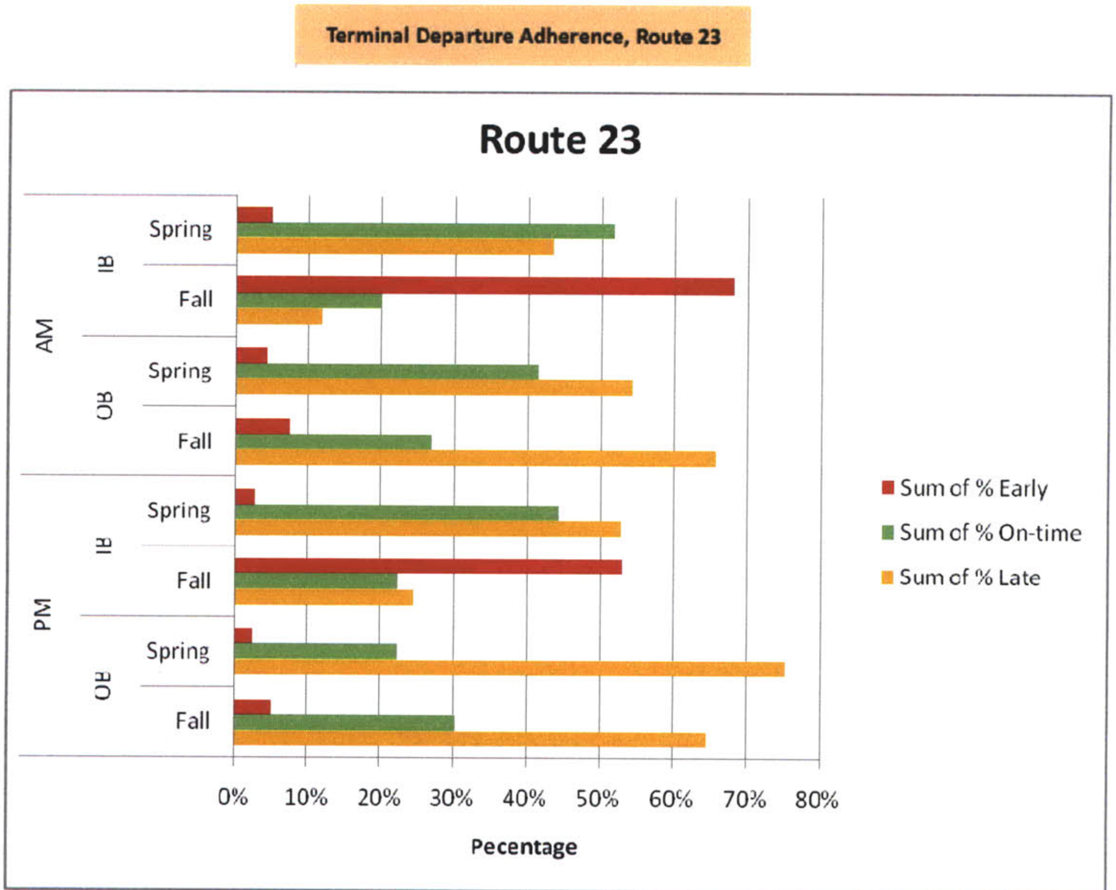


Figure A4-21: Terminal Departure Time Adherence – Route 23

d. Headway ratios

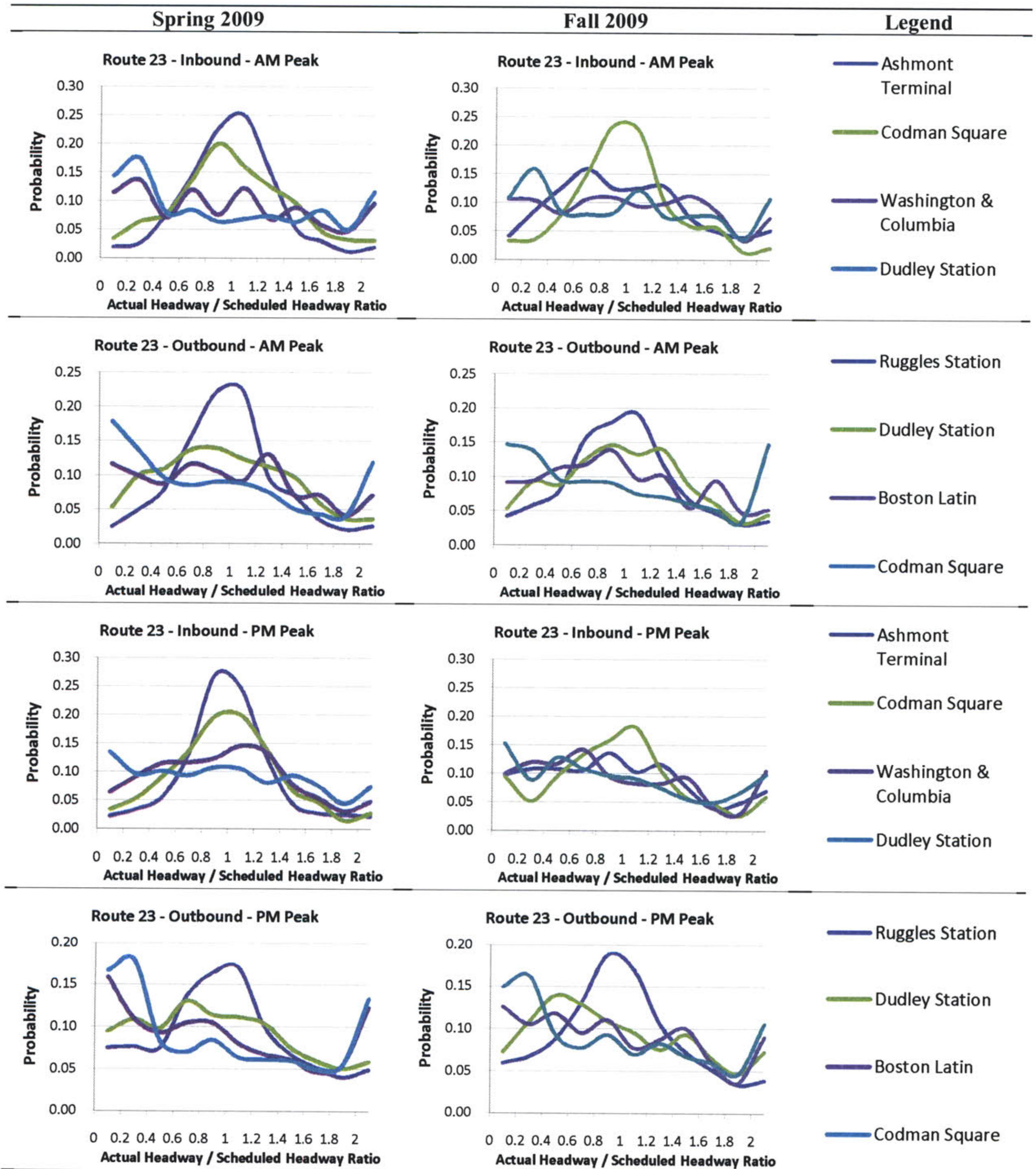


Figure A4-22: Headway Ratio Distributions – Route 23

e. Dwell Time (measured at the median boarding stop, here: Washington Columbia for the inbound direction and Dudley for the outbound direction).

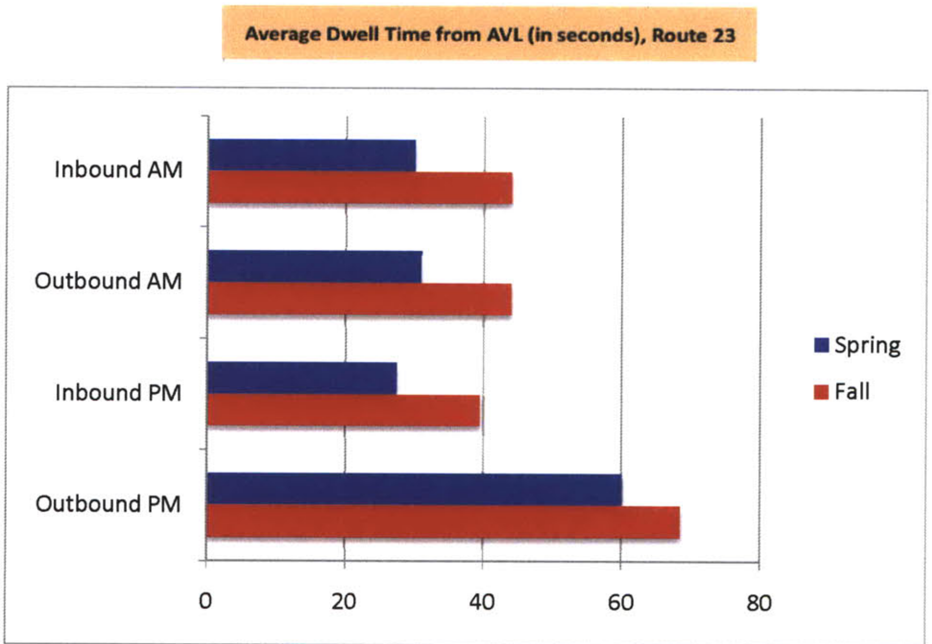


Figure A4-23: Average Dwell Times at Median Stop – Route 23

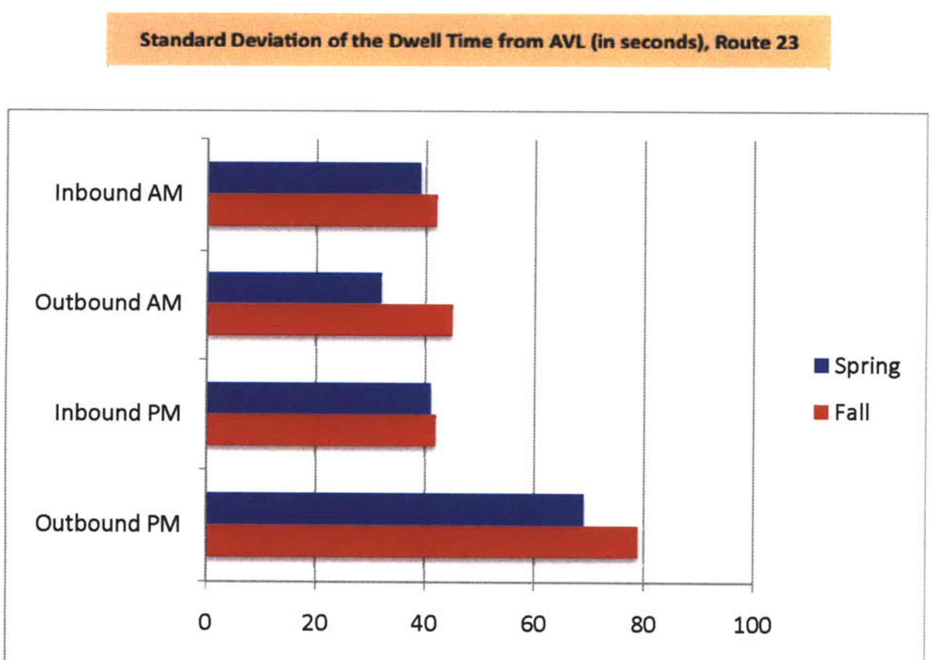


Figure A4-24: Standard Deviation of Dwell Times at Median Stop – Route 23

<u>**Appendix 4 – Route 28 Summary**</u>

<u>1. Summary</u>

Route 28 is the 6th highest ridership route in the greater Boston area, providing bus service within Boston between Ruggles to Mattapan with ridership levels measured at 10,607 for 2007. Inbound service runs from Mattapan to Ruggles, with outbound providing return service.

Route 28 began its history as Route 28 Arborway-Mattapan via Cummins Hwy. This route, which paralleled Route 32 to Forest Hills and Arborway and was used during rush hours only, was discontinued in 1981. Route 29 (Mattapan-Egleston via Blue Hill Ave – Seaver St) handled all service on Blue Hill Avenue until a new version of Route 28 was established in 1987. This new Route 28 served between Mattapan station and the new Orange Line station at Ruggles, and in turn took over all service. Route 29 was relegated to a rush-hours only route, but only to Jackson Square. Late night service does run to Ruggles, but Route 28 handles all service throughout the week. Until 2003 it operated out of the Bartlett garage; when Arborway opened in 2003, Route 28 was shifted to the Cabot garage.

Stops include Metropolitan Ave & Central Ave, Mattapan Station Blue Hill Ave & Wilmore St, Blue Hill Ave & Morton St, Blue Hill Ave & Talbot Ave, Blue Hill Ave & Ellington St, Warren St & Sunderland St, Warren St & Quincy St, Warren St & Moreland St, Dudley Station, Malcolm X Blvd & Tremont St, Ruggles Sta.

Figure A4-25: Route 28 Map

2. KBRI Schedule Adjustments for Route 28

No significant schedule changes were implemented along this route.

- AM Peak: Cycle time was increased slightly from 95 to 98 minutes, with running and recovery time mix adjusted. Outbound to Mattapan, running time was increased from 36 to 38 minutes while recovery time at the Mattapan terminal was increased from 11 to 12 minutes. Inbound to Ruggles, running time was reduced from 40 to 36 minutes while recovery time at the Ruggles terminal was increased from 8 to 12 minutes.

- PM Peak: Cycle time was reduced from 122 to 112 minutes, with running and recovery time mix adjusted. Headways were reduced from 10 to 9.5 minutes. Outbound to Mattapan, running time was reduced from 55 to 51 minutes while recovery time at the Mattapan terminal was increased from 10 to 11 minutes. Inbound to Ruggles, running time remained constant at 38 minutes and recovery time at the Ruggles terminal was reduced from 19 to 12 minutes.

3. Performance Metrics

a. Running Time Distribution

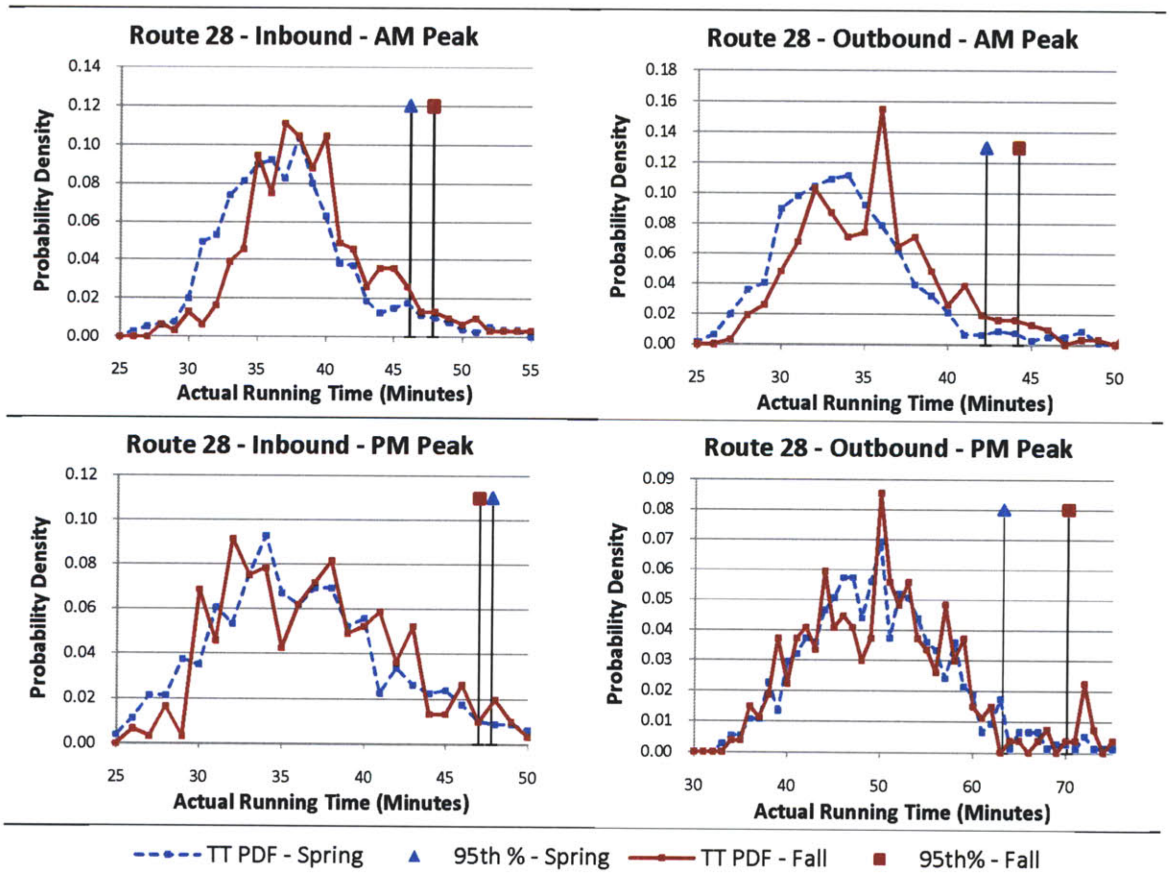


Figure A4-26: Running Time Distributions – Route

b. Expected Wait Time (measured at the median boarding stop, here: Morton Street for inbound direction and Dudley for outbound).

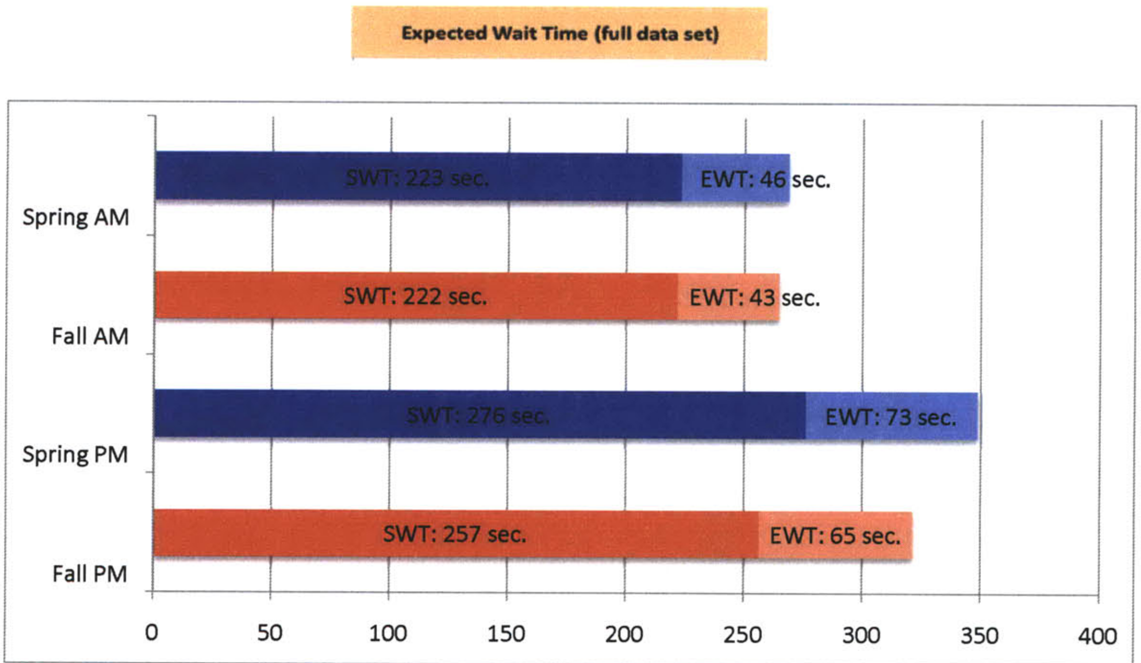


Figure A4-27: Expected Wait Time – Route 28 – All Days

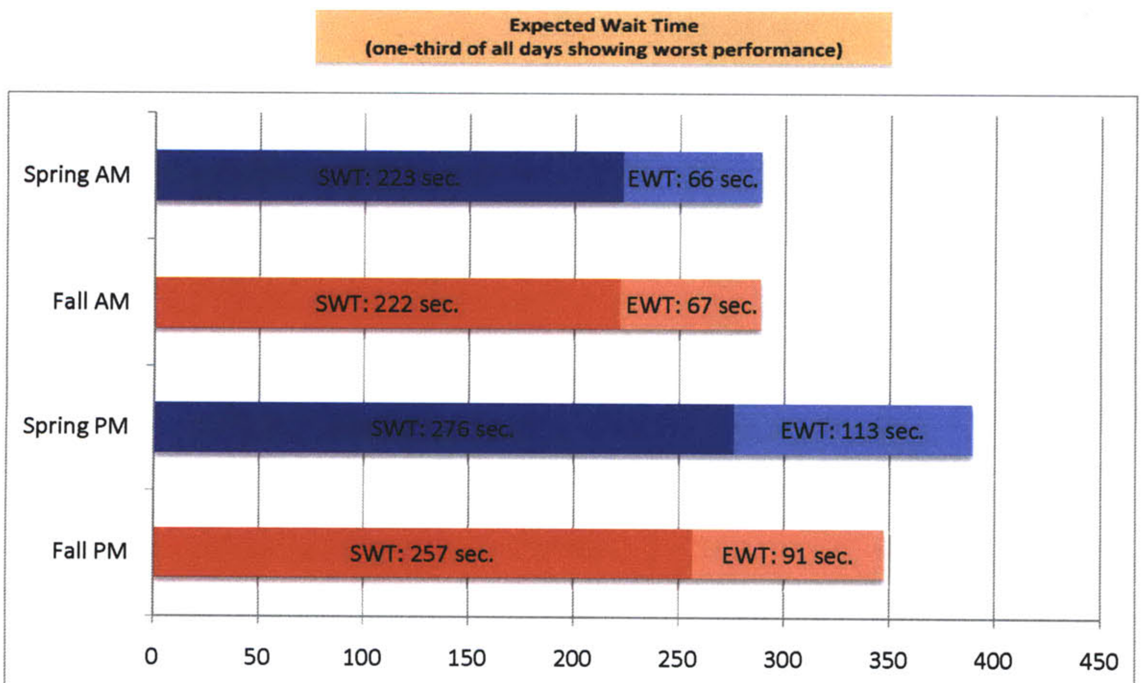


Figure A4-28: Expected Wait Time – Route 28 – Worst Days

c. Terminal Departure Adherence

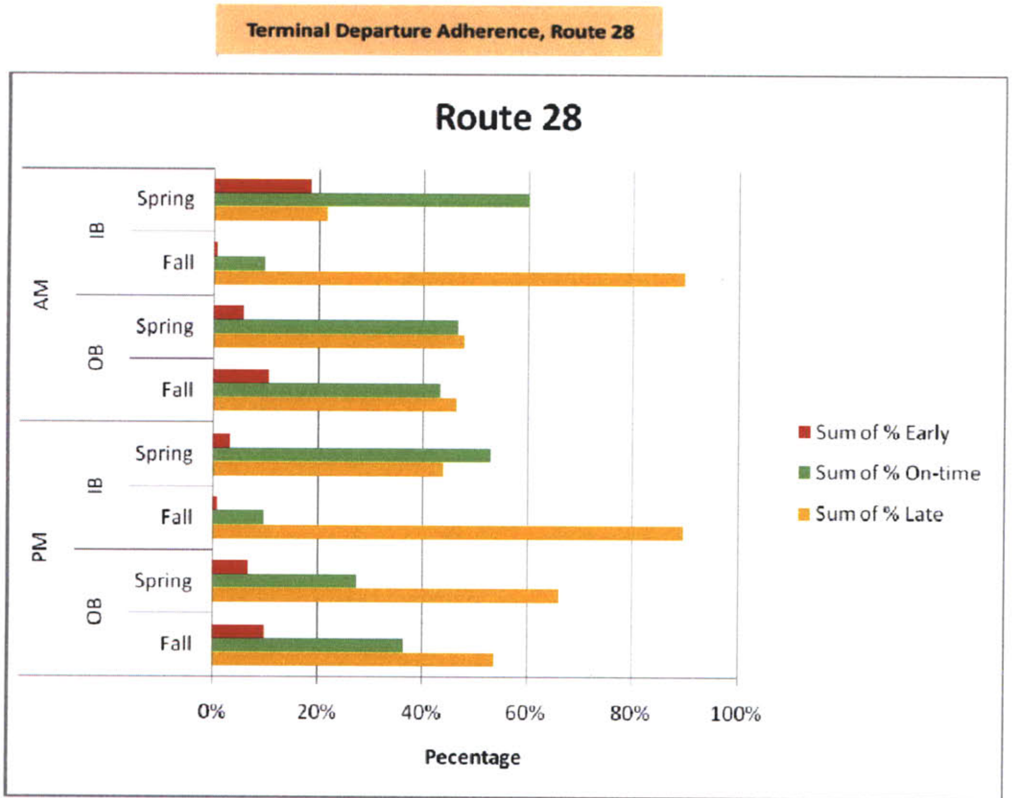


Figure A4-29: Terminal Departure Time Adherence – Route 28

d. Headway Ratios

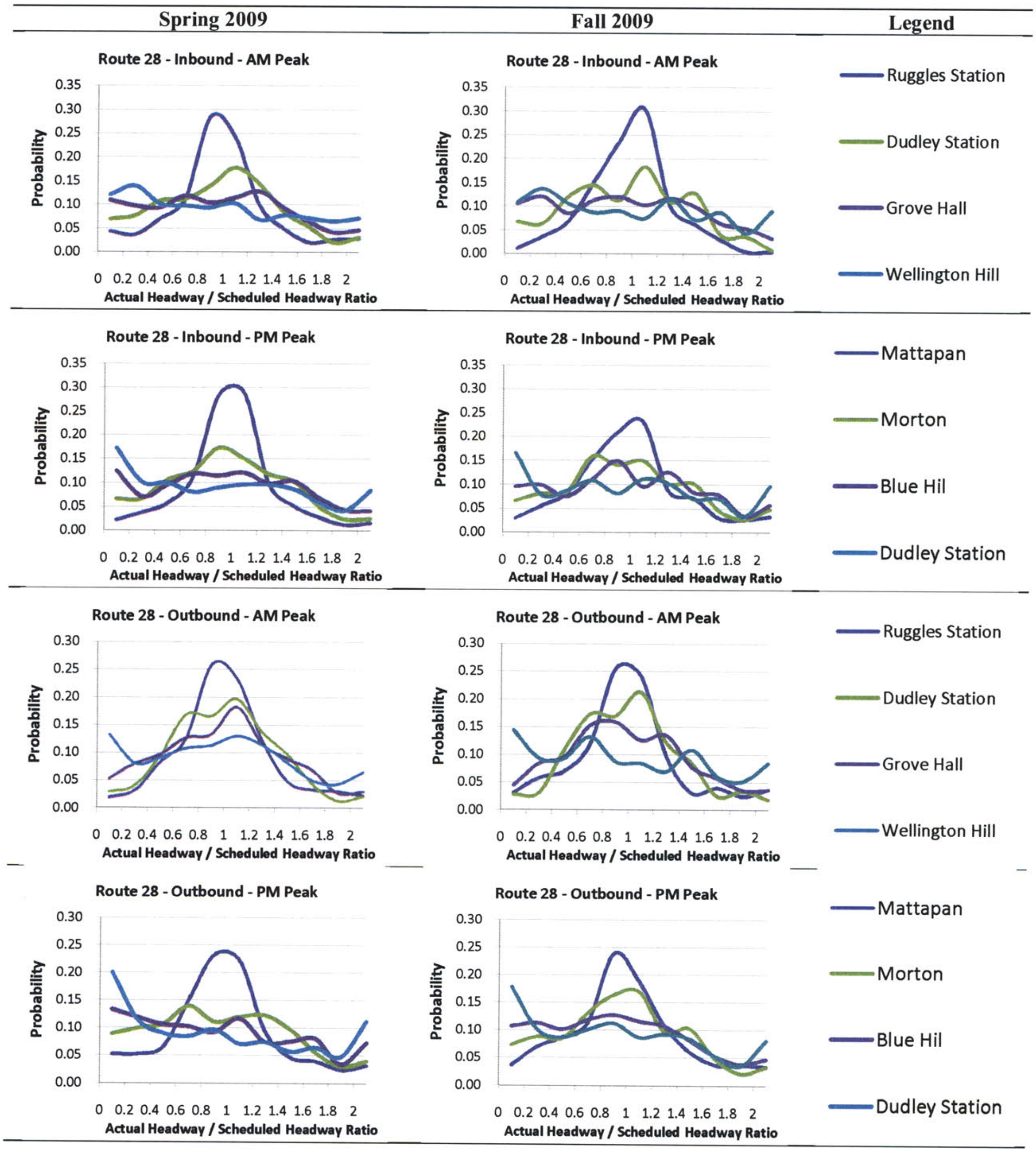


Figure A4-30: Headway Ratio Distributions – Route 28

e. Dwell Time (measured at the median boarding stop, here: Dudley Square for both inbound and outbound directions).

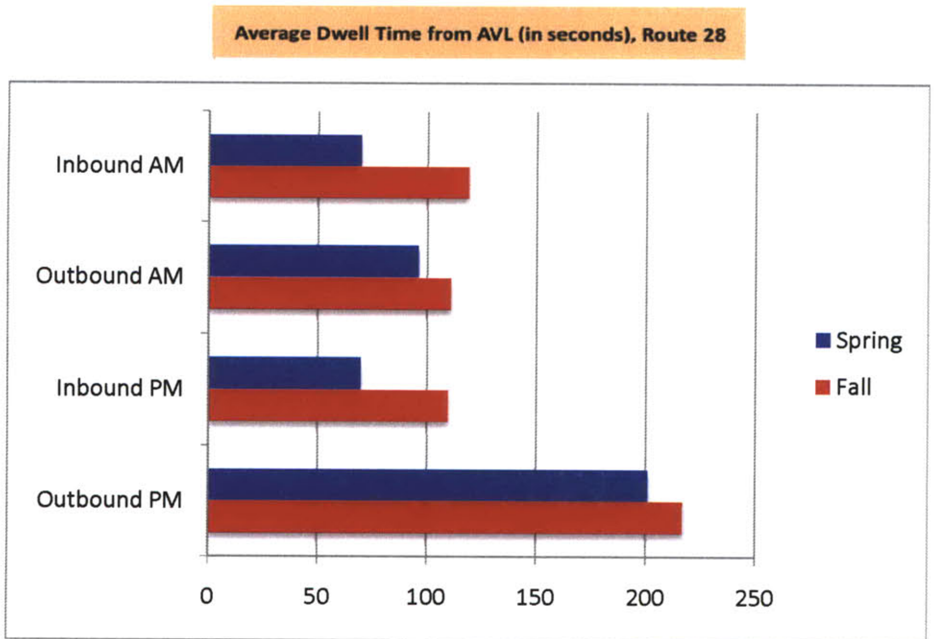


Figure A4-31: Average Dwell Times at Median Stop – Route 28

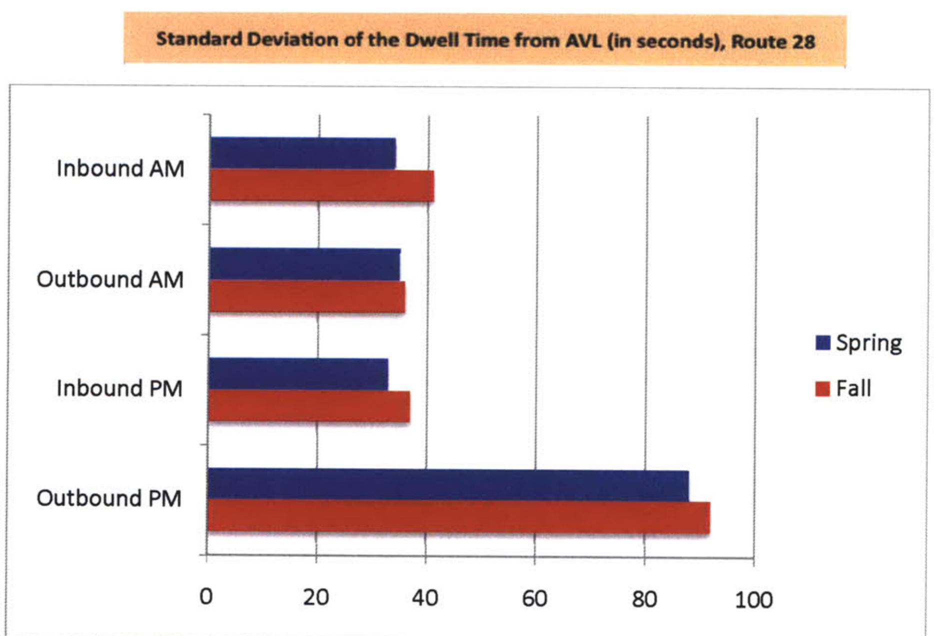


Figure A4-32: Standard Deviation of Dwell Times at Median Stop – Route 28

Appendix 4 - Route 66 Summary

1. Summary

Route 66 is the 5th highest ridership route in the greater Boston area, providing bus service between Cambridge and downtown Boston with ridership levels measured at 11,088 in 2007. Inbound service runs from Harvard Square to Brookline, with outbound providing return service.

Route 66 starts at Dudley Square in Roxbury, paralleling Route 39 from Brigham Circle to the Boston city limits. Via Harvard Avenue, Route 66 serves Brookline and Allston before terminating at Harvard Square, Cambridge

Stops include Harvard Sq & Garden St, N Harvard St & Western Ave, Cambridge St & Hano St, Cambridge St & Warren St, Cambridge St & Barrows St, Harvard Ave & Commonwealth Ave, Harvard St & Beacon St, Washington & Walnut, Huntington Ave Opp Fenwood Rd, Tremont St & Columbus Ave, and Dudley Station.

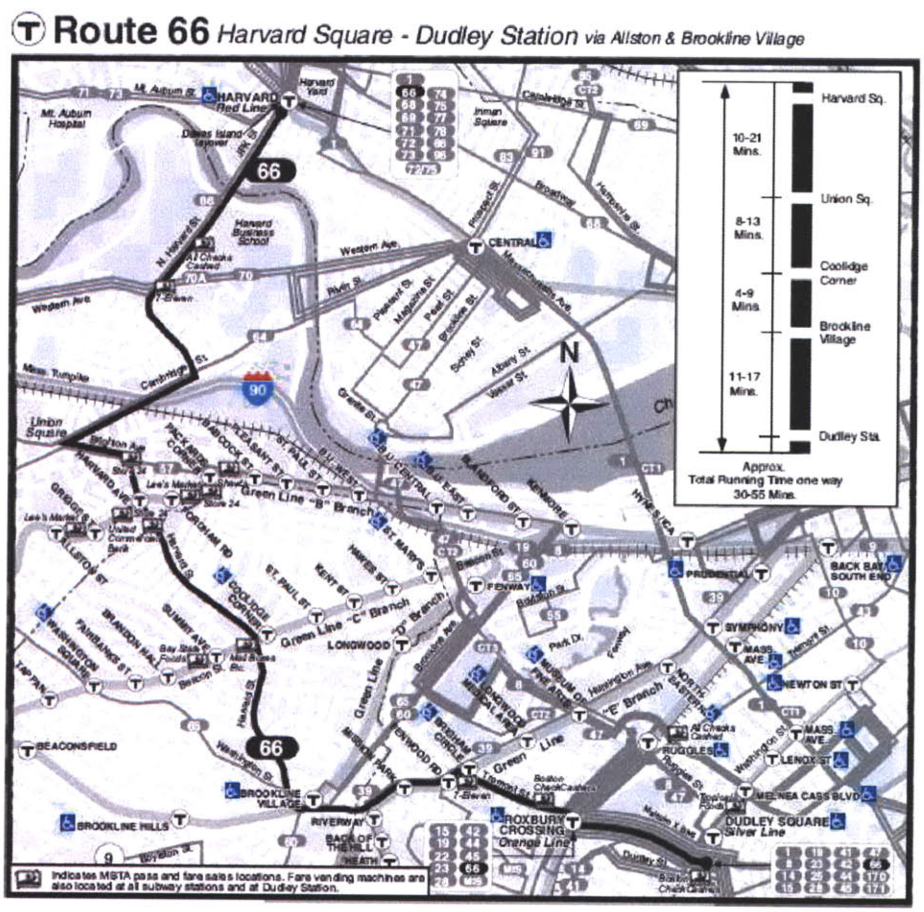


Figure A4-33: Route 66 Map

2. KBRI Schedule Adjustments for Route 66

Below is a summary of schedule changes implemented on 7 November 2009 along this route:

- AM Peak: One bus was added to the route, allowing for a decrease in headways from 9 to 8.5 minutes and increase in cycle time from 119 to 122. Outbound to Harvard, running time was reduced from 54 to 52 minutes while recovery time at the Harvard terminal was increased from 4 to 11. Inbound to Dudley, running time was reduced from 50 to 47 minutes while recovery time was increased from 11 to 12.

- PM Peak: Cycle time was reduced from 133 to 126 minutes, with running time and recovery time mix also adjusted. Headways were reduced from 10 to 9.5 minutes. Outbound to Harvard, running time was increased from 54 to 56 minutes while recovery time at the Harvard terminal was decreased from 13 to 7. Inbound to Dudley, running time was increased from 49 to 51 minutes while recovery time at the Dudley terminal was decreased from 17 to 12.

3. Performance Metrics

a. Running Time Distribution

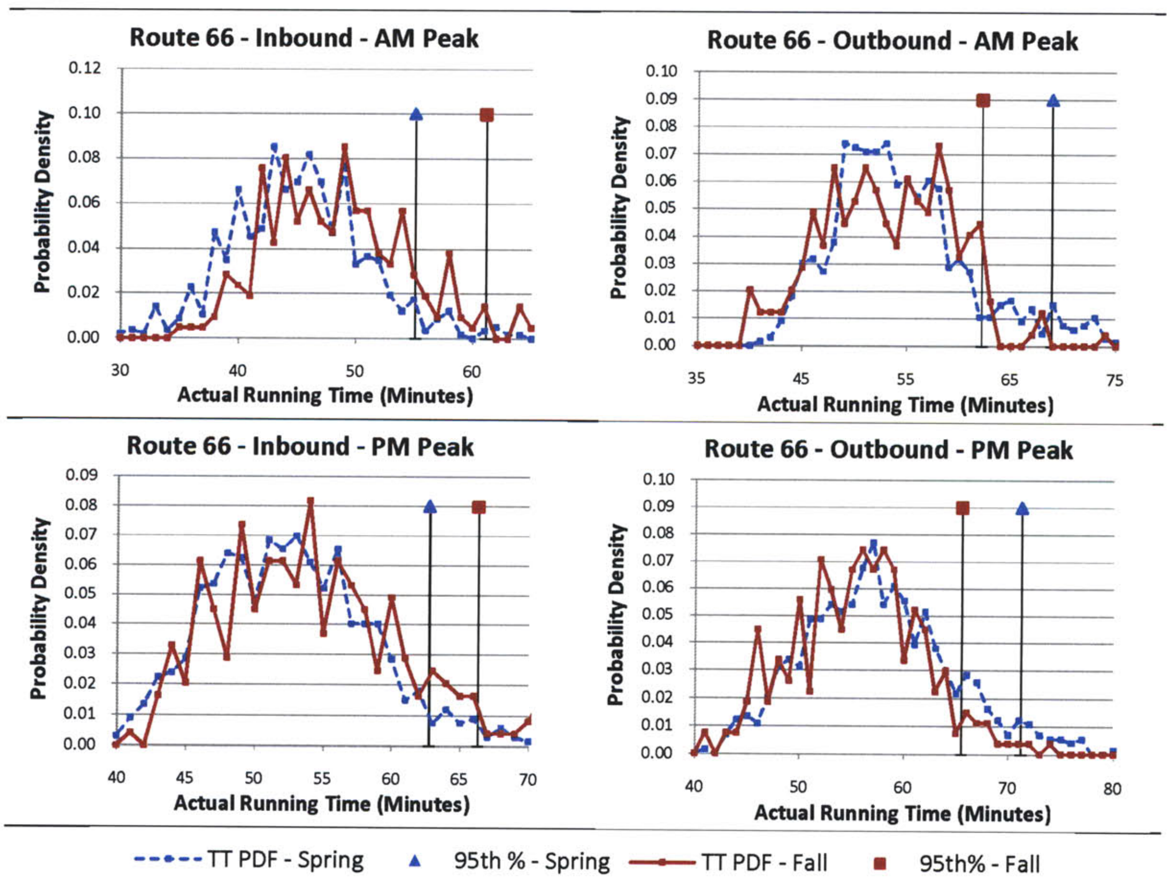


Figure A4-34: Running Time Distributions – Route 66

b. Expected Wait Time (measure at the median boarding stop, here: Union Square for inbound direction and Brigham Circle for outbound).

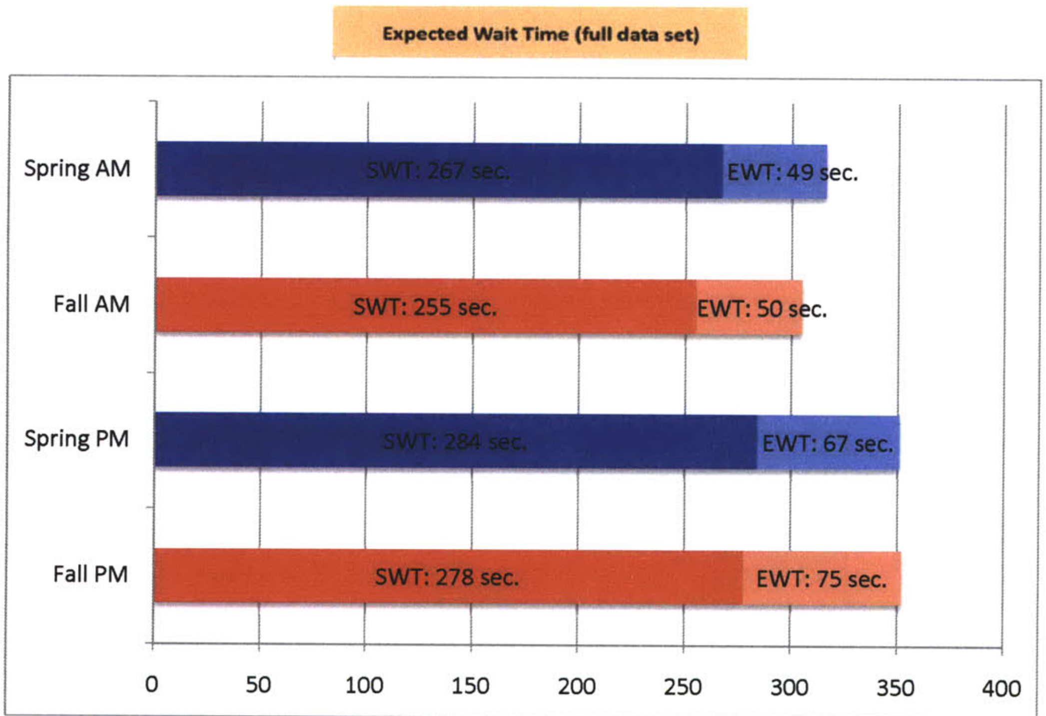


Figure A4-35: Expected Wait Time – Route 66 – All Days

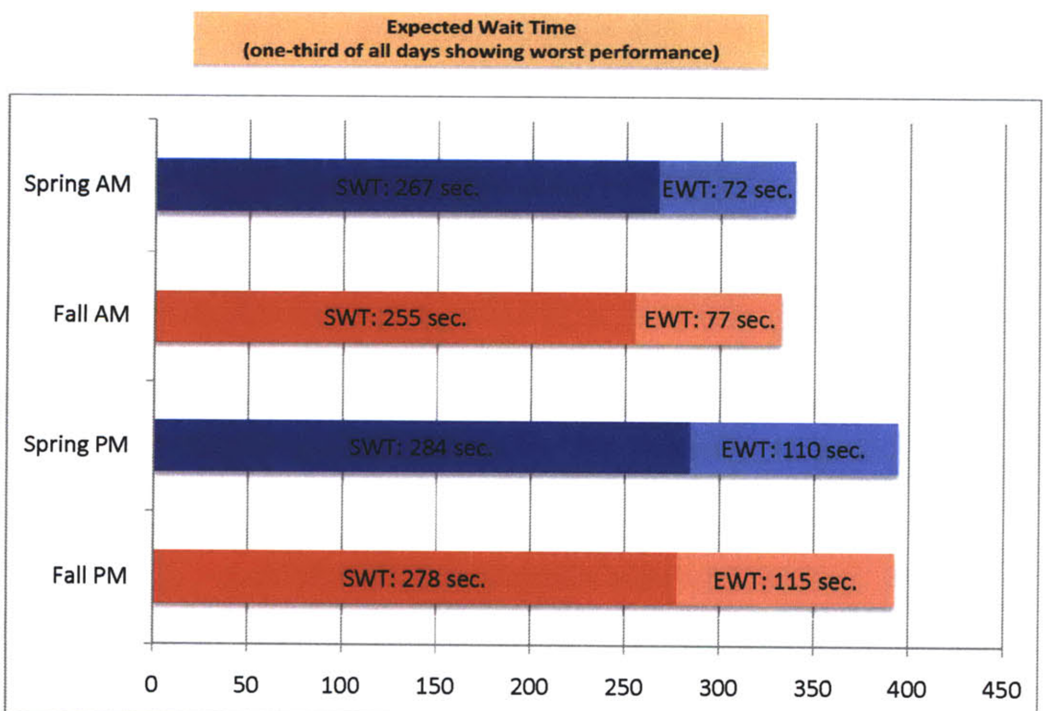


Figure A4-36: Expected Wait Time – Route 66 – Worst Days

c. Terminal Departure Adherence

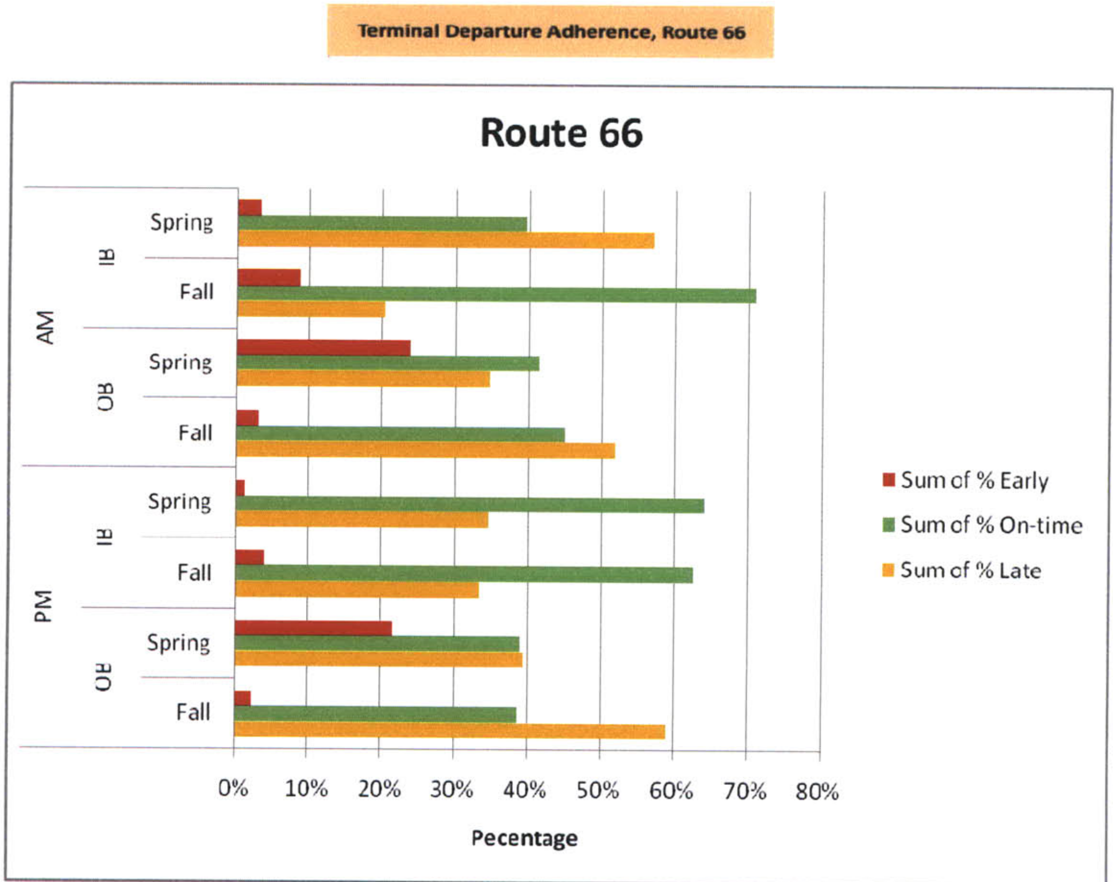


Figure A4-37: Terminal Departure Time Adherence – Route 66

d. Headway Ratios

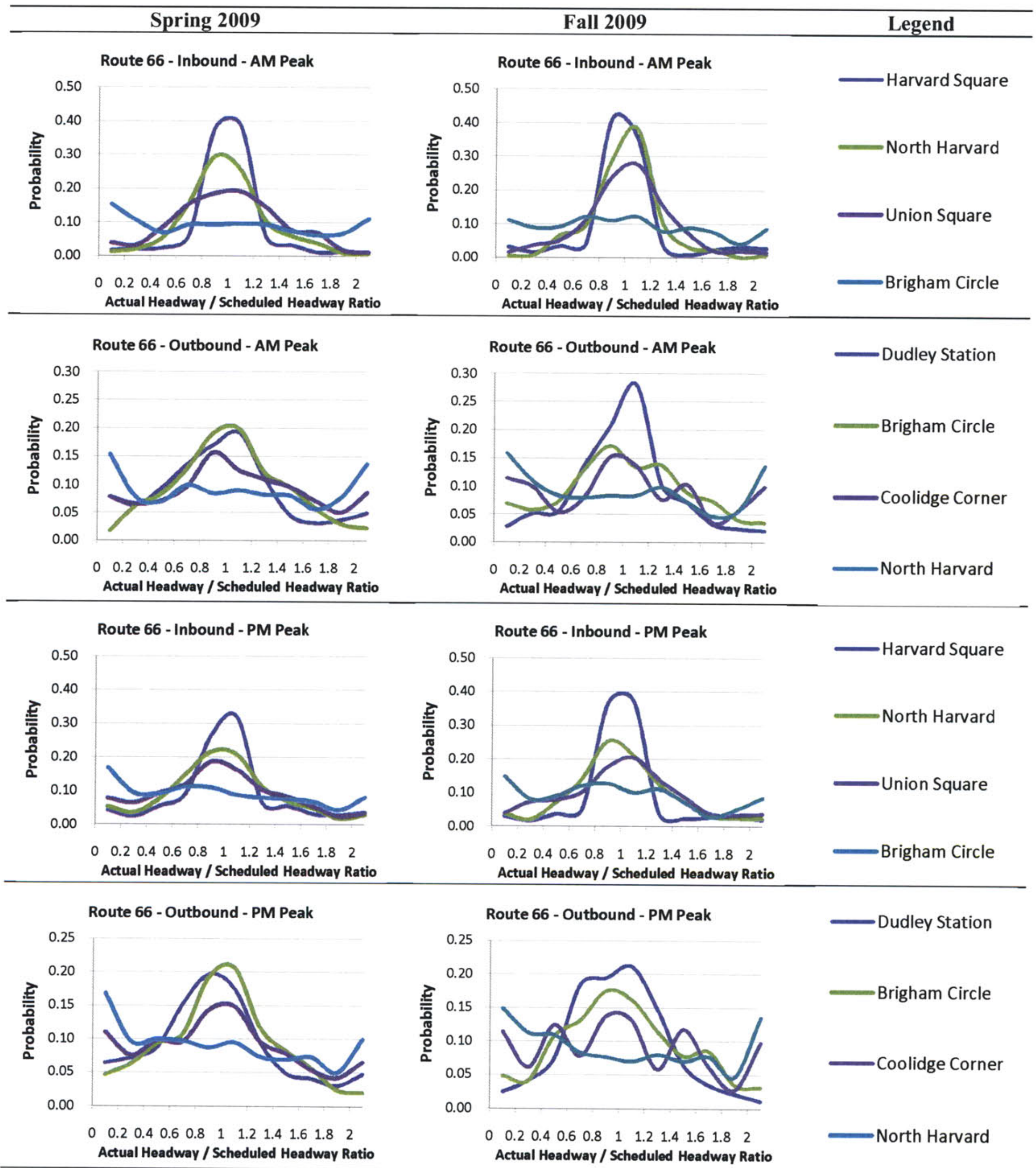


Figure A4-38: Headway Ratio Distributions – Route 66

e. Dwell Time (measured at the median boarding stop, here: Coolidge in the inbound direction and Brigham in the outbound direction).

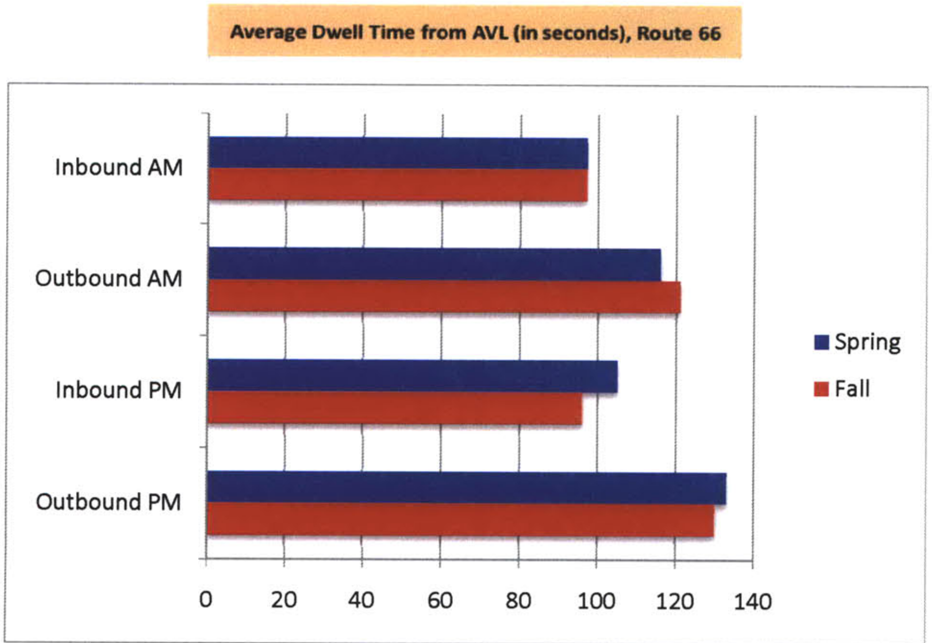


Figure A4-39: Average Dwell Times at Median Stop – Route 66

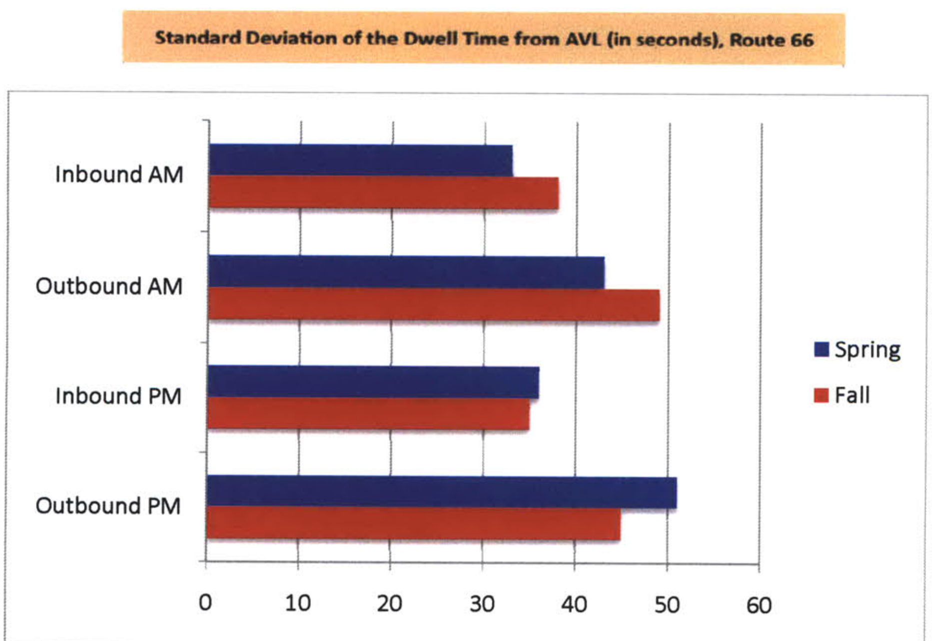


Figure A4-40: Standard Deviation of Dwell Times at Median Stop – Route 66