IMPROVING THE TRANSFER EXPERIENCE AT INTERMODAL TRANSIT STATIONS THROUGH INNOVATIVE DISPATCH STRATEGIES

by

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Abstract

This research introduces the concept of a bus hold light system that is based on headways of arriving trains in an effort to improve rail-to-bus transfer connectivity through a simple-to-implement, low-cost dispatching strategy. An analytical model and a simulation model are developed to analyze the impacts of the proposed headway-based hold light system on total passenger wait time and other relevant measures of transfer performance.

The application of the two models to the cases of Alewife and Wellington Stations in the Massachusetts Bay Transportation Authority (MBTA) system and to 79th Street Station in the Chicago Transit Authority (CTA) system shows that the headway-based hold light system can produce substantial passenger wait time savings if implemented in an appropriate setting. Throughout these analyses, the sensitivity of the headway-based hold light system to various factors is analyzed, and the results obtained with the headway-based hold light system are compared with those obtained from the application of other bus dispatching strategies, most notably the strategy of holding each departing bus for passengers transferring from the next train arrival. Based on the case study results and sensitivity analyses, a set of guidelines for the implementation of headway-based hold light systems is proposed.

In the comparison of the headway-based hold light system and the hold-all-buses strategy, it is shown that the headway-based hold light system is superior when a large number of downstream boardings occur, due to its tendency to avoid holding bus trips with very few transferring passengers but many downstream passengers.

Thesis Supervisor: Nigel H.M. Wilson

Title: Professor of Civil and Environmental Engineering

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Biography

A native of Colorado Springs, CO, Andrew T. Desautels graduated with a Bachelor's degree in civil engineering from the University of Arizona in 2004. At Arizona, Andrew served as president of the Institute of Transportation Engineers Student Chapter, as a representative to Engineering Student Council, and as design captain of the concrete canoe team for the American Society of Civil Engineers Student Chapter. During his time at the University of Arizona, Andrew received a number of transportation-related honors, including the 2003 Arizona Society of Civil Engineers Scholarship and the 2003 Southern Arizona Transportation Council Engineering Scholarship. Also while at Arizona, Andrew took his love of sports to the airwaves, hosting weekly talk shows "The Sports Nerds" and "Talkin' Baseball" on KAMP Radio.

Seeking a challenge and a taste of the notorious East Coast lifestyle, Andrew moved to Boston to study at MIT in 2004. In his two years at MIT, Andrew has taken courses in the areas of Public Transit Operations and Management, Airline Operations and Management, Operations Research, and Transportation Policy. Andrew was also a teaching assistant for 1.225 – Transportation Flow Systems in Fall 2005. While at MIT, Andrew was a 2004 recipient of the Dwight D. Eisenhower Graduate Fellowship and the 2005 winner of the UTC Region 1 Student of the Year Award.

As a complement to his academic pursuits, Andrew has held internships with a variety of transportation entities, including the Massachusetts Bay Transportation Authority, the San Francisco Municipal Railway, and MMLA, Inc. Andrew is a registered Engineer-In-Training in the State of Arizona.

Andrew's ambitions include traveling the world, learning to fly, appearing on "Jeopardy," becoming a scratch golfer, and attending a game at every Major League ballpark in a single season.

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1 INTRODUCTION

This research examines the problem of intermodal transfers at large transfer stations in public transportation systems and the use of a headway-based hold light system to improve transfer connectivity in these situations. First, an analytical model and a simulation model are developed to provide the capability to estimate the impacts of implementing the headway-based hold light system. The two models are then applied to a general case and the real-life cases of Alewife Station and Wellington Station in the MBTA system and 79th Street Station in the CTA system. Within the discussion of these case studies, a number of sensitivity analyses that serve to shed light on the behavior of the headway-based hold light system and on the appropriate locations for such a system are also presented.

1.1 Passenger Transfers in Public Transportation

In order to understand the potential for the hold light system[1] developed in this research, it is necessary to first understand the importance of the transfer in any transit network. As large transit networks offer service to thousands of destinations, it would be implausible and uneconomical to offer direct service between each origin-destination pair. As a result, transit agencies use transfer-dependent networks, where riders are required to make connections at transfer points or hubs, greatly reducing the number of vehicles and labor required to serve all the points in the agency's network. Additionally, passengers are often required to transfer between various types of service (e.g. rail and bus, express and local), as transit agencies use a diverse array of services to cater to specific travel markets on different portions of their networks. To illustrate the importance of the transfer, take the example of the Massachusetts Bay Transportation

[1] Hold light systems typically instruct bus operators through indicator lights (located in bus terminal areas) whether to wait for passengers just transferring from arriving trains or to depart as scheduled. Indications are generally based on train location and/or track occupancy data.

Authority (MBTA) system, in which approximately 30-40% percent of all passenger trips involve at least one transfer (Derived from MBTA 2003-2004 Ridership and Service Statistics), a value that is typical among large transit agencies.

1.1.1 The Transfer-Dependent Network

The advantages of this type of network – loosely related to a hub-and-spoke network in the airline industry – are numerous. Most importantly, the transfer-dependent network allows the service provider to consolidate the majority of its riders on a limited number of major routes, while providing connections to these major routes on a more limited basis from a very large number of points in the network. Intuitively, this allows the provider to save a great deal of cost, including ownership cost, labor cost, and operating cost, by operating much less service when compared with the provision of direct service between every combination of points on a similar network. Additionally, the transfer-dependent network allows maintenance and other units to be centralized at a smaller number of points.

Consider the simple network in Figure 1-1 below, consisting of 6 nodes.

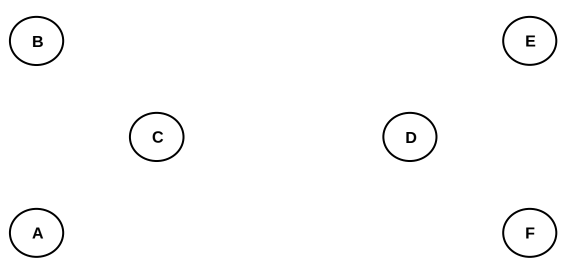

Figure 1-1: Six-node Network Example

Note that if the transit agency wishes to provide direct service between each possible origin/destination pair, it must operate ${}_6C_2 = 15$ routes as shown in Figure 1-2 below.

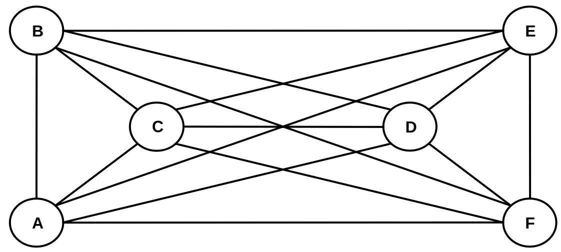

Figure 1-2: Six-node Network with Direct Service between Each O-D Pair

However, if the agency uses nodes C and D as "hubs" – meaning passengers are required to transfer between routes at these points – it is able to connect each possible origin/destination pair with a total of 5 routes (or fewer if the main trunk route(s) are extended to serve some of the outer nodes). A possible five-route transfer-dependent network configuration for this simple network is shown in Figure 1-3 below.

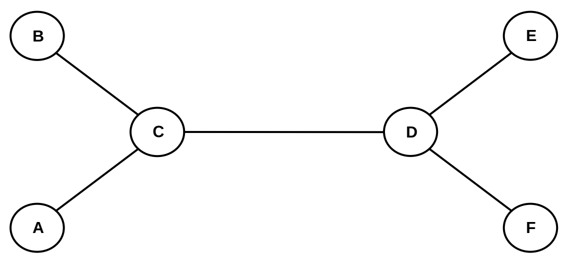

Figure 1-3: Six-node Transfer-Dependent Network

The above figures serve to clearly demonstrate the efficiency afforded by a transfer-dependent network, which relies heavily on the agency's ability to accommodate passengers transferring between routes (and modes).

1.1.2 The Intermodal Transfer

While transfers in general are inevitable in virtually all transit networks, intermodal transfers exist in almost all large networks. Transit agencies offer multiple modes of service in order to tailor transit service to travel needs, which results in using high-capacity rail service on very heavily traveled corridors, flexible bus service on relatively lightly traveled corridors, and medium capacity light rail or bus rapid transit (BRT) service on medium ridership routes. As a result, bus routes often act as feeders to light or heavy rail lines.

In large radial transit networks such as the MBTA, numerous feeder bus routes generally serve as collectors and distributors for the radial rail system. In the morning, as workers are traveling to jobs in the CBD, the feeder routes collect riders from outlying areas and transport them to rail terminals, where they transfer and continue into the CBD. In the evening, the system works in reverse; once commuters arrive at the rail terminals, buses distribute them to the outlying areas where they reside. During the morning peak period, this type of service is generally effective, as rail service is usually very frequent, and therefore passengers do not have to wait long once they arrive at the rail terminal. In the evening peak, however, passengers can encounter long delays transferring from high-frequency rail service to low-frequency bus service.

1.2 Improving the Transfer Experience

With the importance of the transfer well established, the next issue to be addressed is the multitude of disbenefits the transfer provides to passengers and how these disbenefits can be mitigated. Among the inconveniences commonly associated with transit transfers are the following:

- *Increased trip times*: A trip between two points that includes a transfer will almost certainly have a greater duration than a trip made on direct service between the same two points. This effect is a combination of the increase in travel time due to a less direct route and the time spent waiting for the second vehicle at the transfer point.

- *Increased trip costs*: Many transit agencies charge a transfer fare in addition to the fare charged to board the vehicle serving the initial leg of the trip. While the transfer fare is usually small relative to the initial fare, this can still be seen by some as an impediment to making trips involving transfers.

- *Decreased reliability*: As riders making trips involving transfers must depend on multiple vehicles functioning properly and adhering to the schedule, there is a significant decrease in reliability, particularly if on-time arrival is a primary concern.

- *Uncomfortable transfer environments*: Riders are often required to transfer at points which may be uncomfortable for a number of reasons. This is particularly important when considering bus-to-bus transfers, which often take place on street corners with little or no protection from the weather.

- *Difficulty of execution*: In many cases, the act of executing a transfer (particularly an intermodal transfer) is not intuitive. This problem can be compounded when certain passenger types (i.e. children, seniors, disabled persons) are involved.

For these reasons and others, many potential riders are hesitant to make transit trips requiring transfers. In many cases, these passengers choose instead to walk, drive, or in a longer term sense, to live and work at points connected by direct service. In order to reduce the perceived disbenefits of the transfer, and in turn increase the number of choice passengers attracted to transit, a substantial portion of the negative impacts of the above factors must be mitigated.

Many methods for improving elements of the transfer experience have been examined in previous work. In 2002, Crockett identified a set of 13 elements critical to transfer connectivity as shown in Table 1-1 below.

Table 1-1: Elements of Connectivity (Adapted from Crockett, 2002)

Category	Element
System Elements	Transfer Price
	Pre-trip Information
	Fare Media
	In-vehicle Information
	Fare Control
Facility Elements	Weather Protection
	En-route Information
	Changing Levels
	Road Crossings
	Walking Distance
	Concessions
Service Elements	Transfer Waiting Time
	Span of Service

Crockett uses these 13 elements of connectivity and her understanding thereof as a framework to critique the Chicago Transit Authority's (CTA) transfer connectivity on a network-wide level and to develop a plan for improvement. She concludes that the two service elements, transfer waiting time and span of service, are the most appropriate short-term targets, and recommends that these be improved largely through low-impact schedule modifications. Crockett recommends that facility elements be reviewed on a regular basis, and that opportunities for system element improvements be examined at the relatively rare times these improvements are possible.

Approaching the transfer connectivity problem from a more operations-focused standpoint, Younan examined the use of a number of operations planning and operations control strategies in 2004. In the area of operations planning, Younan developed a model that leads to reductions in transfer wait times by modifying the schedule on one bus line in order to better coordinate transfers with intersecting bus lines. Younan also examined the strategy of adding slack time to the schedule with limited success. Younan's work in the area of operations control found mixed results. However, this was largely due to his attempt to hold buses at multiple mid-line stations without impacting recovery times on the route. Although Younan did not recommend holding buses in many cases, it is clear that situations exist where such strategies could be quite beneficial.

1.3 Research Objectives

The general objective of this research is to examine opportunities for improving the overall transfer experience at intermodal transfer stations in large transit networks. On a more specific level, the goals are to reduce total transfer wait time to passengers and to improve the reliability of transfers through the use of operations control strategies. These goals are to be accomplished with a specific interest in wait time savings at terminal stations while placing a strong emphasis on simple, cost-efficient methods for improving the transfer experience. This research focuses on the application of operations control strategies during the PM peak period, defined as the period from 4:30 PM (16:30) to 7:00 PM (19:00). While the results can be generalized to any transit system, it should be noted that one of the main forces driving this research was an effort to make such improvements at Alewife and Wellington Stations in the Massachusetts Bay Transportation Authority (MBTA) system.

1.4 Research Approach

The approach taken to this research was first to collect and analyze data at Alewife and Wellington Stations, at which improving the transfer experience was the initial motivation for the work. This data collection, which took place over the course of six PM peak periods in November 2004 and October 2005, consisted of collecting train arrival times, bus departure times, and passenger counts at Alewife and Wellington Stations, two key terminals in the MBTA system. The data collection effort is described in detail in Chapter 3, and the raw data is included in Appendix A. After the data collection was completed, the next step was to determine from the analysis of the data the most appropriate method(s) for improving the transfer experience while placing a large emphasis on feasibility given current technology.

Two operations control methods were analyzed: the simple method of holding each bus trip for the next arriving train, and a headway-based hold-light system which instructs bus operators to hold for arriving trains only when long headways occur on the rail side. Once these two operations control methods were identified as feasible alternatives, the modeling phase of the analysis began. First, an analytical model was developed in order to estimate the effects of the two methods under various conditions. Subsequently, the analytical model was further developed into a simulation model in order to incorporate important stochastic elements into the analysis.

The simulation model is first applied to a simple hypothetical scenario, in an effort to gauge the effectiveness of the headway-based hold light system in a controlled environment. The model is then applied to the case of Alewife Station in the MBTA system to study the effects of the system in a situation where bus routes act as pure feeder/distributor routes. The model is then applied to Wellington Station in the MBTA system and 79th Street Station in the CTA system. These applications are part of a step-by-step effort to build upon the capabilities of the original model.

Throughout the development and application of the model, a number of sensitivity analyses were performed. These analyze the time-savings estimated by the model with respect to various characteristics of the scenario being analyzed, such as headway holding threshold, maximum hold time, and bus route headway. These sensitivity analyses are described in detail in Chapters 3-5.

1.5 Thesis Organization

This thesis is divided into five chapters. The second chapter presents a review of previous operations control research and details the state of the practice in terms of terminal control strategies, focusing specifically on hold light systems. Also featured in Chapter 2 is a discussion of the potential advances that could be made in this area with the application of current technology. Chapter 3 discusses the development of the analytical and simulation models used to analyze the potential benefits of the headway-based hold light system. Chapter 4 presents the application of the models to the case of Alewife Station in the MBTA system. Chapter 5 explains the application of the simulation model to the cases of Wellington Station in the MBTA system and 79th Street Station in the CTA system. The sixth and final chapter concludes the thesis by providing a summary of the findings and tying them into the research objectives as outlined above.

2 BUS HOLDING FRAMEWORK

There has been a great deal of research in the general area of transit operations control, however there is no significant academic research that relates directly to hold light systems. This chapter presents a review of some of the pertinent bus holding research, followed by a discussion of situational bus holding concerns, a discussion of the current state of hold-light systems, and finally an introduction to the headway-based hold light system which is modeled in subsequent chapters.

2.1 Transfer Coordination Cost Structure

Figure 2-1 below presents a cost structure for transfer coordination measures developed by Ting (1997).

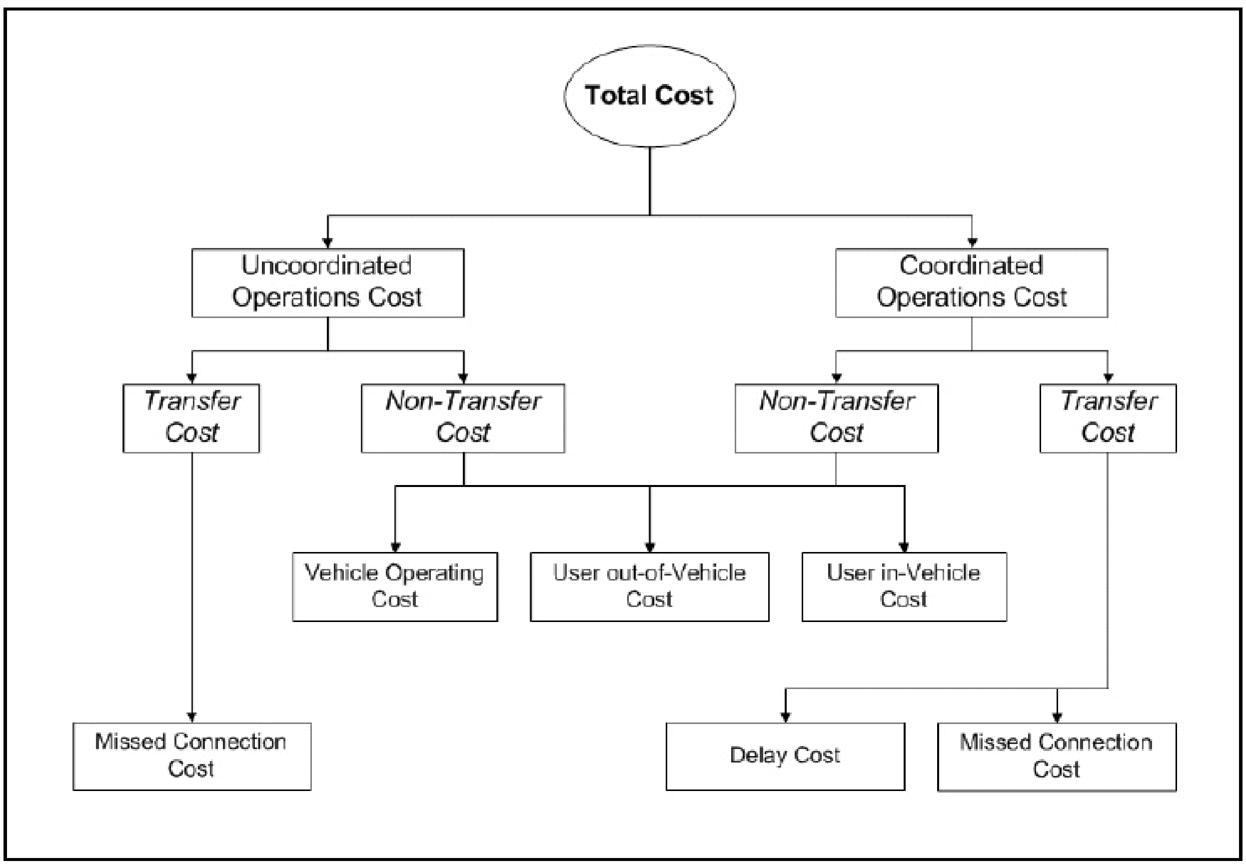

Figure 2-1: Cost Structure (Derived from Ting [1997] and Younan [2004])

Ting's cost structure identifies all the costs of efforts to coordinate transit services for the purpose of improving transfer connectivity. Ting makes distinctions between the various costs involved in running a coordinated operation so it is possible to evaluate a transfer coordination action or strategy based on each individual cost category. The majority of the research in the area of transfer coordination has attempted to minimize the sum of the numerous costs identified by Ting.

2.2 *Bus Holding Research*

The general strategy of holding a vehicle for other vehicle(s) carrying transferring passengers to arrive has been examined by a number of researchers. This section presents a review of previous bus holding literature that is pertinent to this research.

Prior to the majority of the research related specifically to bus holding, a number of researchers including Hall (1985), Abkowitz et al. (1987), Keudel (1988), Lee and Schonfeld (1991), Bookbinder and Desilets (1992), Vuchic (1993), Bakker and Becker (1994), and Clever (1997), examined the potential for improving transfer connectivity through various transfer coordination methods. These methods include coordinating schedules on intersecting routes in an effort to facilitate timed transfers and optimizing the amount of slack time present in schedules. To examine these strategies, a number of analytical and simulation models were developed, which were essentially used to minimize the costs identified in Ting's transfer connectivity cost structure. In spite of this body of research on the benefits of transfer coordination, Chowdhury (2000) found that pure schedule synchronization is not a viable strategy for reducing transfer wait time, due to stochastic headway variations.

Abkowitz et al. (1987) simulate the application of a number of holding strategies to intersecting bus routes. The result of the simulation is that holding generally increases net costs when headways of connecting routes are incompatible, therefore it is most beneficial in this case to schedule the buses to meet at the transfer point, but for neither bus to hold. When headways of connecting routes are compatible, the strategy of double-holding – the bus that arrives at the transfer point first holds for the second bus – is recommended.

Dessouky et al. (1999) examine the application of Intelligent Transportation Systems (ITS) to bus-to-bus transfers in the Los Angeles County Metropolitan Transit Authority (LACMTA) system in an effort to reduce transfer wait times. Their results indicate that the application of ITS can produce reductions in delay on the order of 20 seconds per transferring passenger. Dessouky et al. also note that the simple policy of holding all buses (without any real time information) until all intended connections are made is generally beneficial in terms of passenger delay. In a related study, Dessouky et al. (2003) develop a simulation model that is used to compare the results of seven holding strategies with varying levels of technology-dependence. The findings of this study were that technology-dependent holding strategies are most beneficial when the schedule slack is near zero, the number of connections is large, and the bus headway is large. This study is particularly noteworthy because it considers the impact to downstream passengers as well as through passengers at the transfer station rather than solely considering impacts on passengers boarding at the transfer station.

Hall et al. (1999) apply a number of control strategies to LACMTA data also aiming to minimize total wait time for bus transfers. Particular attention is paid to the situation where arrival times of connecting buses are identically normally distributed. In this case, Hall et al. show that there exists at most one non-boundary local minimum point in the total expected waiting time function. In general, depending on a number of factors including scheduled arrival times and the number of transfer passengers, Hall et al. find that it can be best either to dispatch buses immediately upon arrival, or to wait until a local optimum point.

Wong (2000) examined the potential for holding to improve transfers between high-frequency transit services, when he developed an analytical model and a simulation model to estimate the effects of holding trains on the Green Line at Park Street Station in the MBTA system for passengers transferring from the Red Line. Wong's models use real-time information on vehicle location and passenger transfers to estimate the benefits of a potential hold, then hold the train if the estimated benefits are greater than a predetermined threshold.

Wong experimented with different holding thresholds, and determined that higher minimum thresholds improve average benefits per train. He also found the results of his simulation model to be very sensitive to the relative weighting of in-vehicle hold time versus out-of-vehicle waiting time. Also notable is the fact that Wong's approach yielded the greatest benefits in the off-peak periods, when service is less frequent. Wong's research, which showed that his holding strategy can produce substantial passenger wait time savings, is an example of the successful application of a holding model in a situation where it could feasibly be applied to the actual system.

One important area where Wong's approach differs from the approach presented in this thesis is the treatment of passengers boarding downstream from the transfer point. Since Wong's case involves passengers transferring to high-frequency service where boarding passengers do not target specific trips (the MBTA Green Line), he acknowledges that holding vehicles at a transfer station may benefit passengers boarding downstream. In this thesis, it is assumed that, since primarily low-frequency bus service is considered, passengers time their arrivals downstream based on the published schedule, and are generally negatively impacted by bus holds at the transfer station.

Chowdhury and Chien (2001) developed a procedure to dynamically optimize dispatch times for vehicles departing an intermodal transfer station based on a time varying total cost function. The method uses the prediction capabilities afforded by real-time data to determine dispatch times that minimize the total cost function, which includes connection delay cost, missed connection cost, and vehicle holding cost. It is assumed that perfect information is available in terms of predicted arrival times and transfer volumes. This information is used at the time each trip is scheduled to depart, to evaluate the total cost function and optimize the holding time for that vehicle. If the optimal hold time for a trip is greater than a pre-set evaluation interval, the total cost function is re-evaluated after the evaluation interval passes. For long holds, the total cost function of a single departure could be evaluated many times before the vehicle departs. The application of this model to a hypothetical four-route transfer station indicates that the method can significantly reduce total transfer time.

For the most part, previous bus holding research has failed to focus on methods that can feasibly be applied in the near future. Most researchers have developed models where bus hold times are theoretically optimized. However, these models are commonly based on perfect information rather than the information that is generally known at the time a holding decision must be made. Additionally, much of the previous bus holding research fails to take into account the effects of bus holding on passengers boarding downstream as well as passengers traveling through the transfer station. The feasibility of implementation and the impact to passengers other than those boarding at the transfer station are two focal points of this research.

2.3 Situational Bus Holding Considerations

When determining if bus holding is appropriate, it is important to consider the characteristics of the routes involved. Among the most important characteristics is the frequency. While it is generally agreed that holding has vastly different impacts on short-headway routes versus long-headway routes, the boundary between the two is not nearly as clear. According to Furth (2006), this boundary is generally between 8 and 14 minutes in large US transit systems, depending on passenger indifference values of schedule inconvenience. Other important considerations include the location of the transfer point on the route and the complexity of the holding protocol.

2.3.1 Low-frequency Routes

In general, low-frequency routes present the ideal situation for bus holding. There are a great deal of wait time savings that can be achieved through holding low-frequency bus trips, as passengers are subject to significant penalties if connections are missed. From an operations standpoint, low-frequency bus routes are also more amenable to holding. As long as buses are not held for excessive amounts of time, it is unlikely that holding such trips will significantly affect operations in terms of headways.

Holding low-frequency bus trips can produce negative effects on downstream passengers however. Passengers on low-frequency routes generally time their arrival at a stop to catch a particular trip, rather than showing up simply with the intent to board the next bus as would be the case with a high-frequency route. If trips on low-frequency bus routes are held, downstream passengers will likely see poorer schedule adherence than they would without holding. On the other hand, it is possible that downstream passengers on low-frequency routes can actually benefit from short holds. This often occurs on bus trips with faster-than-average operators, where these holds can improve schedule adherence by counteracting the speed of the operator.

2.3.2 High-frequency Routes

Schedule adherence is much less important than headway maintenance on high-frequency routes. On such service, rather than arriving at a stop/station with the intent to catch a bus at a specific time, passengers arrive with the intent to simply board the next bus. As a result, passengers are not nearly as sensitive to trips arriving past their scheduled times, but are instead sensitive to long headways. Although this can provide increased latitude for a transit agency holding buses on high-frequency routes as long as even headway spacing is a priority, there are a number of concerns with the strategy of bus holding as it relates to this type of service:

- *Limited time savings potential*: In contrast to passengers on low-frequency bus routes, high-frequency bus route passengers do not typically incur significant penalties for missed trips since headways are relatively small. As a result, passengers exhibit the untargeted arrival behavior discussed above. This extreme difference in passenger behavior from the low-frequency service case calls into question the strategy of holding buses on high-frequency bus routes due to the significantly reduced potential for wait time savings.

- *Headway irregularity*: Since hold durations are determined by arrival times of rail vehicles, or buses, on routes other than the bus route to which the holding strategy is being applied, successive buses may be held in a manner that contributes to the problem of headway irregularity – which manifests itself to passengers in the form of long headways – a problem that is often a concern to transit agencies on high-frequency services.

- *Recovery time issues*: High-frequency routes are generally routes that are heavily loaded, sometimes in both directions, and can be subject to significant schedule deviation. In these cases, recovery time is critical in allowing operators to compensate for the possible delays they encounter and leave on their return trips on time. As a result, it becomes important not to significantly cut into recovery time with operations control strategies such as bus holding.

2.3.3 Additional Considerations

Another important consideration in the decision whether to hold buses is the location on the route, as terminal holding and mid-line holding have very different implications. Holding at terminal stations is one of the simplest and most common types of bus holds to execute for a number of reasons. Often, bus terminals are located at stations that feature at least one other mode of transit, such as heavy rail. In many of these cases, the bus routes exist primarily to feed passengers to the rail service at times when people are traveling into the downtown area, and to distribute passengers traveling from the downtown area at times when people are traveling away from downtown. Usually, these feeder routes operate with relatively low frequencies, making them ideal candidates for bus holding as discussed in Section 2.3.1.

Transit agencies may also hold buses at terminal stations for operations reasons (generally to ensure appropriate headways on routes). In these cases, it is feasible that agencies could also consider impacts on transferring passengers when making holding decisions, regardless of whether reducing wait time was a goal when the holding procedures were implemented.

In contrast to terminal holding, mid-line holding is generally limited by the fact that the operator is solely responsible for executing the hold, as there are seldom hold-lights or supervisors at mid-line stops. However, one advantage of mid-line holding is that it has the potential not only to save transferring passengers wait time, but also to adjust headway spacing, or schedule adherence, in the middle of the route. Since passengers boarding downstream of the point where a hold takes place are among those who may incur delay, mid-line holding can also reduce the overall impact on the line's passengers by causing fewer passengers to be negatively affected. Although mid-line holding on high-frequency routes has the advantage of allowing an agency to regulate headways, Younan (2004) found that when schedules on such routes with multiple major transfer points are well coordinated to allow for timed transfers, mid-line holding generally does not produce significant wait time savings.

Transit agencies also have the flexibility to define holding procedures with varying levels of complexity. The simplest and most commonly used procedure is to instruct operators of all routes leaving a station to hold for an arriving train if a hold light is active, and proceed as scheduled if no hold light is active. There is also potential for agencies to give specific holding instructions to operators on each route or even each trip, such as instructing operators of some routes/trips to ignore hold lights altogether, or assigning unique maximum hold times to each route/trip. This ability to differentiate holding procedures allows the agency to mold each route or trip's holding behavior to its individual characteristics. However, one significant drawback to the differentiation of holding procedures across routes/trips is that one would expect lower operator compliance when more complex holding procedures are used.

2.4 Existing Hold Light Systems

This section outlines the hold light systems currently in place in transit systems, with particular attention paid to those in place in the MBTA and CTA systems. A discussion of the current and future applications of technology to hold light systems is also included.

2.4.1 General

Many transit agencies have traditionally used hold lights in an effort to coordinate rail-to-bus transfers. These hold lights are usually set up in bus boarding areas where they are visible to all bus operators, and are used to signal operators to wait for passengers transferring from arriving trains, which are not visible to bus operators. Usually, hold lights are activated when a train reaches a specific track circuit, then remain "on" for a specified interval so that passengers arriving on that train have time to transfer to buses which are about to depart. Generally, bus operators on all routes are instructed not to depart when the hold lights are "on," but it is sometimes the case that unique instructions are given to operators of each route or trip.

While this type of hold light can provide significant time savings to transferring passengers at relatively little cost, this system generally causes the hold light to be "on" for an excessive amount of time. Other negative effects are immediately apparent. For example, if two trains arrive in rapid succession, the hold light will be "on" for the second arrival even though there may be few if any transferring passengers. Another possible problem with such a hold light system is bus operator compliance. Since the hold lights are activated by every train arrival, the lights are active for a large portion of the time, particularly during the peak periods. As a result, bus operators may frequently ignore the indicator lights.

2.4.2 MBTA System

Traditional bus hold light systems are currently in place at a number of locations in the MBTA system, including the following six stations.

- Alewife Station (Red Line)
- Ashmont Station (Red Line)
- Forest Hills Station (Orange Line)
- Harvard Station (Red Line)
- Wellington Station (Orange Line)
- Wonderland Station (Blue Line)

From observations of operations at these stations, it is apparent that bus operators do not always hold for transferring passengers when the hold lights are active. Additionally, at many of these stations, the hold-light system hardware is not well maintained. Often, bulbs are burned out or otherwise not well maintained, causing the system not to function properly, or at all. With respect to specific stations, the Harvard Station busway is a single-lane facility, which causes problems if a bus near the rear of the busway is holding at the same time another bus is arriving at the station. For this reason, the Harvard Station hold light is not used. Additionally, the Ashmont Station hold lights – which are intended to alert Mattapan Trolley operators to the arrival of Red Line trains – are not currently in operation. The hold lights at Wellington Station are also not currently in operation.

2.4.3 CTA System

Traditional bus hold light systems are currently installed at many of the major rail-to-bus transfer points in the CTA system. With its current hold light systems, the CTA has seen a significant disparity in operator compliance between situations where supervisors are present to enforce holding instructions and situations where no supervisors are present. In addition to operator compliance issues, lack of maintenance and issues with the rail signal system interface in some cases diminish the effects of the hold light systems. As in the MBTA system, many of the systems are not well maintained. Since the construction of the Orange Line, bus hold lights have been a standard feature of CTA rail station construction.

2.4.4 Applications of Technology

Currently – as more real-time data becomes available – it is becoming more feasible to incorporate this data into dispatch systems that can help reduce transfer wait times. Automated Vehicle Location (AVL) technology is becoming widespread, allowing transit agencies to estimate the arrival time of the next train or bus, which in turn provides operations control personnel or software with the information necessary to determine if holding a bus trip will allow passengers to transfer to it from an arriving vehicle. This use of reliable AVL data in holding decisions can allow a transit agency to avoid no-benefit holds. Another type of data that would be extremely useful to operations control is passenger count data. If decision-makers know how many passengers are on an arriving vehicle as well as its estimated arrival time, they can better estimate the number of passengers transferring to the bus trip that is to be held and the benefits to these passengers. As technology continues to advance, another significant development in bus holding strategy will be the ability to provide specific instructions to each route and even each individual trip so that operations control personnel can more closely match hold strategies to the characteristics of each bus trip and the current status of the system.

An example of the application of real-time information to the bus holding problem is the Utah Transit Authority's (UTA) Connection Protection Program. This program, implemented as part of a set of improvements prior to the 2002 Winter Olympic Games in Salt Lake City, utilizes real-time train arrival data to determine bus hold times that minimize transfer times to passengers. The system determines optimal hold times based on the time saved by connecting passengers and on the estimated delay incurred by passengers boarding downstream, while "protecting" passengers from missed connections in the case of a late train arrival. It is worth noting, that even with technological advances, hold light systems are still subject to some of the same long-standing problems. For example, in the UTA's experience with its Connection Protection Program, driver compliance has estimated at only 51% (Cluett et al., 2005).

The potential for wait-time savings from incorporating basic real-time information into headway-based hold light system is examined in Chapter 4.

2.5 Headway-based Hold Light System

Recognizing the benefits provided by hold light systems, but understanding that too frequent activation is one of the major shortcomings of the systems currently in place, this research aims to develop a hold light system that leads to improved transfer connectivity in situations where there are disruptions in the mainline portion of the trip, and does not activate when operations are normal.

The initial application of this hold light system is focused on feeder/distributor bus routes in the PM peak period. This is the case for a number of reasons. In the PM peak period, it stands to reason that most passengers are not trying to meet strict deadlines since they are generally traveling home from work. Therefore, passengers are not as sensitive to small departure delays as they would be on trips into a downtown area in the AM peak. Feeder/distributor routes tend to have very heavy directionality among bus travel in the PM peak, which reduces the concern of negative operating impacts on the return trip from headway-based hold lights. The focus on rail-to-bus transfers is a reflection of the large potential for wait time savings when holding for passengers that are transferring from high-frequency rail service to low-frequency bus service.

The headway-based hold light system developed in this research uses the existing track circuitry to detect when a train enters the transfer station. When a train enters the station, a timer is activated and when this timer reaches a predetermined long headway threshold, it is immediately reset and a flashing light at the bus boarding level of the station is activated. When the light is flashing and another train arrives, the light continues to flash for an interval sufficient for passengers to transfer from the rail platform to the bus platform, and then ceases to flash. Bus operators, if this light is flashing at their scheduled departure time, are instructed to wait until the light stops flashing before departing the station. If the light is not flashing, bus operators are instructed to depart at the scheduled time. This strategy is effective if, on the trips that are held, few riders are on the bus at the scheduled departure time and many rail-to-bus transfer passengers, who would have had to wait a significant length of time for the next bus, are transferring from the next rail trip (the trip for which the bus is holding).

In this research, only the simple case is considered, but it should be understood that a simple indicator light is not the only means of providing an interface between the headway-based hold light system and bus operators. The use of indicator lights is appropriate when all bus trips should react similarly to arriving trains. In cases where routes at a transfer station have very different characteristics and as a result are expected to react differently to arriving trains, a number of options are available. One of these options is to issue different procedures for reacting to hold lights to operators on each route. This option uses the simple indicator light, but allows operators on certain routes to ignore the hold instruction or to otherwise treat it differently than operators on other routes.

Another option is to have a supervisor at the station responsible for processing rail and bus data and determining what operations control actions to take. This allows for unique treatment of each bus route, but can be difficult if simultaneous or near-simultaneous departures are scheduled. Potentially the most desirable option is to electronically provide specific holding instructions for each bus trip, either directly to the on-board computer of each bus or to a supervisor who can give each operator instructions and make sure they are carried out. This system can determine holding instructions based on potentially complex criteria, and then provide information tailored to each bus trip without placing a great deal of responsibility on supervisors.

A discussion of the headway-based hold light system's performance compared to that of the traditional hold light systems described in Section 2.4 is presented in Chapter 1.

2.6 Hold-all-buses Strategy

This research also examines the alternative strategy of holding all buses for passengers transferring from the next train arrival. This holding strategy allows an agency to eliminate the problem of transferring passengers narrowly missing connections at transfer stations, without requiring significant investment in equipment or technology. The major downside of this holding strategy is that all bus trips are delayed, regardless of how many passengers are transferring from rail. The fact that all bus trips are delayed can also contribute heavily to operational problems such as long headways and late return trips. For the purposes of analysis, it is important to note that this strategy is identical to the headway-based hold light system with the long-headway threshold set to zero.

2.7 *Holding Strategy Expectations*

When examined with the models developed in this research, both of the strategies described above are expected to produce substantial amounts of wait time savings when used in the appropriate settings. While the strategy of holding all bus trips for the next train arrival is expected to produce a greater amount of wait time savings, the advantage of the headway-based hold light system is that bus trips to be held are chosen more selectively, resulting in most of the wait time savings associated with the hold-all-buses strategy while affecting a fraction of the bus trips.

Not unlike that of traditional hold light systems, the success of the headway-based hold light system and the hold-all-buses strategy depend of a number of situational factors, including the following.

- *Rail frequency:* It is expected that when used in situations with low-frequency rail service, the headway-based hold light system and the hold-all-buses strategy would provide more benefits to transferring passengers. If train headways are small, intuitively passengers should be spread evenly over a large number of trips, rather than concentrated on a small number of trips. Since this is the case, holding a bus will only save a few passengers time, while delaying a much larger number of passengers that have arrived on earlier trains. On the other hand, if train headways are large, the transferring passengers are concentrated on a small number of arriving trains. If a bus trip is held for one of these train arrivals delivering a large number of transfer passengers, a substantial amount of wait time can be saved, while delaying fewer passengers already on board the bus than in the high-frequency case.

- *Bus frequency*: Bus frequency is an extremely important factor to consider when determining if a route is appropriate for implementation of the headway-based hold light system or the hold-all-buses strategy. As discussed in Section 2.3.2, when bus service is frequent, the negative impacts of holding are more pronounced, as headway regularity is of greater importance to the transit agency. The fact that the headway-based hold light system will cause fewer holds than traditional hold light systems will help to lessen these negative impacts, but not eliminate them entirely. In the case of low-frequency bus routes, headway regularity is less of a concern than schedule adherence, making these situations more conducive to the headway-based hold light system. Also of great importance is the impact of bus frequency on passenger arrival patterns. Intuitively, for low-frequency service, passengers will attempt to be more conservative with their arrivals than for high-frequency service, since penalties for missed connections are larger.

- *Passenger mix:* While the attraction of the headway-based hold light system is a result of its effects on passengers at the transfer station, the system's effects on two types of downstream passengers must also be considered. The first type of downstream passenger is one who boards before the transfer station and alights downstream. If a bus is held, these passengers will be on the bus, and will be subject to delay due to the hold. The second type of downstream passenger is one who boards downstream of the transfer station. In the context of low-frequency routes, these passengers generally are delayed by upstream holding since specific bus trips are targeted. In contrast, similar passengers boarding high-frequency routes can be positively or negatively affected depending on their arrival in relation to the bus hold. As a result of the primarily negative effects to downstream passengers on low-frequency routes, it is expected that the application of the system to bus routes with a dominant transfer point will be much more effective than routes where boardings are distributed evenly between stops, due to the presence of fewer downstream passengers. Additionally, the balance of transfer and walk-in passengers boarding at the transfer station plays an important role. Since walk-in passengers presumably have more control over when they arrive at the station, they will not be as conservative with their arrival times as transferring passengers attempt to be. While it is possible for walk-in passengers to be helped by a bus hold (most likely in the case of an early departure), it is assumed in this research that all walk-in passengers boarding at transfer stations are on board when the holding decision is made. Essentially, these passengers are treated as through passengers, subject to an amount of delay equal to the duration of the bus hold if one is performed. This will cause the model to return slightly conservative values of wait time savings.

- *Wait time perception:* In transit operations analysis, it is generally accepted that passengers (negatively) value out-of-vehicle wait time more than in-vehicle delay time, meaning they would rather be delayed while on a vehicle than have to wait the same amount of time for a vehicle to arrive. To represent this, researchers often weigh out-of vehicle wait time more heavily than in-vehicle delay time. Since both the headway-based hold light system and the hold-all-buses strategy should cause out-of-vehicle wait time to decrease and in-vehicle delay time to increase, the effectiveness of these strategies should be positively correlated with the value of out-of-vehicle wait time relative to that of in-vehicle delay time.

- *Route interdependence:* Frequently, multiple routes which share a common transfer point serve the same area. When this is the case, it is often feasible for passengers to choose between multiple routes that serve their destinations. While the effects of route interdependence are difficult to quantify, it is clear that interdependence causes a reduction in total passenger wait times.

3 MODEL DEVELOPMENT

In order to estimate the effects of implementing the headway-based hold light system at a transfer station, the first step was to develop an analytical model. This model is designed to analyze data collected in the field to determine what would have happened at a particular station if the headway based hold light system had been in place.

Since the analytical model requires actual data – which is often difficult and time-consuming to obtain – to evaluate the effectiveness of such a system, a simulation model was developed to account for stochasticity that is present in real life, and to allow for analysis of the headway-based hold light system in cases where field data is not available. The simulation model generates train arrival and bus departure times, and then uses the same methods as the analytical model to estimate the effects of implementing the headway-based hold light system.

This chapter describes the analytical and simulation models, and examines their application to a general scenario.

3.1 Data Collection

In order to facilitate the application of the analytical model to the Alewife and Wellington Station cases, rail and bus data was collected at both stations. Data were collected at Alewife Station during six PM peak periods in November 2004 (4^{th}, 9^{th}, and 16^{th}) and October 2005 (6^{th}, 11^{th}, and 20^{th}). Three PM peak periods of data were collected at Wellington Station in November 2004 (4^{th}, 9^{th}, 16^{th}). This data, which includes scheduled and actual train arrival times, scheduled and actual bus departure times, rail alighting counts and bus boarding counts, was used primarily in the application of the analytical model to the Alewife Station case and is presented in Appendix A.

3.2 *Measures of Effectiveness*

Regardless of which model is used (analytical or simulation), a well-defined set of measures is needed to evaluate the effectiveness of the headway-based hold light system.

3.2.1 Definitions

The chosen measures of effectiveness are defined and discussed below.

- *Transfer passenger wait time:* This measure is the amount of wait time saved by passengers attempting to transfer from an arriving train to a bus that may or may not be held for the arriving train. If the bus trip is held, these passengers will be able to make their connection, while if the bus trip is not held; these passengers will have to wait until the next departure on their bus route. The value of transfer passenger wait time is generally reduced with a bus hold.

- *On-board bus passenger delay time:* This measure is the amount of delay incurred by passengers who are already on board when a bus is held for an arriving train. This measure only includes delay that can be attributed to bus holding. If the bus is not held, this value is zero.

- *Net change in total wait time:* This measure is simply the aggregate of the two previous measures. Transfer passenger wait time can be weighted relative to on-board passenger delay time if passengers perceive these types of waiting time differently. Initially, in this research, all wait and delay time is weighted evenly for simplicity. The effects of different weightings are examined in Section 4.6.3.

- *Number of bus trips affected:* As one of the goals of the headway-based hold light system is to minimize interference when rail service is operating normally, it is essential to pay attention to the number of bus trips that are affected.

- *Number of passengers affected (positively and negatively):* Generally, use of the headway-based hold light system will result in significant wait time savings for a relatively small number of passengers who otherwise would have missed their connection, while imposing small amounts of delay on a larger number of passengers who would have made their connections regardless of whether their bus was held. As a result, it is important to consider the number of passengers affected positively and negatively, as an extreme imbalance is not ideal even though this may deliver the greatest wait time savings.

- *Impact on operations:* One potential problem with bus holding strategies is that delays to buses departing from terminal stations can cause return trips to be late. It is important to consider the percentage of trips that will be delayed more than the scheduled recovery time, and as a result will most likely be late returning. The average delay per held bus is also calculated.

- *Impact on operating cost:* Operating cost impacts would clearly play a significant role in a transit agency's decision to implement a headway-based hold light system, or any other piece of equipment. For the purposes of this research, it is assumed that the system can operate using existing equipment, and therefore the impact on operating cost is zero. It should be noted that since held trips can cut into recovery times, it may be necessary to add a bus to a particular route in order to maintain the base amount of service. The operating cost impacts of these situations are not considered as they are not quantified in this research.

3.2.2 Computation

The wait time saved (lost) by passengers transferring to a bus trip i, held by the headway-based hold light system is calculated with the following equation:

$$\Delta WT_i = TP_i\left[DEP_{i+1} - \left(TT + ARR_{i+}\right)\right] - OBP_i\left[\left(TT + ARR_{i+}\right) - DEP_i\right] \quad (3\text{-}1)$$

where:

ΔWT_i = change in total wait time for bus trip i

TP_i = passengers transferring to bus trip i (arriving at time ARR_{i+})

DEP_i = base departure time of bus trip i

TT = transfer time (time needed for all transferring passengers to travel from train to bus)

ARR_{i+} = arrival time of first rail trip following (DEP_i - TT)

OBP_i = on-board passengers for bus trip i (arriving prior to time ARR_{i+})

We can then introduce a dummy variable, β_i, the value of which is determined by the following relationship between the base departure time of bus i, the time of the previous train arrival, the previous rail headway, the long-headway threshold, and the transfer time:

$$\beta_i = \begin{cases} 1 & if \quad ARR_{i-} + LHT < DEP_i \quad or \quad RH_{i-} > LHT \ and \ ARR_{i-} + TT > DEP_i \\ 0 & otherwise \end{cases} \quad (3\text{-}2)$$

where:

β_i = 1 when bus trip i is held, 0 otherwise

ARR_{i-} = arrival time of rail trip immediately prior to DEP_i

LHT = long headway threshold

RH_{i-} = preceding headway of rail trip arriving at time ARR_{i-}

Including the dummy variable, β_i, allows us to aggregate over all bus trips that can be held at a transfer station. The following expression is obtained for total change in wait time over a given period.

$$\Delta WT = \sum_{I} \beta_i \left[TP_i \left(DEP_{i+1} - \left(TT + ARR_{i+} \right) \right) - OBP_i \left(\left(TT + ARR_{i+} \right) - DEP_i \right) \right] \tag{3-3}$$

where:

I = set of bus trips that can potentially be held at the transfer point

Values for the other measures of effectiveness are presented in the following expressions:

Transfer passenger wait time savings, TWTS

$$TWTS = \sum_{I} \beta_i \left[TP_i \left(DEP_{i+1} - \left(TT + ARR_{i+} \right) \right) \right] \tag{3-4}$$

On-board passenger delay, OBD

$$OBD = \sum_{I} \beta_i \left[OBP_i \left(\left(TT + ARR_{i+} \right) - DEP_i \right) \right] \tag{3-5}$$

Bus trips affected, BTA

$$BTA = \sum_{I} \beta_i \tag{3-6}$$

Average Hold, AH

$$AH = \frac{\sum_{I} \beta_i \left[\left(TT + ARR_{i+} \right) - DEP_i \right]}{BTA} \tag{3-7}$$

Passengers positively affected, P+

$$P+ = \sum_{I} \beta_i \cdot TP_i \tag{3-8}$$

Passengers negatively affected, P-

$$P- = \sum_{I} \beta_i \cdot OBP_i \tag{3-9}$$

3.3 Analytical Model

The analytical model simply applies the above relationships to train arrival data, bus departure data, and bus ridership data collected in the field. The result is an estimate of what the outcome would have been had the headway-based hold light system been in place during the period of analysis. This model is applied to the general scenario (Section 0) and Alewife Station (Section 4.3).

3.4 Simulation Model

To supplement the basic field data collected and the accompanying application of the analytical model, an event-based simulation model was developed. The simulation model uses inputs of route, station, and individual trip characteristics to generate train arrival times and bus departure times. This information is then analyzed in a manner identical to the analytical model. In order to minimize error in the analysis, the model simulates the given period 1,000 times, and then averages the results computed in each run.

The simulation model serves two primary purposes.

1. For the Alewife case study (described in detail in Chapter 4), since it was not possible to physically test the system at the station, the simulation model allows

the use of detailed information gathered in the extensive analysis of this particular case to approximate the effects on the proposed hold light system on the chosen case.

2. In order to expand this research from simply analyzing one case to develop a broadly applicable strategy, the simulation model is customizable in terms of station and route characteristics. This allows the model to be applied to other stations within the MBTA system and in other transit systems.

In order to generate train arrival times and bus departure times from empirical data, the simulation model is a Monte Carlo simulation, as described in the following two sections.

3.4.1 Train Arrival Process

In order to generate train arrival times in the simulation model, the inverse transform method based on random number generation is used. This method was selected over attempting to predict train arrival times based on characteristics of each rail trip.

Specifically, the inverse transform method is used to generate rail headways, which are then transformed into train arrival times. The probability distribution chosen for the purposes of train arrival generation is the log-normal distribution, as this distribution was determined to best fit empirical headway data obtained from the MBTA Red Line. Note that it is technically possible to obtain train headways near zero from this method; however, considering the log-normal distribution with the parameters used in this research, the probability of generating headways less than 30 seconds is negligible.

The log-normal distribution is the probability distribution of a continuous random variable whose natural logarithm is normally distributed. The log-normal distribution is defined by two parameters: μ and σ, the mean and standard deviation, respectively, of the random variable's logarithm. The distribution is defined where x>0. Expressions for the probability density function and the cumulative distribution function of the log-normal distribution are given in Equations 3-10 and 3-11 below, and shown graphically in Figures 3-1 and 3-2.

$$f(x) = \frac{1}{x\sigma\sqrt{2\pi}} e^{-(\ln(x)-\mu)^2/2\sigma^2} \tag{3-10}$$

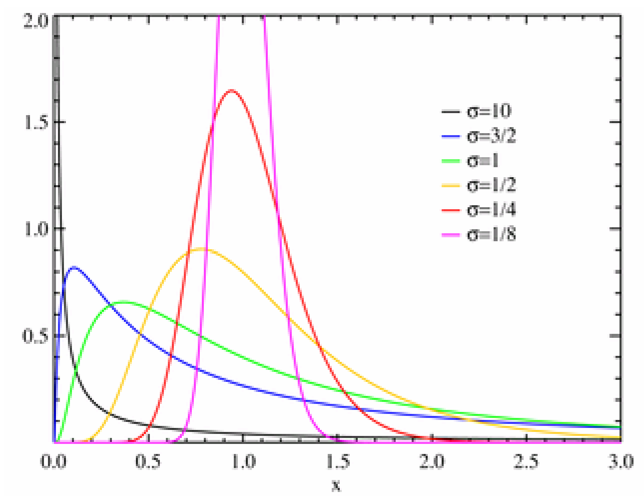

Figure 3-1: Log-normal Distribution Probability Density Function (source: wikipedia.org)

$$F(x) = \frac{1}{2} + \frac{1}{2} Erf\left[\frac{\ln(x) - \mu}{\sigma\sqrt{2}}\right] \tag{3-11}$$

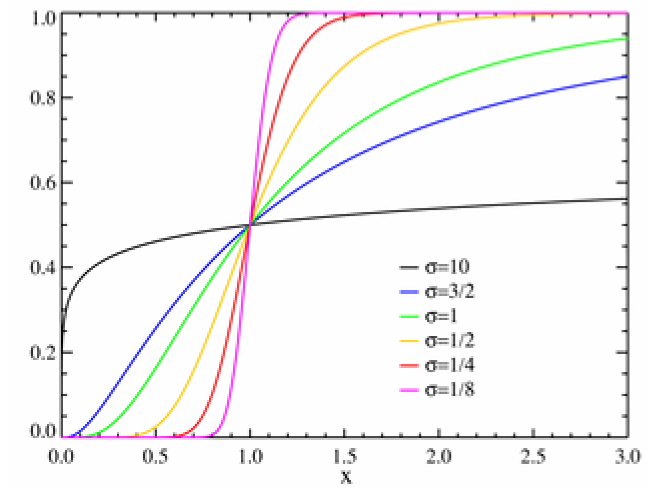

Figure 3-2: Log-normal Distribution Cumulative Distribution Function (source: wikipedia.org)

Figure 3-3 below shows the probability density function of the log-normal distribution with parameters μ=1.3591 and σ=0.47492 compared to a histogram of 738 observations of weekday PM Peak headway on the Red Line at Alewife Station. The fit of this distribution passes the Kolmogorov-Smirnov goodness-of-fit test with significance level α=0.1. The Red Line headway data used in this analysis were obtained from an event recorder placed at Alewife Station by MBTA Signals Department personnel.

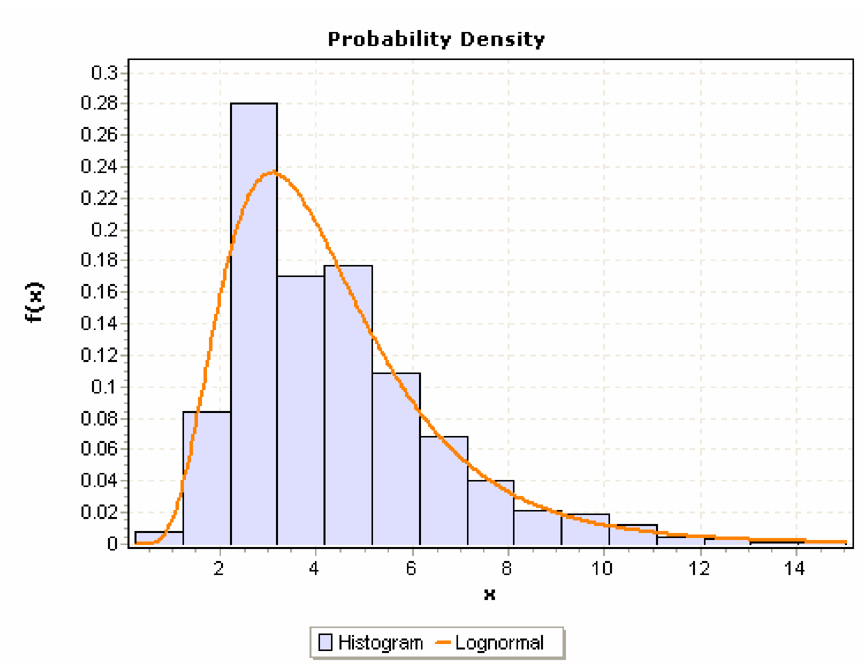

Figure 3-3: Alewife Rail Headway Histogram with Log-normal PDF

Figure 3-4 below shows the cumulative distribution function of the log-normal distribution with parameters μ=1.3591 and σ=0.47492 compared to the cumulative distribution function of the same 738 observations of weekday PM Peak headway on the Red Line at Alewife Station.

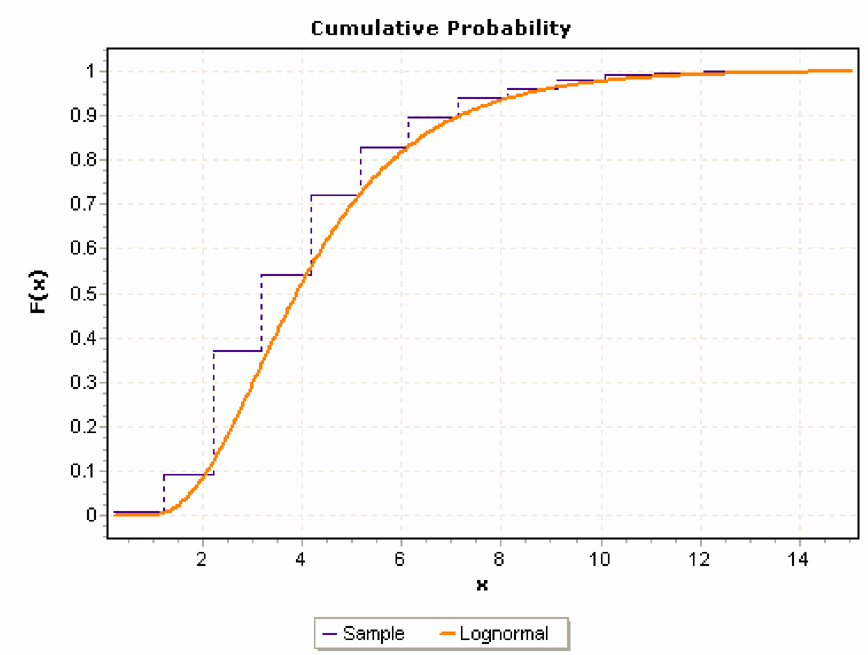

Figure 3-4: Cumulative Rail Headway Distribution – Observed vs. Log-normal

The probability density function of the log-normal distribution with parameters μ=1.3591 and σ=0.47492 (used for generating rail headways in the general scenario, Alewife Station, and 79th Street cases) is shown in Figure 3-5 below.

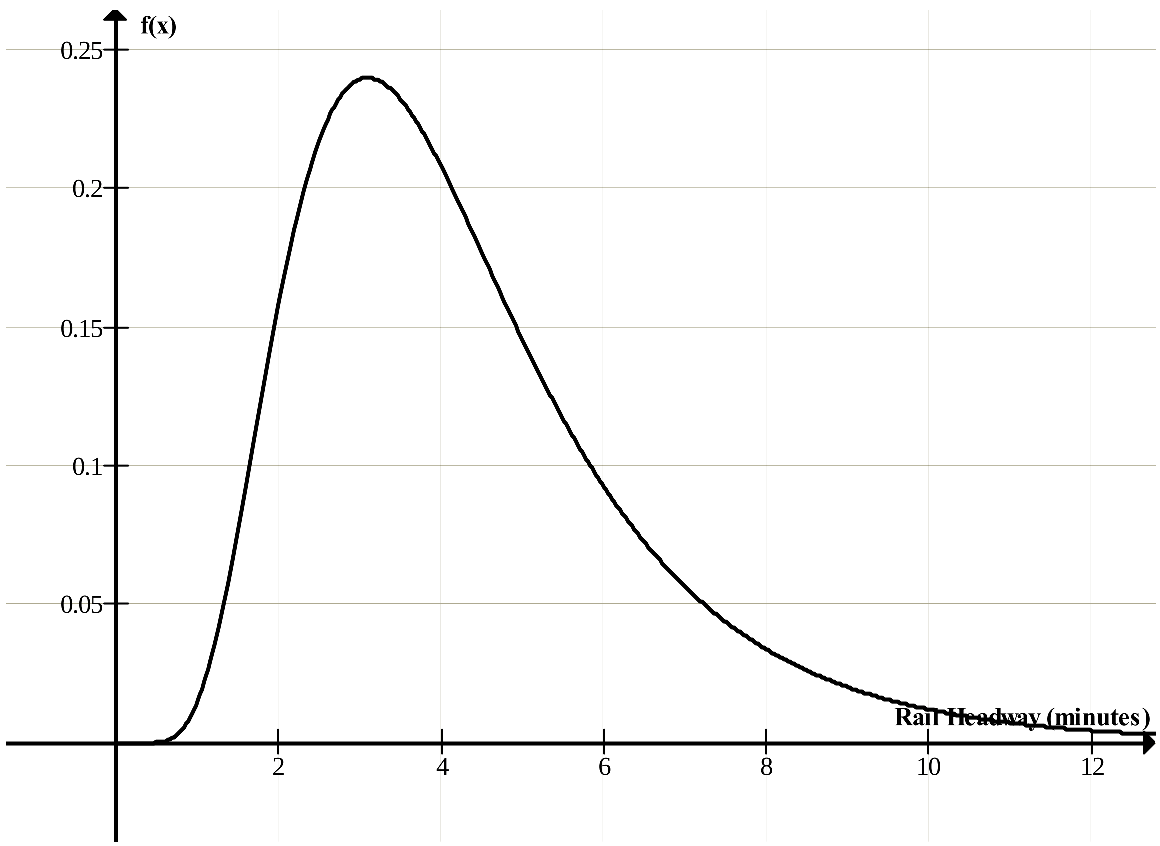

Figure 3-5: Probability Density Function of Log-normal Distribution – μ=1.3591, σ=0.47492

3.4.2 Bus Departure Generation

The inverse transform method based on random number generation was also used to generate bus departure times in the simulation model. In this process, the inverse transform method is used to generate a value of schedule deviation for each bus departure. These values are then combined with the scheduled departure times to obtain actual departure times. The chosen probability distribution for the purposes of bus departure generation is a modified form of the log-normal distribution, as this distribution (with an additional shift parameter included) was determined to best fit empirical Alewife Station schedule deviation data obtained from the MBTA's Automated Vehicle Location (AVL) database. The shift parameter, δ, is simply a parameter that shifts the distribution to the left a number of minutes equal to the value of the parameter. The addition of the shift parameter is necessary because schedule deviation takes on a negative value when a trip leaves early. The addition of the shift parameter results in the following probability density function:

$$f(x) = \frac{1}{(x+\delta)\sigma\sqrt{2\pi}} e^{-(\ln(x+\delta)-\mu)^2/2\sigma^2} \tag{3-12}$$

For the Alewife Case Study (Chapter 4), the parameters of the modified Erlang Distributions are calibrated individually for each route using actual bus departure time data obtained from the MBTA Automated Vehicle Location (AVL) database. In the other cases, typical values of the parameters estimated from the Alewife case are used. Figure 3-6 below shows the cumulative distribution function of the three-parameter log-normal distribution with parameters μ=1.43419, σ=0.45633, and δ=2.23602 compared to the cumulative distribution of 38 observations of weekday PM Peak bus departure schedule deviation on Route 79 at Alewife Station. The fit of this distribution passes the Kolmogorov-Smirnov goodness-of-fit test with significance level α=0.2.

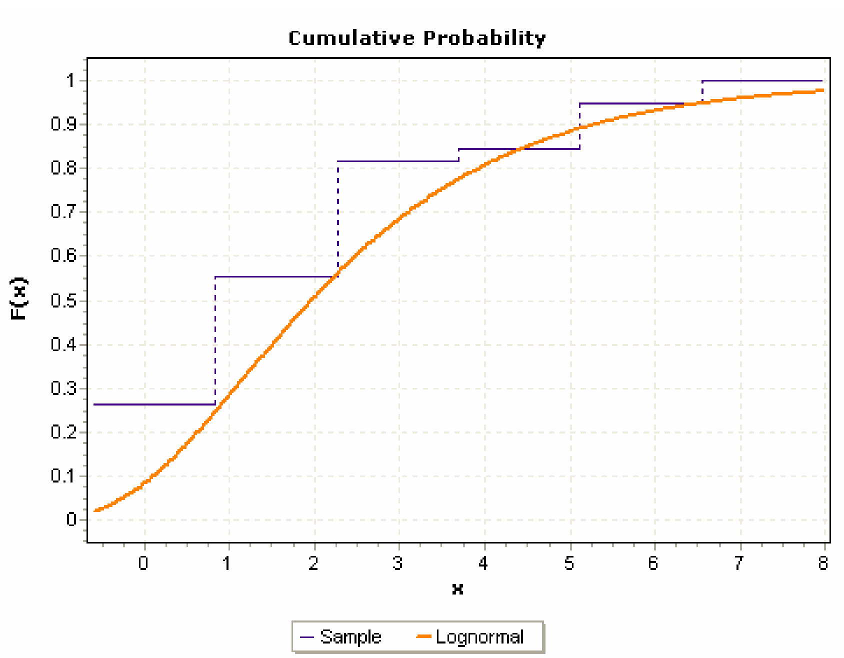

Figure 3-6: Cumulative Bus Schedule Deviation Distribution – Observed vs. Log-normal, MBTA Route 79

The probability density function of the three-parameter log-normal distribution with parameters μ=2.30623, σ=0.20709, and δ=8.69108 (used for generating values of bus schedule deviation in the general scenario, Wellington Station, and 79th Street cases) is shown in Figure 3-7 below. These parameters were selected as they were best fit to the distribution of schedule deviation for the aggregate set of Alewife bus routes. Once again, schedule deviation data is taken from the MBTA's AVL database.

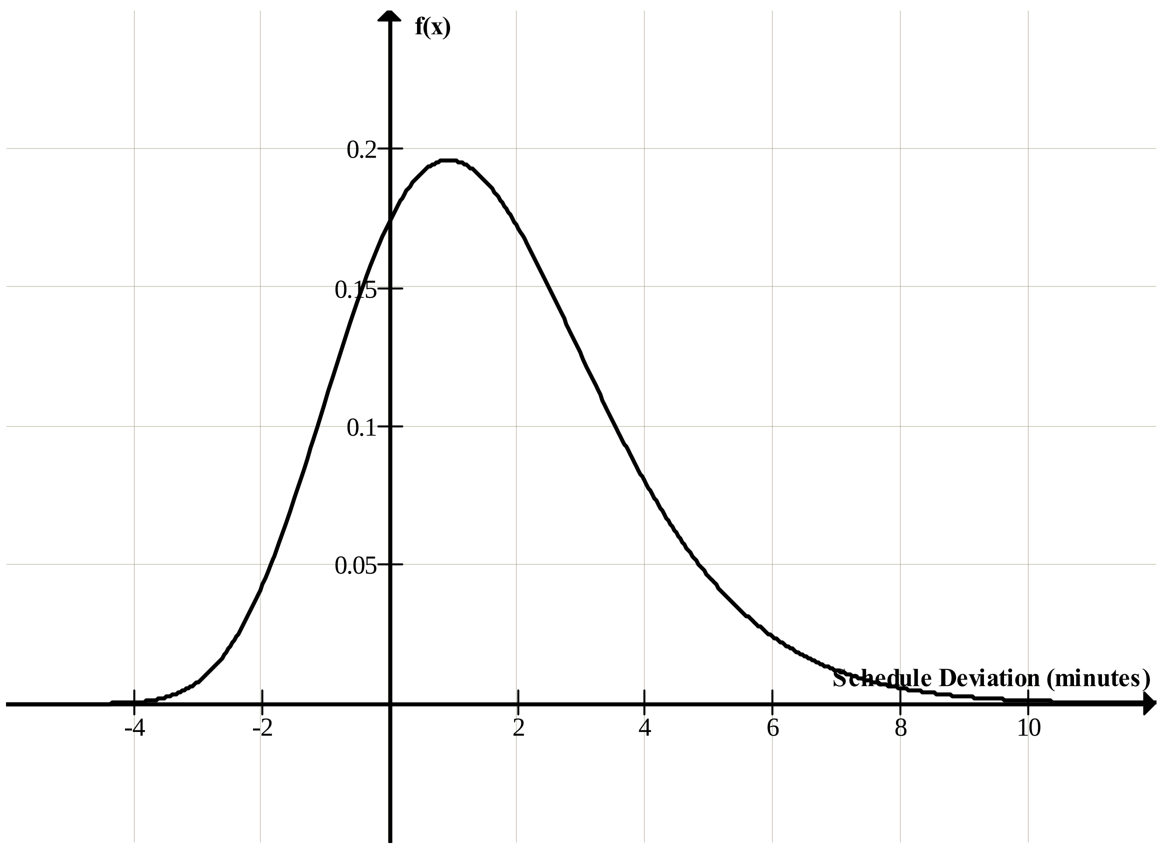

Figure 3-7: Probability Density Function of Log-normal Distribution – μ=2.30623, σ=0.20709, δ=8.69108

3.5 Passenger Mix

In order to allow the simulation model to be applied to any situation beyond the pure feeder terminal with no through bus routes and no downstream boardings, we must equip the model to consider various types of passengers. The simulation model allows the user to select a mix of the following four passenger types:

- *Type A passengers:* These are passengers who board at a point on the route before the transfer point and alight at (or before) the transfer point. As a result, these passengers are not affected by any holding actions.

- *Type B passengers:* These are passengers who board before the transfer station and alight after the transfer station. If a bus is held, these passengers will be on the bus, and will be subject to delay due to the hold.

- *Type C passengers:* These passengers board at the transfer station. They may arrive at the station either before a bus hold takes place, in which case they will be on board the bus and incur delay, or they will arrive on the train for which the bus is holding, and will save time as they will not have to wait for the next bus.

- *Type D passengers:* These are passengers who board after the transfer point. In this research, since the focus is primarily on low-frequency bus routes, these passengers are subject to an amount of delay equal to the duration of the bus hold. However, in the case of high-frequency bus service, where boarding passengers do not target specific trips, Type D passengers can be benefited by upstream holding. In some low-frequency cases, Type D passengers may decide to utilize other transit services or other means of transportation to make their trips, if service becomes unreliable. For the purposes of this research, however, it is assumed that no Type D passengers will choose not to make transit trips due to unreliability introduced into the system by bus holding.

It is also important to distinguish between transfer passengers and walk-in passengers at the transfer station. Since walk-in passengers do not depend on the schedule adherence of a previous trip, it is reasonable to assume that these passengers will be able to control their arrival times better than transferring passengers. For the purposes of this research, walk-in passengers at transfer stations are assumed to be on board the bus at the departure time, and as a result are treated as through passengers (Type B).

3.6 Passenger Arrival Behavior

In developing the passenger behavior model included in the analytical and simulation models, it was assumed that each passenger transferring from rail to a low-frequency bus route has a "target arrival time." This target arrival time is the arrival time at the transfer station relative to the scheduled departure time of the bus trip to which the passenger intends to transfer, assuming normal rail operations. It should be noted that a passenger's position within the target arrival time distribution is a reflection of that passenger's sense of the system's reliability as well as the implications of missing the desired connection.

Since every passenger does not have an identical target arrival time, a probability density function is used to describe this variable. Since this research initially focuses on low-frequency routes (usually 15-40 minute headways), it is assumed that the distribution of target arrival times is an equilateral triangular distribution spanning the period from 14 minutes before the scheduled bus departure to 1 minute after the scheduled bus departure time. The reason the function extends past the scheduled bus departure is that a small percentage of transferring passengers will miss their transfer due to personal reasons (i.e. not due to abnormal train arrivals or bus departures). See Figure 3-8 below for an illustration of the probability density function of passenger arrivals.

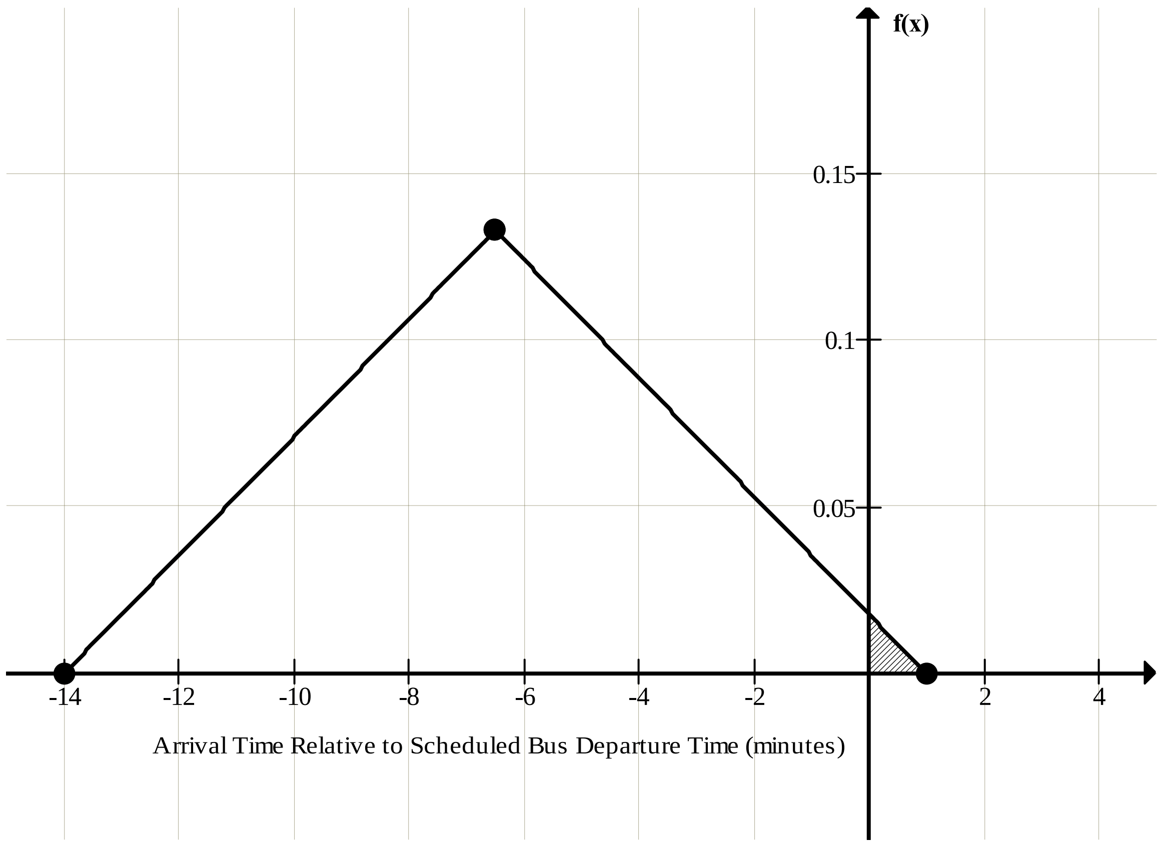

Figure 3-8: Probability Density Function of Passenger Target Arrival Times

Assuming travel times are consistent along the rail line, we can assume that a passenger will arrive at the transfer station on the next train arrival after the passenger's target arrival time. For example, if we start observing 14 minutes prior to a scheduled bus departure, and the first train arrives 11 minutes prior to the scheduled bus departure; this train will deliver all the transfer passengers with target arrival times between -14 and -11. If the second train arrives 9 minutes prior to the scheduled bus departure, it will then deliver all the transfer passengers with target arrival times between -11 and -9. Note that in the above figure, the shaded area to the right of the y-axis represents passengers who arrive late even if all rail trips arrive on schedule. Since it is intuitive that passenger arrival behavior will be highly variable between transfer points with differing train and bus headways, an analysis of the sensitivity to the size and location of the triangular passenger arrival probability density function is presented in Chapter 4.

3.7 *General Scenario*

This section describes the application of the analytical and simulation models to a simple hypothetical scenario in an effort to understand the effects of the headway-based hold light system in a controlled environment.

Consider a transfer station where passengers transfer from a rail line with a four-minute headway to a bus route with a 30-minute headway. Consider the PM peak period (16:30 to 19:00). For the purposes of this scenario, we will assume the following bus schedule and transfer volumes.

Table 3-1: Scheduled Bus Departure Times and Transfer Volumes, General Scenario

Scheduled Departure	Transfers from Rail
16:30	45
17:00	45
17:30	45
18:00	45
18:30	45
19:00	45

3.7.1 Analytical Model Application

For the purpose of testing the analytical model, consider the case of deterministic train arrivals where arrivals are scheduled every four minutes, but every fourth train is two minutes late. For the hypothetical three-hour period, 50% of the train headways are four minutes, 25% are two minutes, and 25% are six minutes. In this analysis, the long-headway threshold is set to four minutes, the scheduled rail headway. Note that if all train arrivals were on time, the light would never be activated during the period of interest. In this scenario, all buses depart on time unless they are held for an arriving train.

Table 3-2 below presents the results obtained by applying the analytical model to the general scenario with the headway-based hold light system.

Table 3-2: Analytical Model HBHL Results – General Scenario

	Station	On-Board
Bus Trips Affected	17%	
Average Hold Duration	0:01:30	
Passengers Affected	7%	9%
Wait Time Saved (Added) Per Passenger	0:28:30	(0:01:30)
Total Wait Time Saved (Added)	9:07:12	(0:38:06)
Net WT Savings per Affected Passenger	0:11:25	
Net Wait Time Savings per Bus Hold	8:29:06	
Net Total Wait Time Savings	8:29:06	

The application of the analytical model to this scenario with the headway-based hold light system results in savings totaling 8 hours 29 minutes of passenger wait time over the period. This savings represents 21% of the total wait time incurred by transfer passengers during this period in the base case. This is a result of saving 7% of the passengers an average of 28:30, but delaying 9% of the passengers by an average of 1:30. 17% of the bus trips (1 of 6) were held by the hold-light system. On average, each affected passenger saves 11 minutes, 25 seconds of wait time.

Looking more closely at the trip-by-trip results of this analysis, we see that the hold light is activated at 16:28:00, since the timer has reached the long-headway threshold with no train arrival. Once the train arrives at 16:30:00, the light continues to flash for an additional 1 minute, 30 seconds until 16:31:30.

As a result, the light is flashing at the departure time of the bus scheduled to depart at 16:30:00. Since the light is flashing at the scheduled departure time of this bus, it is held for passengers to transfer from the 16:30:00 train arrival. Since transferring passengers take until 16:31:30 to reach and board the bus, the bus is held for 1 minute, 30 seconds from 16:30:00 to 16:31:30. As a result, the 25 passengers that were already on board the bus at 16:30:00 are delayed 1 minute, 30 seconds until 16:31:30. The 19 passengers that were on the 16:30:00 train arrival, for which this bus was held, each save 28 minutes, 30 seconds as they now depart immediately upon reaching the bus, rather than having to wait 28 minutes, 30 seconds for the 17:00:00 bus departure as they would have if no hold light system were in place.

Due to the deterministic assumptions made in this application of the analytical model, this example is presented to illustrate the mechanics of the headway-based hold light system rather than to draw conclusions regarding its effectiveness.

In order to examine the effects of the passenger arrival model discussed in Section 3.5, we will revisit the scenario previously analyzed with the assumption that transferring passengers arrive on each train trip at a rate that is proportional to that trip's preceding headway. For the purpose of this analysis, assume the relationship between train headway and transferring passengers shown in Table 3-3 below.

Table 3-3: Assumed Relationship between Rail Headway and Transferring Passengers: General Scenario

Rail Headway (minutes)	Transferring Passengers
2	3
4	6
6	9

Table 3-4 below shows the results obtained by applying the analytical model to the general scenario with the assumption that passenger arrivals are evenly distributed across the analysis period using both the headway-based hold light system. Once again, the long-headway threshold for the headway-based hold light system is set to four minutes.

Table 3-4: Analytical Model HBHL Results – General Scenario (Passengers Distributed with Rail Headway)

	Station	On-Board
Bus Trips Affected	17%	
Average Hold Duration	0:01:30	
Passengers Affected	3%	16%
Wait Time Saved (Added) Per Passenger	0:28:30	(0:01:30)
Total Wait Time Saved (Added)	4:16:30	(1:03:00)
Net WT Savings per Affected Passenger	0:03:48	
Net Wait Time Savings per Bus Hold	3:13:30	
Net Total Wait Time Savings	3:13:30	

Under the assumption that passenger arrivals are evenly distributed, the headway-based hold light system results in savings of 3 hours 13 minutes of passenger wait time over the period. This savings represents 5% of the total wait time incurred by transfer passengers over this time period in the base case. This is a result of saving 3% of the passengers an average of 28:30, but delaying 16% of the passengers by an average of 1:30. Once again, 17% of the bus trips (1 of 6) were held by the hold-light system. On average, each affected passenger saves 3 minutes, 48 seconds of wait time.

Since there has been no change in either train arrival times or bus departure times, the headway-based hold light system holds the same trip as with the more advanced passenger arrival model in place. Once again, the 16:30:00 trip is held 1 minute, 30 seconds for the 16:30:00 train arrival. On this trip, the 42 passengers that were already on board the bus at the scheduled departure time, 16:30:00, are delayed 1 minute, 30 seconds until 16:31:30. The 9 passengers that transfer from the 16:30:00 train arrival, for which this bus was held, each save 28 minutes, 30 seconds as they now depart immediately upon reaching the bus, rather than having to wait 28 minutes, 30 seconds for the 17:00:00 bus departure as they would have if no hold light system were in place.

From comparison of these two analyses we see that total wait time savings is greatly reduced when passengers arrive evenly over time compared to the case where each passenger targets a specific bus trip, and attempts to arrive shortly before this trip's scheduled departure time. This supports the belief that hold light systems are much more appropriate for use on low-frequency bus routes, as passengers on these routes tend to plan their arrivals, whereas passengers on high-frequency bus routes generally do not time their arrivals at the transfer station, but rather travel to the transfer station with the intention of simply boarding the next bus that departs, regardless of the schedule. This issue is revisited in the analysis of 79th Street Station in the CTA system (Section 5.2).

3.7.2 Simulation Model Application

In order to test the simulation model, consider the same scenario with passengers transferring from a rail line to a single bus route. Instead of assuming deterministic arrivals, however, we now assume train arrivals and bus departures are both stochastic.

Train headways are assumed to be log-normally distributed with parameters μ=1.3591 and σ=0.47492, and bus departure schedule deviation log-normally distributed with parameters μ=2.30623, σ=0.20709, and δ=8.69108. We will also assume that transferring passengers target a specific bus trip, and arrive according to the passenger arrival model described in Section 3.5. Once again, the long-headway threshold is four minutes. The bus schedule is as in Section 3.5.

Table 3-5 below shows the results obtained by applying the simulation model to the general scenario using the headway-based hold light system and the traditional hold light system.

Table 3-5: Simulation Model Results – General Scenario Hold Light Comparison

Hold Light System	Headway-based		Traditional	
	Station	On-Board	Station	On-Board
Bus Trips Affected	39%		45%	
Average Hold Duration	0:02:12		0:01:00	
Passengers Affected	13%	26%	10%	34%
Wait Time Saved (Added) Per Passenger	0:27:11	(0:02:13)	0:28:46	(0:01:01)
Total Wait Time Saved (Added)	17:34:36	(2:46:53)	12:59:38	(1:37:56)
Net WT Savings per Affected Passenger	0:08:25		0:05:45	
Net Wait Time Savings per Bus Hold	6:15:02		4:14:11	
Net Total Wait Time Savings	14:47:43		11:21:43	

As Table 3-5 shows, the application of the simulation model to the general scenario with the headway-based hold light system in place results in savings of 14 hours 48 minutes of passenger wait time over the period. This savings represents approximately 26% of the total wait time incurred by transfer passengers. This is a result of saving 13% of the passengers an average of 27:11, but delaying 26% of the passengers by an average of 2:13. 39% of the bus trips were held for an average duration of 2:12 by the headway-based hold light system, resulting in a wait time savings of 8:25 per affected passenger. In this case, 6 hours 15 minutes of passenger wait time is saved per bus hold.

The large increases in both wait time savings and the number of bus trips affected when compared to the analytical model results can be attributed to the train and bus schedules in this particular scenario, and the fact that train arrivals and bus departures are assumed to be deterministic in the application of the analytical model. In actual situations, we would expect the results to be closer to those obtained with the simulation model.

Table 3-5 also shows the simulation model results from analyzing the same scenario with a traditional hold light system. In this system, the hold light is activated 30 seconds prior to each train arrival, and deactivated 90 seconds after each train arrival. The application of the simulation model to the general scenario with a traditional hold light system results in savings of 11 hours 22 minutes of passenger wait time over the period. This savings represents approximately 20% of the total wait time incurred by transfer passengers over this time period in the base case. This is a result of saving 10% of the passengers an average of 28:46, but delaying 34% of the passengers by an average of 1:01. 45% of the bus trips were held for an average duration of 1:00 by the traditional hold light system, resulting in a wait time savings of 5:45 per affected passenger. In this case, 4 hours 14 minutes of passenger wait time is saved per bus hold.

Comparing the results of the two hold light systems shows that the headway-based hold light system produces 30% more wait time savings than the traditional hold light system, while only requiring 87% of the bus holds. Additionally, the ratio of negatively affected passengers to positively affected passengers is much better with the headway-based system (2.0 to 1) than with the traditional hold light system (3.4 to 1).

This example illustrates the major advantage of the headway-based hold light system: that it holds buses only in situations where it is likely that large benefits will be produced (long train headway situations). As is evident in this general scenario, the traditional hold light system holds buses in a number of cases that result in benefits to very few passengers. In this case, although the average delay per delayed passenger is less for the traditional hold light system than the headway-based hold light system, the imbalance of passengers positively and negatively affected is such that the traditional hold light system produces fewer net benefits.

3.7.3 Sensitivity to Long Headway Threshold

In order to ensure the ideal long headway threshold is chosen, we must check the sensitivity of the headway-based hold light system to changes in this parameter. Sensitivity to a number of other factors is examined in subsequent chapters.

An analysis of the sensitivity to changes in the long headway threshold in the general scenario is displayed in Table 3-6 and Figure 3-9 below.

Table 3-6: Sensitivity to Long Headway Threshold – General Scenario

	Long Headway Threshold (minutes)	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
	% Trips Affected	100%	100%	86%	60%	39%	24%	15%	9%	5%
	Average Hold Duration	0:04:12	0:03:13	0:02:36	0:02:23	0:02:12	0:01:53	0:01:24	0:01:00	0:00:39
Station	% Passengers Positively Affected	19%	18%	17%	15%	13%	10%	7%	5%	4%
Station	Time Saved (Added) per Passenger	0:30:15	0:30:39	0:30:33	0:29:19	0:27:11	0:22:37	0:16:57	0:11:49	0:07:38
Station	Total Time Saved (Lost)	25:24:40	24:56:23	23:03:44	20:44:11	17:34:36	13:04:56	9:32:38	6:41:20	4:46:52
On-Board	% Passengers Negatively Affected	81%	81%	69%	44%	26%	14%	7%	4%	1%
On-Board	Time Saved (Added) per Passenger	(0:04:11)	(0:03:14)	(0:02:41)	(0:02:27)	(0:02:13)	(0:01:54)	(0:01:24)	(0:01:00)	(0:00:38)
On-Board	Total Time Saved (Lost)	(15:17:50)	(11:52:59)	(8:19:12)	(4:52:00)	(2:46:53)	(1:29:04)	(0:45:35)	(0:24:11)	(0:10:28)
	Net WT Savings per Aff. Passenger	0:02:15	0:02:55	0:03:50	0:05:58	0:08:25	0:10:57	0:13:29	0:15:56	0:19:26
	Net Wait Time Savings per Bus Hold	1:41:08	2:10:35	2:51:01	4:25:32	6:15:02	8:06:57	10:00:57	11:48:57	14:23:43
	Net Total Wait Time Saved (Lost)	10:06:51	13:03:25	14:44:32	15:52:11	14:47:43	11:35:52	8:47:02	6:17:10	4:36:23

From the results of this sensitivity analysis, it is clear that as the long headway threshold decreases, there is a significant increase in the number of passengers and trips affected, while average wait times saved/added per passenger also increase. Total wait time savings increase to a peak when the long headway threshold is 3 minutes, then decrease as the threshold decreases to zero. We can also see that with a 4-minute threshold, we produce more than 90% of the savings that could be produced with a three-minute long headway threshold (where total wait time savings is maximized) while we hold only 39% of the bus trips, compared with 60% if the long headway threshold is 3 minutes.

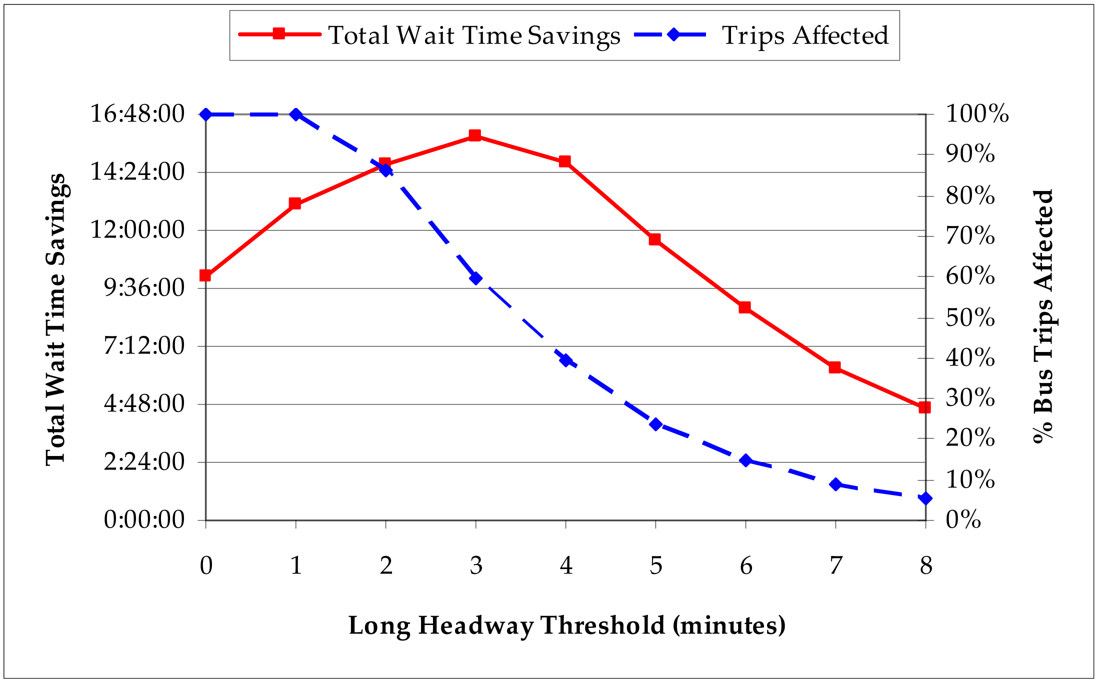

Figure 3-9: Sensitivity to Long Headway Threshold – General Scenario

As the threshold increases from three minutes to four minutes, the percentage of passengers negatively affected also drops substantially. As the threshold increases from four minutes to five minutes, there is a significant decline of approximately 20% in total wait time savings, as well as less significant decreases in the number of passengers and bus trips affected than between three and four. Due to these natural boundaries, a four-minute long headway threshold is most likely the ideal integer long headway threshold for the general scenario; however, this does depend on how the transit agency prioritizes the measures of effectiveness. This sensitivity analysis also shows that when the long headway threshold is set to zero (e.g. every bus trip is held), significantly less wait time savings result than when the long headway threshold is near its optimal value.

The results of this sensitivity analysis serve to illustrate why wait-time savings cannot be used as the sole measure of effectiveness for such a system. As the long headway threshold decreases, the percentage of time the hold light is active increases, and in turn more bus trips are held. As a result, we generally see an increase in overall wait time savings. However, simply maximizing the total wait time savings is almost certainly not ideal for the operating agency, as there will be a much greater chance that bus holds will infringe upon recovery times, making more return trips late, and there will be a heavier imbalance in the number of passengers positively and negatively affected.

3.7.4 General Scenario Summary

In the application of the analytical and simulation models to the general scenario and the accompanying sensitivity analyses, we have seen that the headway-based hold light system, the traditional hold light system, and the hold-all-buses strategy can produce significant wait-time savings in a simple case. These savings are magnified when passengers target specific bus trips. Although both the headway-based and traditional hold light systems can produce benefits, it has been demonstrated that the headway-based hold light has the advantage of avoiding many of the no-benefit holds caused by the traditional hold light system, providing more wait time savings per bus trip held. In the sensitivity analysis, it has been shown that total wait time savings and the percentage of bus trips held by the headway-based hold light system are inversely related to the long-headway threshold. As the ideal long headway threshold is unique to each case, transit agencies must make trade-offs among measures of effectiveness when choosing the appropriate value of long headway threshold.

4 ALEWIFE STATION (MBTA) CASE STUDY

This chapter presents the application of the analytical and simulation models to the case of Alewife Station in the MBTA system. The selection of Alewife as the primary case examined in this research is due to a number of reasons that make Alewife Station a near-ideal real life case in which to apply a headway-based hold light system. Before the application of the models is discussed, relevant background information on Alewife Station is presented. Following the analytical and simulation model results, sensitivity analyses which examine the response of the headway-based hold light system to changes in long headway threshold, passenger arrival behavior, and wait time perceptions are presented. This chapter also includes discussions on the potential benefits available from the integration of real-time data into the headway-based hold light system, and the effects of bus route interdependence.

4.1 MBTA System Characteristics

The MBTA System consists of 3 heavy rail lines, 1 light rail line, 1 bus rapid transit line, 13 commuter rail lines, 244 bus routes (including contracted service), and 5 scheduled ferry boats. The system provides approximately 803,010 linked trips per day, servicing the 175 cities and towns of the Boston Metropolitan Area and their 4.7 million residents (MBTA 2003-2004 Ridership and Service Statistics, 2005). Figure 4-1 below shows a map of the MBTA's rail services.

Figure 4-1: MBTA Rail Map (source: mbta.com)

4.2 *Alewife Station and Local Area Characteristics*

Alewife Station is the north terminal of the MBTA's Red Line. At this key transfer point, there are 2,595 parking spaces, and 6 bus routes to and from which rail passengers transfer. The station is also adjacent to the Minuteman Bikeway, which provides pedestrian and bicycle access to and from Arlington, Lexington, and Bedford. Alewife Station is used each day by a large number of commuters from northwestern suburbs who travel to places of employment in downtown Boston and Cambridge.

The area surrounding Alewife consists primarily of high-density commercial development. Major generators in the area include Fresh Pond Shopping Center (which includes a cinema), and the Rindge Avenue Extension Office Park. While these sites are major generators of trips, these trips do not generally involve bus transfers as commercial development in the area is concentrated near Alewife Station. Approximately 9,500 passengers board the Red Line at Alewife each weekday.

4.2.1 Red Line

The Red Line, generally considered to be the MBTA's flagship rail line, runs from Alewife Station on the northern edge of Cambridge, across the Charles River and through downtown Boston, then south to the branch terminals at Braintree and Ashmont (see Figure 4-2 below). Popular destinations along the Red Line include Harvard Square and neighboring Harvard University, the Massachusetts Institute of Technology, Park Street Station, Downtown Crossing (a major shopping district), South Station (one of Boston's key transportation hubs), and UMASS-Boston. All northbound trains terminate at Alewife, while southbound trains alternate between serving the Ashmont and Braintree branches. Scheduled PM peak Red Line headways are three to four minutes.

Figure 4-2: MBTA Red Line (source: mbta.com)

4.2.2 Bus Routes

Six bus routes serve Alewife station from the northwestern suburbs of Boston. In the AM peak, these routes principally carry passengers from the suburbs to Alewife Station, where they transfer to rail to continue their trips into Cambridge and Boston. In the PM peak (16:30 to 19:00), the vast majority of passengers on these six routes are passengers who have transferred from rail at Alewife Station, and are destined for suburban locations.

Average weekday boardings on the bus routes serving Alewife Station are shown in Table 4-1 below. Boarding data is from the 2003-2004 MBTA Ridership and Service Statistics.

Table 4-1: Average Weekday Boardings – Alewife Station Bus Routes

Route	Daily Boardings
62	1,122
67	493
76	626
79	1,579
84	221
350	1,537

The bus routes operate according to the schedule shown in Table 4-2 below, which also shows the average observed demand for each trip, calculated from the field data introduced in Section 3.1.

Table 4-2: Alewife Station Scheduled Bus Departures with Average Loads per Trip

62		67		76		79		84		350	
16:45	24	16:45	12	16:30	17	16:44	14	16:33	5	16:40	16
17:15	29	17:10	24	17:00	24	17:00	16	17:07	10	17:00	19
17:37	23	17:35	31	17:30	35	17:16	18	17:24	11	17:20	20
17:48	39	18:00	25	18:00	39	17:32	18	17:41	15	17:40	26
18:20	35	18:25	18	18:40	23	17:48	15	17:58	21	18:00	27
19:00	27					18:04	21	18:15	12	18:20	20
						18:20	17			18:50	17
						18:36	17				
						18:52	8				

Maps of the six bus routes serving Alewife Station are included in Appendix B.

4.3 *Case Framework*

Since the six bus routes that serve Alewife act as virtually pure feeder/distributor routes, we can assume that in the PM peak, almost all passengers boarding buses at Alewife Station are transferring from Red Line trains. In this case we will assume 95% of the passengers boarding buses at Alewife transfer from rail, and the remaining 5% are walk-in riders. The feeder/distributor nature of these bus routes is also conducive to operations control strategies as there are very few passengers that board these routes downstream in the PM peak. For the purposes of this analysis, the few downstream passenger boardings are ignored. It is also assumed that passengers who miss a bus trip will board the next departure on the same route, rather than board an earlier departure on a different route. For Alewife Station, this assumption may tend to overestimate wait time savings, as a number of the bus routes serving the station have overlapping service areas and thus cannot be fully estimated without a more detailed analysis. However, this issue is unlikely to change the overall conclusion for this case. A further discussion of route interdependence is included in Section 4.8.

Table 4-3 below shows the average round-trip weekday PM peak recovery times for the bus routes serving Alewife Station. Recovery times are derived from the MBTA schedule.

Table 4-3: Average Weekday PM Peak Round-trip Recovery Times – Alewife Station Bus Routes

Route	Recovery Time (min.)
62	17
67	10
76	27
79	21
84	9
350	20

The scheduled recovery times are used to determine how many bus holds are longer in duration than the scheduled recovery time, possibly causing the next outbound trip to be late. In this case, late inbound trips are ignored due to the high-directionality of ridership on these routes during the PM peak.

4.4 Analytical Model Application

This section describes the application of the analytical model to the Alewife Station case. In this analysis, two bus dispatch methods are applied: the headway-based hold light system with the long-headway threshold set to four minutes (meaning buses will be instructed to hold if a train has not arrived in the four minutes prior to departure) and the hold-all-buses method. Four minutes is selected as the initial long headway threshold because it is the average Red Line headway rounded up to the next integer. In this analysis, all buses depart at the actual departure time (on-time or otherwise) unless they are held for an arriving train.

Table 4-4 below presents the results obtained by applying the analytical model to Alewife using the headway-based hold light system and the hold-all-buses strategy.

Table 4-4: Analytical Model Results – Alewife Station

Holding Strategy	HBHL		Hold-all-buses	
	Station	On-Board	Station	On-Board
Bus Trips Affected	16%		100%	
Average Hold Duration	0:01:59		0:02:53	
% Trips Held > Recovery Time	0.0%		0.0%	
Passengers Affected	5%	13%	21%	79%
Wait Time Saved (Added) Per Passenger	0:20:33	(0:01:45)	0:18:55	(0:03:02)
Total Wait Time Saved (Added)	13:09:21	(3:02:05)	52:51:18	(32:30:17)
Net WT Savings per Affected Passenger	0:04:15		0:01:29	
Net Wait Time Savings per Bus Hold	1:41:13		0:39:23	
Net Total Wait Time Savings	10:07:16		20:21:01	

As shown in Table 4-4, the application of the analytical model to this scenario with the headway-based hold light system results in daily savings of 10 hours, 7 minutes of passenger wait time, a savings of approximately 8% of total wait time during this period. This is a result of saving 5% of the passengers an average of 20:33, but delaying 13% of the passengers by an average of 1:45. 16% of the bus trips were held for an average duration of 1:59 by the headway-based hold light system, resulting in a wait time savings of 4:15 per affected passenger. In this case, 1 hour 41 minutes of passenger wait time is saved per bus hold, and no bus trips are held longer than the scheduled round-trip recovery time.

The application of the analytical model to this scenario with the hold-all-buses strategy results in savings totaling 20 hours, 21 minutes of passenger wait time. This represents a savings of approximately 16% of total wait time during this period. This is a result of saving 21% of the passengers an average of 18:55, but delaying 79% of the passengers by an average of 3:02. The average bus hold duration is 2:53 with the traditional hold light system, resulting in a wait time savings of 1:29 per affected passenger. In this case, 39 minutes of passenger wait time are saved per bus hold.

From these results, we see that holding all bus trips has the potential in the right situation to save significantly more total wait time than the headway-based hold light system. However, the trade-off is that the headway-based hold light system affects far fewer bus trips. For Alewife Station, the headway-based approach produces a total wait time savings that is approximately 50% of that of holding all buses, while holding only 16% as many buses. Additionally, the headway-based hold light system avoids the adverse impacts on operations (by not affecting nearly as many bus trips) that the hold-all-buses strategy produces.

4.5 Simulation Model Application

This section discusses the calibration of the simulation model and its application to the Alewife Station Case. First the calibration of the model to the Alewife case is discussed, and then results of the application are presented.

As described in Section 3.4.1, train arrivals are generated from a log-normal distribution. For the Alewife Station case, it was determined (as shown in Figure 3-3 and Figure 3-4) that the distribution with parameters μ=1.3591 and σ=0.47492 best fits the empirical PM peak Red Line headway data.

As described in Section 3.4.2, bus departures are also generated from a log-normal distribution. Table 4-5 below shows the parameters of the log-normal distribution best fit to empirical schedule deviation data from the MBTA's AVL database for each of the Alewife Station bus routes with the exception of Route 84, for which no AVL data was available. The distribution based on the aggregate of the other five Alewife bus routes was used for this route. Table 4-5 also shows, D_n, the goodness-of-fit parameter obtained from the Kolmogorov-Smirnov (K-S) Test, and the significance level for which the fit is acceptable.

Table 4-5: Schedule Deviation Parameters – Alewife Station Bus Routes

Route	μ	σ	δ	D_n	α
62	1.24706	0.52366	2.55454	0.10620	0.2
67	3.51384	0.05029	32.65940	0.20445	0.01
76	1.76959	0.39586	4.32039	0.10481	0.2
79	1.43419	0.45633	2.23602	0.0762	0.2
84	2.30263	0.20709	8.69108	N/A	N/A
350	3.95897	0.03293	51.34322	0.15893	0.01

Table 4-6 below shows the results obtained by applying the simulation model to the Alewife Station case. The long headway threshold is set to four minutes (the average scheduled rail headway rounded up to the next integer value) for this initial analysis.

Table 4-6: Simulation Model HBHL Results by Bus Route – Alewife Station

	Route	62	67	76	79	84	350	Aggregate
	% Trips Affected	39%	39%	39%	39%	39%	39%	39%
	Average Hold Duration	2:12	2:10	2:09	2:19	2:11	2:16	0:02:19
	% Trips Held > Recovery Time	0.2%	1.9%	0.0%	0.0%	3.2%	0.0%	0.1%
Station	% Passengers Positively Affected	13%	14%	11%	10%	12%	13%	12%
Station	Time Saved (Added) per Passenger	0:29:46	0:23:59	0:31:33	0:17:06	0:18:35	0:20:37	0:26:22
Station	Total Time Saved (Lost)	12:05:37	6:38:00	9:15:57	4:03:18	2:53:11	6:52:46	41:48:49
On-Board	% Passengers Negatively Affected	26%	25%	27%	29%	26%	25%	26%
On-Board	Time Saved (Added) per Passenger	(0:02:15)	(0:02:12)	(0:02:11)	(0:02:22)	(0:02:13)	(0:02:19)	(0:02:24)
On-Board	Total Time Saved (Lost)	(1:50:24)	(1:07:05)	(1:31:13)	(1:40:16)	(0:46:37)	(1:28:50)	(8:24:25)
	Net WT Savings per Aff. Passenger	0:09:02	0:07:46	0:08:42	0:02:34	0:04:29	0:05:51	0:06:36
	Net Wait Time Savings per Bus Hold	0:41:44	0:22:09	0:31:24	0:09:43	0:08:40	0:22:01	2:15:56
	Net Total Wait Time Saved (Lost)	10:15:13	5:30:55	7:44:44	2:23:02	2:06:34	5:23:56	33:24:23

As Table 4-6 shows, the application of the simulation model to the general scenario with the headway-based hold light system results in total wait time savings of 33 hours 24 minutes of passenger wait time over all bus routes in one PM peak period. This represents a savings of approximately 25% of total wait time. This is a result of saving 12% of the passengers an average of 26:22, but delaying 26% of the passengers by an average of 2:24. 39% of the bus trips were held for an average duration of 2:19 by the headway-based hold light system, resulting in a wait time savings of 6:36 per affected passenger. In this case, 2 hours 16 minutes of passenger wait time is saved per bus hold, while 0.1% of bus holds last longer than the allotted recovery time.

When we examine the results on a route-by-route basis, we see that wait time savings result on each of the bus routes when the headway-based hold light system is applied. Since Route 62 has the highest ridership of these routes during the period, it is not surprising that it sees the most wait time savings from the headway-based hold light system. On the other hand, Route 84 has the lowest ridership during the period, and Route 84 sees the least wait time savings from the system. This high correlation between route ridership and total wait time savings holds true for the Alewife bus routes with one exception. Route 79 has the third highest ridership during the period, but experiences the second fewest wait time savings. This is due to the relatively short headways on the route, meaning the penalty for missing a connection on this route is much less severe than on other routes, and therefore the benefits of the headway-based hold light system are greatly reduced. Analysis of the headway-based hold light on a route-by-route basis is potentially useful for an agency that is considering applying different holding strategies to bus routes at a single transfer station.

When we compare the results produced by the analytical and simulation models with the headway-based hold light system (long headway threshold = 4 minutes), we see that the simulation model produces a significantly higher estimate of total wait time savings. The primary reason for this is the small size of the data sample used in the application of the analytical model. The data collection performed, which required three man-hours per hour of observation, is an expensive endeavor, and is limited for this reason. It is expected that, due to better incorporation of the stochasticity of bus departures and train arrivals, results from an implementation of this headway-based hold light system at Alewife would be more in line with the results produced by the simulation model.

This initial application provides a base result for the Alewife Station case with which we can compare results as the sensitivity to various factors is examined in the following section.

4.6 Sensitivity Analysis

The next step in the analysis is to examine the sensitivity of the headway-based hold light system to changes in various model parameters. In this section, the system's sensitivity is examined with respect to long headway threshold, changes in passenger arrival behavior, and passenger perceptions of in-vehicle delay and out-of-vehicle waiting time.

4.6.1 Long Headway Threshold

The results of an analysis of the sensitivity of the headway-based hold light system to changes in the long headway threshold at Alewife are shown in Table 4-7 and Figure 4-3 below.

Table 4-7: Sensitivity to Long Headway Threshold – Alewife Station

	Long Headway Threshold (minutes)	0	1	2	3	4	5	6	7	8
	% Trips Affected	100%	100%	86%	60%	39%	24%	14%	9%	6%
	Average Hold Duration	0:04:13	0:03:14	0:02:37	0:02:24	0:02:19	0:02:14	0:02:09	0:02:01	0:01:44
	% Trips Held > Recovery Time	0.9%	0.6%	0.4%	0.3%	0.1%	0.1%	0.1%	0.0%	0.0%
Station	% Passengers Positively Affected	17%	17%	16%	15%	12%	9%	7%	5%	4%
Station	Time Saved (Added) per Passenger	0:27:30	0:27:53	0:27:29	0:26:58	0:26:22	0:25:57	0:25:08	0:22:57	0:19:00
Station	Total Time Saved (Lost)	62:46:33	62:59:38	59:05:02	51:42:24	41:48:49	31:20:00	23:21:08	16:46:47	11:50:34
On-Board	% Passengers Negatively Affected	82%	82%	69%	45%	26%	14%	7%	4%	2%
On-Board	Time Saved (Added) per Passenger	(0:04:13)	(0:03:17)	(0:02:43)	(0:02:29)	(0:02:24)	(0:02:19)	(0:02:17)	(0:02:09)	(0:01:53)
On-Board	Total Time Saved (Lost)	(45:35:15)	(35:21:59)	(24:42:04)	(14:46:43)	(8:24:25)	(4:23:12)	(2:19:39)	(1:10:30)	(0:37:13)
	Net WT Savings per Aff. Passenger	0:01:19	0:02:07	0:03:03	0:04:42	0:06:36	0:08:45	0:11:15	0:13:35	0:15:39
	Net Wait Time Savings per Bus Hold	0:27:08	0:43:38	1:02:55	1:36:33	2:15:56	3:00:28	3:51:56	4:37:50	5:19:53
	Net Total Wait Time Saved (Lost)	17:11:18	27:37:39	34:22:58	36:55:41	33:24:23	26:56:47	21:01:29	15:36:16	11:13:21

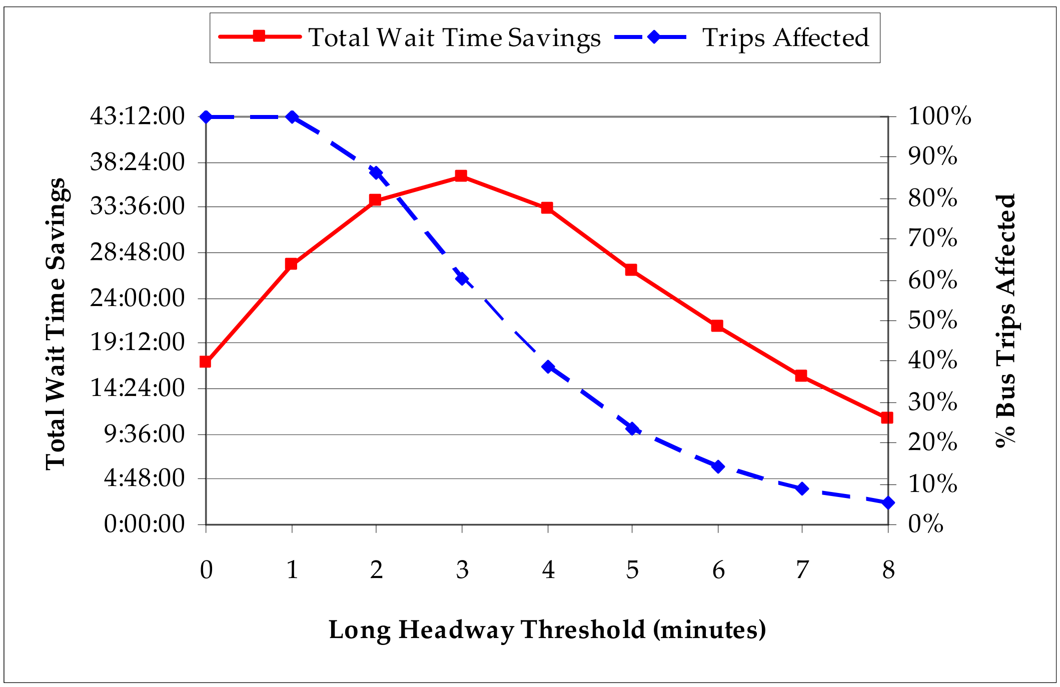

Figure 4-3: Sensitivity to Long Headway Threshold – Alewife Station

Once again, we see that as the long headway threshold decreases, there is a significant increase in the number of passengers and trips affected, while average wait times saved/added per passenger also increase. As in the general scenario, total wait time savings increase to a peak when the long headway threshold is 3 minutes, then decrease as the threshold decreases to zero. Again with a 4-minute threshold, we produce approximately 90% of the savings that could be produced with a three-minute long headway threshold (where total wait time savings is maximized) while we hold only 39% of the bus trips, compared with 60% if the long headway threshold is 3 minutes. As the threshold increases from three minutes to four minutes, the percentage of passengers negatively affected also drops approximately 42%. As the threshold increases from four minutes to five minutes, there is a significant decline of approximately 18% in total wait time savings, as well as less significant decreases in the number of passengers and bus trips affected than between the three- and four-minute thresholds. Due to these natural boundaries, a four-minute long headway threshold is most likely the ideal integer long headway threshold for Alewife Station case; however, this does depend on how the transit agency prioritizes the measures of effectiveness. We also see in this sensitivity analysis that as in the general scenario, when the long headway threshold is set to zero (e.g. every bus trip is held), significantly less wait time savings are produced than when the long headway threshold is near its optimal value.

4.6.2 Passenger Arrival Behavior

One of the key assumptions of this research is that passengers target specific bus trips, an assumption that is certainly valid on low-frequency routes. The range over which passengers plan to arrive for each departure, however, is much less clear. In order to better understand how the headway-based hold light system reacts to changes in passenger arrival behavior, two sensitivity analyses were performed. The first examines the sensitivity of the system to changes in the spread of the passenger arrival distribution while the second examines the sensitivity of the system to changes in the location of the passenger arrival distribution.

An analysis of the sensitivity of performance to the spread of the passenger arrival distribution at Alewife Station is shown in Table 4-8 below. In this analysis, the trailing vertex of the triangular passenger arrival distribution is fixed at a point one minute past the scheduled bus departure. The arrival range refers to the distance (in terms of time) between the mode of the distribution and the vertices.

Table 4-8: Sensitivity to Spread of Passenger Arrival Distribution – Alewife Station

	Range (minutes+/- from mode)	2.5	3.5	4.5	5.5	6.5	7.5	8.5
Station	% Passengers Positively Affected	30%	27%	23%	19%	15%	12%	10%
Station	Time Saved (Added) per Passenger	0:25:13	0:25:45	0:25:44	0:26:12	0:26:12	0:26:22	0:26:22
Station	Total Time Saved (Lost)	98:07:24	90:15:10	77:08:16	65:15:55	52:41:38	41:48:49	33:45:22
On-Board	% Passengers Negatively Affected	7%	10%	15%	20%	23%	26%	29%
On-Board	Time Saved (Added) per Passenger	(0:02:32)	(0:02:31)	(0:02:29)	(0:02:26)	(0:02:25)	(0:02:24)	(0:02:23)
On-Board	Total Time Saved (Lost)	(2:18:26)	(3:27:10)	(4:53:18)	(6:20:00)	(7:29:06)	(8:24:25)	(9:02:42)
	Net WT Savings per Aff. Passenger	0:20:03	0:17:48	0:14:36	0:11:35	0:08:55	0:06:36	0:04:54
	Net Wait Time Savings per Bus Hold	6:26:20	5:53:27	4:54:39	3:56:36	3:02:37	2:15:56	1:40:32
	Net Total Wait Time Saved (Lost)	95:48:58	86:48:00	72:14:58	58:55:55	45:12:32	33:24:23	24:42:39

A companion analysis of the sensitivity of the headway-based hold light system to the location of the passenger arrival distribution (with the spread of the distribution held at 15 minutes) at Alewife Station is shown in Table 4-9 below.

Table 4-9: Sensitivity to Location of Passenger Arrival Distribution – Alewife Station

	Mode of Arrival Dist. (minutes prior to departure)	8.5	8	7.5	7	6.5	6	5.5
Station	% Passengers Positively Affected	9%	9%	9%	11%	12%	14%	15%
Station	Time Saved (Added) per Passenger	0:26:36	0:26:44	0:26:43	0:26:23	0:26:22	0:26:12	0:26:02
Station	Total Time Saved (Lost)	31:14:18	31:41:43	33:09:03	37:24:50	41:48:49	47:07:58	51:30:08
On-Board	% Passengers Negatively Affected	29%	30%	30%	28%	26%	25%	23%
On-Board	Time Saved (Added) per Passenger	(0:02:21)	(0:02:19)	(0:02:22)	(0:02:25)	(0:02:24)	(0:02:24)	(0:02:24)
On-Board	Total Time Saved (Lost)	(9:07:35)	(9:00:23)	(9:24:41)	(8:55:54)	(8:24:25)	(7:54:53)	(7:20:07)
	Net WT Savings per Aff. Passenger	0:04:23	0:04:29	0:04:35	0:05:36	0:06:36	0:07:45	0:08:48
	Net Wait Time Savings per Bus Hold	1:30:29	1:32:44	1:35:22	1:55:04	2:15:56	2:38:56	2:58:44
	Net Total Wait Time Saved (Lost)	22:06:43	22:41:20	23:44:22	28:28:56	33:24:23	39:13:05	44:10:01

Since passenger arrivals do not affect holding decisions, changing the passenger arrival range has no effect on the percentage of bus trips held or hold times. As the range decreases, however, meaning passenger arrivals are grouped more closely together in time, total wait time savings generated by the headway-based hold light system increase dramatically. It stands to reason that if passenger arrivals at the transfer station are closer together, more passengers transferring to the same bus trip arrive on the same train. When this occurs, a bus trip that is held for a train from which a large number of passengers transfer will produce substantial wait time savings. Possibly more important, however, is that since the trailing vertex of the distribution is fixed at one minute past the scheduled departure time in the first sensitivity analysis, as the range narrows, a greater percentage of transfer passengers have target arrival times after the scheduled bus departure time. Naturally, these are passengers that benefit tremendously from bus holds, as they would have otherwise had to wait nearly an entire headway for the next bus. This sensitivity is extremely important as it can increase savings from the system dramatically, as shown in Table 4-8. Future research is needed in this area to better understand passenger arrival behavior and its impacts on operations control.

From the analysis of the system's sensitivity to the location of the arrival distribution we see that in the range where the distribution does not contain the scheduled bus departure time (e.g. where mode ≥ 7.5 minutes prior to scheduled departure time), the percentage of passengers affected is very stable. On the other hand, as the distribution moves forward in time so that more passengers arrive late, the benefits of the headway-based hold light system rise dramatically. This is a result of the passengers with target arrival times later than the scheduled bus departure time being ideally positioned to benefit from the headway-based hold light system.

We can also analyze the Alewife case under the assumption that passenger arrivals are distributed with train headways. The results of this analysis are shown in Table 4-10 below. While this passenger behavior is unrealistic in this situation due to the long bus headways at Alewife, it provides a lower bound for wait time savings as passenger arrival behavior changes.

Table 4-10: Simulation Model HBHL Results – Alewife Station (Passengers Distributed with Train Headway)

	Station	On-board
Bus Trips Affected	39%	
Average Hold Duration	0:02:19	
% Trips Held > Recovery Time	0.2%	
Passengers Affected	9%	28%
Wait Time Saved (Added) Per Passenger	0:20:50	(0:02:21)
Total Wait Time Saved (Added)	25:43:20	(8:41:53)
Net WT Savings per Affected Passenger	0:03:27	
Net Wait Time Savings per Bus Hold	1:09:53	
Net Total Wait Time Savings	17:01:28	

In Table 4-10 we see that when analyzed with passengers distributed with train headways, the headway-based hold light produces slightly more than 50% of the total wait time savings in the base case. This is due to the transfer passengers being spread more evenly over the set of train arrivals, making it less likely that there is a large number of transfer passengers on a single train who would benefit significantly from the headway-based hold light system.

4.6.3 Wait Time Perception

In transit operations analysis, it is generally accepted that passengers value out-of-vehicle wait time more than in-vehicle delay time, meaning they would rather be delayed while on a vehicle than have to wait the same amount of time for a vehicle to arrive. To represent this, researchers often weigh out-of vehicle wait time more heavily than in-vehicle delay time.

An analysis of the sensitivity of the system to changes in the weighting of out-of-vehicle wait time (OVT) with respect to in-vehicle delay time (IVT) in the Alewife Station case is displayed in Table 4-11 below. The mean value of time is constant in this analysis.

Table 4-11: Sensitivity to Wait Time Perception – Alewife Station

	OVT/IVT	1.00	1.25	1.50	1.75	2.00	2.25	2.50
Station	Time Saved (Added) per Passenger	0:26:22	0:29:18	0:31:38	0:33:33	0:35:09	0:36:30	0:37:40
	Total Time Saved (Lost)	41:48:49	46:27:34	50:10:34	53:13:02	55:45:05	57:53:44	59:44:01
On-board	Time Saved (Added) per Passenger	(0:02:24)	(0:02:08)	(0:01:55)	(0:01:45)	(0:01:36)	(0:01:29)	(0:01:22)
	Total Time Saved (Lost)	(8:24:25)	(7:28:23)	(6:43:32)	(6:06:51)	(5:36:17)	(5:10:25)	(4:48:14)
	Net WT Savings per Aff. Passenger	0:06:36	0:07:43	0:08:36	0:09:19	0:09:55	0:10:26	0:10:52
	Net Wait Time Savings per Bus Hold	2:15:56	2:38:38	2:56:48	3:11:39	3:24:02	3:34:31	3:43:30
	Net Total Wait Time Saved (Lost)	33:24:23	38:59:11	43:27:02	47:06:11	50:08:48	52:43:19	54:55:46

It is clear that weighting out-of-vehicle wait time more heavily than in-vehicle delay time only makes the headway-based hold light system more attractive. As the weighting of out-of-vehicle wait time with respect to in-vehicle delay time increases, the effective time saved per positively affected passenger and total time saved by station passengers increase while the effective delay time to on-board passengers decreases, resulting in an increase in effective total wait time savings.

4.7 Benefits from Real-time Information

If an agency has access to advanced real-time information, meaning a reliable estimate of the time until the next train arrival and a reliable estimate of the number of passengers wishing to transfer from the next arriving train to each bus trip, it may be able to reduce total passenger wait time by integrating this information into its operations control systems. If it is possible to estimate the benefits of a hold when the decision must be made, no-benefit holds can be avoided and the agency can also avoid any other hold where costs will outweigh benefits. A comparison of the application of the simulation model to the headway-based hold light system with and without the integration of real-time in the Alewife Station case is shown in Table 4-12 below.

Table 4-12: Impacts of Real Time Information – Alewife Station

Real-time Information	No		Yes	
	Station	On-board	Station	On-board
Bus Trips Affected	39%		30%	
Average Hold Duration	0:02:19		0:01:55	
% Holds > Recovery Time	0.1%		0.0%	
Passengers Affected	12%	26%	11%	19%
Wait Time Saved (Added) Per Passenger	0:26:22	(0:02:24)	26:43	(0:01:54)
Total Wait Time Saved (Added)	41:48:49	(8:24:25)	39:57:15	(4:41:51)
Net WT Savings per Affected Passenger	0:06:36		0:08:53	
Net Wait Time Savings per Bus Hold	2:15:56		3:04:43	
Net Total Wait Time Savings	33:24:23		35:15:24	

As shown in Table 4-12, the incremental total wait time savings attained by integrating real-time information into the headway-based hold light system is relatively small, however the difference in the number of trips affected and the net wait time savings per passenger are substantial. The question that remains for transit agencies is whether the incremental benefits gained are worth the cost of acquiring and integrating this real-time information. With the continued penetration of advanced AVL, APC, and AFC equipment, many agencies find themselves in a position where advanced equipment is available, but they often do not choose to utilize it. If agencies can begin to take advantage of these situations by making an effort to utilize their equipment to enhance operations, significant improvements could be made at relatively low costs.

4.8 Bus Route Interdependence

While it is assumed in this research that passengers who miss a bus trip will board the next departure on the same route rather than board an earlier departure on a different route, this is not always the case. In many cases, passengers living in neighborhoods served by multiple routes board the first bus departure from the set of those routes. While the effects of route interdependence are difficult to quantify, it is clear that interdependence causes a reduction in total passenger wait times.

In order to provide a preliminary estimate of these effects, each stop served by the six Alewife bus routes was placed into one of thirteen categories, according to the route(s) by which it is served. Six of the thirteen categories contained stops served by only one route, while the other seven categories contained stops served by a specific combination of routes (e.g. 62 and 76). Passengers alighting at stops in the former group were assigned to their original routes, while passengers alighting at stops in the latter group were assigned to proxy routes to account for the multiple services available to these individuals. The analytical model, when applied to this set of 13 (6 actual and 7 proxy) routes for one PM peak period at Alewife with the headway-based hold light system resulted in a 12 % decrease in total wait time savings from the original savings estimate. While this single result is not robust enough to draw general conclusions, due to the very small sample size and the stop-based rather than area-based approach, it indicates that the effects of bus route interdependence may significantly affect the effectiveness of bus holding strategies, and that future research in this area is necessary.

4.9 Alewife Station Summary

The Alewife Station case has provided an extensive examination of the headway-based hold light system in a real life situation. It is apparent that in this case – nearly the ideal case for the application of the headway-based hold light system – significant wait time savings are attainable through the application of the headway-based hold light system or the strategy of holding all bus trips for the train arrival. When compared with the strategy of holding all buses for the next arriving train, the headway-based hold light system emerges as a clearly more efficient means of bus holding. Although the analytical model (but not the simulation model) estimated that the hold-all-buses strategy would provide almost twice as much passenger wait time savings, efficiency is the strong point of the headway-based hold light as it only holds a fraction of the bus trips.

Sensitivity analysis has shown that the headway-based hold light system is sensitive to the long headway threshold and especially sensitive to the assumed passenger arrival time distribution for each bus route. It was also shown that if out-of-vehicle wait time is weighed more heavily than in-vehicle delay time, as is common practice in transportation modeling, the headway-based hold light system is even more attractive, as the system saves passengers from having to wait at a station, while causing a relatively short in-vehicle delay to other passengers. The results of these sensitivity analyses serve to underscore the importance of the trade-offs the transit agency must make in setting the hold light system parameters. In terms of the use of real-time data in holding systems, as transit agencies continue to increase their use of advanced data collection equipment, efficiency of bus holding strategies should improve considerably. It should also be noted that the potential savings at Alewife will be reduced to the extent that passengers can take more than one of the routes serving the station on their trip home.

5 ADDITIONAL APPLICATIONS

This chapter presents the application of the simulation model to the case of Wellington Station in the MBTA system (Section 5.1) and the application of the simulation model to the case of 79th Street Station in the CTA system (Section 5.2). These cases are included to test the effectiveness of the headway-based hold light in situations which include factors that may reduce the benefits of the system.

5.1 Wellington Station (MBTA) Case Study

This section presents the application of simulation model to the case of Wellington Station in the MBTA system. The primary motivation for including this case study is that many of the routes serving Wellington Station have significant downstream boardings, which will substantially decrease the benefits provided by the headway-based hold light system

5.1.1 Station and Local Area Characteristics

Wellington Station is on the northern end of the MBTA's Orange Line. At this key transfer point, there are 1,316 parking spaces, and 9 bus routes to and from which rail passengers can transfer. Like Alewife Station, Wellington Station is used by a large number of commuters each day who travel to places of employment in downtown Boston.

Although the area surrounding Wellington station contains some office buildings and retail stores, the station is primarily used by people who access the station by car or bus. Approximately 7,000 passengers board the Orange Line at Wellington each weekday.

a) Orange Line

The MBTA Orange Line runs from the northern suburbs of Boston through downtown to the southwestern section of the city. Major points of interest include Bunker Hill Community College, North Station, Downtown Crossing, the New England Medical Center, Back Bay Station, and Northeastern University (see Figure 5-1 below). During the PM Peak, Orange Line trains run every four to five minutes.

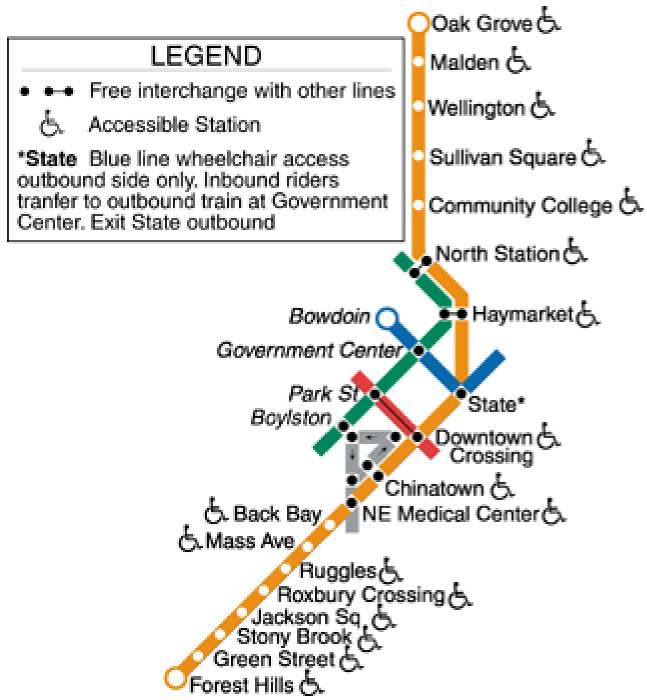

Figure 5-1: MBTA Orange Line Map (source: mbta.com)

b) Bus Routes

Wellington Station is served by nine bus routes, all of which have Wellington as a terminal station. These nine routes fan out to a number of locations but are different from those at Alewife since on many routes additional passengers do board at downstream stops. Average weekday boardings on the bus routes serving Wellington Station are shown in Table 5-1 below. Boarding data is from the 2003-2004 MBTA Ridership and Service Statistics.

Table 5-1: Average Weekday Boardings – Wellington Station Bus Routes

Route	Daily Boardings
90	1,280
97	535
99	1,681
100	955
106	2,308
108	2,708
110	2,392
112	1,338
134	1,605

The bus routes operate according to the schedule shown in Table 5-2 below, which also shows the average observed demand for each trip, calculated from the field data introduced in Section 3.1. These values are average demands for travel on the entire route, not average passenger loads leaving Wellington Station.

Table 5-2: Wellington Station Scheduled Bus Departures with Average Loads per Trip

90		97		99		100		106		108		110		112		134	
16:30	20	16:35	5	16:30	17	16:40	24	16:40	76	16:30	23	16:30	33	16:50	48	16:30	39
17:05	30	17:05	20	16:55	63	17:00	13	17:00	64	16:50	43	16:40	17	17:25	24	16:50	32
17:40	4	17:35	30	17:25	19	17:20	28	17:20	50	17:10	37	16:50	38	18:00	19	17:10	45
18:15	10	18:05	11	17:45	51	17:40	17	17:40	76	17:30	29	17:00	32	18:35	16	17:30	24
18:50	6	18:35	10	18:10	42	18:00	26	18:00	36	17:50	34	17:10	42			17:50	61
				18:35	39	18:20	18	18:20	24	18:10	34	17:20	33			18:10	38
				19:00	29	18:40	13	18:45	26	18:30	14	17:30	21			18:30	30
						19:00	22			19:00	43	17:40	17			19:00	32
												17:50	51				
												18:00	31				
												18:10	22				
												18:20	35				
												18:40	21				

Note that headways of the Wellington bus routes are on par with those of the Alewife bus routes and that demands are generally larger than those at Alewife. This is largely due to the fact that the bus routes serving Wellington support more diverse travel needs than are served by the simple feeder routes serving Alewife, causing boardings to be more spread out over the length of the route. Additionally, Wellington is not as dominant a transfer point as Alewife on the routes it serves, as many of the routes stop at significant transfer points in addition to Wellington. Maps of the nine bus routes serving Wellington Station are included in Appendix B.

5.1.2 Case Framework

Since the nine bus routes serving Wellington Station can be considered feeder/distributor routes and walk-in boardings are rare, we will assume that 95% of passengers that board buses at Wellington in the PM peak are transferring from Orange Line trains. For the purposes of this analysis, it is assumed that passengers who miss a bus trip will board the next departure on the same route, rather than board an earlier departure on a different route. For Wellington Station, this assumption may tend to overestimate wait time savings, as a number of the bus routes serving the station have overlapping service areas and thus cannot be fully estimated without a more detailed analysis. However, this issue is unlikely to change the overall conclusion for this case.

The additional challenge of the Wellington Station case not present at Alewife is that many of the routes serving Wellington Station have significant downstream boardings. Since not all passengers that board the nine bus routes board at Wellington Station, we must also consider Type D passengers. The passenger mix for each route (as calculated from MBTA ride check data) and the average weekday PM peak recovery times for each route serving Wellington (derived from the MBTA schedule) are shown in Table 5-3 below. In this case, recovery times are for outbound trips only, since ridership on these routes in the PM peak is much more directionally balanced than that of the Alewife routes.

Table 5-3: Passenger Mix and Average Weekday PM Peak Recovery Times– Wellington Station Bus Routes

Route	C	D	Recovery Time (min.)
90	50%	50%	14
97	44%	56%	10
99	59%	31%	18
100	89%	11%	3
106	42%	58%	5
108	35%	65%	6
110	78%	22%	7
112	63%	37%	3
134	66%	34%	6

5.1.3 Simulation Model Application

This section discusses the calibration and application of the simulation model to the Wellington Station Case. First the calibration of the model to the Wellington case is discussed, and then the application results are presented.

As described in Section 3.4.1, train arrivals are generated from a log-normal distribution. For the Wellington Station case, it was determined (as shown in Figure 3-3 and Figure 3-4) that the distribution with parameters μ=1.51222 and σ=0.43998 best fits the empirical PM peak Orange Line headway data. The fit of this distribution passes the Kolmogorov-Smirnov goodness-of-fit test with significance level α=0.2. Orange Line headway data was obtained as part of the data collection effort described in Section 3.1.

As described in Section 3.4.2, bus departures are also generated from a log-normal distribution. As no AVL data was available for the bus routes serving Wellington Station, a distribution fit to the schedule deviation of the aggregate set of Alewife bus routes is used. The parameters of this distribution are μ=2.30623, σ=0.20709, and δ=8.69108.

Table 5-4 below shows the results obtained by applying the simulation model to Wellington Station. The long headway threshold is set to five minutes (the average scheduled rail headway rounded up to the next integer value) for this initial analysis.

Table 5-4: Simulation Model HBHL Results – Wellington Station

	Station	On-board	Downstream
Bus Trips Affected	30%		
Average Hold Duration	0:02:21		
% Trips Held > Recovery Time	3%		
Passengers Affected	7%	10%	12%
Wait Time Saved (Added) Per Passenger	0:21:24	(0:02:26)	
Total Wait Time Saved (Added)	49:55:22	(17:37:24)	
Net WT Savings per Affected Passenger	0:03:22		
Net Wait Time Savings per Bus Hold	1:40:14		
Net Total Wait Time Savings	32:17:58		

As Table 5-4 shows, the application of the simulation model to Wellington Station with the headway-based hold light system results in savings of 32 hours 18 minutes of passenger wait time in one PM peak period, approximately an 11% savings in total passenger wait time. This is a result of saving 7% of the passengers an average of 21:24, and delaying 22% of the passengers by an average of 2:26. 30% of the bus trips were held in this scenario.

Table 5-5 below shows the results obtained by applying the simulation model to Wellington Station for the hold-all-buses strategy.

Table 5-5: Simulation Model HBHL Results – Wellington Station (Hold-all-buses Strategy)

	Station	On-board	Downstream
Bus Trips Affected	100%		
Average Hold Duration	0:04:32		
% Trips Held > Recovery Time	25%		
Passengers Affected	12%	48%	39%
Wait Time Saved (Added) Per Passenger	0:22:54	(-0:04:32)	
Total Wait Time Saved (Added)	87:31:20	(129:41:14)	
Net WT Savings per Affected Passenger	(0:01:18)		
Net Wait Time Savings per Bus Hold	(0:38:55)		
Net Total Wait Time Savings	(42:09:54)		

As Table 5-5 shows, the application of the simulation model to Wellington Station with the hold-all-buses strategy results in a wait time increase of 42 hours 10 minutes of passenger wait time in one PM peak period, approximately a 14% increase. This is a result of saving 12% of the passengers an average of 22:54, and delaying 87% of the passengers by an average of 4:32. 25% of the bus trips in this scenario were held past the scheduled recovery time. This high value would have significant negative impacts on operations, as it means one out of every four return trips will be late as a result of holding alone.

Obviously, the headway-based hold light system is preferred to the hold-all-buses strategy in this case because it results in a decrease in total passenger wait time where the hold-all-buses strategy results in an increase. The extreme difference in the results of these two strategies can be attributed to the many negative-benefit holds that are caused by the hold-all-buses strategy but not by the headway-based hold light. On the 70% of total trips that are held with the hold-all-buses strategy but not with the headway-based hold light, there are generally very few transfer passengers who benefit from holding, while many downstream passengers are negatively affected, resulting in a large increase in net total wait time. Since the headway-based hold light system is able to avoid holding these trips by targeting bus trips that depart following large train arrival gaps (where holding generally produces substantial passenger wait time savings) the extremely large increase in net total wait time seen in the hold-all-buses case is not experienced. Another advantage of the headway-based hold light system is that it delays only 3% of trips longer than the scheduled recovery time compared to 25% for the hold-all-buses case, and therefore has much less of an impact on operations.

This initial application provides a base result for the Wellington Station case with which we can compare results as the sensitivity to various factors is examined in the following section.

5.1.4 Sensitivity Analysis

The next step in the analysis is to check the sensitivity of the headway-based hold light system to changes in various parameters. In this section, the sensitivity of performance is examined with respect to the long headway threshold and the passenger mix.

a) Long Headway Threshold

The results of an analysis of the sensitivity of performance to changes in the long headway threshold at Wellington are shown in Table 5-6 and Figure 5-2 below.

Table 5-6: Sensitivity to Long Headway Threshold – Wellington Station

	Long Headway Threshold (minutes)	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
	% Trips Affected	100%	100%	89%	67%	46%	30%	19%	11%	7%
	Average Hold Duration	0:04:32	0:03:31	0:02:52	0:02:37	0:02:26	0:02:21	0:02:16	0:02:09	0:01:56
	% Trips Held > Recovery Time	25%	17%	11%	7%	4%	3%	2%	1%	1%
Positive	% Passengers Positively Affected	12%	12%	11%	10%	9%	7%	6%	4%	3%
Positive	Time Saved (Added) per Passenger	0:22:54	0:23:21	0:23:14	0:22:32	0:22:04	0:21:24	0:21:21	0:21:20	0:20:36
Positive	Total Time Saved (Lost)	87:31:20	88:16:00	85:01:47	76:16:30	63:27:00	49:55:22	38:38:19	26:37:14	19:28:50
Negative	% On-board Negatively Affected	48%	48%	41%	29%	18%	10%	6%	3%	1%
Negative	% Downstream Negatively Affected	39%	39%	35%	26%	18%	12%	8%	4%	3%
Negative	Time Saved (Added) per Passenger	(-0:04:32)	(0:03:34)	(0:02:56)	(0:02:41)	(0:02:31)	(0:02:26)	(0:02:23)	(0:02:24)	(0:02:11)
Negative	Total Time Saved (Lost)	(129:41:14)	(102:09:23)	(73:47:20)	(49:08:11)	(30:09:42)	(17:37:24)	(10:27:41)	(5:48:43)	(3:11:36)
	Net WT Savings per Aff. Passenger	(0:01:18)	(0:00:26)	0:00:23	0:01:15	0:02:14	0:03:22	0:04:32	0:05:39	0:06:45
	Net Wait Time Savings per Bus Hold	(0:38:55)	(0:12:49)	0:11:38	0:37:22	1:06:32	1:40:14	2:16:08	2:49:02	3:23:30
	Net Total Wait Time Saved (Lost)	(42:09:54)	(13:53:23)	11:14:27	27:08:18	33:17:18	32:17:58	28:10:38	20:48:31	16:09:28

In this sensitivity analysis, we see that, as expected, the percentage of bus trips held is inversely related to the long headway threshold. Interestingly, we see that when all buses are held (long headway threshold = 0), total wait time actually increases. This is due to the high percentage of passengers who board downstream on the routes serving Wellington. The sum of these passengers and those already on board at Wellington is much greater than the number of passengers saving wait time (even though these passengers save much more time on average than the delayed passengers lose) to result in a positive total wait time impact.

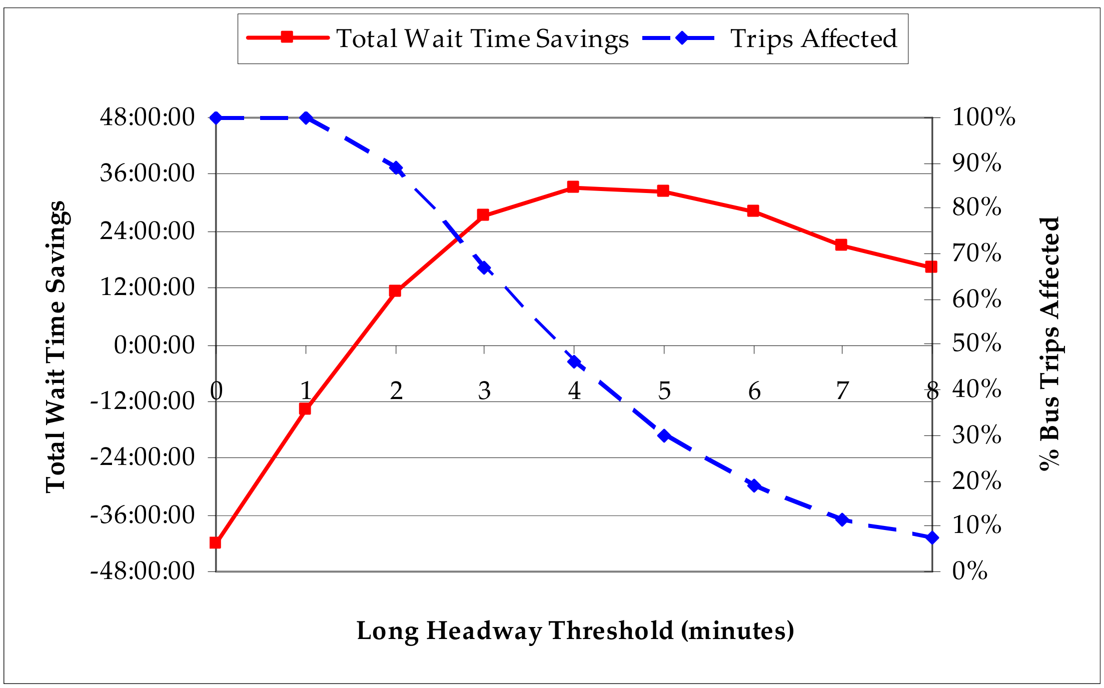

Figure 5-2: Sensitivity to Long Headway Threshold – Wellington Station

As the long headway threshold increases, total wait time savings increases, peaks at a long headway threshold of four minutes, then falls. In this case, we see that the total wait time savings peaks when long headway threshold equals 4 minutes, and is relatively flat between 3 and 6 minutes. Although the total wait time savings is relatively flat through this region, the number of held bus trips is falling rapidly. With a long headway threshold of 6 minutes, we are able to capture almost all (approximately 85%) of the potential wait time savings while only holding 19% of the bus trips.

b) Passenger Mix

An analysis of the sensitivity of the results to changes in the number of downstream boardings on Route 100 is shown in Table 5-7 and Figure 5-4 below. Route 100 was chosen in an effort to remove headway variability from this analysis as Route 100 operates on a consistent 20-minute headway throughout the PM peak period. Note that all passengers at on this route are either Type C passengers (who board at the transfer station) or Type D passengers (who board downstream) since Wellington is a terminal station.

Table 5-7: Sensitivity to Passenger Mix – Route 100

	% Type C Passengers	100%	90%	80%	70%	60%	50%	40%	30%	20%
Positive	% Passengers Positively Affected	9%	8%	7%	6%	5%	5%	3%	3%	2%
	Time Saved (Added) per Passenger	0:16:14	0:15:37	0:16:04	0:16:22	0:15:49	0:16:15	0:15:55	0:15:42	0:16:35
	Total Time Saved (Lost)	4:53:57	4:21:48	4:02:43	3:31:29	3:00:52	2:32:06	1:54:21	1:26:23	1:01:58
Negative	% On-board Negatively Affected	10%	8%	7%	7%	6%	5%	4%	3%	2%
	% Downstream Negatively Affected	0%	2%	4%	6%	7%	10%	11%	13%	15%
	Time Saved (Added) per Passenger	(0:02:29)	(0:02:28)	(0:02:26)	(0:02:29)	(0:02:26)	(0:02:28)	(0:02:20)	(0:02:27)	(0:02:20)
	Total Time Saved (Lost)	(0:38:05)	(0:40:06)	(0:42:53)	(0:49:53)	(0:51:25)	(0:57:08)	(0:53:46)	(1:01:05)	(1:03:36)
	Net WT Savings per Aff. Passenger	0:08:38	0:07:42	0:06:48	0:05:20	0:04:19	0:03:07	0:02:07	0:00:52	(0:00:03)
	Net Wait Time Savings per Bus Hold	2:52:50	2:34:35	2:15:07	1:44:52	1:27:03	1:03:06	0:42:35	0:17:35	(0:01:05)
	Net Total Wait Time Saved (Lost)	4:15:52	3:41:41	3:19:50	2:41:36	2:09:27	1:34:58	1:00:35	0:25:18	(0:01:38)

Since the boarding location of the passengers is the only factor that is changing in this analysis, there is no impact on the percentage of bus trips held or the duration of the holds. As the percentage of Type C passengers (those boarding at Wellington Station) increases, total wait time savings increases linearly. We also see that the point where we no longer see a decrease in total wait time is approximately where the mix is 20% Type C passengers and 80% Type D passengers.

5.1.5 Wellington Station Summary

Building on the basic case of Alewife Station, the Wellington Station case allows us to see the very significant effects of downstream boardings on the effectiveness of headway-based hold light systems. While one might be inclined to think this would make the headway-based hold light system produce more total delay than wait time savings, the system is still able to produce significant wait time savings at Wellington Station, but we would expect some of the routes that serve Wellington Station are approaching levels of downstream boardings that would not be conducive to the use of the headway-based hold light system. When the application of the headway-based hold light system and the hold-all-buses strategy to the Wellington case are compared, we see that headway-based hold light system captures a large portion of the total potential positive wait time benefits with the 30% of bus trips it holds, and by not holding the remaining 70% (which are held by the hold-all-buses strategy) is able to avoid a substantial increase in total wait time.

In the sensitivity analysis in this section, it was demonstrated that when dealing with strictly Type C and Type D passengers, the passenger mix is linearly related to the total wait time savings. This shows the importance of setting the long headway threshold as high as possible while still maintaining the overall wait time savings, especially when there are large numbers of downstream boardings. It should also be noted that the potential savings at Wellington will be reduced to the extent that passengers can take more than one of the routes serving the station on their trip home.

5.2 79th Street Station (CTA) Case Study

This section presents the application of the simulation model to the case of 79th Street Station in the CTA system. This station was included to get a better sense of the model's applicability to higher-frequency bus routes, and to transfer points that are not the single dominant transfer point on a bus route. Since the CTA's grid bus network, which connects with radial rail service, produces bus trips with vastly different characteristics than those seen on feeder/distributor routes in the MBTA system, this is a good chance to see how the headway-based hold light system behaves in an environment with transfers between a much more diverse set of transit services. Additionally, the impacts of through passengers are introduced, as 79th Street is a mid-line stop on one of the routes analyzed.

5.2.1 CTA System Characteristics

The CTA System consists of 7 heavy rail lines and 150 bus routes. The system provides approximately 1.5 million passenger trips per day, providing mobility to the people of Chicago and 40 surrounding suburbs (CTA, 2006). See Figure 5-3 below for a map of the CTA's rail services.

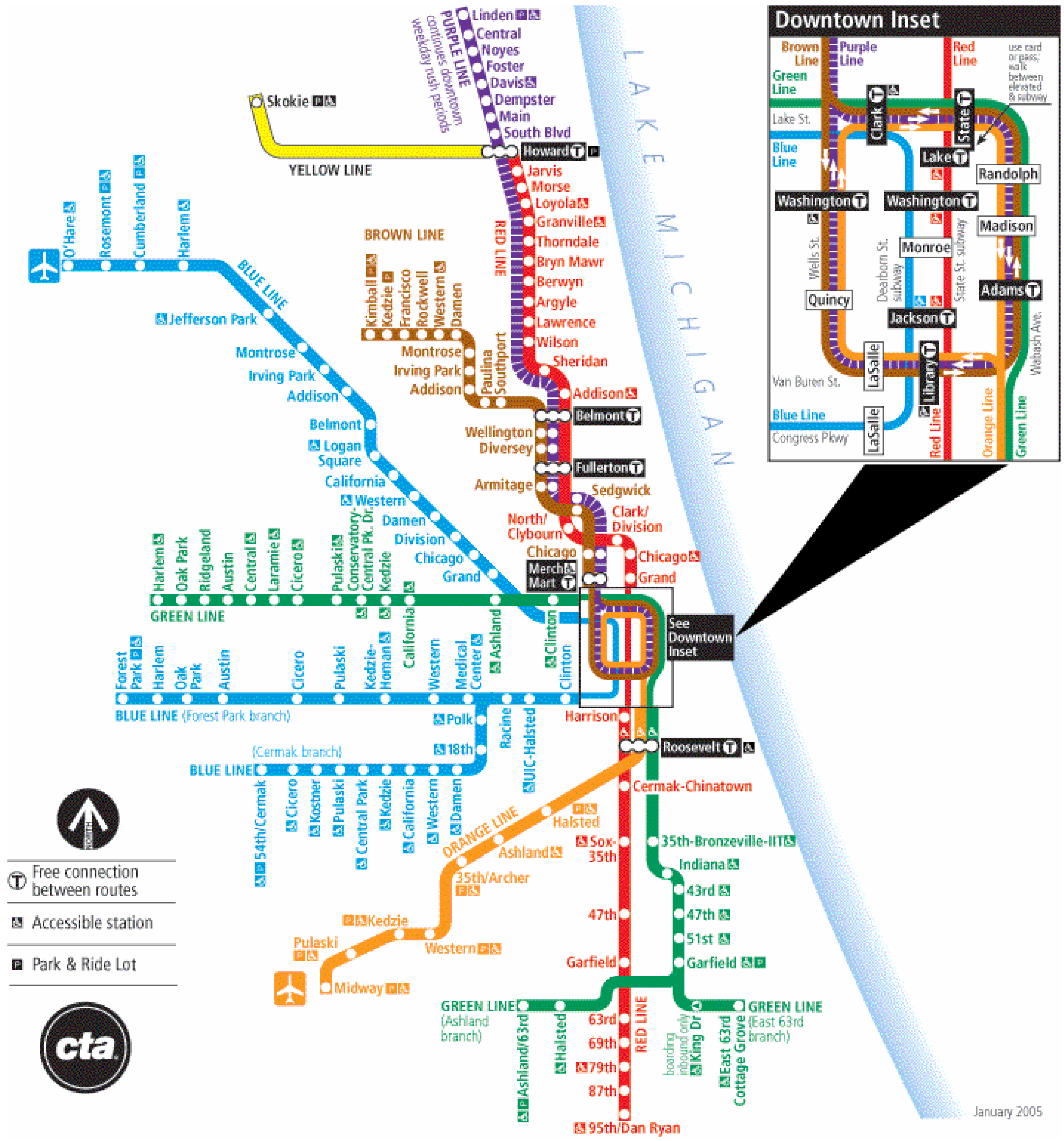

Figure 5-3: CTA Rail Map (source: transitchicago.com)

5.2.2 Station and Local Area Characteristics

79th Street Station is on the southern portion of the CTA's Red Line. While 79th Street Station is not the dominant transfer point on this portion of the Red Line, many outbound passengers transfer from rail to bus at this point as they are traveling to destinations served by CTA buses on Chicago's south side. See Figure 5-4 below for a map of the CTA service surrounding 79th Street Station.

Figure 5-4: 79th Street Station Area Map (source: transitchicago.com)

79th Street Station is located in the median of the Dan Ryan Expressway at its interchange with 79th Street. The surrounding area is primarily residential, with some businesses located on the major streets. There are also small amounts of both commercial and industrial development in the area. Approximately 7,500 passengers board the Red Line at 79th Street each weekday.

a) Red Line

The CTA Red Line runs from the northern edge of Cook County south into the downtown loop and continues through the south side to 95th Street. Major points of interest include DePaul University, Wrigley Field, the Loop (downtown area), Chinatown, and U.S. Cellular Field. During the PM Peak, Red Line trains run every four to five minutes.

b) Bus Routes

Although 79th Street Station is served by five bus routes in addition to the Red Line; only two are examined in this case study. Route 8A terminates at 79th Street, while Route 75 passes through the station mid-route, serving it only on eastbound trips. Routes 24, 29, and 79 also serve 79th Street Station, but are not included in this analysis. Routes 24 and 29 run parallel to the Red Line, and as a result have very low volumes of passengers transferring from the Red Line at 79th Street Station. The negative effects on the vast majority of the passengers traveling on these routes would far outweigh any benefits to the few transferring passengers. Route 79 is not considered because its extremely short headways (2 to 6 minutes) would make it pointless to hold buses. Since 79th Street Station is one of many major transfer points on the two routes analyzed, there are a significant number of downstream boardings.

Average weekday boardings on the bus routes analyzed in the 79th Street Station case are shown in Table 5-8 below. Boarding data is from the March 2006 CTA Bus Ridership by Route Report.

Table 5-8: Average Weekday Boardings – 79th Street Station Bus Routes

Route	Daily Boardings
8A	3,787
75	7,934

Routes 8A and 75 (eastbound) operate according to the schedule displayed in Table 5-9 below, which also shows the average load for each trip (calculated from CTA AVL and APC data). Note that these demands are for the entire length of the route, and are not average passenger loads leaving 79th Street.

Table 5-9: 79th Street Station Scheduled Bus Departures with Average Loads per Trip

8A		75-E	
16:32	79	16:32	92
16:44	34	16:44	52
16:56	45	16:56	29
17:08	28	17:08	115
17:20	11	17:20	57
17:32	22	17:32	46
17:44	28	17:44	92
17:56	28	17:57	75
18:08	22	18:10	75
18:20	11	18:25	69
18:35	34	18:40	109
18:50	17	18:56	46

Note that headways of the 79th Street bus routes are much smaller than those of the Alewife and Wellington bus routes. Loads on Route 8A are similar to loads on many of the MBTA routes, while loads on Route 75 are higher than typical loads at Alewife and Wellington. Although these routes carry as much or more traffic than the MBTA routes, there are generally fewer boardings at the transfer station than in the two MBTA cases, due to the structure of the CTA network. The CTA's grid bus network provides many more major points at which passengers can transfer to Routes 8A and 75, leading to a more even spatial distribution of boardings, and often the lack of one dominant transfer point. Maps of Route 8A and Route 75 are included in Appendix B.

5.2.3 Case Framework

Since not all passengers that board Routes 8A and 75 (eastbound) board at 79th Street, and the station is mid-line on Route 75, we must consider Type A, B, C, and D passengers. The passenger mix for each route (as calculated from CTA AVL and APC data) and the average weekday PM peak recovery time for each route (derived from the CTA Supervisor Guide) are shown in Table 5-10 below. In this case, recovery times are for outbound trips only, since ridership on these routes in the PM peak is much more directionally balanced than the Alewife routes.

Table 5-10: Passenger Mix and Average Weekday PM Peak Recovery Times– 79th Street Station Bus Routes

Route	A	B	C	D	Recovery Time (min.)
8A	0%	5%	13%	82%	4
75	28%	22%	12%	38%	6

Since the volumes of through and downstream passengers are much higher in the 79th Street case than at Alewife or Wellington, we should expect to see far fewer benefits, if any, from the application of the headway-based hold light system to this case. No consideration of route interdependence is necessary in this case as the two routes do not overlap.

5.2.4 Simulation Model Application

This section discusses the calibration of the simulation model and its application to 79th Street Station. First the calibration of the model is discussed, and then the application results are presented.

As described in Section 3.4.1, train arrivals are generated from a log-normal distribution. Since no CTA Red Line headway data was available, the log-normal distribution fit to the MBTA Red Line is used. The parameters of this distribution are $\mu=1.3591$ and $\sigma=0.47492$.

As described in Section 3.4.2, bus departures are also generated from a log-normal distribution. Since no schedule deviation data was available for the CTA bus routes, the log-normal distribution fit to the aggregated Alewife buses is used. The parameters of this distribution are $\mu=2.30623$, $\sigma=0.20709$, and $\delta=8.69108$.

Since the headways of the bus routes serving 79th Street Station are much smaller than the routes considered when the parameters of the initial passenger arrival model were selected, this model needs to be reconsidered for this case. For the initial application of the simulation model, we will assume passengers still target specific trips, although headways at 79th Street are near the boundary where passenger arrival patterns change significantly. We will use a similar triangular distribution as in the Alewife and Wellington cases, with a mode 2:30 prior to scheduled bus departures and a range of +/- 3:30, meaning with no train delays, passengers would arrive for a bus trip in the interval from 6 minutes prior to departure to 1 minute after departure.

Table 5-11 below shows the results obtained by applying the simulation model to the 79th Street Station case. The long headway threshold is set to five minutes (the average scheduled rail headway rounded up to the next integer value) for this initial analysis.

Table 5-11: Simulation Model HBHL Results – 79th Street Station

	Station	On-board	Downstream
Bus Trips Affected	24%		
Average Hold Duration	0:02:16		
% Trips Held > Recovery Time	3%		
Passengers Affected	2%	5%	12%
Wait Time Saved (Added) Per Passenger	0:11:38	(0:02:20)	
Total Wait Time Saved (Added)	5:35:03	(7:53:57)	
Net WT Savings per Affected Passenger	(0:01:39)		
Net Wait Time Savings per Bus Hold	(0:15:24)		
Net Total Wait Time Savings	(2:18:54)		

As Table 5-11 shows, the application of the simulation model to 79th Street Station with the headway-based hold light system results in a wait time increase of 2 hours 19 minutes in the PM peak period. This is a result of saving only 2% of the passengers an average of 11:38, but delaying 17% of the passengers by an average of 2:20. 24% of the bus trips were held an average of 2:16 by the headway-based hold-light system. 3% of trips were held longer than the scheduled recovery time.

This initial application provides a base case for the 79th Street case with which we can compare results as the sensitivity to various factors is examined in the following section.

5.2.5 Sensitivity Analysis

The next step in the analysis is to check the sensitivity of the headway-based hold light system to changes in various parameters. In this section, the sensitivity is examined with respect to long headway threshold and changes in passenger arrival behavior.

a) Long Headway Threshold

An analysis of the sensitivity of the system to changes in the long headway threshold in the 79th Street Station case is displayed in Table 5-12 and Figure 5-5 below.

Table 5-12: Sensitivity to Long Headway Threshold – 79th Street Station

	Long Headway Threshold (minutes)	0	1	2	3	4	5	6	7	8
	% Trips Affected	100%	100%	86%	61%	39%	24%	14%	9%	5%
	Average Hold Duration	0:04:13	0:03:12	0:02:36	0:02:23	0:02:19	0:02:16	0:02:10	0:01:51	0:01:27
	% Trips Held > Recovery Time	31%	19%	12%	7%	4%	3%	2%	1%	1%
Positive	% Passengers Positively Affected	6%	6%	5%	5%	4%	2%	2%	1%	1%
Positive	Time Saved (Added) per Passenger	0:13:56	0:14:05	0:13:43	0:12:53	0:12:13	0:11:38	0:10:41	0:09:19	0:07:10
Positive	Total Time Saved (Lost)	17:22:35	16:36:09	15:03:24	12:00:19	8:41:29	5:35:03	3:27:26	2:09:47	1:18:28
Negative	% On-board Negatively Affected	23%	23%	19%	13%	8%	5%	3%	2%	1%
Negative	% Downstream Negatively Affected	51%	51%	44%	31%	20%	12%	7%	4%	3%
Negative	Time Saved (Added) per Passenger	(0:04:13)	(0:03:13)	(0:02:38)	(0:02:25)	(0:02:21)	(0:02:20)	(0:02:22)	(0:02:25)	(0:02:24)
Negative	Total Time Saved (Lost)	(63:10:45)	(48:14:25)	(33:55:41)	(21:24:11)	(13:19:44)	(7:53:57)	(4:45:56)	(2:57:33)	(1:47:08)
	Net WT Savings per Aff. Passenger	(0:07:45)	(0:05:24)	(0:03:45)	(0:02:40)	(0:02:01)	(0:01:39)	(0:01:33)	(0:01:34)	(0:01:33)
	Net Wait Time Savings per Bus Hold	(1:12:19)	(0:49:59)	(0:34:31)	(0:24:30)	(0:18:36)	(0:15:24)	(0:14:33)	(0:14:22)	(0:14:13)
	Net Total Wait Time Saved (Lost)	(45:48:10)	(31:38:16)	(18:52:17)	(9:23:52)	(4:38:15)	(2:18:54)	(1:18:30)	(0:47:46)	(0:28:40)

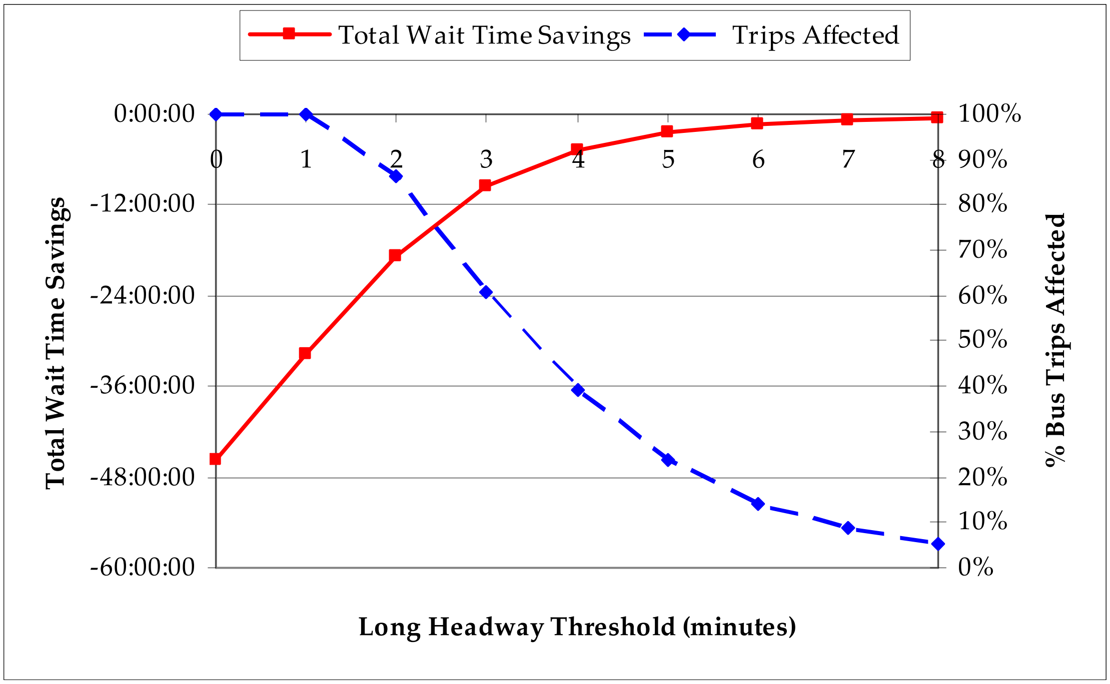

Figure 5-5: Sensitivity to Long Headway Threshold – 79th Street Station

In this sensitivity analysis, we see that regardless of what long headway threshold is chosen, the implementation of the headway-based hold light system will result in an increase in passenger wait time. Likewise, the hold-all-buses strategy will result in an extremely large increase in passenger wait time, while large values of long headway threshold correspond to smaller increases in total wait time, simply because fewer buses are held and therefore fewer passengers are affected. As expected, the high volume of downstream passengers and the small penalties for missing connections on high-frequency routes make 79th Street an inappropriate location for the headway-based hold light system, and bus holding in general, as the relatively small delays to the large numbers of upstream and downstream boardings, as well as passengers boarding at the transfer point who arrive on time, far outweigh the large savings to the few passengers who benefit from buses held at the transfer station.

b) Passenger Arrival Behavior

As mentioned earlier, the headways of the bus routes serving 79th Street Station (10-12 min.) are near the boundary between low-frequency and high-frequency routes, which see very different passenger arrival behavior. Table 5-13 below shows the result of applying the headway-based hold light to the 79th Street case under the assumption that passenger arrivals are distributed with train headways, meaning passengers do not target individual trips, but rather arrive at the transfer station with the intent of boarding the next bus on a specific route, regardless of schedule.

Table 5-13: Simulation Model HBHL Results – 79th Street Station (Passengers Distributed with Train Headways)

	Station	On-board	Downstream
Passengers Affected	2%	5%	12%
Wait Time Saved (Added) Per Passenger	0:10:49	(0:02:21)	
Total Wait Time Saved (Added)	3:38:16	(8:13:54)	
Net WT Savings per Affected Passenger	(0:01:12)		
Net Wait Time Savings per Bus Hold	(0:18:38)		
Net Total Wait Time Savings	(4:35:38)		

In this analysis, we see that the application of the simulation model to 79th Street Station with the headway-based hold light system results in a wait time increase of 4 hours 36 minutes in the PM peak period, which is approximately equal to the result with a 4-minute long headway threshold when we assume passengers target specific trips. This is a result of saving only 2% of the passengers an average of 10:49, but delaying 17% of the passengers by an average of 2:21. As in the base analysis, 24% of the bus trips were held an average of 2:16 by the headway-based hold-light system and 3% of trips were held longer than the scheduled recovery time.

Comparing this with the analysis performed with the assumption that passengers target specific trips, we see that – relative to the results with mid-range values of long-headway threshold – the shift to passengers not timing their arrivals has relatively little effect on the total wait time savings produced by the headway-based hold light system. This is due to the fact that the fraction of total route boardings that take place at the transfer station is very low, and as a result, their timing has little effect on the overall result. Note that this does not reflect a lack of sensitivity to passenger arrival behavior, but rather a case where the fraction of transferring passengers is so small that there is almost no potential for improvement in terms of wait time savings regardless of how passengers time their arrivals. Since the timing of passenger arrivals is the only factor that has changed, there is no effect on the number of bus trips held or the duration of these holds.

c) Passenger Mix

In this analysis, the sensitivity of the headway-based hold light system with respect to passenger mix is examined. The percentage of Type C passengers (who transfer from the Red Line at 79th Street) is changed in order to determine the mix where we first see a decrease in total passenger wait time. The percentage of Type C passengers is examined in increments of 5%, with 12% included in the analysis as the base case. As the share of Type C passengers is increased, the percentages of Type A, B, and D passengers are reduced proportionally. Table 5-14 and Figure 5-6 below show the results of this analysis.

Table 5-14: Sensitivity to Passenger Mix – 79th Street Station

	% Type C Passengers	**10%**	**12%**	**15%**	**20%**	**25%**	**30%**
Positive	% Passengers Positively Affected	2%	2%	3%	4%	5%	6%
	Time Saved (Added) per Passenger	0:11:28	0:11:38	0:11:39	0:11:32	0:11:38	0:11:35
	Total Time Saved (Lost)	4:29:35	5:35:03	6:45:37	9:14:58	11:30:56	13:37:09
Negative	% On-board Negatively Affected	4%	5%	4%	5%	4%	4%
	% Downstream Negatively Affected	12%	12%	12%	11%	11%	10%
	Time Saved (Added) per Passenger	(0:02:18)	(0:02:20)	(0:02:20)	(0:02:21)	(0:02:19)	(0:02:21)
	Total Time Saved (Lost)	(7:54:06)	(7:53:57)	(7:47:05)	(7:38:28)	(7:02:52)	(6:48:45)
	Net WT Savings per Aff. Passenger	(0:02:39)	(0:01:39)	(0:00:41)	0:00:56	0:02:25	0:03:17
	Net Wait Time Savings per Bus Hold	(0:22:40)	(0:15:24)	(0:06:43)	0:10:28	0:29:11	0:44:37
	Net Total Wait Time Saved (Lost)	(3:24:31)	(2:18:54)	(1:01:28)	1:36:30	4:28:04	6:48:23

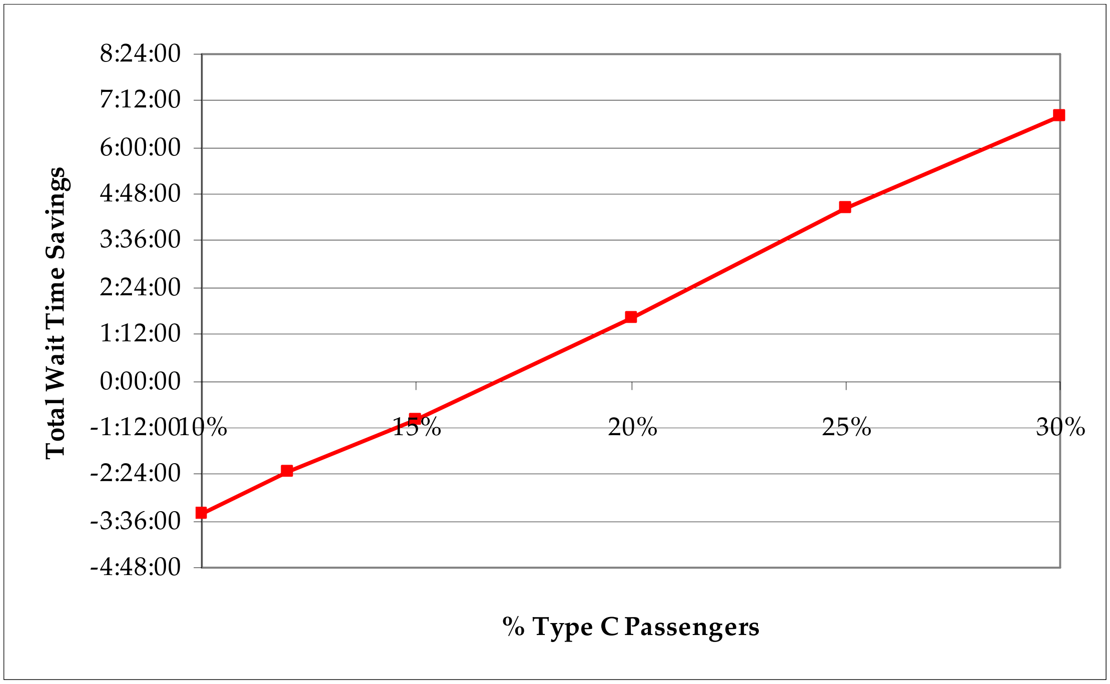

Figure 5-6: Sensitivity to Passenger Mix – 79th Street Station

As shown in Figure 5-6, total wait time savings increases linearly with the percentage of passengers boarding from rail at 79th Street (Type C passengers). We can see that a one percent increase in Type C passengers causes roughly a 30-minute increase in total wait time savings. More importantly, we see that the headway-based hold light system produces overall wait time savings when Type C passengers constitute approximately 17% of total ridership, which is near the value, 20%, found in the similar analysis of Wellington Station in Section 5.1.4b. The total wait time savings reaches 10% of the base passenger wait time when the percentage of C passengers is approximately 35%, and reaches 25% of the base passenger wait time when the percentage of C passengers is approximately 60%. Since passenger arrivals do not affect holding decisions, changing the passenger mix has no effect on the percentage of bus trips held or hold times.

d) Bus Headway

In this analysis, the scheduled headways of Routes 8A and 75 are artificially increased to determine the effects on the results of the headway-based hold light system. The range of headways from 10 to 20 minutes is examined in intervals of 2 minutes, with 12 minutes as the base case. In the analysis, the size of the portion of the target arrival time distribution prior to the scheduled departure is adjusted proportionally to the headway (i.e. the earliest passengers target 5 minutes prior to the scheduled departure for the 10-minutes headway case, and 6 minutes prior to the scheduled departure for the 12-minute headway case). Also, the total number of riders on each route is evenly distributed over all trips.

Table 5-15 below shows the results of the sensitivity analysis of the headway-based hold light system with respect to variation in scheduled bus headway for the 79th Street case.

Table 5-15: Sensitivity to Scheduled Bus Headway – 79th Street Station

	Scheduled Bus Headway (minutes)	**10**	**12**	**14**	**16**	**18**	**20**
Positive	% Passengers Positively Affected	2%	2%	2%	2%	2%	2%
	Time Saved (Added) per Passenger	0:08:18	0:11:38	0:12:20	0:14:22	0:16:14	0:17:59
	Total Time Saved (Lost)	3:18:36	5:35:03	5:45:07	6:05:58	6:47:37	6:48:46
Negative	% On-board Negatively Affected	5%	5%	5%	5%	5%	5%
	% Downstream Negatively Affected	12%	12%	12%	12%	12%	12%
	Time Saved (Added) per Passenger	(0:02:21)	(0:02:20)	(0:02:17)	(0:02:19)	(0:02:19)	(0:02:20)
	Total Time Saved (Lost)	(8:12:03)	(7:53:57)	(7:47:49)	(7:55:18)	(8:15:13)	(8:12:56)
	Net WT Savings per Aff. Passenger	(0:03:30)	(0:01:39)	(0:01:27)	(0:01:19)	(0:01:01)	(0:01:00)
	Net Wait Time Savings per Bus Hold	(0:31:05)	(0:15:24)	(0:13:28)	(0:12:10)	(0:09:29)	(0:09:13)
	Net Total Wait Time Saved (Lost)	(4:53:27)	(2:18:54)	(2:02:41)	(1:49:20)	(1:27:36)	(1:24:10)

As shown in Table 5-15, total wait time begins to decrease rapidly as scheduled bus headway increases from ten minutes, but the decrease slows as total wait time savings approaches zero. We can see that this is caused by an increase in wait time savings per positively affected passenger as the scheduled headways increase and penalties for missing a connection become more severe. Once again, there is no effect on the percentage of bus trips held or hold times. From this sensitivity analysis we can draw the conclusion that passenger mix is essential to the success of the headway-based hold light system. Although bus headway and passenger arrival behavior are important factors, if the passenger mix is not strongly transfer-oriented, there is no chance at achieving wait time savings.

5.2.6 79th Street Station Summary

From the 79th Street Station case study, we see that although the headway-based hold light system can produce substantial wait time savings in the proper environment, the same system can produce significant passenger delays if conditions are not right. It would be possibly worth considering the use of the headway-based hold light system at locations such as 79th Street during the non-peak hours when headways are longer and passengers are more averse to missed connections. From the sensitivity analysis of this case, we see that the fraction of total route boardings that take place locally is small enough that the distribution of these boardings has a relatively small impact on total wait time savings produced by the headway-based hold light system. We also see that the percentage of route passengers boarding at the transfer station can make the difference between the success and failure of the system, with the point of indifference at approximately 17% transfer passengers in this case. The total wait time savings reaches 10% of the base passenger wait time when the percentage of C passengers is approximately 35%, and reaches 25% of the base passenger wait time when the percentage of C passengers is approximately 60%.

6 CONCLUSION

This chapter concludes the thesis by providing a summary of the results of the research conducted. The chapter includes a review of the framework for the models developed, a description of the headway-based hold light system analyzed, a summary of the major findings for each of the three cases studied, guidelines for selecting transfer stations appropriate for implementation of the headway-based hold light system, and suggestions for further research in the area of bus holding, specifically relating to the headway-based hold light system and similar systems.

6.1 Summary

While transfers are a necessity in large transit networks, they carry significant disbenefits, which can sometimes cause passengers to use other modes of transportation or to avoid making trips. As a result, it is in the best interest of transit agencies to make the transfer process as efficient and reliable as possible. This research focused on attempting to make improvements in these areas through the use of operations control methods, specifically bus holding strategies. In the effort to improve transfer connectivity through a simple-to-implement, low-cost dispatching strategy, the concept of a headway-based hold light system was introduced. An analytical model and a simulation model were then developed to analyze the impacts of this system on transfer performance.

The models developed were first applied to a simple hypothetical scenario in an effort to gain an understanding of the effects of external factors on the headway-based hold light system. The models were then applied in the context of the PM peak period (4:30 to 7:00) to the cases of Alewife and Wellington Stations in the Massachusetts Bay Transportation Authority (MBTA) system and to 79th Street Station in the Chicago

Transit Authority (CTA) system. Throughout these analyses, the sensitivity to various factors was analyzed, and the results obtained with the headway-based hold light system were compared with those obtained from the application of other bus dispatching strategies, specifically the hold-all-buses strategy (where every departing bus is held for passengers transferring from the next arriving train).

The headway-based hold light system is similar to a traditional hold light system (where a hold light is activated when a train reaches a specific track circuit, then remains "on" for a specified interval) in the way it operates from a bus operator's point of view, but instead of simply being activated when a train reaches a specific track circuit, the hold light is activated when the gap between train arrivals reaches a pre-set length. In the case of long train headways, it is often the case at these times that passenger loads are higher than average, since passengers have had more time between trains to arrive on the platforms at upstream stations. In this vein, we can generally assume that more passengers who plan to transfer to bus routes are on these trains. Additionally, since passengers target specific bus trips when scheduled bus headways are large, there are generally even more passengers transferring to a particular bus trip on trains arriving just prior to the scheduled departure time of the target bus trip. These high transfer volumes arriving on trains immediately before target bus departures make these connections vulnerable to even minor rail disruptions. The headway-based hold light is a potential solution to this problem, as it ensures that, if a long-headway occurs immediately prior to a bus departure, the bus will hold for the expected high volume of passengers transferring from the next arriving train.

The effectiveness of this system is dependent on several characteristics of the service at stations where the system is implemented, particularly bus and rail frequency, and the percentage of total bus route riders who transfer to the route from rail at the transfer station. In appropriate situations, the system is expected to produce substantial savings in passenger wait time, as it results in a portion of the transfer passengers (those who are transferring from the train for which the bus is holding) saving a large amount of wait time, since they otherwise would have had to wait for the next trip, while a relatively large number of passengers must endure a short extra wait.

6.2 *Key Findings*

The application of the analytical and simulation models to the three cases confirmed expectations that significant wait time savings can be realized through the implementation of the headway-based hold light system when the system is used in an appropriate environment. While wait time savings will often be less than if a traditional hold light system or a strategy of holding all buses for the next arriving train were in place, the headway-based hold light system has a number of characteristics that make it superior to the traditional hold light systems, in particular that it only affects a relatively small portion of the bus trips and passengers.

6.2.1 Alewife Station

Alewife Station was selected as the primary case for the application of the headway-based hold light system as it is an ideal location for such a system. During the PM peak, the vast majority of passengers on bus routes serving Alewife Station transfer from rail and board at the station. During this period, the routes have large headways, generally 20-40 minutes, meaning holding buses for short intervals is not likely to adversely affect operations, while wait time savings for transferring passengers who make their connections as a result of a hold are substantial.

The base application of the simulation model to the Alewife Station resulted in 33 hours of passenger wait time savings per PM peak period with the headway-based hold light (long headway threshold = 4 min.) compared with only 17 hours of passenger wait time savings with the hold-all-buses strategy. This supports the hypothesis that significant wait time savings are attainable through either strategy when the setting is conducive to bus holding. While both strategies were successful in terms of total passenger wait time savings, one significant advantage of the headway-based hold light system is its efficiency. In this case, only 39% of bus trips were held. Although the analytical model (but not the simulation model) estimated that the hold-all-buses strategy would provide almost twice as much passenger wait time savings, efficiency is the strong point of the headway-based hold light system as it only holds a fraction of the bus trips. This is important because frequent and significant delays can have severe negative impacts on operations.

Sensitivity analysis showed that the headway-based hold light system is quite sensitive to the long headway threshold (i.e. the threshold headway selected for holding). The system is also quite sensitive to passenger arrival behavior, particularly the size of the interval over which passengers plan to arrive. When passenger target arrival times are concentrated near the scheduled bus departure time, wait time savings are much greater than the case where target arrival times are spread evenly over a larger interval. It was shown that if out-of-vehicle wait time is weighed more heavily than in-vehicle delay time, as is common practice in transportation modeling, the headway-based hold light system is even more attractive, as the system saves some passengers from having to wait at a station, while causing a relatively short in-vehicle delay to other passengers. The results of these sensitivity analyses serve to underscore the importance of the trade-offs the transit agency must make in setting the hold light system parameters. Additionally, the incremental benefits of incorporating real-time information into the headway-based hold light system in terms of total wait time savings were estimated to be 6.3%. The issue of route interdependence is not considered in this analysis although it causes wait time savings to be overestimated.

6.2.2 Wellington Station

Wellington Station was selected as a case for the application of the headway-based hold light system as it exhibits many of the ideal characteristics of Alewife Station, while presenting the challenge of many passengers boarding downstream. The routes serving Wellington have long headways like the Alewife routes, meaning holding buses for short intervals is still not likely to adversely affect operations. Additionally, there are very few walk-in bus boardings at Wellington in this period. Since many of the bus routes serving Wellington Station do have significant downstream boardings, it was expected that the relative wait time savings produced by the headway-based hold light system and the hold-all-buses strategy would be much less than if all passengers were to board at Wellington.

As expected, the Wellington Station case allowed us to see the very significant effects of downstream boardings on the effectiveness of the headway-based hold light system. While one might be inclined to think this would make the headway-based hold light system produce more total delay than wait time savings, the system is still able to produce significant wait time savings at Wellington Station (approximately 32 hours per PM peak period with long headway threshold = 5 minutes), but we would expect some of the routes that serve Wellington Station are approaching levels of downstream boardings that would not be conducive to the use of the headway-based hold light system. Unlike the Alewife case however, the strategy of holding all buses was not able to produce positive benefits in terms of total wait time savings, as the application of this strategy resulted in a 42-hour increase in total wait time. In the sensitivity analysis of this case, it was demonstrated that when dealing strictly with Type C passengers (who board at the transfer point) and Type D passengers (who board downstream), the passenger mix is linearly related to the total wait time savings, where the critical value of Type C passengers (the value at which wait time savings is zero) is approximately 20%. This results of this sensitivity analysis show that the importance of setting the long headway threshold correctly is magnified greatly by the presence of large numbers of downstream boardings.

6.2.3 79th Street Station

In an effort to build on the positive characteristics of the previous cases, while introducing one additional challenge to the application of the proposed system, 79th Street Station in the CTA system was selected as it is served by bus routes with significantly shorter scheduled headways than those serving Alewife or Wellington. The different structures of the MBTA and CTA bus networks causes this difference, and causes the percentage of total route boardings taking place at 79th Street to be very small (e.g. 12-13% of total boardings as compared to 35-89% at Wellington), since it is not a single dominant transfer station as was the case with Alewife and Wellington. The combination of these characteristics was expected to substantially limit the benefits produced by each of the holding strategies.

From the 79th Street Station case study, we see that although bus holding at transfer stations can produce substantial wait time savings in the proper environment, the same systems can produce significant passenger delays if conditions are unfavorable. The application of the headway-based hold light model to the 79th Street case resulted in a 2-hour increase in total passenger wait time per PM peak period, while the hold-all-buses strategy resulted in a considerable 46-hour increase. The sensitivity analysis of this case showed that the negative effects of the headway-based hold light system so far outweigh the benefits provided in this case that a net positive result was not possible, regardless of the long headway threshold. This is because the fraction of total route boardings that come from rail transfers is so small that the wait time savings from these boardings is a very small portion of the total delays for through and downstream passengers produced by the headway-based hold light system. The most significant sensitivity analysis of the 79th Street case showed that the passenger mix is much more influential than the scheduled bus headway in determining the success of the headway-based hold light system. When 17% of passengers transfer at 79th Street, the total wait time savings become positive, at 35% transfer passengers approximately 10% of total wait time is saved, and at 60% transfer passengers approximately 25% of total wait time is saved.

6.3 Guidelines for Headway-based Hold Light System Implementation

Following are a preliminary set of guidelines drawn from this research regarding the selection of transfer points where headway-based hold light systems may be effective. The guidelines are based on the case study results and the related sensitivity analyses performed in this research.

- *Passenger mix*: As shown in the 79th Street Station case, passenger mix – which is linearly related to total wait time savings – is the most important single determinant of the headway-based hold light's success. In order to produce wait time savings, no fewer than approximately 20% of passengers riding the route of interest should board at the transfer station. Substantial wait time savings (on the order of 25%) can be achieved when approximately 60% of the passengers board at the transfer station.

- *Frequency*: The ideal situation for the headway-based hold light is a transfer point where passengers transfer from high-frequency rail service to low-frequency bus service. In order to produce wait time savings, it is not essential to operate low-frequency bus service, but the wait time savings per passenger will be less with high-frequency service since penalties for missing connections are not as significant as with low-frequency service. Bus frequency is also the main driver of passenger arrival behavior, as passengers transferring to low-frequency bus routes will target a specific trip, whereas passengers transferring to high-frequency service will arrive at the transfer station simply planning to board the next trip. Additionally, operations considerations may make it infeasible to hold buses on high-frequency routes. The boundary between high- and low-frequency routes generally occurs at a headway value between 8-14 minutes according to Furth (2006).

- *Passenger arrival behavior*: As mentioned above, passenger arrival behavior is heavily dependent on scheduled bus headway. Since passengers target specific bus trips on low-frequency routes, transferring passengers are usually concentrated on a small number of arriving trains. If one of these trains is delayed, this could cost a large number of transfer passengers the chance to make their connection. If the headway-based hold light is in place, however, the bus will be held for the connections to be made. Because of the large potential for savings in these situations, the headway-based hold light system generally produces greater wait time savings at transfer stations served by low-frequency bus routes. Conversely, since passengers transferring to high-frequency routes do not target specific bus trips, transferring passengers are spread evenly over all train arrivals, meaning if a hold does occur, a smaller fraction of total transfer passengers will benefit than in the low-frequency service case. With regard to bus routes with headways 20 minutes or greater, this research showed that wait time savings can be significant (up to 25% of total passenger wait time). This assumes a relatively wide distribution of passenger arrival times. If passenger arrival behavior is actually more focused on the bus departure time, this research suggests that much larger wait time savings are possible.

- *Directionality of travel*: From an operations standpoint, it is useful if travel in the analysis period is highly skewed toward trips heading outbound from the transfer point. When a bus trip is held past its scheduled recovery time, it is likely that the return trip will be late. In the case where travel is highly directional, rather than considering only the recovery time following the outbound trip, we can consider the round-trip recovery time, because it is of lesser concern whether the inbound trip is late. The ability to consider round-trip rather than one-way recovery times gives the agency the potential to hold trips longer without significant risk of causing operations issues.

- *Long headway threshold*: the long headway threshold should generally be set equal to or slightly higher than the average scheduled rail headway. The ideal value is where the majority of the potential wait time savings can be captured, while only holding a relatively small number of bus trips. See Sections 4.6.1 and 5.1.4a for examples of long-headway threshold selection.

6.4 Further Research

While this research introduces the headway-based hold light system and examines its application to three cases of increasing complexity, many areas remain in which further research relating to the headway-based hold light system and bus holding strategies in general would be useful in supporting or extending the findings of this thesis. Five of the most significant of these topics are identified in this section.

6.4.1 Passenger Arrival Behavior

Probably the most important area for further research relating to bus holding strategies, and particularly the headway-based hold light, is that of passenger arrival behavior. As the simulation model developed in this research is heavily reliant on the somewhat arbitrary triangular passenger arrival time distribution presented in Section 3.6 (which is designed to apply to low-frequency bus routes), the true effects of the underlying passenger behavior with regard to their targeted times of arrival at a transfer station on the headway-based hold light system and other operations control strategies remain unclear. Evidence suggests that the holding strategies will be much more beneficial if passengers tend to arrive closer to scheduled bus departures than assumed in this research. In this research specifically, it would be much more desirable to utilize a model which more realistically estimates the arrival behavior of passengers transferring from rail to bus as well as walk-in passengers. While research in this area could be tremendously beneficial, it is not particularly easy to pursue, as the data collection aspect of the research is daunting.

6.4.2 Impacts of Bus Route Interdependence

While it is assumed in this research that passengers who miss a bus trip will board the next departure on the same route rather than board an earlier departure on a different route, this is not always the case. In many cases, passengers living in neighborhoods served by multiple routes board the first bus departure from the set of those routes. While the effects of route interdependence are difficult to quantify, it is clear that interdependence causes a reduction in total passenger wait times.

As mentioned in Section 4.8, a simple analysis of this topic using data from one PM peak period at Alewife Station estimated that 12% of the wait time savings estimated by the analytical model would be lost due to bus route interdependence. A more advanced and extensive approach to examining these effects would be very useful in estimating the true effects of bus route interdependence on operations control strategies. Additionally, a better understanding of how passengers choose between routes would be beneficial to operations and planning personnel.

6.4.3 Operations Impacts

One potentially useful extension of this research would be to integrate the headway-based hold light model with a simulation model of bus route operations to see on a closer level the impacts of holding buses in certain situations. This could be a valuable tool in analyzing the trade-offs between the increase in total wait time savings and the increase in bus holds generally produced by shorter long headway intervals. If transit agencies were able to utilize knowledge on a microscopic level of the interaction between buses operating on a common route, it seems a great deal more could be learned about the benefits and costs of operations control strategies, particularly with regard to high- and medium-frequency bus routes.

6.4.4 Network Effects

In addition to the potential for research in more basic areas of operations, there is potential for research into the effects of holding strategies at one station on operations at other stations in the network, particularly those served by common bus routes. In addition to examining the effects of holding on operations at other stations, such research would allow agencies to explore more complex issues such as whether passenger wait time could be saved by coordinated holding strategies at multiple stops on a single bus line.

6.4.5 Impacts of Technology

A final topic which could potentially be valuable to explore is the way in which new technology and the more advanced use of current technology can be used to improve the efficiency of bus holding strategies and how extensive these improvements will be. As transit agencies are just beginning to realize the potential benefits of new technology, it is reasonable to expect that advances in the near future, primarily those improving the distribution of information, will play a significant role in improving operations control strategies.

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Appendix A: Alewife and Wellington Data

Alewife Station Red Line Data

Alewife Station – November 4, 2004 (Thursday)

Train Arrival Time	Est. Pass. Leaving Station	Comments
16:13:13	31	
16:17:28	16	
16:25:43	102	Held for one departure
16:27:05	68	
16:30:44	51	
16:33:15	49	
16:39:38	94	
16:42:11	57	
16:46:16	84	
16:56:10	152	
16:58:09	64	
17:01:03	--	In from Bay behind station
17:04:08	126	
17:10:26	118	
17:15:11	66	
17:17:35	75	
17:20:07	72	
17:26:50	254	Held for one departure
17:30:14	137	
17:34:40	115	
17:36:46	93	
17:40:59	147	
17:44:25	112	
17:47:43	94	
17:50:40	111	
17:55:42	118	
18:00:12	74	
18:04:52	175	
18:19:06	270	
18:21:39	157	
18:24:32	55	
18:29:12	57	
18:42:21	231	Removed from service
18:46:05	96	
18:50:54	53	
18:59:18	180	

Alewife Station – November 9, 2004 (Tuesday)

Train Arrival Time	Est. Pass. Leaving Station	Comments
16:28:10	50	
16:36:50	157	First 10 people running very fast out of the gates.
16:39:50	67	
16:45:25	48	
16:48:13	46	
16:55:20	94	
16:58:12	88	
17:04:38	154	
17:09:20	135	No runners, people slow to mezz area (20 seconds)
17:15:07	84	
17:17:32	0	*** Train from back storage ***
17:20:54	110	
17:23:58	142	
17:27:46	122	
17:30:16	107	10 + runners
17:34:15	219	
17:39:29	203	
17:41:54	155	
17:47:15	115	
17:53:03	262	
17:56:52	82	
18:02:54	99	
18:12:49	150	Tracks empty after 18:09:51 departure
18:16:42	194	
18:22:05	186	Train went out of service for 9 minutes
18:26:10	132	
18:30:22	50	
18:33:51	149	
18:38:41	100	
18:43:26	58	
18:46:55	39	
18:51:36	163	Out of service for 11 minutes
18:54:57	46	
18:59:37	74	
19:01:31	47	
19:04:38	52	
19:08:06	23	

Alewife Station – November 16, 2004 (Tuesday)

Train Arrival Time	Est. Pass. Leaving Station	Comments
16:34:08	47	
16:39:00	43	
16:47:56	135	
16:50:36	76	
16:53:04	43	
16:57:04	73	
17:02:17	55	
17:04:21	55	
17:06:50	69	
17:09:06	75	
17:15:08	46	
17:18:16	145	
17:20:43	88	
17:24:25	75	
17:27:17	95	
17:32:03	176	
17:36:21	151	
17:47:05	134	
17:53:39	147	<===Between 5:45 PM and 5:52 PM, counts were interrupted by passenger
17:58:26	132	
18:01:18	84	
18:03:48	87	Between 5:45 PM and 5:52 PM, counts were interrupted by passenger ===>
18:07:53	100	
18:14:52	149	
18:18:42	86	
18:21:59	91	
18:25:37	61	
18:28:08	105	
18:35:24	106	
18:41:50	74	
18:42:54	48	
18:46:48	53	
18:49:51	52	
18:52:52	63	
18:58:04	62	
19:01:21	63	

Alewife Station – October 6, 2005 (Thursday)

Train Arrival Time	Est. Pass. Leaving Station	Comments
17:44:00	28	
17:49:00	50	
17:51:31	21	
17:57:44	36	
18:06:26	49	
18:12:04	43	
18:17:35	19	
18:20:30	17	
18:23:01	12	
18:26:18	15	
18:28:03	16	
18:32:29	11	
18:34:19	17	
18:42:38	32	
18:45:43	9	
18:48:18	13	
18:52:31	16	
18:57:21	17	

Alewife Station – October 11, 2005 (Tuesday)

Train Arrival Time	Est. Pass. Leaving Station	Comments
16:29:12	16	
16:31:12	15	
16:37:30	29	
16:43:49	33	
16:50:41	32	
16:55:37	25	
16:58:58	17	
17:08:38	48	
17:12:50	21	
17:22:04	64	
17:24:45	24	
17:27:49	22	
17:30:34	27	
17:33:10	27	
17:36:54	52	
17:39:59	30	
17:43:06	29	
17:47:29	30	
17:53:06	57	
18:00:06	61	
18:06:28	48	
18:09:44	34	
18:12:04	20	
18:18:07	9	
18:20:36	22	
18:25:23	19	
18:28:51	12	
18:31:50	13	
18:36:52	37	
18:41:26	16	
18:45:36	16	
18:50:05	28	
18:52:30	16	
19:01:44	18	
19:05:49	5	

Alewife Station – October 20, 2005 (Thursday)

Train Arrival Time	Est. Pass. Leaving Station	Comments
17:26:42	20	
17:31:30	48	
17:34:00	18	
17:36:14	16	
17:48:37	49	
17:51:17	34	
17:54:07	26	
17:58:47	22	
18:01:00	14	
18:04:25	21	
18:06:42	18	
18:15:37	34	
18:17:53	19	
18:27:39	32	
18:34:34	25	
18:37:49	9	
18:42:00	9	
18:46:30	9	
18:49:03	7	
18:52:43	12	
18:56:37	5	
19:02:49	10	
19:04:07	12	

Alewife Station Bus Data

Alewife Station – November 4, 2004 (Thursday)

Route	Sched. Leav. Time	Bus #	Pass. at Sched. Dep. Time	Total Pass.	Actual Dep. Time
62	16:45	0069	21	21	16:45:22
62	17:15	0229	20	20	17:15:00
62	17:37	0041	17	24	17:41:30
62	17:48	0117	23	31	17:51:39
62	18:20	0041	21	34	18:23:56
62	19:00	0243	21	31	19:02:00
67	16:45	0439		9	16:49:32
67	17:10	0369	18	18	17:10:13
67	17:35	0437	25	25	17:35:13
67	18:00	0369	19	21	18:01:52
67	18:25	0437	16		18:25:17
76	16:30	0321	14	14	16:31:23
76	17:00	0357	18	23	17:01:52
76	17:30	0243	32	32	17:30:06
76	18:00	0321	18	23	18:03:45
76	18:40	0357		8	18:42:22
79	16:36	0029	25	25	16:36:16
79	16:47	0015	6	6	16:47:32
79	16:58	0487		6	16:59:57
79	17:09	0353		11	17:12:27
79	17:20	0067	5	8	17:20:28
79	17:31	0029		27	17:33:09
79	17:43	0015		18	17:45:40
79	17:55	0045	15	15	17:55:32
79	18:10	0055	22	22	18:09:20
79	18:25	0067	10	10	18:25:01
79	18:40	0015	9	9	18:40:22
79	18:52	0045	18	18	18:52:19
84	16:33	8018	10	10	16:33:50
84	16:50	0239	7	7	16:50:29
84	17:07	8018			
84	17:24	0239	9	9	17:25:14
84	17:41	8016	8	8	17:41:15
84	17:58	0239	14	17	
84	18:15	8018	11	11	18:16:06
350	16:40	0355	11	16	16:41:41
350	17:00	0329	14		17:00:15
350	17:20	0051	20		17:20:22
350	17:40				17:39:00
350	18:00	0369		15	18:00:24
350	18:20	0125	10	10	18:22:11
350	18:50	0355	15	17	18:52:55

Alewife Station – November 9, 2004 (Tuesday)

Route	Sched. Leav. Time	Bus #	Pass. at Sched. Dep. Time	Total Pass.	Actual Dep. Time
62	16:45	0025	16	20	16:47:35
62	17:15	0087	30	34	17:17:15
62	17:37	0357	34	45	17:42:42
62	17:48	0021	36	43	17:50:10
62	18:20	0357	30	35	18:21:02
62	19:00	0043		30	19:09:40
67	16:45	0439	13	15	16:46:29
67	17:10	0055	16	18	17:11:44
67	17:35	0439	20	29	17:37:05
67	18:00	0055	25	25	18:00:09
67	18:25	0439	15	16	18:26:38
76	16:30	0075	10	10	16:31:52
76	17:00	0363	20	20	17:01:17
76	17:30	0043	20	44	17:37:00
76	18:00	0075	20	40	18:05:00
76	18:40	0363	30	30	18:41:40
79	16:36	0057	20	25	16:38:52
79	16:47	0063		9	17:02:51
79	16:58				
79	17:09	0241	8	8	17:09:10
79	17:20	0041	10	30	17:25:00
79	17:31	0057	28	21	17:33:00
79	17:43				
79	17:55	0063		38	17:57:00
79	18:10	0241	7	7	18:10:41
79	18:25	0041	19	20	18:25:20
79	18:40	0327	31	31	18:40:53
79	18:52	0063	1	2	18:53:00
84	16:33	8020	2	2	16:33:30
84	16:50				
84	17:07			5	17:11:15
84	17:24	8018	10	15	17:26:20
84	17:41	8020	20	26	17:45:40
84	17:58	8018	28	32	17:59:10
84	18:15	0041	6	10	18:19:10
350	16:40	0027	16	16	16:40:30
350	17:00	0121	23	23	16:59:57
350	17:20	0125		25	17:23:57
350	17:40	0353		20	17:39:40
350	18:00	0243		30	18:03:02
350	18:20	0089	20	25	18:21:18
350	18:50	0027	13	13	18:50:08

Alewife Station – November 16, 2004 (Tuesday)

Route	Sched. Leav. Time	Bus #	Pass. at Sched. Dep. Time	Total Pass.	Actual Dep. Time
62	16:45	0017	20	20	16:46:20
62	17:15	missed (talking to dispatcher)			
62	17:37	0439	20	31	17:39:48
62	17:48	0247	25	42	17:50:05
62	18:20	0439	24	35	18:26:47
62	19:00	0061	22	25	19:04:40
67	16:45	0447	15	15	16:45:54
67	17:10	0181	30	90	17:10:50
67	17:35	0447	40	45	17:36:20
67	18:00	0181	25	25	18:01:20
67	18:25	0447	22	22	18:26:10
76	16:30				
76	17:00	0359	31	31	17:03:02
76	17:30	0061	38	39	17:30:58
76	18:00	0359	32	43	18:03:28
76	18:40	0359	16	21	18:43:58
79	16:36				
79	16:47	0027	9	9	16:47:29
79	16:58				
79	17:09			10	17:07:20
79	17:20	0015	6	9	17:22:18
79	17:31	0027			
79	17:43	0239	17	17	17:46:05
79	17:55	0087		13	17:58:02
79	18:10	0025	18	18	18:10:18
79	18:25	0015		11	18:28:11
79	18:40	0239		25	18:42:27
79	18:52	0087	8	8	18:52:40
84	16:33				
84	16:50	8014	3	3	16:51:40
84	17:07	8000	8	18	17:10:20
84	17:24	8014	8	8	17:25:26
84	17:41	8000	14	14	17:43:07
84	17:58	8014	12	16	17:59:45
84	18:15	8000	8	14	18:19:40
350	16:40	0387	21	26	16:41:54
350	17:00	0085	18	18	17:03:05
350	17:20	0153	22	28	17:22:10
350	17:40	0381		20	17:39:01
350	18:00	0343		28	18:03:57
350	18:20	0179	21	23	18:22:00
350	18:50	0349	9	10	18:50:48

Alewife Station – October 6, 2005 (Thursday)

Route	Sched. Leav. Time	Pass. at Sched. Dep. Time	Total Pass.	Actual Dep. Time
62	16:45:00		19	16:46:13
62	17:15:00	14	25	17:16:40
62	17:37:00	6	16	17:38:30
62	17:48:00	53	56	17:49:35
62	18:20:00		38	18:23:37
62	19:00:00		24	19:04:56
67	16:45:00		10	16:46:52
67	17:10:00		21	17:09:56
67	17:35:00		20	17:38:47
67	18:00:00	25	27	18:01:05
67	18:25:00	20	20	18:26:25
76	16:30:00	16	18	16:31:50
76	17:00:00		22	17:01:29
76	17:30:00		25	17:35:00
76	18:00:00		53	18:09:39
76	18:40:00		24	18:42:52
79	16:44:00	13	13	16:43:37
79	17:00:00		21	17:00:26
79	17:16:00			
79	17:32:00		15	17:39:47
79	17:48:00			
79	18:04:00	26	26	18:04:29
79	18:20:00	8	16	18:21:00
79	18:36:00	11	24	18:42:18
79	18:52:00		7	18:55:40
84	16:33:00	1	1	16:33:45
84	17:07:00	1	12	17:08:20
84	17:24:00		6	17:25:40
84	17:41:00	10	11	17:41:42
84	17:58:00	19	25	17:58:32
84	18:15:00	9	9	18:15:47
350	16:40:00		2	16:41:43
350	17:00:00		11	17:00:27
350	17:20:00		15	17:24:40
350	17:40:00			
350	18:00:00		38	17:57:57
350			3	18:03:00
350	18:20:00	12	22	18:21:20
350	18:50:00		25	18:54:00

Alewife Station – October 11, 2005 (Tuesday)

Route	Sched. Leav. Time	Pass. at Sched. Dep. Time	Total Pass.	Actual Dep. Time
62	16:45:00	22	33	16:46:08
62	17:15:00		26	17:17:33
62	17:37:00	5	8	17:37:25
62	17:48:00	35	42	17:49:33
62	18:20:00		40	18:23:00
62	19:00:00		25	19:13:32
67	16:45:00	9	9	16:45:08
67	17:10:00	18	25	17:11:10
67	17:35:00	33	33	17:35:30
67	18:00:00	23	27	18:02:47
67	18:25:00	19	19	18:25:27
76	16:30:00		25	16:34:38
76	17:00:00	15	21	17:00:55
76	17:30:00		36	17:36:10
76	18:00:00		40	18:03:02
76	18:40:00	8	26	18:43:30
79	16:44:00	9	18	16:47:16
79	17:00:00	10	10	17:00:03
79	17:16:00	14	18	17:17:30
79	17:32:00	24	24	17:32:51
79	17:48:00	15	21	17:50:50
79	18:04:00			18:04:00
79	18:20:00	8	12	18:30:50
79	18:36:00	14	18	18:44:04
79	18:52:00	5	8	18:52:26
84	16:33:00	10	10	16:33:20
84	17:07:00	8	8	17:07:45
84	17:24:00		13	17:25:18
84	17:41:00		18	17:42:26
84	17:58:00		15	18:00:18
84	18:15:00		19	18:16:48
350	16:40:00	13	13	16:40:25
350	17:00:00	16	17	17:00:18
350	17:20:00	12	12	17:21:03
350	17:40:00	34	34	17:40:10
350	18:00:00	13	13	18:06:55
350	18:20:00	25	27	18:22:45
350	18:50:00	12	13	18:51:10

Alewife Station – October 20, 2005 (Thursday)

Route	Sched. Leav. Time	Pass. at Sched. Dep. Time	Total Pass.	Actual Dep. Time
62	16:45:00		33	16:47:06
62	17:15:00		40	17:16:31
62	17:37:00		15	17:41:00
62	17:48:00	17	17	17:48:04
62	18:20:00		27	18:21:55
62	19:00:00		24	19:07:20
67	16:45:00	14	14	16:45:17
67	17:10:00	25	32	17:11:16
67	17:35:00	26	32	17:36:15
67	18:00:00	20	27	18:02:35
67	18:25:00	17	17	18:25:03
76	16:30:00			16:31:37
76	17:00:00		28	17:03:45
76	17:30:00		36	17:34:47
76	18:00:00		34	18:06:11
76	18:40:00		29	18:43:31
79	16:44:00	9	10	16:46:01
79	17:00:00			
79	17:16:00	17	17	17:14:00
79	17:32:00	16	16	17:28:00
79	17:48:00	8	8	17:46:35
79	18:04:00	12	16	18:04:19
79	18:20:00		22	18:21:37
79	18:36:00	7	9	18:36:26
79	18:52:00		3	18:53:10
84	16:33:00	4	4	16:33:20
84	17:07:00		5	17:08:06
84	17:24:00		12	17:27:28
84	17:41:00		10	17:42:59
84	17:58:00		19	18:00:31
84	18:15:00	7	7	18:16:15
350	16:40:00		22	16:46:02
350	17:00:00	24	31	17:00:49
350	17:20:00	17	17	17:20:48
350	17:40:00	29	29	17:40:12
350	18:00:00		37	18:02:30
350	18:20:00		10	18:21:07
350	18:50:00		26	18:53:24

Wellington Station Orange Line Data

Wellington Station – November 4, 2004 (Thursday)

Train Arrival Time	Est. Pass. Leaving Station	Comments
16:22:18	85	
16:26:36	63	
16:30:49	67	
16:39:25	165	
16:43:06	50	
16:46:09	55	
16:49:31	98	
16:53:18	123	
16:57:58	58	
17:01:00	115	
17:04:52	76	
17:11:33	139	
17:14:36	58	
17:23:23	176	
17:29:41	193	
17:38:50	160	
17:41:30	154	
17:47:05	125	
17:52:44	146	
18:02:17	173	
18:06:01	98	
18:10:10	41	
18:12:50	79	
18:16:31	103	
18:19:51	34	
18:23:27	57	
18:31:54	56	
18:39:57	161	
18:43:48	44	
18:46:21	41	
18:51:18	68	
18:59:38	72	
19:07:08	54	

Wellington Station – November 9, 2004 (Tuesday)

Train Arrival Time	Est. Pass. Leaving Station	Comments
16:26:34	92	
16:33:10	140	
16:37:57	93	
16:44:56	115	
16:48:43	52	train arrived relatively early
16:54:23	108	
16:57:05	79	
17:04:46	141	
17:07:46	49	
17:12:21	141	
17:15:49	75	
17:19:30	123	
17:22:43	124	
17:31:53	159	long headway
17:40:02	142	
17:44:53	106	
17:48:37	93	
17:56:34	158	
18:01:40	146	
18:07:57	97	
18:11:33	63	
18:21:44	176	
18:29:56	154	
18:35:19	106	
18:38:07	24	
18:41:27	36	
18:44:56	42	
18:49:19		held a little further from the station
18:50:25		the same train pulled in the station but didn't open the doors and there were no alightings
18:52:43	69	
18:55:14	51	
18:59:37	43	
19:02:55	21	

Wellington Station – November 16, 2004 (Tuesday)

Train Arrival Time	Est. Pass. Leaving Station	Comments
16:32:26	115+	I was on this train. Number of passengers leaving station may be higher.
16:37:38	81	
16:43:50	132	
16:52:49	160	
17:02:48	156	
17:05:17	110	
17:09:27	89	
17:12:34	97	
17:17:56	165	
17:23:02	172	
17:28:34	163	
17:38:32	167	
17:41:31	153	
17:44:40	116	
17:47:58	111	
17:52:00	112	
17:58:19	123	
18:01:40	100	
18:06:23	101	
18:15:02	151	
18:18:30	50	
18:21:19	82	
18:26:37	60	
18:29:29	47	
18:42:02	114	
18:44:38	46	
18:47:35	42	
18:51:03	64	
18:54:21	20	
18:57:23	44	
19:01:32	56	
19:06:37	36	

Wellington Station Bus Data

Wellington Station – November 4, 2004 (Thursday)

Route	Sched. Leav. Time	Bus #	Pass. at Sched. Dep. Time	Total Pass.	Actual Dep. Time
90	16:30:00	0070	5	10	16:29:56
90	17:05:00	0360	15	15	17:08:48
90	17:40:00	0070	2	2	17:39:00
90	18:15:00				
90	18:50:00	0070		3	18:57:00
97	16:35:00	0120			16:40:44
97	17:05:00	8013		6	17:11:30
97	17:35:00	8011		5	17:54:03
97	18:05:00	8021		5	18:07:06
97	18:35:00	0120		0	18:40:38
99	16:30:00	8807	10	10	16:31:04
99	16:55:00	8895	37	37	16:50:00
99	17:25:00	8667	10	10	17:27:17
99	17:45:00	8807	13	13	17:45:30
99	18:10:00	8895		12	18:12:45
99	18:35:00	8667		4	18:37:23
99	19:00:00	0388	15	17	19:02:32
100	16:40:00	8924	11	11	16:40:40
100	17:00:00	8512	12	12	17:00:00
100	17:20:00	8424	14	14	17:19:50
100	17:40:00	8512	13	13	17:40:02
100	18:00:00	8424	20	20	18:00:27
100	18:20:00	8512		16	18:19:48
100	18:40:00	8424		5	18:40:00
100	19:00:00	8512		20	18:59:38
106	16:40:00	0064	6	6	16:40:44
106	17:00:00	8876			
106	17:20:00	0326	15	15	17:21:14
106	17:40:00				
106	18:00:00	0330	12	12	18:00:50
106	18:20:00	0088		8	18:31:00
106	18:45:00	0228		8	18:47:57
108	16:30:00	0228	5	5	16:30:31
108	16:50:00	0330	5	5	16:50:02
108	17:10:00	0088	13	13	17:10:54
108	17:30:00	0444	7	7	17:29:40
108	17:50:00	0064		7	17:49:57
108	18:10:00	8566		12	18:26:22
108	18:30:00	0326		0	18:31:44
108	19:00:00	0064		15	19:00:05
110	16:30:00	0110		26	16:33:48
110	16:40:00	8668			16:42:48
110	16:50:00	0078	10	10	16:49:41
110	17:00:00	0388	25	25	17:00:40
110	17:10:00	0344	33	33	17:15:00
110	17:20:00	0110	11	11	17:21:14
110	17:30:00	0028	9	16	17:33:01
110	17:40:00	0078	4	13	17:42:27
110	17:50:00	8668	20	20	17:49:22
110	18:00:00	0344		20	18:06:28

110	18:10:00	0388		17	18:13:35
110	18:20:00	0028		25	18:23:25
110	18:40:00	8668		5	18:39:40
112	16:42:00	0346 0436		5 25	16:35:23 17:05:50
112	17:17:00				
112	17:47:00	0104	12	12	17:40:46
112	18:17:00	0360		5	18:23:20
112	18:47:00	0346		10	18:35:37
134	16:30:00	8894	26	26	16:30:31
134	16:50:00	8514	13	13	16:52:07
134	17:10:00	8876	27	27	17:11:25
134	17:30:00	0129	8	8	17:29:32
134	17:50:00	8419	20	20	17:49:31
134	18:10:00	0022	25	25	18:12:32
134	18:30:00	0129		13	18:29:24
134	19:00:00	0162		8	18:59:40

Wellington Station – November 9, 2004 (Tuesday)

Route	Sched. Leav. Time	Bus #	Pass. at Sched. Dep. Time	Total Pass.	Actual Dep. Time
90	16:30:00	0304	0	0	16:30:56
90	17:05:00	0260		2	17:25:23
90	17:40:00				
90	18:15:00				
90	18:50:00				
97	16:35:00	8021	2	2	16:35:21
97	17:05:00	8402		9	17:14:09
97	17:35:00				
97	18:05:00				
97	18:35:00				
99	16:30:00	8419		2	16:43:10
99	16:55:00	8516	17	17	16:55:23
99	17:25:00	8469	6	6	17:26:00
99	17:45:00			10	17:49:00
99	18:10:00	8516		15	18:13:37
99	18:35:00	8469	23	23	18:38:22
99	19:00:00	0066	1	4	19:01:52
100	16:40:00	8481	15	15	16:41:15
100	17:00:00	8400		9	17:05:33
100	17:20:00	8481	12	12	17:20:55
100	17:40:00	8400	15	15	
100	18:00:00	0064	22	23	18:01:55
100	18:20:00	8400	12	12	18:21:55
100	18:40:00	0064	12	12	18:41:00
100	19:00:00	8400	16	18	19:02:20
106	16:40:00	0064	29	32	16:41:10
106	17:00:00	0060	0	0	16:51:56
106	17:20:00	0012 0067	18	 21	17:12:57 17:22:28
106	17:40:00	0222	20	32	17:42:47
106	18:00:00				
106	18:20:00	0254	1	1	18:21:38
106	18:45:00	0380	4	7	18:47:33
108	16:30:00	0380		8	16:42:39
108	16:50:00	0020	2	2	16:49:42
108	17:10:00	0254	7	7	17:10:47
108	17:30:00				
108	17:50:00				
108	18:10:00				
108	18:30:00	0067	4	4	18:30:37
108	19:00:00	8481	5	5	19:04:25
110	16:30:00	0126		10	16:33:17
110	16:40:00	0341	8	13	16:41:22
110	16:50:00	0060		13	16:53:50
110	17:00:00	0066	24	24	17:05:26
110	17:10:00	0352	25	30	17:10:56
110	17:20:00	0126		26	17:23:50
110	17:30:00				
110	17:40:00				
110	17:50:00	0060	20	20	17:48:00
110	18:00:00	0352	22	24	18:00:29
110	18:10:00	0066	10	10	18:11:04
110	18:20:00	0222	12	12	18:20:44
110	18:40:00	0341	16	16	18:40:33

112	16:42:00	0440	20	20	16:36:15
112	17:17:00	0398	14	14	17:05:15
112	17:47:00	0438		10	18:05:42
112	18:17:00	0254			
112	18:47:00	0398	8	8	19:05:41
134	16:30:00	8807		13	16:33:25
134	16:50:00	8411	19	21	16:50:45
134	17:10:00	8868	15	15	17:10:56
134	17:30:00	8807		16	17:33:04
134	17:50:00	8411	30	30	17:50:00
134	18:10:00	0030	20	20	18:10:00
134	18:30:00	8807	12	20	18:33:02
134	19:00:00	0228	6	8	19:02:00

Wellington Station – November 16, 2004 (Tuesday)

Route	Sched. Leav. Time	Bus #	Pass. at Sched. Dep. Time	Total Pass.	Actual Dep. Time
90	16:30:00				
90	17:05:00				
90	17:40:00				
90	18:15:00				18:29:00
90	18:50:00	0004	0	0	18:50:00
97	16:35:00				
97	17:05:00	8540		10	
97	17:35:00	8469		13	17:56:13
97	18:05:00	8013		5	18:08:40
97	18:35:00	8011		0	18:41:28
99	16:30:00				
99	16:55:00	8895		20	16:56:47
99	17:25:00	8807	8	11	17:26:28
99	17:45:00	0120	30	30	17:45:48
99	18:10:00	8895		25	18:10:00
99	18:35:00	8807	5	5	18:35:09
99	19:00:00	0350		11	19:02:09
100	16:40:00	8876	20	21	16:42:09
100	17:00:00	8756	8	8	
100	17:20:00	0086		25	17:25:49
100	17:40:00	8756	8	11	17:42:13
100	18:00:00	0086	20	20	18:01:50
100	18:20:00	8756	9	9	18:21:50
100	18:40:00	0086	2	2	18:41:55
100	19:00:00	8756	9	15	19:00:41
106	16:40:00	0082		10	16:42:50
106	17:00:00	0012		27	17:15:46
106	17:20:00	0032		12	17:23:06
106	17:40:00	0054		11	17:51:00
106	18:00:00	0016		15	18:02:50
106	18:20:00	0398		10	18:22:30
106	18:45:00	0054		11	18:51:46
108	16:30:00				
108	16:50:00	0016	15	15	16:50:40
108	17:10:00	0398		10	17:11:09
108	17:30:00	0166	10	10	17:31:20
108	17:50:00	0082		12	17:53:00
108	18:10:00	0012		10	18:23:06
108	18:30:00	0033	5	5	18:32:05
108	19:00:00	0082	7	7	19:01:04
110	16:30:00				
110	16:40:00	8011	13	13	16:40:24
110	16:50:00	0066		30	16:55:44
110	17:00:00	0077	1	2	
110	17:10:00			25	17:16:57
110	17:20:00	0260		13	17:21:42
110	17:30:00	0430		15	17:37:56
110	17:40:00	0068		40	17:50:00
110	17:50:00				17:50:00
110	18:00:00	0452	15	15	18:01:09
110	18:10:00	0350		13	18:11:47
110	18:20:00	0430		27	18:30:55
110	18:40:00	0068	5	5	18:40:10
112	16:42:00	0114		30	17:08:00

112	17:17:00	0356		15	17:36:30
112	17:47:00	0077		10	18:11:21
112	18:17:00	0438		5	18:39:00
112	18:47:00	0114		10	19:05:45
134	16:30:00				
134	16:50:00	8424	16	16	16:51:02
134	17:10:00	0103	30	30	17:10:29
134	17:30:00	8411		12	17:31:42
134	17:50:00	0118		40	18:09:03
134	18:10:00	8411		5	18:31:24
134	18:30:00			5	18:31:24
134	19:00:00	0236		21	19:04:56

Appendix B: Bus Route Maps

MBTA Routes Serving Alewife Station

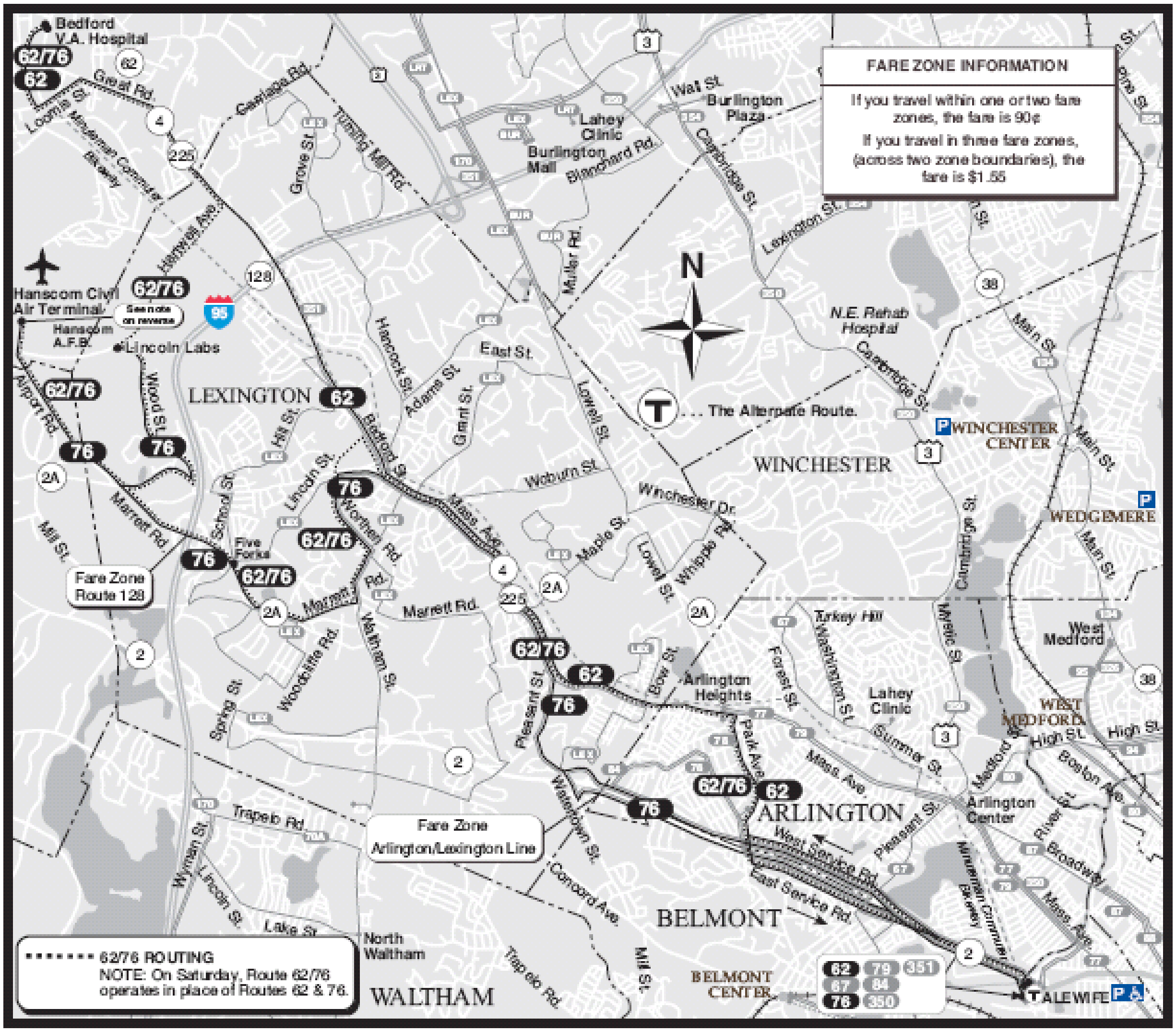

Figure B-1: MBTA Routes 62 and 76 (source: mbta.com)

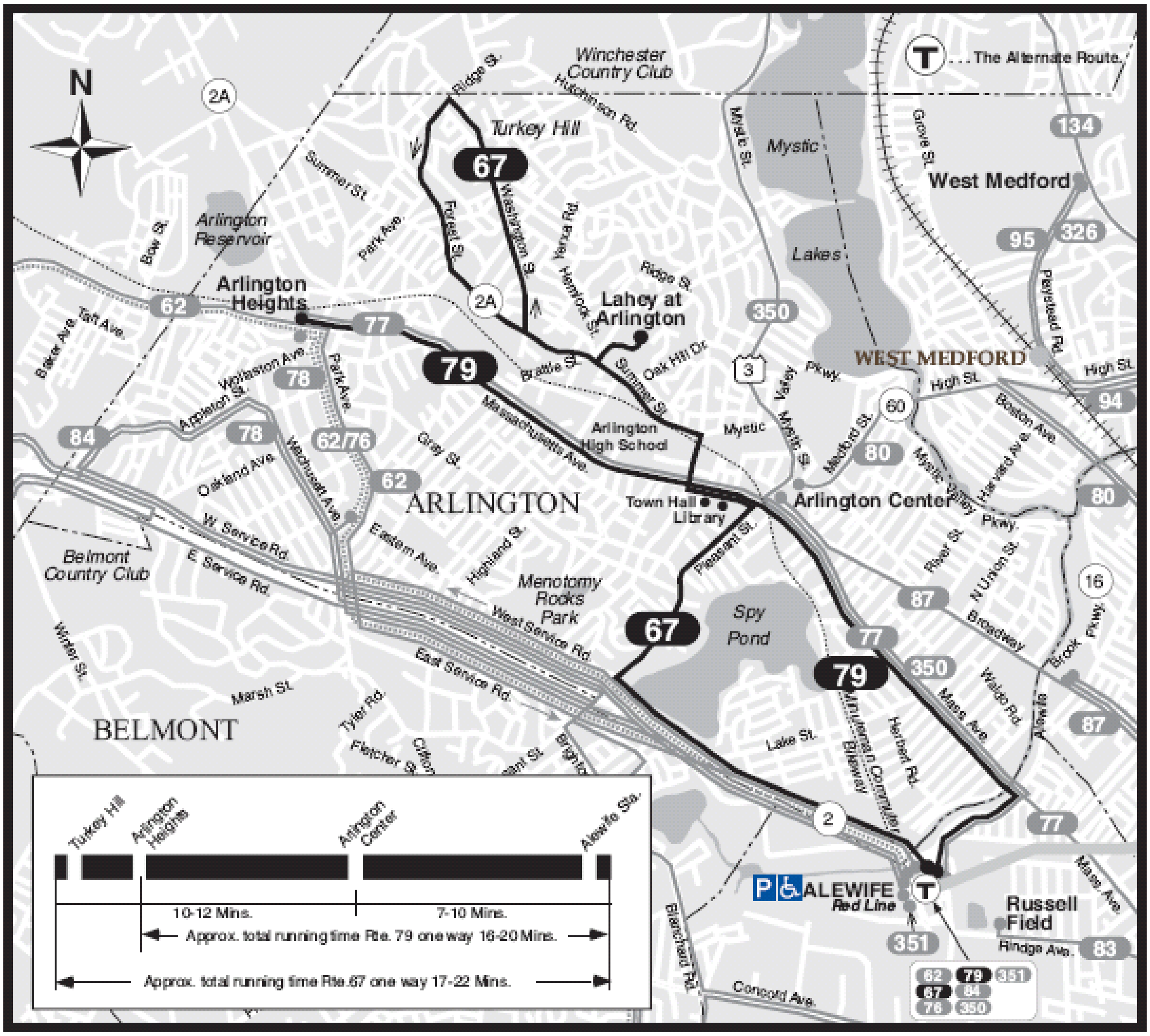

Figure B-2: MBTA Routes 67 and 79 (source: mbta.com)

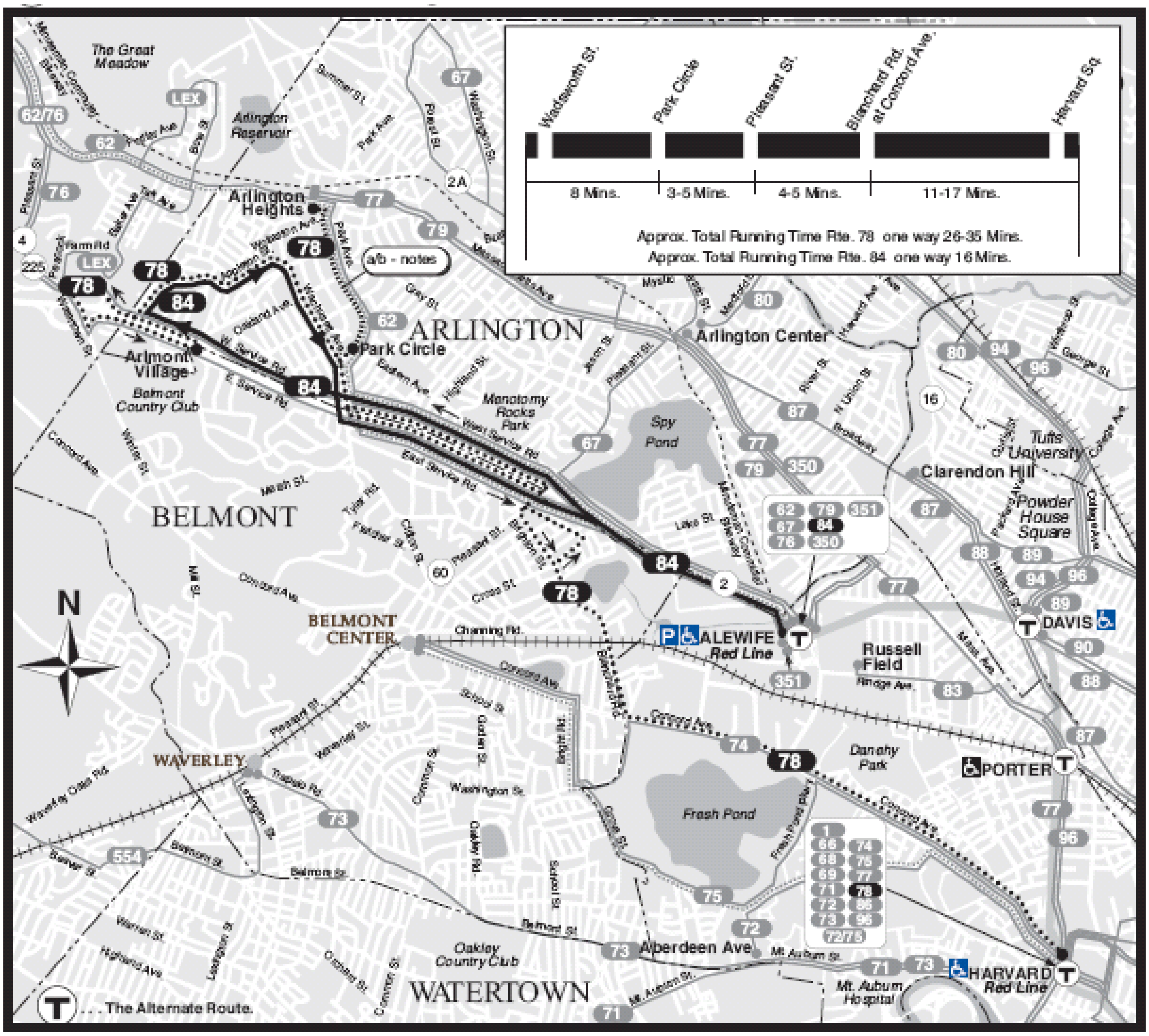

Figure B-3: MBTA Route 84 (source: mbta.com)

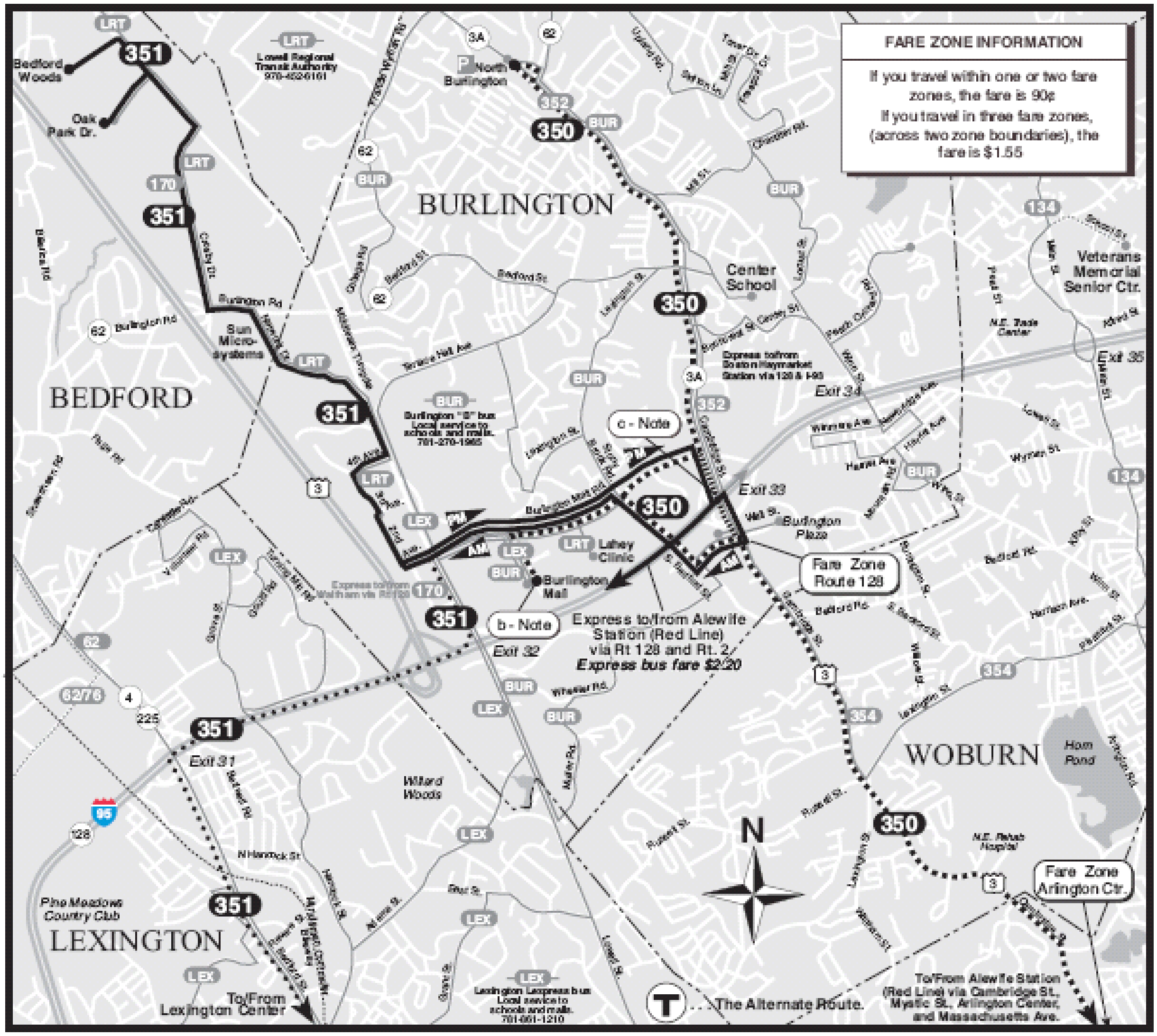

Figure B-4: MBTA Route 350 (source: mbta.com)

MBTA Routes Serving Wellington Station

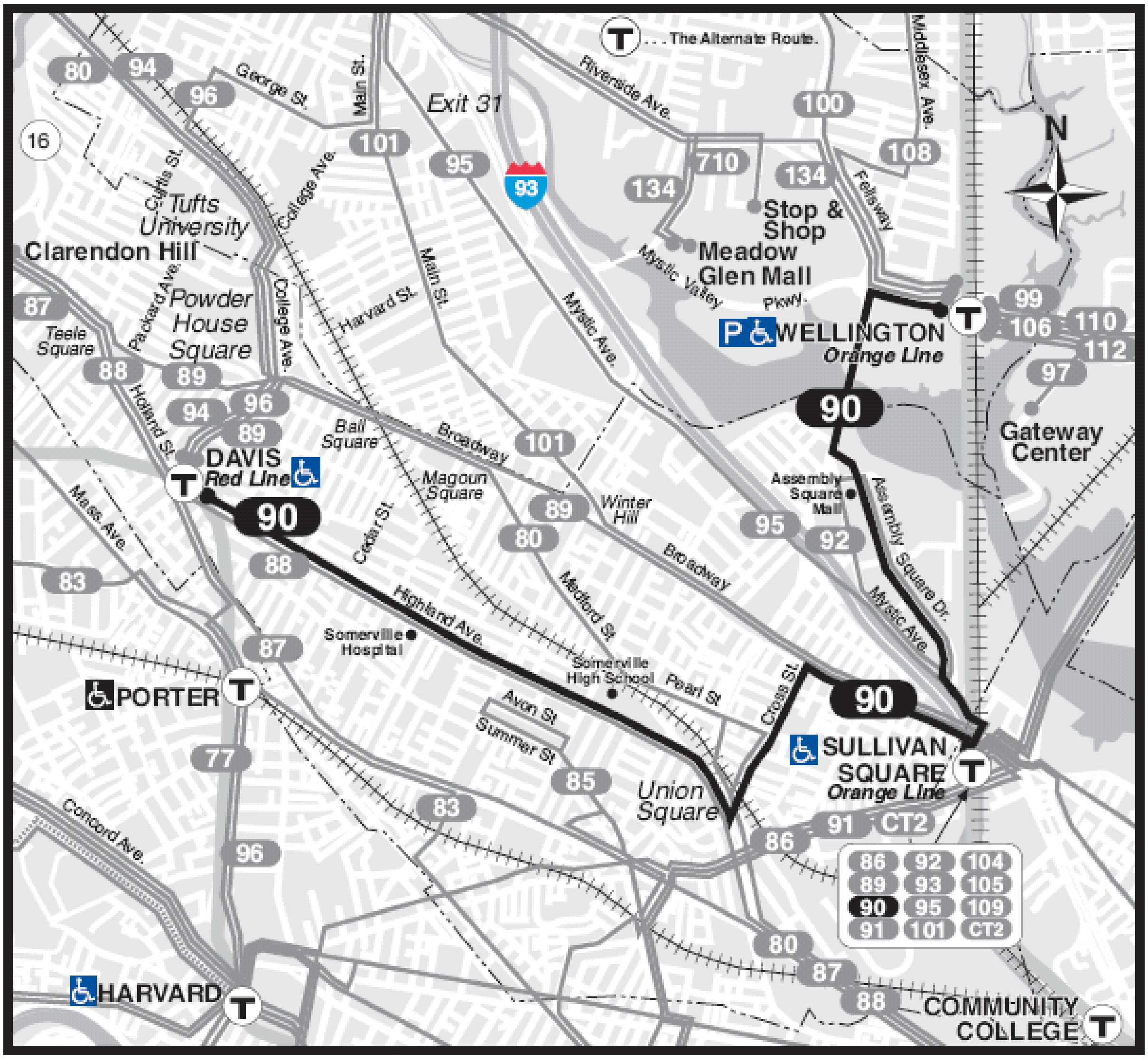

Figure B-5: MBTA Route 90 (source: mbta.com)

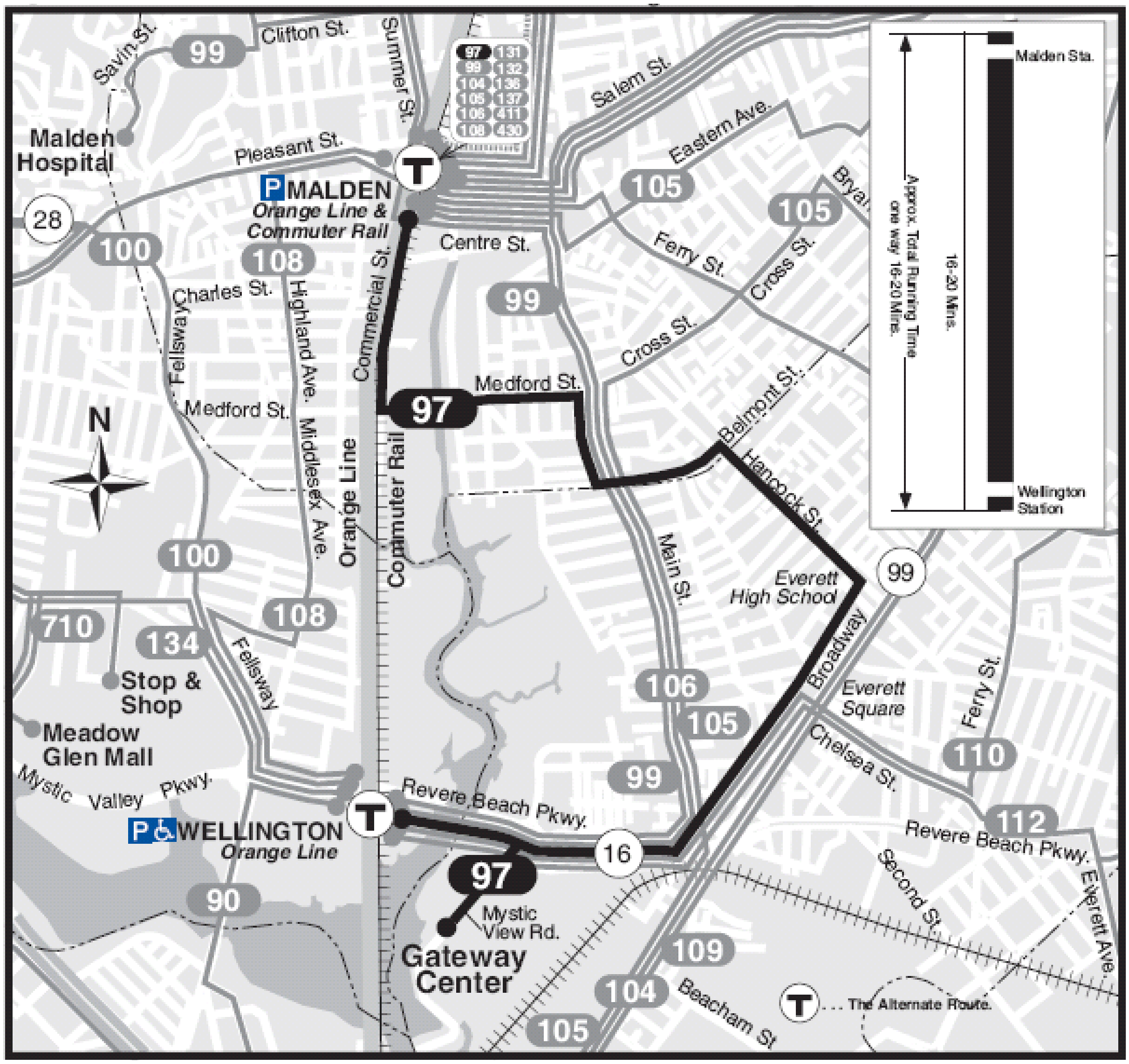

Figure B-6: MBTA Route 97 (source: mbta.com)

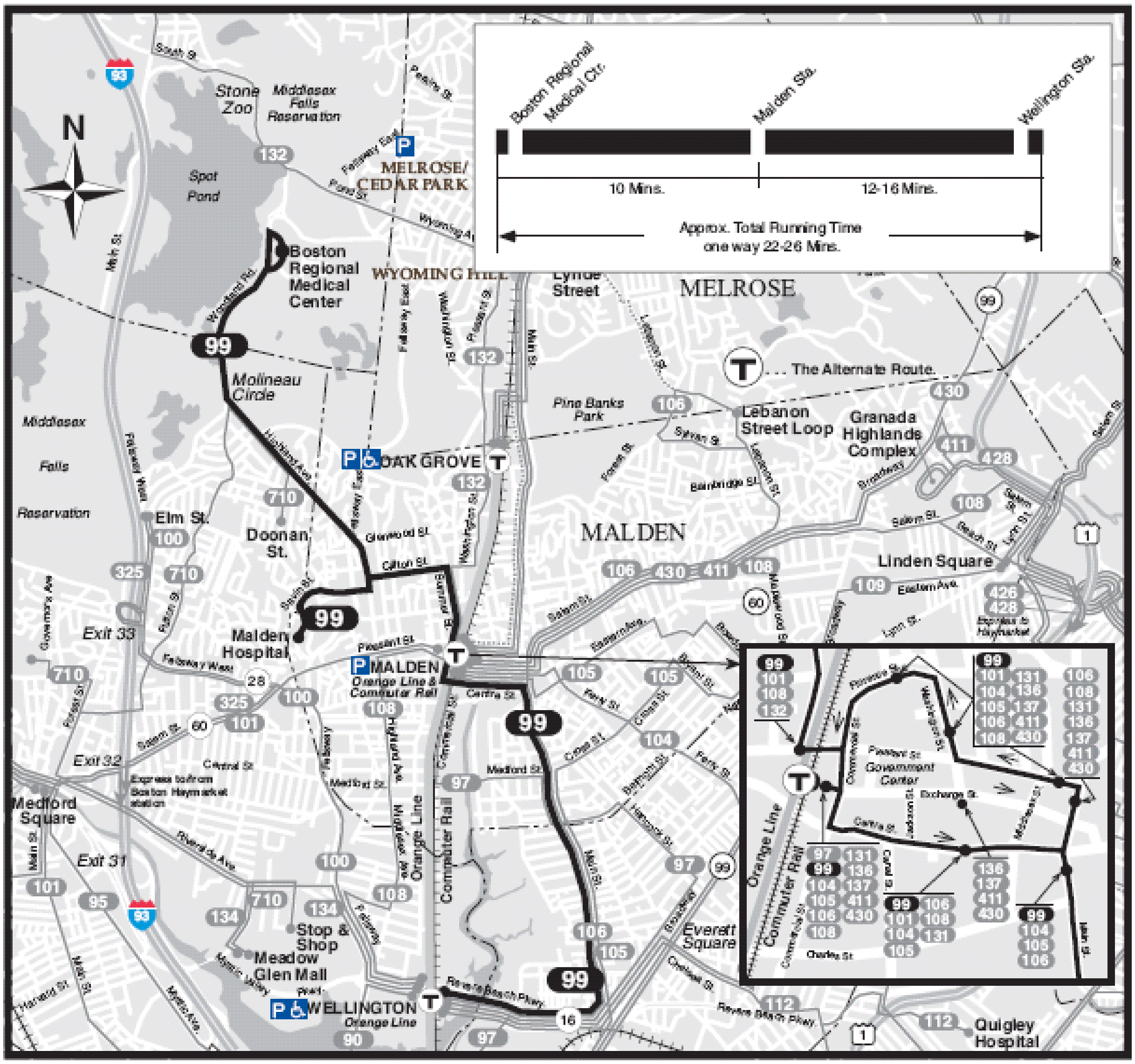

Figure B-7: MBTA Route 99 (source: mbta.com)

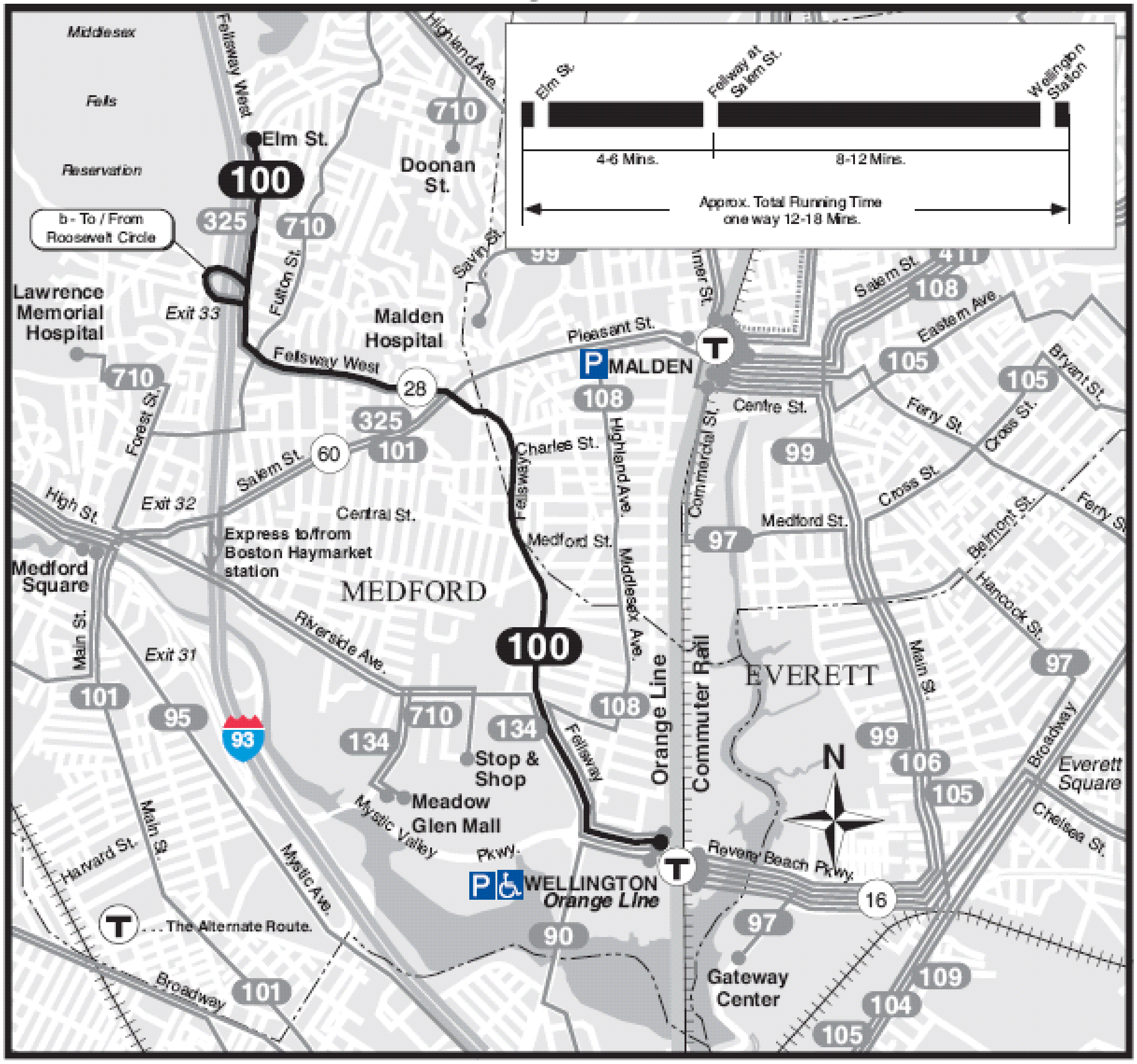

Figure B-8: MBTA Route 100 (source: mbta.com)

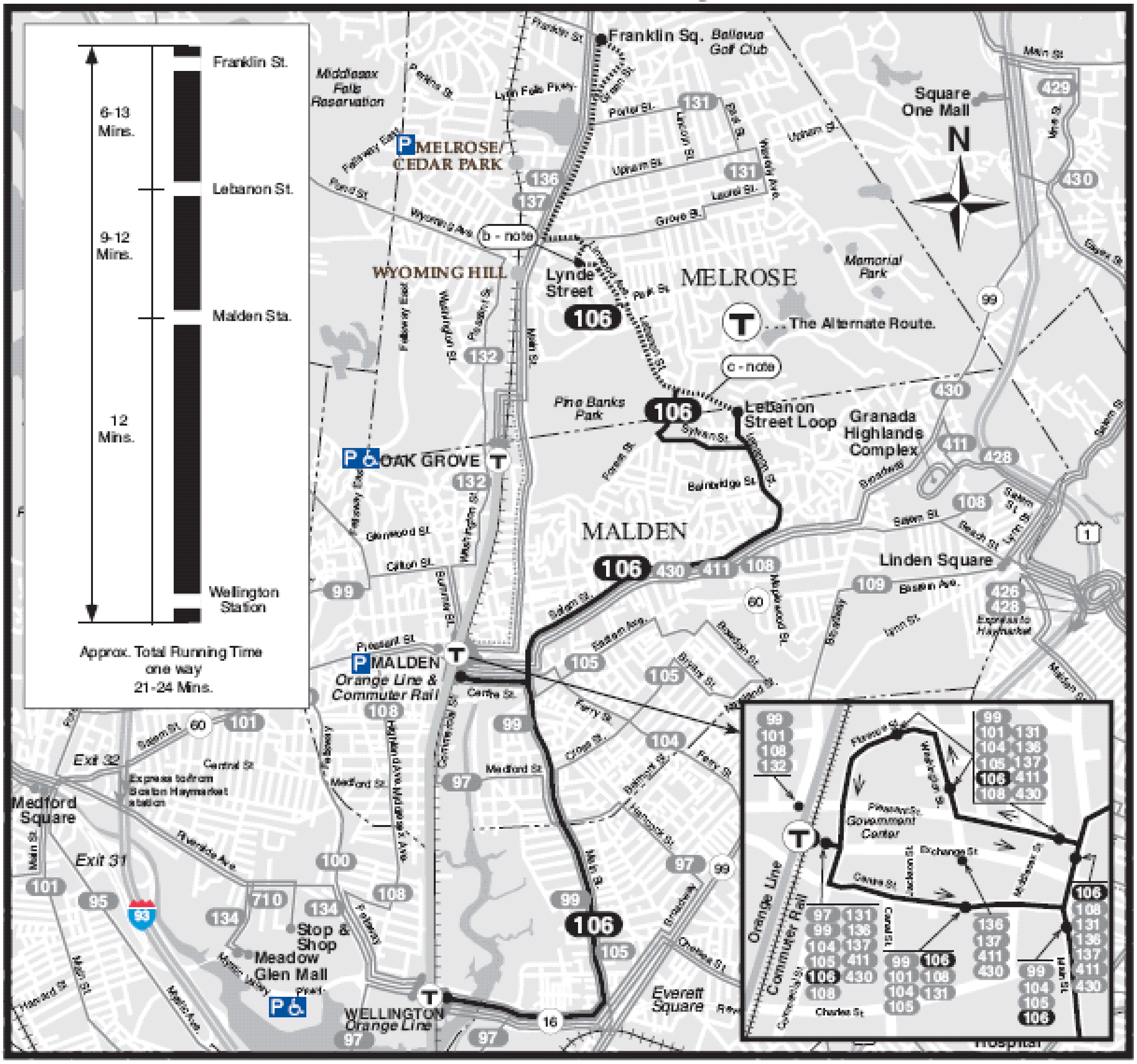

Figure B-9: MBTA Route 106 (source: mbta.com)

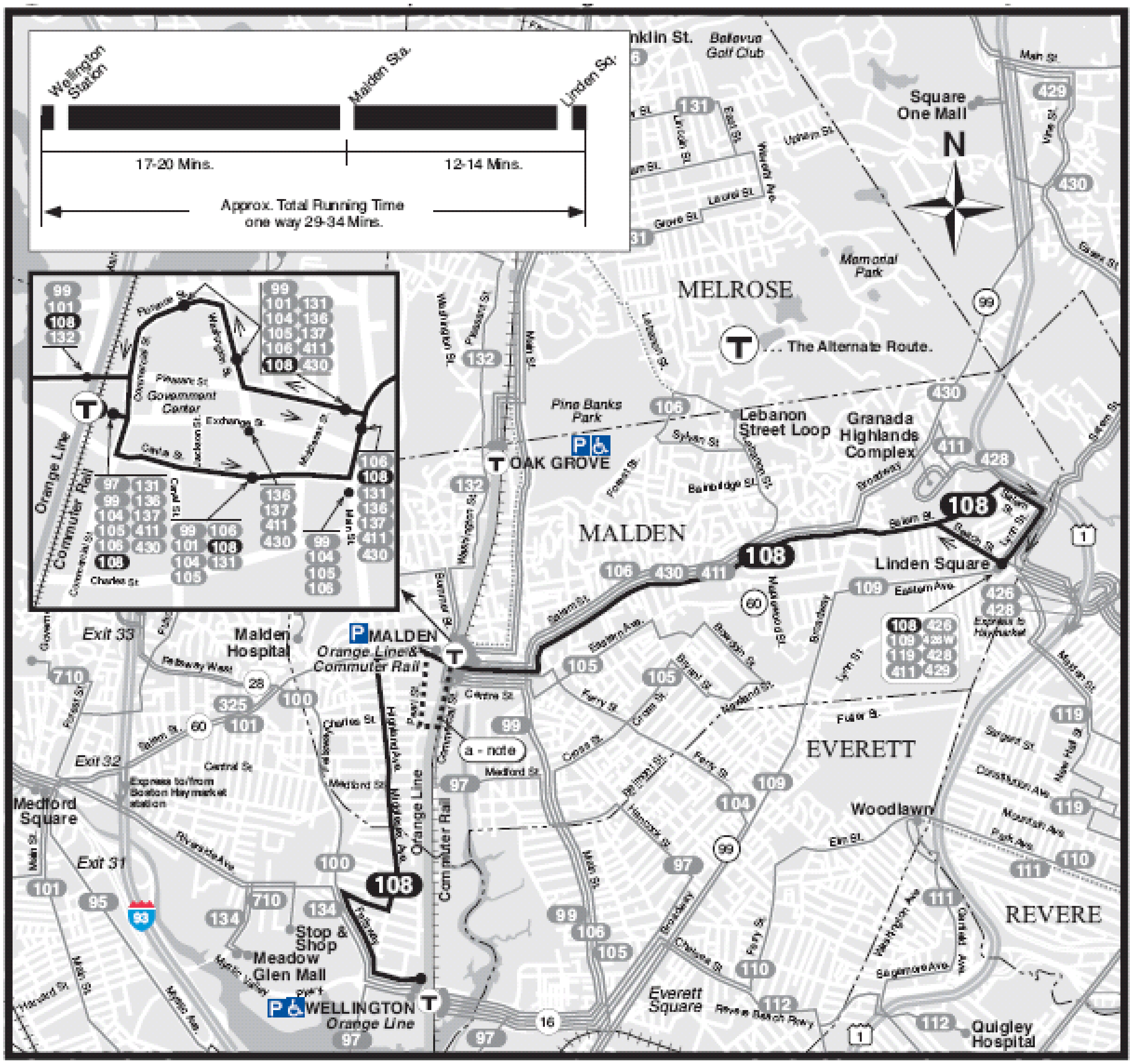

Figure B-10: MBTA Route 108 (source: mbta.com)

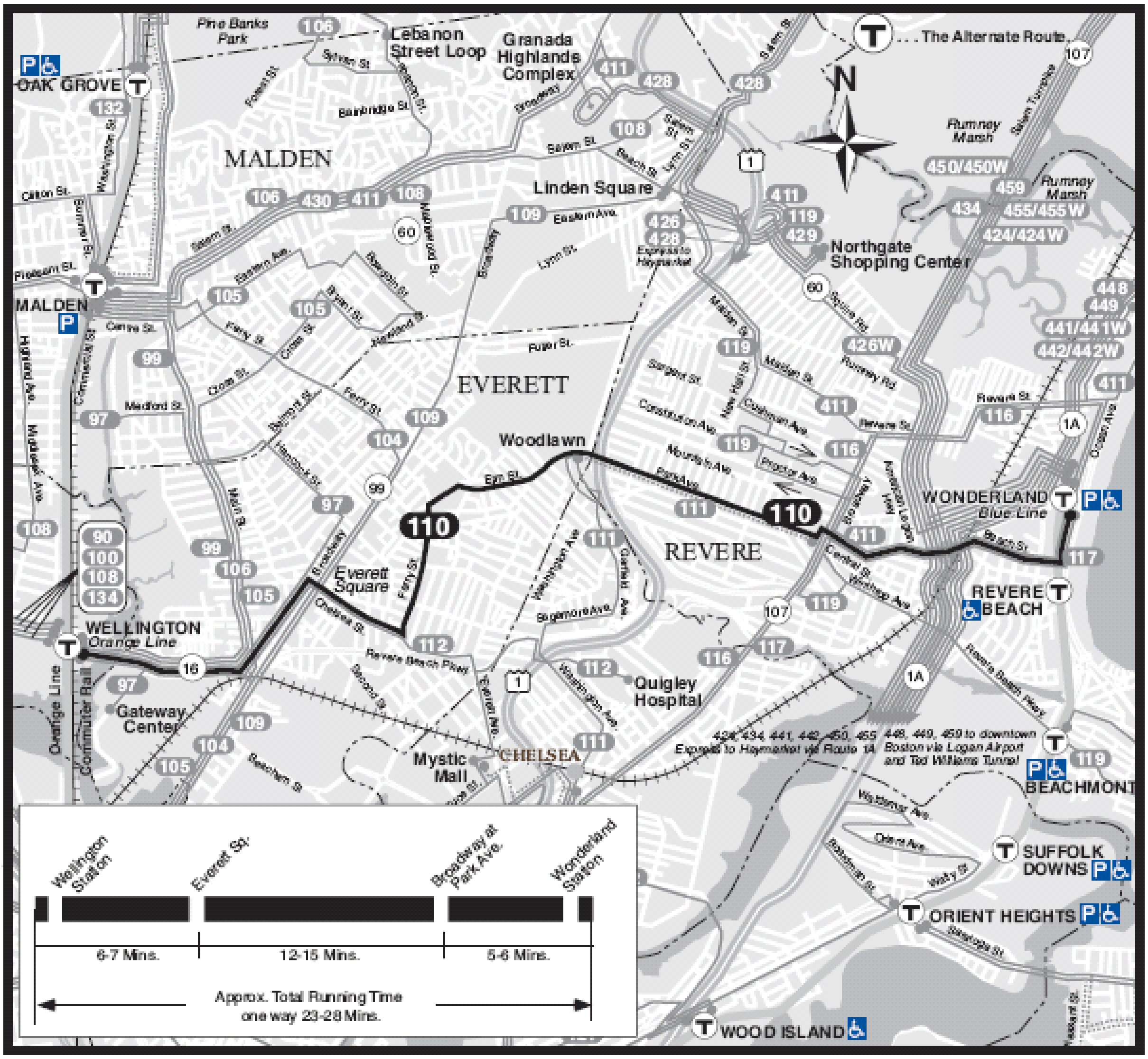

Figure B-11: MBTA Route 110 (source: mbta.com)

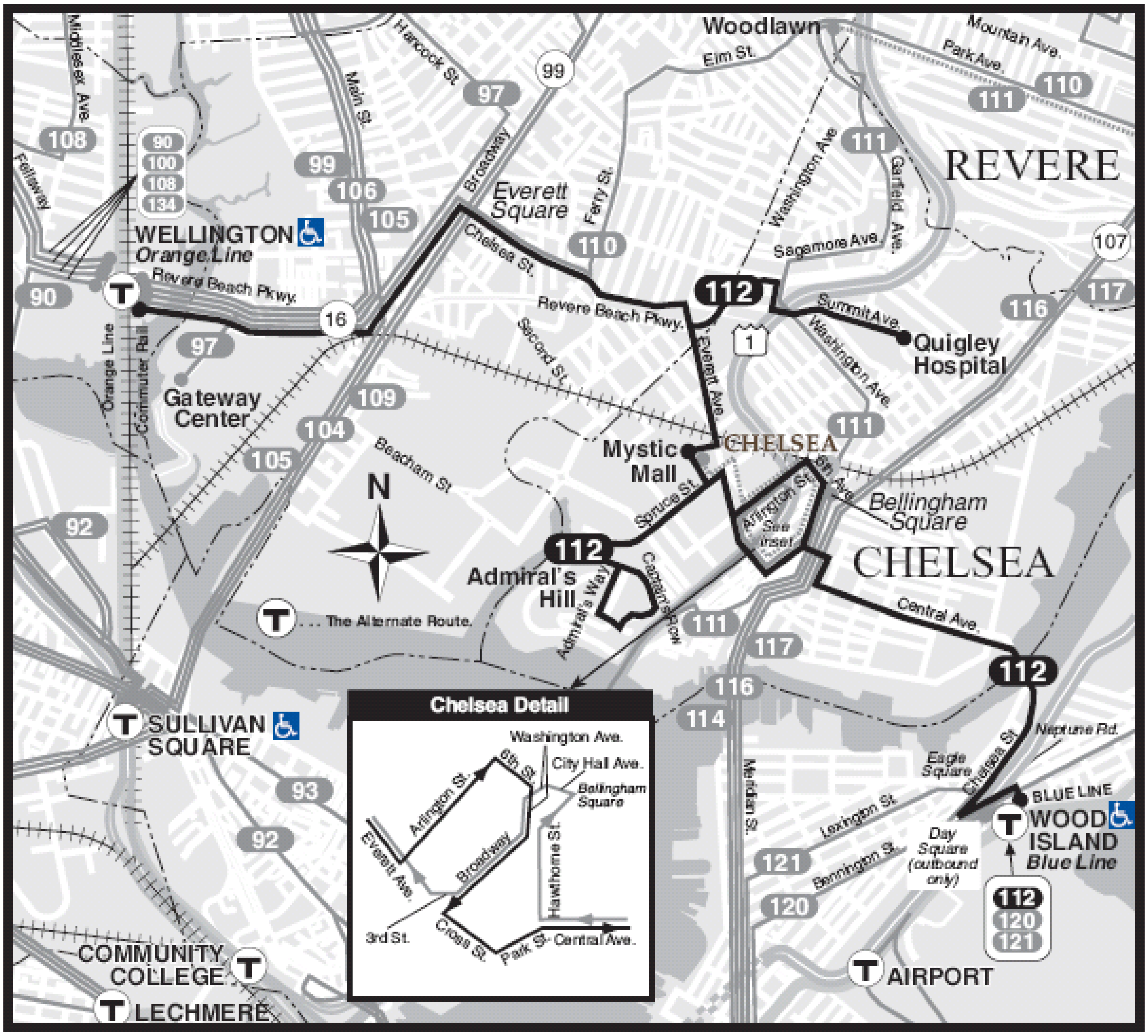

Figure B-12: MBTA Route 112 (source: mbta.com)

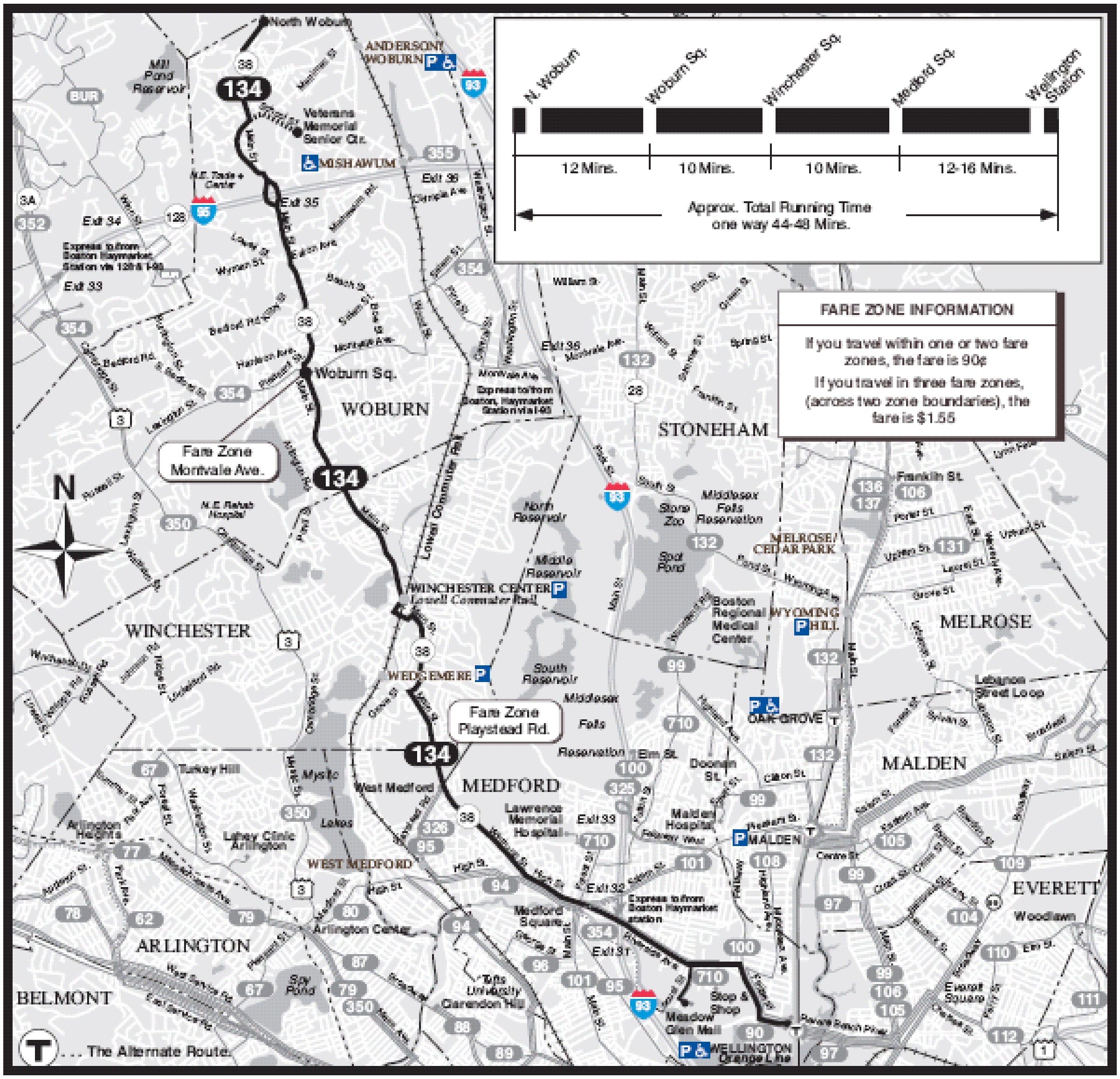

Figure B-13: MBTA Route 134 (source: mbta.com)

CTA Routes Serving 79th Street Station

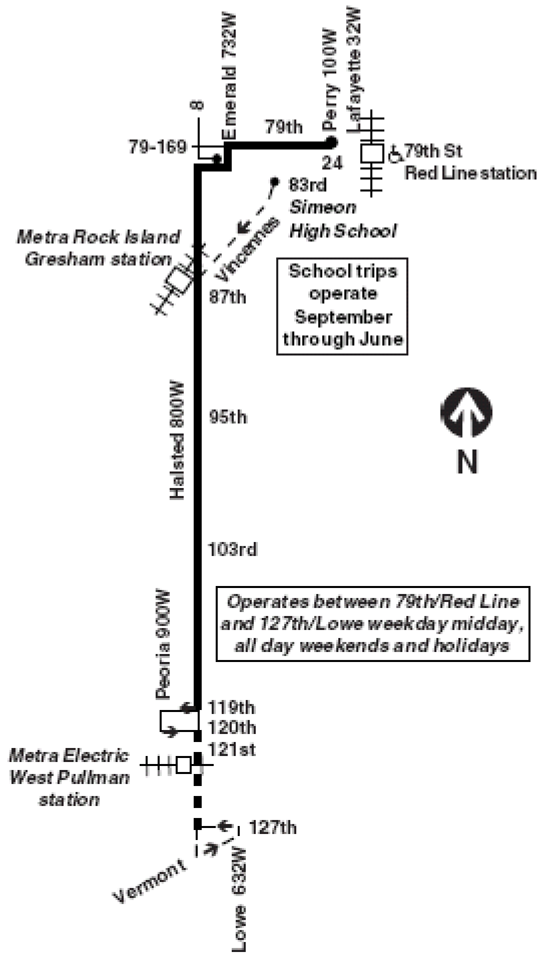

Figure B-14: CTA Route 8A (source: transitchicago.com)

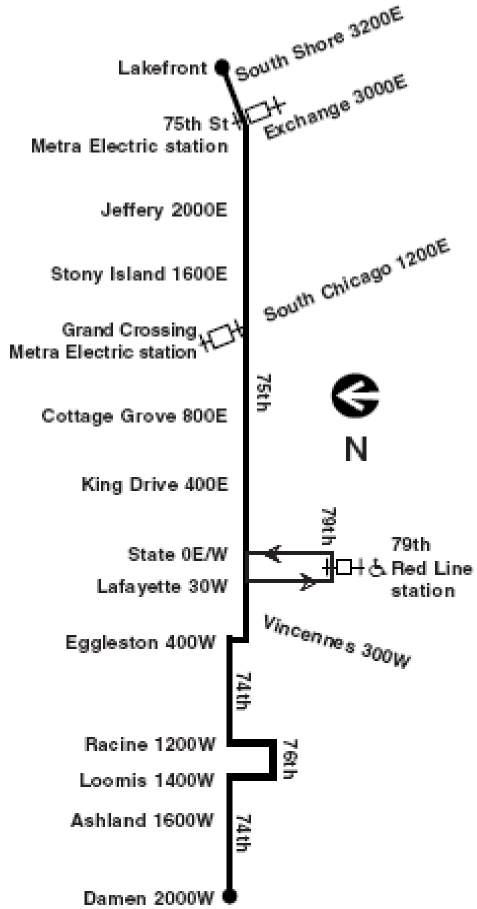

Figure B-15: CTA Route 75 (source: transitchicago.com)