Improving the Network Performance of Urban Transit Systems

by

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Abstract

Poorly coordinated transfers can cause transferring passengers to miss connections and endure long waiting times. Selective holding of vehicles to allow easy connections is one means of improving transfer performance. With reasonably accurate knowledge of vehicle location from APTS and ITS advancements, there is great potential to utilize real-time location information to make better holding decisions.

The Massachusetts Bay Transportation Authority is the initial focus of our research efforts. Park Street, the transfer point between the Green and Red Lines, has the highest transfer activity within the system with over 56,000 daily transfers. In particular transfers from the Red Line to the Green Line Westbound have the greatest potential for significant benefits from coordination.

A deterministic, analytical model is formulated to maximize total expected benefits from a hold, measured in equivalent net in-vehicle minutes saved from coordination recognizing the disbenefits to delayed passengers. An important assumption in the model is that passengers perceive out-of-vehicle time as more onerous than in-vehicle time. The analytical model results suggest that higher minimum holding thresholds eliminate borderline holds and improve the average benefit per held train.

A simulation model is then designed to assess the actual benefits from holding trains, incorporating more realistic assumptions about the actual transferring process. Several assumptions made in the analytical model are relaxed such as the assumptions of fixed dwell times, of perfect prediction capabilities as well as of constant passenger arrivals. The simulation model results show that transfer coordination could produce daily savings of about 6,000 passenger-minutes. Total benefits produced by the analytical and simulation model differ significantly, primarily due to the assumption of perfect prediction capabilities in the analytical model. Sensitivity tests show that the model is most sensitive to changes in α, the perceived waiting time ratio. Decreases in α result in fewer holds, but also affect fewer people and improve passenger-benefit ratios.

Results of the Park Street model are applicable to any rail-to-rail transfer context and could be expanded to improve rail-to-bus and bus-to-bus connections.

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Table of Contents

List of Figures

List of Tables

Chapter 1: Introduction

The quality of service provided by public transit systems is judged by many factors. Transit riders may judge a transit system based on its convenience and ease of accessibility. Others may contend that the most important measures for public transit are schedule adherence and on-time performance. Still others may assess transit based upon its outward appearance such as overall cleanliness and comfort.

Another crucial measure of public transit service quality is the ease and convenience of the transferring process. Poorly coordinated inter-line or intermodal transfers may cause transferring passengers to rush needlessly to the next vehicle, to miss their trip entirely or to endure long and burdensome waits. Persistent missed trips and long delays may cause passengers to become dissatisfied with service and to switch to alternative modes of travel. One obvious means of improving coordination at transfer locations, thereby reducing inconvenience and waiting time for transferring passengers, is to hold transit vehicles until all possible connecting passengers are aboard.

This thesis focuses upon the development of real-time holding strategies at important transfer points facilitating improved transfer performance within the transit network. Contrasting the time savings benefits for transfer passengers with the delay to other passengers from a hold decision, a deterministic model for analyzing different holding strategies at transfer points will be developed. The model will be applied to the Massachusetts Bay Transit Authority (MBTA) which has a rail network well suited for such an endeavor. Lastly a simulation model will be developed, allowing for a more realistic representation of the actual system conditions on any given day.

1.1 The Role of Transfers in Transit Systems

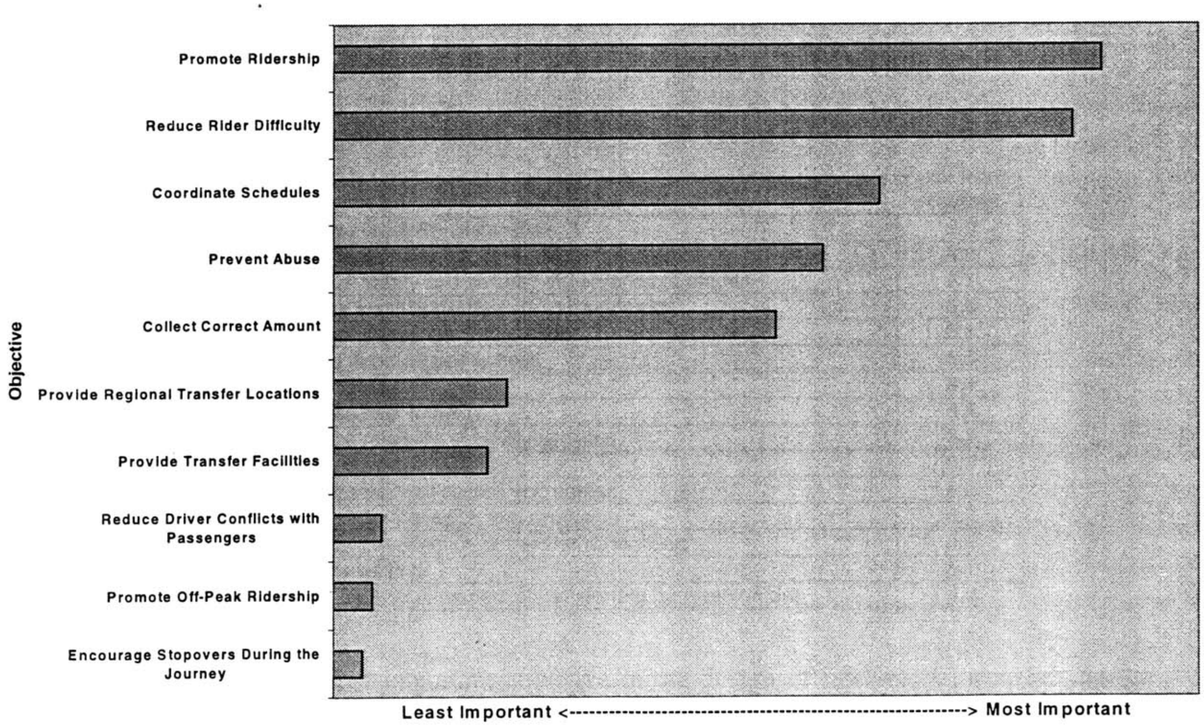
Transit networks are systems of inter-connected routes not individual lines, which must function together as an integrated entity. In many large urban transit systems, a large proportion of the total trips taken involve at least one transfer. The main transit provider in Boston, the Massachusetts Bay Transit Authority (MBTA) is a case in point. The MBTA's major rapid transit transfer station, Park Street, had over 56,000 daily transfers between both the Red and the

Green Lines as of 1997.[1] In fact nearly 25% of all passengers boarding Red Line trains at stations upstream of Park Street, in both Northbound and Southbound directions, transferred to the Green Line Westbound at Park Street, amounting to some 10,000 and 11,000 daily transfers respectively. Thus transfers play a significant role in daily transit operations for the MBTA.

Systems incorporating transfers offer passengers a greater selection of travel destinations than systems with disconnected lines without transfers. Transfers can provide improved area coverage, more flexible schedules, and eventually a higher level-of-service to riders.

Figure 1-1 is a survey ranking the importance of certain transfer objectives for transit agencies in the United States.[2] Figure 1-1 shows that the top priorities for transit systems when designing transfers are to promote ridership and to reduce rider difficulty through improved transfer performance. Transit agencies expect that more efficient transfers should result in a travel journey and experience more satisfying to the customer, which it is hoped will translate into an overall increase in ridership.

Figure 1-1: Transfer System Objectives Survey



[1] Central Transportation Planning Staff (CTPS), "1997 Passenger Counts: MBTA Rapid Transit and Commuter Rail", pp. 6-1 through 6-15.

[2] "Passenger Transfer System Review," TCRP Synthesis 19, 1996.

Although transferring may be an indispensable tool for transit agencies to provide effective service, it is viewed rather unfavorably by most riders as more of a nuisance than anything else. Ideally, transfers would be quick, easy and nearly effortless. Transfers within many transit systems throughout the world are troublesome and contribute to the reluctance of riders to use the service and to the association of transfers with inconvenience. Transfers may require riders to walk long distances or utilize several stairwells in order to board the connecting transit vehicle. Transfers may expose riders to physical discomfort if they are made to wait in unprotected locations, subject to inclement weather or unduly loud ambient noise. Passengers may miss their transfers entirely and be forced to wait long periods of time for the next arriving vehicle. Thus, transfers can be an important influence on the total trip time and the overall perception of trip quality.

1.2 Transfer Reliability

Reliability is a key attribute of any trip taken on transit. Initial waiting time, overall traveling time, as well as promptness are some measures of reliability with which passengers judge the effectiveness of transit upon. The transfer itself can also be a major determinant in overall trip reliability. Figure 1-2 is a survey of frequent and knowledgeable transit users, ranking generic objectives in the planning, design and operation of inter-modal transfer facilities.[3]

Figure 1-2: Objectives Ranking of Inter-Modal Transfer Facility Priorities

(Note: Composite scale based upon 11-point scale with 11 having the most priority and 1 the least)

Rank	Objective	Rating
1	Maximize reliability of transfers	9.0
2	Maximize security	8.8
3	Maximize safety and security of operation of modes	8.7
4	Minimize institutional barriers to transferring	8.6
5a	Maximize passenger information	8.5
5b	Achieve handicapped access	8.5
7a	Maximize safety	8.4
7b	Maximize user benefits	8.4
9a	Maximize reliability of facility services	8.3
9b	Maximize system legibility	8.3
11a	Maximize efficient access and egress	8.2
11b	Minimize disorientation and confusion	8.2
11c	Maximize coordination of transfer scheduling	8.2
14	Minimize waiting	8.1
15	Minimize physical barriers of transferring between modes	8.0

The study found that the most important objective in the design of inter-modal transfer stations for riders is the maximization of the reliability of transfers (Rank #1). The reliability of a transfer incorporates many aspects of the transfer such as the amount of disorientation associated with transferring (Rank #11b), the scheduled arrival of transfer vehicles (Rank #11c) as well as the overall waiting time (Rank #14). The results of the survey in Figure 1-2 the reliability of the transfer process is an important factor in determining trip quality and rider attitudes towards transit.

As Figure 1-2 suggests, the term reliability may connote several different definitions to transfer passengers. Reliability on the one hand can be measured as the chance that a transit vehicle will show up. For a transferring passenger, the chance that a connecting transit vehicle will fail to arrive is not an overriding concern on any given day. It may however become a concern when unforeseen events such as bomb scares or fires occur which significantly disrupt service and could force the cancellation of service. More likely however, reliability in this context may become a chief concern during late evening hours near closing time when there is some uncertainty as to whether or not a connecting vehicle will arrive at all.

Primarily though, reliability for transfer passengers is defined as the length of time a passenger must wait to transfer. This is the context with which reliability will be used from now on. Poor transfer reliability, consistently resulting in missed trips or long delays, inconvenience and annoy riders and reflect poorly upon the transit system itself. Riders dissatisfied with transfer performance and reliability may choose alternative modes of travel. While reliability of transfers may not be the most crucial factor in the decision to take public transit, it is nevertheless a very important piece of the overall puzzle, making it imperative for transit agencies to improve them to provide a better level-of-service to its riders.

1.3 Previous Research

Previous research on transfer performance, including reliability as we define it, has concentrated upon scheduling strategies to improve the overall reliability of a transfer and minimize overall waiting time. Over the last decade and a half, several analytical models and simulation models have been designed with this objective in mind.

Hall (1985) analyzes simple models to optimize slack time when vehicles are delayed according to an exponential probability distribution. The models showed that coordinating arrivals with

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[3] Horowitz, J. and N.A. Thompson, "Generic Objectives for Evaluation of Intermodal Passenger Transfer Facilities".

departures is most valuable when the expected vehicle delay is small relative to the average line headway on the transfer line.

Abkowitz (1987) develops a simulation model to represent a range of route characteristics in a timed-transfer system. Timed-transfer systems attempt to coordinate routes in such a manner that the vehicles meet at transfer locations (hubs) during a given window called contact periods. Four different timed-transfer strategies are analyzed for connecting bus routes:

1) Unscheduled-Buses are not scheduled to meet at a focal point and do not wait for each other. Referred to as the do-nothing scenario.
2) Scheduled-Buses are scheduled to meet simultaneously at the focal point, but do not wait for each other.
3) Waiting/Holding-Buses are scheduled to meet simultaneously. The bus with the longer headway holds for the next arriving bus
4) Double Holding-Buses are scheduled to meet simultaneously and the first arriving bus waits for the next arriving bus from the other route.

Model results suggest that the scheduled strategy is effective compared to the do-nothing one when headways are incompatible between the two lines. The waiting/holding strategy yields similar results to the scheduled one, except for an increased sensitivity to boarding and alighting profiles along the route. The double holding strategy outperforms all other timed-transfer strategies when headways on intersecting routes are compatible.

Lee and Schonfeld (1991) formulate an analytical model to estimate the slack time needed in a schedule to minimize a total cost function incorporating all transfer-related elements in a rail-bus transfer. The cost function was composed of three major costs sensitive to slack time, identified as:

1) The scheduled delay cost of buses and bus passengers (due to holding the buses, their drivers, and non-transferring passengers).
2) The missed connection cost of bus passengers transferring to rail.
3) The missed connection cost of rail passengers transferring to bus.

Results from the analytical model give some guidance on desirable slack times and suggest schedule coordination between two routes is not worth attempting if the standard deviation of arrivals exceeds certain levels.

Bookbinder and Desilets (1992) identify transfer optimization as yet another means of transfer coordination. In transfer optimization, the addition of layover time to assure connections at a focal point is unneeded since terminal departures are scheduled in order to minimize the overall disutility to transfers. A simulation model is created to optimize a bus network with three similar, but different objective functions D(w), where w is the waiting time. The first objective function assumes a linear relationship between the disutility and the mean waiting time where D = E(w). A second function, placing more penalty on longer waits assuming D= $E(w^2)$. A third disutility function takes reliability into account, D = Var(w).

Results show that in optimizing transfers, negative consequences result if deterministic bus travel times are assumed while in fact these travel times are random. The disutility function should be a combination of the expected wait and variance, but for the choice of a single objective function, the $E(w^2)$ function appears to best represent the perceived disutilities of groups of passengers.

Vuchic (1993) provides a systematic classification of transfers according to transit line types and attributes. By type, a line is either a terminating or a through line. Line attributes are represented by service frequency, capacity or physical characteristics such as mode. A line with considerably higher frequency, capacity or performance than the other line is referred to as a trunk line, while feeder lines with lower frequencies serve a collection/distribution function. The applicability of a timed-transfer system is discussed.

Bakker and Becker (1994) show the benefits of a timed-transfer system for a small-medium sized transit system in Norfolk, Virginia, the Tidewater Transit System (TTS). In the 1980's, TTS experienced a drop in ridership amounting to nearly 40% of its initial ridership. In the period between 1988-1991, transferring increased from 35% to 45% after implementation of a timed-transfer system. Of those aware of the transfer system, 62% viewed it favorably, 77% felt schedules improved, 81% felt on-time performance improved, 90% felt transferring was easier, and 79% felt overall travel time decreased. Not surprisingly, annual ridership and revenue both increased by about 1.5% per year after nearly a decade of continuous decline. It is conjectured that the increase in ridership is due in some part to the improved service quality and passenger satisfaction emanating from transfer coordination.

Clever (1997) looks at an extension of the timed-transfer concept prevalent in Europe called integrated time-transfer (ITT). ITT incorporates trains, buses, boats and other means of local and long-distance public transportation into a cohesive regional network operating on a fixed-interval schedule and connecting in such a manner as to minimize transfer times. ITT systems may have as many as 100 hubs compared to the small number in TT systems. Clever notes that ITT is ideal in the United States where large regional areas contain several metropolitan areas whose public transit networks are poorly connected to each other and thus hinder easy transfers and access to other parts of the region. The paper cites the San Jose-San Francisco Bay Area-Sacramento corridor in Northern California as a prime candidate for ITT application.

Hall and Randolph (1999) develop analytical models to determine optimal holding times for buses at a timed-transfer stop. For known bus arrival times and bus passengers aboard, the optimal policy is shown to be to dispatch at the arrival time of the connecting incoming bus. The stochastic case produces a waiting time function possessing more than one local minimum. There is however, at most one local minimum when the arrival times for incoming buses are identically normally distributed.

1.4 Improving Transfer Performance

The transfer process becomes arduous for passengers when they miss connections and are made to wait long periods of time, unassured of the arrival time of the connecting vehicle. This situation generally occurs when variability in the running times of vehicles is high compared to the scheduled arrival headways. The variability may be the result of highly variable dwell times from fluctuations in passenger demand or even blocking by vehicles preceding it.

Historically, there have been two approaches to improving the problem of transfer reliability and performance. The simplest approach to improving transfers is simply to increase vehicle arrival frequencies, placing more trains into scheduled service at any given time. Such a strategy should result in shorter average waiting times and less burden and annoyance to all passengers, including transfers, as inter-arrival headway periods are shortened. This strategy is not always feasible for a transit agency for a myriad of reasons. Vehicles and manpower are typically at a premium and the additional costs of improved service may be too great for the agency. Lastly, automated control systems may be unable to handle the additional vehicles and still operate the system efficiently and effectively.

The second and most common approach to improve transfer performance is the implementation of some sort of transfer coordination scheme. Transfer coordination can come in the form of schedule coordination, or real-time transfer coordination involving holding actions.

- **Schedule Coordination**

Schedule coordination involves modifying the schedule in order to minimize overall passenger waiting time and to increase the chances of completing a transfer. This type of coordination is referred to as timed-transfer. Similar to the hubbing concept commonplace in the airline industry, timed-transfer is common in small networks, usually bus ones, where ridership is of low-to-medium volume and service frequencies are similar. Timed-transfer systems schedule trips on different routes to meet at central locations at certain time banks where passengers may interchange between vehicles.

There are several problems with the timed-transfer concept however, when it is applied to high-volume transit networks in urban areas. Timed-transfer systems add layover times to the run time of a given vehicle so that connection at a focal point is assured, thus vehicles must adhere to scheduled times as closely as possible in order to arrive at the focal point within the given transfer window. Rail transit lines operate with short headways and can have high variability in their running and dwell times, relative to the headway, making it difficult to assure that a train will arrive within a given window. In a timed-transfer system, a late bus could be driven faster to make up for the lost time. The operation of rail transit systems however, requires the maintenance of safe following distances to prevent collisions between two trains, thus precluding the ability to easily make up lost time.

Furthermore, long transfer windows are infeasible for such networks. The large passenger demand typical in the central, downtown areas may result in crowded platforms and tightly packed transit vehicles if the window is extended too long. There is also a need to maintain a level-of-service satisfactory to passengers. Long transfer windows may increase the chance of a transfer, however passengers not needing to transfer will experience longer overall trips times and those waiting at locations downstream of the focal point can also experience longer waiting times and a decreased service level. Overall, timed-transfer is best-suited for system where vehicles are run at low frequencies and routes possess similar headways, thus minimizing the overall detrimental effects of a late vehicle.

- **Real-Time Coordination**

Real-time transfer coordination systems utilize current system information to assess the feasibility and desirability of holding a train. Real-time transfer coordination systems can be local for a specific area or station. For instance, many rail-to-bus interchanges have blinking lights to notify bus drivers of the impending arrival of a train. The triggering mechanisms for such a system are track sensors located prior to the platforms. Although triggering of a track sensor can be considered real-time vehicle location information, it does not provide information about the whole system in a broader sense. The decision to hold is a local one made by the driver and the overall effect on the system is not considered. This usually does not present a problem however as at rail-to-bus connections, departing buses are considered distributor routes.

Communication between operators and an inspector or dispatcher may also be considered to be a rudimentary form of a local real-time transfer coordination system. The inspector or dispatcher may have access to some real-time information, such as radio dispatches from operators of incoming trains and can then decide to initiate a hold based on the expected arrival time of a train. Coordination is again local because the inspector only has knowledge of vehicle locations directly preceding the station as well as those of the vehicles that just passed. The inspector bases the decision on what he has observed and has heard, but cannot wholly assess the overall effect of a hold on the entire system.

One noteworthy real-time transfer coordination system is found on the buses of the Ann Arbor Transportation Authority (AATA) operating in Ann Arbor and Ypsilanti, Michigan.[4] In conjunction with Rockwell, the AATA currently has in operation the Advanced Operating System (AOS) billed as the first fully-integrated public transit communication, operating, and maintenance system. One of its unique attributes is a computer-assisted transfer system. Once a transfer request is input into the Mobile Display Terminal, a dispatch computer calculates the feasibility of holding based upon the current location of the initial and the requested vehicles from AVL data. If the hold is accepted, the driver of the connecting vehicle is instructed to hold at the next stop. The overall effect of a hold on the network performance, is still not considered however.

Automated systems such as the transfer coordination system in the AATA rely upon APTS and ITS technologies (such as AVL) to provide real-time vehicle location information. Therein lies great potential for APTS and ITS technologies to provide the basis for a transfer coordination system that will consider the effect of a potential hold upon the entire network. Previously defined transfer coordination schemes fail to consider the additional delay experienced by riders waiting at downstream locations. An overall snapshot of the network allows a transit system to see beyond the immediate train and look at the positions of the most recent train departures and the positions of the following trains. A hold can then be based on not just the benefit to the immediate transfer passengers at the next stop, but on the overall effect on all passengers on the route. More effective holding decisions should then result, increasing system and transfer performance.

1.5 Objectives and Goals of Research

Research and practical application of transfer coordination in public transit has concentrated mainly upon scheduling issues such as timed-transfers and transfer optimization to reduce the waiting time and the subsequent burden upon transfer passengers. Strategies such as schedule coordination and optimization when applied to high-frequency rail-rapid transit and bus networks are highly susceptible to the inherent stochasticity of the system at any given moment, variable to the whims of passenger demand and operating constraints. Any feasible transfer coordination system in a high-volume transit network must account for the ever-present changes within the system.

The development of APTS and ITS has primarily targeted development of real-time control strategies such as holding, short-turning, and expressing on a single line to improve performance, as well as improved provision of information to passengers. Public transit, besides the Ann Arbor Transit example has for the most part, yet to realize the potential benefits of using APTS and ITS technologies to provide real-time decision support to improve the performance of transfers within a transit network. Real-time information is vital to allow inspectors or dispatchers to make sound, informed control decisions, based upon actual operating conditions in the field that can affect the entire transit network.

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[4] AATA information is taken from agency website: http://www.aata.org.

This thesis is one of the first to address the design of real-time holding strategies at key transfer points in a high-frequency transit network, recognizing the benefit and disbenefit to transfer passengers and to other passengers on the line.

The objectives of this thesis are therefore:

1) To develop real-time holding strategies for important transfer points in high frequency transit networks;
2) To estimate the potential benefits and improvements in service quality for transfer passengers resulting from implementation;
3) To recommend appropriate design of the control system including the type and amount of informational inputs, centralized vs. decentralized, and the benefits of more complex vs. simpler decision criteria.

The transfer coordination system envisioned will consist of an automated system to provide decision support to transit system personnel. It will evaluate the costs and benefits of a holding decision to improve transfer performance and leave the ultimate holding decision in the hands of the platform inspector. The initial focus of the thesis is on the rail-rail transfer context, however the ultimate applicability of these findings also includes rail-bus and bus-bus connections. The initial case study for the methods to be developed is the Massachusetts Bay Transit Authority (MBTA) which has a network well suited to a proposed transfer coordination system.

1.6 System Description

The Massachusetts Bay Transportation Authority (MBTA) has been metropolitan Boston's primary public transportation provider for the better part of the last century. Its service district includes seventy-eight communities in eastern Massachusetts and it carries approximately 695,000 passengers per day on the subway, bus and commuter rail systems. The MBTA has four major urban rail lines, consisting of three heavy-rail transit lines, the Red, Blue, and Orange Lines, as well as a light-rail line, the Green Line. The Green Line is unique for its branching network at its western end. Figure 1-3 shows a map of the current system and Table 1-1 shows some of the operating characteristics of each rail line. Table 1-2 shows the approximate operating schedule for each rail line during the peak, base and evening periods in Spring 2000.

Figure 1-3: Map of the MBTA System

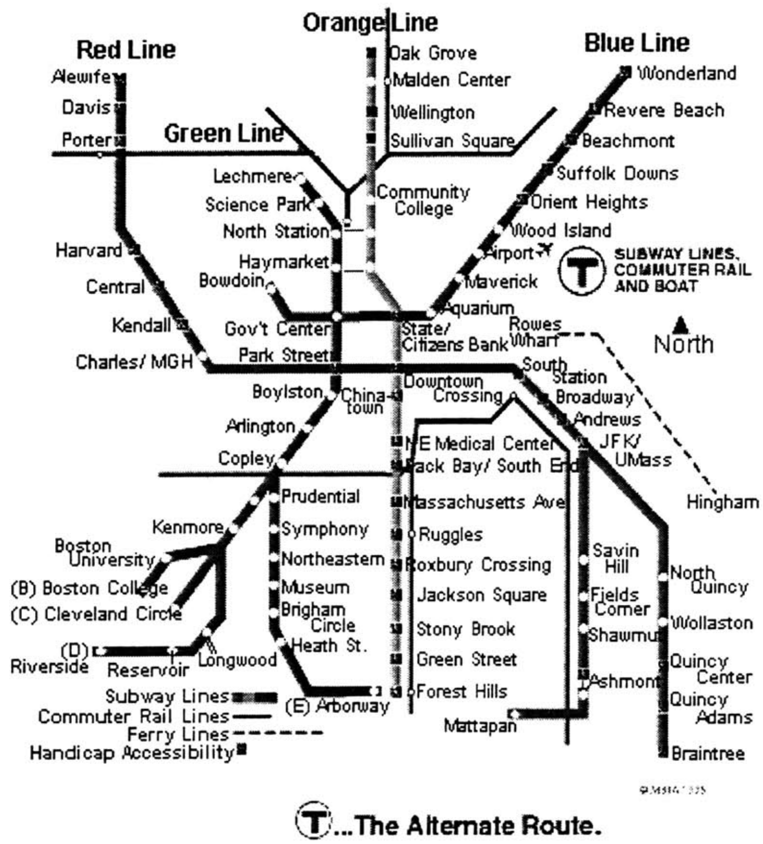


Table 1-1: Operating Characteristics of MBTA Rail Lines[5]

Rail Line	Miles of Track	Daily Boardings
Green Line	25.4	234,000
Red Line	23.1	225,000
Orange Line	11.1	124,000
Blue Line	5.9	61,000

(Note: Red Line includes Mattapan Trolley)

[5] Information taken from MBTA Website, http://www.mbta.com, April 2000.

Table 1-2: MBTA Daily Service Schedule (Valid as of Spring 2000)

Red Line Schedule					
			Headway in Minutes		
Direction	Terminal	Destination	Peak	Mid-Day (Base)	Late Evening
Southbound	Alewife	Braintree	7	12	12
Southbound	Alewife	Ashmont	8	12	12
Northbound	Braintree	Alewife	7	12	12
Northbound	Ashmont	Alewife	8	12	12
Green Line Schedule					
			Headway in Minutes		
Branch	Terminal	Destination	Peak	Mid-Day(Base)	Late Evening
B	Boston College	Gov't Center	5	8	8
B	Gov't Center	Boston College	5	8	8
C	Cleveland Circle	Gov't Center	6	6	10
C	Gov't Center	Cleveland Circle	6	6	10
D	Riverside	Lechmere	5	10	10
D	Lechmere	Riverside	5	10	10
E	Heath St.	Lechmere	9	9	10
E	Lechmere	Heath St.	9	9	10
Orange Line Schedule					
			Headway in Minutes		
Direction	Terminal	Destination	Peak	Mid-Day(Base)	Late Evening
Southbound	Oak Grove	Forest Hills	5	8	13
Northbound	Forest Hills	Oak Grove	5	8	13
Blue Line Schedule					
			Headway in Minutes		
Direction	Terminal	Destination	Peak	Mid-Day(Base)	Late Evening
Southbound	Wonderland	Gov't Center	4	9	13
Northbound	Gov't Center	Wonderland	4	9	13

There are four major downtown rail transfer stations, each connecting a pair of lines, and four major rapid transit / commuter rail transfer stations as well as numerous major rail-bus transfer locations. Any of the four major rail transfer stations are suitable as the initial case study to assess our system. Table 1-3 shows the overall number of daily transfers from line-to-line at the four transfer locations.

Table 1-3: Breakdown of Transfers at the Four Downtown Transfer Points[6]

Transfer Station	Park Street	Downtown Crossing	Government Center	State Street
Lines Served	Green/Red	Orange/Red	Blue/Green	Blue/Orange
Total Transfers	56,048	33,768	22,181	13,647

Park Street, the interchange between the Red and the Green Lines is chosen over the other three candidates for two specific reasons. First within the entire MBTA system, Park Street has the most transfers during a day with about 56,000 passengers transferring between the lines in both directions, this is some 22,000 more transfers per day than the station with the next most transfers, Downtown Crossing. Second, Park Street has an extremely unique station design due to the branching characteristics of the Green Line, with multiple platforms for boarding in each direction. If the system can be applied successfully to Park Street, it should be easier to implement it at other transfer stations devoid of the branching complications and complexities of Park Street.

1.7 Modeling Approach

The modeling approach to be taken will include optimization, heuristics, as well as simulation. We first develop an analytical model to evaluate an objective function maximizing the expected benefit to transferring passengers, while considering the negative time impacts for on-board passengers, and those already waiting at downstream locations. The main objective of the analytical model is to assess the expected benefits of transfer coordination at Park Street.

Constraints on the optimization, limiting expected benefits for transfer passengers, will include vehicle capacities, following headways of impending vehicles, and minimum benefit criterion to name just a few. As will become clear in the model, headway and vehicle location data allows us to predict arrival times, approximate waiting times, as well as train loads and passenger demand throughout the transit system. Several simplifying assumptions will be made to allow us to solve the problem heuristically, for possibly a more suitable implementation approach. Both the optimized and heuristic solutions will suggest reasonable control strategies to assess, as well as the suitability of our assumptions and system constraints.

[6] Central Transportation Planning Staff (CTPS), "1997 Passenger Counts: Volume 2", Page 6-2.

The operational guidelines validated by the results of the analytical model will then be applied in a simulation model providing a more precise representation of the actual field conditions. The simulation will build on the analytical model by estimating the actual benefits of a hold, instead of the expected ones. The simulation model will allow us to evaluate real-time control strategies in a more stochastic environment, devoid of the deterministic inputs assumed in the analytical model. For instance instead of assuming a uniform and constant arrival pattern for passengers, a more realistic representation of the arrival process may be as a Poisson process. Finally, the simulation model will allow us to test the sensitivity of our model to different assumptions or variables and will suggest to us the appropriate amount of detail and reality that we must incorporate into the model to accurately portray the system.

1.8 Thesis Organization

This thesis is organized into five chapters. Chapter Two describes the MBTA Park Street Station and identifies features that make it a logical choice for the analysis of potential benefits of transfer coordination for passengers. The current state of transfer coordination at Park Street is described. Lastly, passenger transfer data at Park Street is presented to support the argument for concentrating transfer enhancement efforts on transfers to the Green Line instead of to the Red Line.

Chapter Three outlines development of an analytical model for evaluating holding decision and making holding recommendations based upon the total waiting time saved, measured in passenger-minutes. The basic elements of the general analytical model are introduced such as the identification of impacted passengers and the guidelines governing potential holds. Next, the general analytical model is applied to the Park Street case study. Assumptions about system operating and transfer characteristics and their application to the analytical model are explained. Finally the results of the analytical model are analyzed as they apply to the Park Street case study. Benefits and shortcoming of different holding strategies are discussed.

Chapter Four covers the development of the simulation model and the basic distinctions between the analytical model and the simulation model. Various probability distributions are utilized to better represent random events such as travel times of trains, dwell times, and passenger demand. The results from the simulation model are reviewed and compared with the results from the analytical model. The sensitivity of the simulation model to variable changes is also noted. Finally recommendations for system implementation at Park Street are made.

Chapter Five summarizes the findings and discusses the ultimate application of these findings to the MBTA as well as to transit systems in general. The direction and scope of future research in the field is proposed.

Chapter 2: Park Street

This chapter will first generally describe the MBTA Park Street Station (hereafter simply referred to as Park Street) and will identify the features that make it a logical choice for the analysis of the potential benefits of transfer coordination. Passenger transfer data at Park Street will be presented to support the argument for choosing to model the transfer process from the Red Line to the Green Line Westbound. The current state of transfer coordination between the Red and Green Line at Park Street will be described, in addition to the potential feasibility of such a system.

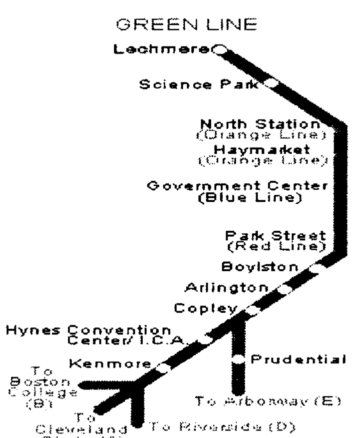
2.1 Role of Park Street in the MBTA Subway Network

Park Street, located in the heart of Boston's downtown business district, is the interchange between the Red and Green Lines. Park Street serves as a major hub of activity for both the Red and Green Lines, serving as a transit point between the two lines as well as a major destination point on both lines.

2.1.1 Park Street and the Green Line

On the Green Line, Park Street is located in the Central Subway section that is comprised of all stations between the terminus at Lechmere and Kenmore (see Figure 2-1). Park Street, along with Government Center, Haymarket and North Station are commonly referred to as the Downtown Transfer Stations on the Green Line.

Figure 2-1: The Green Line



The Central Transportation Planning Staff (CTPS) conducted passenger counts in 1997 that showed that the four Downtown Transfer stations had by far the highest ridership within the Central Subway section.[7] Of all trips taken on the Green Line on a given day, the Downtown Transfer stations accounted for about 37% of the activity or nearly 151,000 passenger boardings and alightings out of a total of 405,000 for the entire Green Line. Furthermore, Park Street and Government Center together were involved in approximately 32% or 128,000 passenger boardings and alightings of the total daily Green Line passenger

[7] Central Transportation Planning Staff, "1997 MBTA Passenger Counts: Volume 2", Page 6-2.

movements.

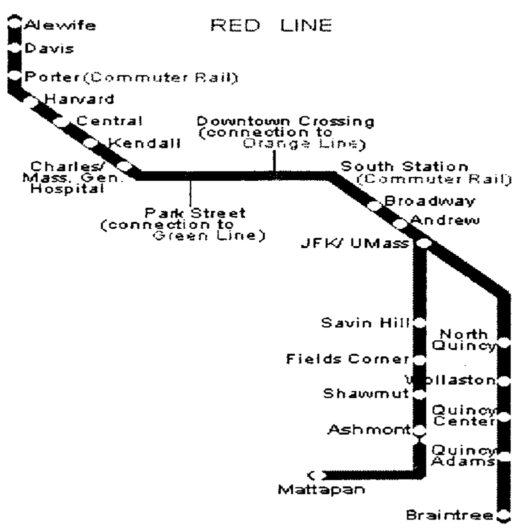
CTPS found that among trips originating west of Park Street (either on the B, C, D, or E surface lines, or in the Central Subway from Kenmore to Boylston) and headed Eastbound, 55% of these trips continued at least as far as Park Street. Of the total trips, 37% terminated at Park Street (including transfers), and 18% continued past Park Street to Government Center and beyond. Among Westbound riders, CTPS found that of those trips originating at Lechmere and Science Park, only 35% terminated at Park Street or a station further west.[8]

2.1.2 Park Street and the Red Line

On the Red Line, Park Street is located near the center of the Red Line between the northern terminus at Alewife and the joint-southern termini at Ashmont and Braintree (see Figure 2-2). Park Street and Downtown Crossing are the two transfer stations for the Red Line. Stations north of Park Street are deemed the Red Line Northwest stations such as Harvard and Porter Square. Those south of Downtown Crossing are called the Red Line South stations and include South Station and JFK/UMASS.

Park Street plays a similar role for the Red Line as it does for the Green Line: as a high activity generator due to both transfers and terminating/originating trips. The same 1997 CTPS counts, found that total boardings and alightings at Park Street and Downtown Crossing, the two transfer stations, accounted about 30% of all activity on the Red Line. Collectively, Park Street and Downtown Crossing had close to 130,000 total boardings and alightings out of nearly 436,000 daily movements on the entire Red Line.

Figure 2-2: The Red Line



CTPS found that the 13 stations comprising the Red Line South stations, between Ashmont and Braintree through South Station, were involved in about 36% of all boardings and alightings, while the Red Line Northwest stations, between Alewife and Charles/MGH accounted for nearly

[8] The actual proportion of riders continuing past Park Street cannot be determined from the count because on and offs at all of the transfer stations includes some riders going to or from other transfer stations.

35% of all boardings and alightings. Collectively, the Red Line South and the Red Line Northwest have nearly 155,000 and 151,000 total daily boardings and alightings respectively.

Among trips originating at Red Line Northwest stations, 72% ended at either Park Street or a station south of it.[9] Only 24% of these trips however, continued past Downtown Crossing and terminated at a station within the Red Line South segment. For those trips beginning at a Red Line South station, 53% terminated at one of the two transfer stops. Only 23% of these total trips ended at a station in the Park Street Northwest section.

2.2 Park Street Configuration

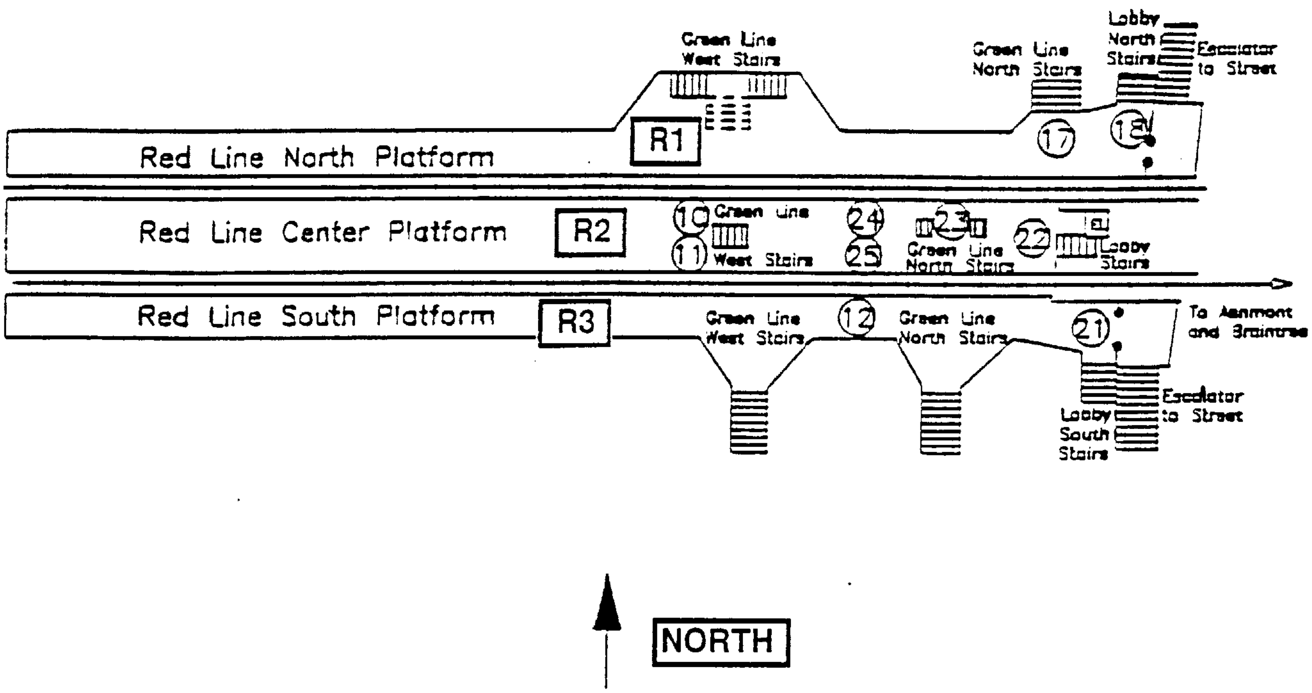
Park Street consists of two platform levels, one for the Red Line and one for the Green Line, connected by a series of stairwells, as well as a lobby area connecting Park Street to the Orange Line at Downtown Crossing via the Winter St. Concourse. Both platform levels have unique characteristics that distinguish it from other stations within the MBTA subway network.

Red Line trains arrive on the lower level (see Figure 2-3 for a schematic). Although the lower level has two tracks, the North and South tracks, there are three platforms for boarding and alighting, the North (R1), the Center (R2), and the South (R3) Platforms.[10] Red Line trains open doors on both sides of the train to allow boarding and alighting, with the doors opening onto the Center platform generally opening a few seconds later than those opening onto either the North or South Platforms. Northbound passengers headed towards Alewife may disembark on either the North or the Center Platforms. Similarly, Southbound riders, going in the direction of Ashmont or Braintree, may alight on either the South or Center Platforms.

The Red Line level has two escalators ascending directly to the street level above at the east ends of both the North and South Platforms. All three platforms have stairwells leading to the Green Line Westbound and Green Line Eastbound[11] platforms, as well as to the lobby area. The Center

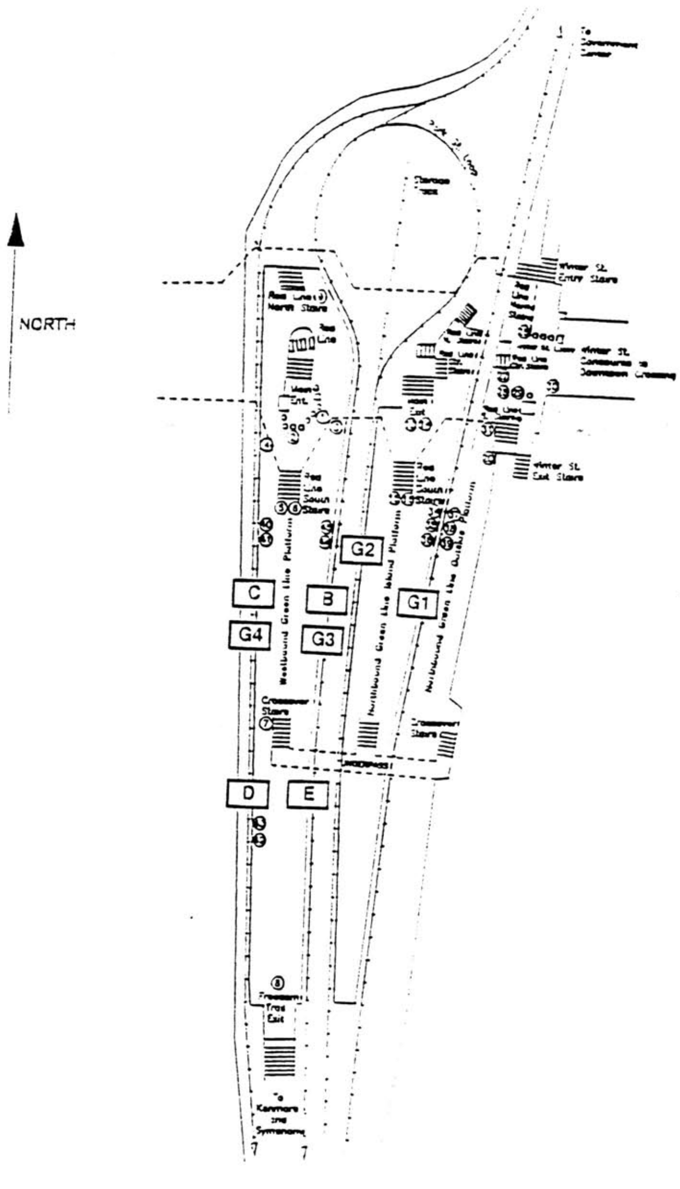
[9] Same as Footnote 2
[10] Track and platforms names are unofficial names created to provide clarity.
[11] The Eastbound and the Northbound Green Lines are the same. The name Eastbound will be used throughout this thesis as it is the preferred name by some MBTA personnel and will avoid confusion with the Northbound Red Line.

Figure 2-3: Park Street, Red Line Platforms



- Circled Numbers Indicate Checker Locations for 1985 Passenger Counts
- R1, R2, and R3 Refer to North, Center and South Platforms Respectively

Figure 2-4: Park Street, Green Line Platforms



- **Circled Numbers Indicate Checker Locations for 1985 Passenger Counts**
- **G1, G2, G3 and G4 Refer to Tracks**
- **B, C, D and E Indicate Approximate Boarding Location in Westbound Direction**

platform has an additional stairwell leading to the Green Line Eastbound platform. The Eastbound platform is also accessible from the lobby area.

The upper, Green Line level has dual tracks in each direction (see Figure 2-4). The Eastbound Green Line platform consists of a track adjacent to the east wall, Track G1, whose trains proceed onto Government Center and Lechmere. A center track,
labeled Track G2, is used exclusively for alighting purposes because it allows Eastbound trains to be short-turned back in the Westbound direction without having to proceed to Government Center. The Westbound Green Line platform consists of a central track, Track G3, and a track adjacent to the west wall, Track G4. C and D branch trains, going to Cleveland Circle and Riverside respectively, board on Track G4, with C trains boarding at the entrance to Park Street, while D trains board at the edge of the westbound tunnel to Kenmore and outlying regions. B and E trains, heading to Boston College and Arborway, board on Track G3 with B trains boarding at the entrance to the station and E trains boarding at the mouth of the westbound tunnel. Any train short-turned at Park Street also arrives on Track G3, regardless of destination.

2.3 Daily Transfers at Park Street

Altogether, Park Street has the greatest number of transfers throughout the day of the four major MBTA transfer stations. Of these 56,000 daily transfers at Park Street, transfers may be classified under three categories, transfers between Red and Green, those between Orange and Green, and those between Red and Orange, with the great majority, over 90%, falling under the Red and Green category. The Orange Line transfers occur via the Winter St. Concourse connecting the Downtown Crossing Orange Line platform to the Park Street lobby. Since these Orange Line transfers are essentially inter-station transfers between Park Street and Downtown Crossing instead of intra-station ones occurring solely inside the confines of Park Street, we choose to focus upon transfer movements taking place within Park Street, i.e. transfers between the Red and Green Lines.

Table 2-1 below shows a summary of the latest count of daily transfers at Park Street taken in 1997 by CTPS. Table 2-1 shows that overall weekday transfers from the Green Line to the Red Line at Park Street are higher than transfer movements in the opposite direction by nearly 2,000 daily transfers throughout the entire day (between 6AM and 11PM). During the AM Peak, defined by the MBTA as the time period between 6:30-9:30AM[12], there are almost 2,500 more transfers to the Green Line than to the Red Line. Conversely, the PM Peak, defined by the MBTA as the time period from 3:30-6:30PM, has nearly 2,300 more transfers to the Red Line than to the Green Line. This shows the distributional function the Green Line plays to access Back Bay employment.

Table 2-1 Summary of Total Weekday Park Street Transfers

	TO: Green West		TO: Green East		TO: RED SOUTH		TO: RED NORTH	
	From: Red North	From: Red South	From: Red North	From: Red South	From: GL West	From: GL East	From: GL West	From: GL East
Mean Hourly Transfers between 6AM and 11PM	626	584	125	259	266	720	252	463
Overall Standard Deviation	406	307	58	84	143	369	92	228
Total Number of Transfer between 6AM and 11PM	10,641	9,924	2,118	4,396	4,530	12,243	4,283	7,863
Overall Directional Transfers	20,565		6,514		16,773		12,146	
Overall Line Transfers	27,079				28,919			
Mean Hourly Transfers during AM Peak Period	1,268	968	137	264	273	766	366	421
Overall Standard Deviation	444	351	91	63	88	251	104	133
Total Number of Transfer in Peak Period	3,805	2,903	412	792	820	2,297	1,097	1,264
Overall Directional Transfers	6,708		1,204		3,117		2,361	
Overall Line Transfers	7,912				5,478			
Mean Hourly Transfers during PM Peak Period	815	856	155	349	481	1,349	289	826
Overall Standard Deviation	225	152	10	52	190	257	68	151
Total Number of Transfer in Peak Period	2,445	2,567	464	1,047	1,443	4,046	867	2,478
Overall Directional Transfers	5,012		1,511		5,489		3,345	
Overall Line Transfers	6,523				8,834			

Looking at directional transfer movements, average daily transfers are greatest from either of the Red Lines to the WB Green Line, about 20,500 passengers. Transfers to the Red Line Southbound (SB) and Northbound (NB) rank second and third respectively with about 16,500 and 12,000 daily passenger transfers. The Eastbound Green Line (EB) receives the fewest number of passenger transfers, at about 6,500, almost 14,000 fewer than its counterpart in the westbound direction. The situation in the peak periods largely mirrors that occurring during the rest of the

[12] AM and PM Peak used in Table 2-1 is defined as the time period between 7:00-10:00AM and 4:00-7:00PM respectively, instead of the MBTA standard because of the manner in which data was collected, unless otherwise noted.

day, except during the PM Peak when transfers to the Red Line Southbound are slightly larger than transfers to the Green Line Westbound.

The largest single transferring volumes occur from the Green Line Eastbound to the Red Line Southbound, followed by transfers to the Green Line Westbound from the Northbound and Southbound Red Lines.

Overall, the total number of transferring passengers to the Red and the Green Lines is a major determining factor in the likely benefits of a transfer coordination system. Since transfer passengers are the main beneficiaries of such transfer coordination schemes, it is likely that the rail line with the highest number of transfers will benefit the most from any efforts towards improving transfers. However, there are several other factors that need to be considered, that can also play a major role in evaluating a transfer coordination system; notably the number of passenger who may be negatively affected by holding trains for transferring passengers. These issues will be discussed in Section 2.5.

2.4 Current State of Transfer Coordination at Park Street

Currently there is little or no systematic coordination to benefit transfers occurring at Park Street in any direction. The initial interest in a transfer coordination system at Park Street was based on the presence of a blinking light-system visible on the Green Line level near the inspector's booth, indicating the arrival of a Red Line train at the lower level. It was originally conjectured that the lights were used by the Green Line inspectors as a rudimentary means of determining when and how long to hold a vehicle for transferring passengers from the Red Line. Consultations with several platform supervisors revealed that the lights were intended as a security precaution. They allowed Green Line passengers, transferring to the Red Line, to wait at the Green Line level which is supervised by station inspectors in both directions, instead of the Red Line level which usually has one inspector at most for all three platforms, situated midway down the Center Platform. There are however, some elements of real-time transfer coordination at Park Street.

- **Real-Time Information at Park Street**

In terms of real-time transfer coordination, platform inspectors at Park Street are privy to radio dispatches from operators of incoming trains, as well as observations from other inspectors along the route giving approximate vehicle locations and system operating conditions such as headway and incident reports. For the most part though, the Park Street inspector is on his own making the hold decision, and bases the decision upon experience, direct observations and second-hand information on special circumstances which may affect Park Street service. On many occasions, the Park Street inspector lacks knowledge of the following headways of incoming trains as well as the potential pitfalls of a holding decision upon downstream passengers. It is manifest that if the inspector is to make a beneficial holding decision, accurate and up-to-date information must be at his disposal to facilitate the decision.

- **The AVI System and OCS**

The Green and Red Line do offer some real-time information capabilities. The Green Line has had an Automated Vehicle Identification (AVI) system in place for about ten years. The Green Line AVI system consists of 31 detectors, called "keypoints", placed throughout the line.[13] The keypoints, actually loop detectors, send packets of information to the MBTA control center when triggered by a passing Green Line train. The system relays route, train number, train length (consist), detection time, and detector location information to the central processor. When the information is received at the control center, it is displayed on video terminals in its raw form, as well as on a large, wall-mounted schematic diagram of the Green Line. The presence of a train between two detectors is indicated by an illuminated light on the diagram. Figure 2-5 shows a schematic of the AVI system within the Central Subway. On average, AVI detectors are separated by about half a mile within the Central Subway (with much longer average distances on the surface portion of the line). For the entire Green Line, the longest distance separating two successive AVI detectors is nearly 6.6 miles between detector K14 and K16 on the surface portion of the D Line.

The Red Line has a somewhat different means of gathering vehicle location data, called the Operation Control System or OCS. The Red Line uses a specific circuit occupancy method, called "control lines", to determine the maximum permitted speed of a train, and to maintain a safe stopping distance between trains.[14] The Red Line control system divides the track into a series of blocks and indicates the occupancy of a block by a passing train to the main controller in digital form which is also displayed graphically. The information relayed to the main controller includes the train number, the block occupancy (unoccupancy) time, as well as the block location. Block length is on average much shorter than the distance between successive AVI detectors on

[13] Soeldner, D.W. "A Comparison of Control Options on the MBTA Green Line," Page 30.
[14] Song, W. "Real Time Dispatching Control in Transit Systems," Pages 14-15.

the Green Line. Figure 2-6 shows a schematic of the OCS around Park Street. The average block length is about 500 feet, with the longest blocks being around 1,100 feet.

As of now, it is intended that the real-time information capabilities of both the AVI and OCS be used by dispatchers to assess the current situation, to monitor the system-wide conditions, to make control decisions and to help resolve problems on the line. The detection times at keypoints or blocks allow dispatchers to estimate headway sequences before and after a train as well as to (roughly) estimate the impacts that control decision would have upon the system. Dispatchers accustomed to making decisions based upon experience, would then be able to make better and more knowledgeable and informed control decisions. Dispatchers, after surveying the situation, may decide that a train should be expressed, deadheaded, or short-turned to avoid an incident on the track or at a station or to meet unexpectedly heavy demand. Both systems serve the dual-purposes of a decision-support apparatus and an archive, by recording operational data on the system and vehicle performance. AVI and OCS are currently not used in any manner to improve transfers.

The AVI system and the OCS are not without their shortcomings. The AVI system only notes the time that a detector is passed, but does not give any other information on the exact location of a train. Therefore if a train is between two detection points, the AVI system can indicate only the most recent detector the train has passed. The train could be approaching the next detector, or still be close to the previous detector, but the system cannot differentiate between the two situations. Multiple trains at any point between two detectors appear on the wall panel queued up right next to each other before the next detector, thus giving dispatchers the impression that two successive trains are bunched closely together, when in fact they may be separated by a much greater distance. With some AVI detectors separated by as much as six miles, there is no doubt that the AVI resolution could be greatly enhanced to improve the quality of information available to dispatchers.

The OCS on the Red Line notes the occupancy (and unoccupancy) of a certain block. Thus similar to the dilemma with the AVI system on the Green Line, the OCS only provides the approximate location of the train within a given block segment. The precision in approximating vehicle location is better in the OCS than the AVI considering its much shorter average block lengths compared to the average distances between successive AVI detectors. However the OCS

Figure 2-5: Green Line AVI Schematic in Central Subway

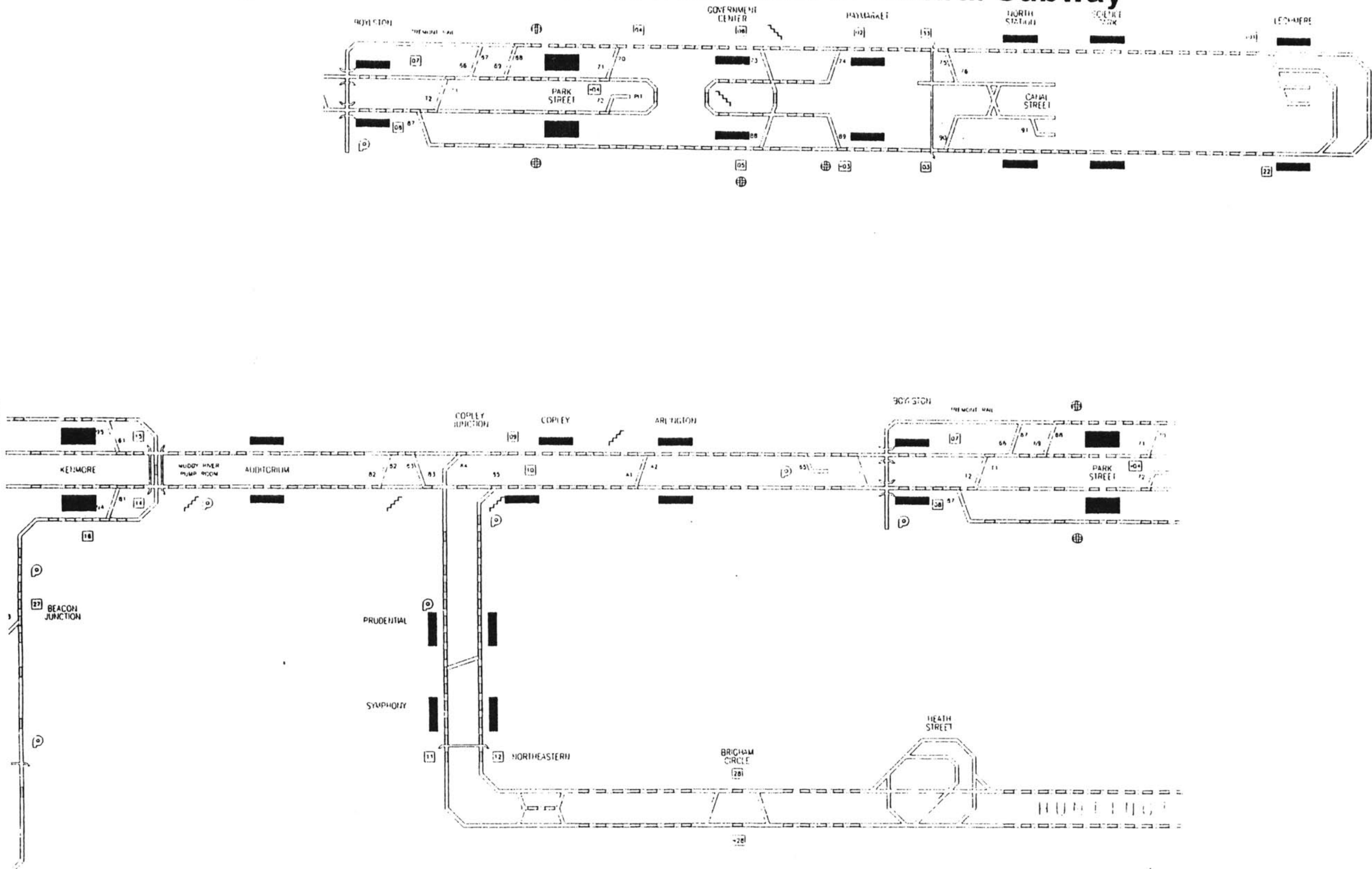
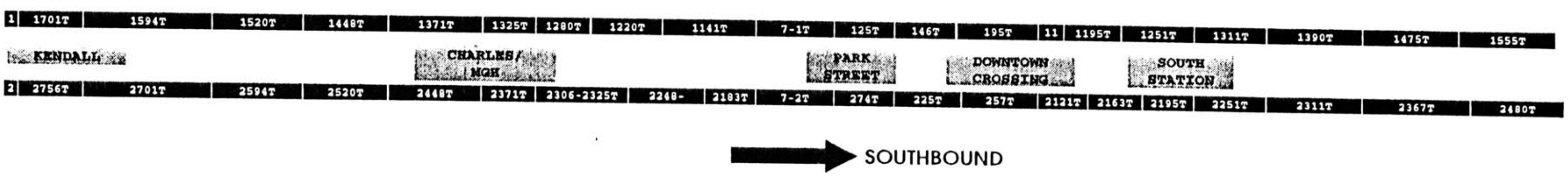


Figure 2-6: Red Line OCS Schematic Around Park Street



does not provide dispatchers with any information about the speed of a train. The speed of a train is important considering that the OCS is able to automatically slow trains that are approaching the minimum safe following distances determined by the location of the preceding train and the block circuits. It may be difficult for dispatchers to estimate Red Line arrivals into successive blocks if necessary, as a dispatcher will not know if the train is decelerating, accelerating, or maintaining a constant speed entering or exiting a block.

On a real-time basis, decision support provided by the AVI system and the OCS is problematic as the copious amounts of information may serve to overwhelm dispatchers. Moreover, it may be difficult to choose correct control strategies, especially complex ones such as short-turns which have large impacts upon passengers along the line, in a short period of time.

While the OCS assigns certain block circuits to represent the Park Street platform and thus gives a good idea of when a Red Line train stops at Park Street to load and unload passengers, the AVI system is limited by its system configuration in making such estimates. From Figure 2-5, the Eastbound Green Line has AVI detectors at Boylston (K08) and at Government Center (K05), but none at or near the Eastbound Park Street platform. For all Westbound trains running from Government Center to Park Street, the Park Street detector, K04, is located some distance from the platform prior to the track switch for Tracks G3 and G4.

Dispatchers have no idea when the train actually reaches the boarding platform. In addition, any trains short-turned at Park Street and entering the Westbound Platform on Track G3 are not detected at all. A short-turned train is last detected at the Eastbound Boylston detector, K08, but its position and headway are not updated again until the train has passed the Westbound Boylston detector, K07, near the entrance to the Boylston platform, making it difficult to accurately determine the arrival time into Park Street. These issues will arise again in Chapter 4 when discussing the formulation of the simulation model.

Overall, the AVI system and the OCS provide approximate train locations and trigger times, giving dispatchers a general idea of the location of each train, the headways directly preceding and following it, as well as the general operating conditions on the Green and Red Lines. There is great potential for utilizing systems such as AVI and OCS to more accurately locate trains and estimate their approximate positions to improve transfer reliability.

2.5 Selection of Directional Transfer Movement for Case Study

It is apparent that with the large numbers of transfers at Park Street to both the Red and Green Line, some sort of transfer coordination system utilizing the existing AVI system and OCS can be designed to benefit transferring passengers at Park Street. Transfer coordination between the Green and Red Lines may seem like a novel idea, but there is no doubt that without concrete and clear benefits from such a system, the MBTA will be unable to justify the incremental project cost. Consequently, we want to focus our efforts upon the transfer movement with the greatest potential benefits from coordination and which can best exemplify a successful application of transfer coordination. In the Park Street context, there are four major factors that enter into the decision whether to concentrate our coordination initiatives upon a particular transfer movement to either the Red Line or the Green Line:

1) Total Passengers Benefiting
2) Variance of Headway
3) Total Passengers Delayed
4) Park Street Location and Station Layout

Each of these issues is discussed below.

2.5.1 Total Passengers Benefiting

The major group of passengers benefiting from transfer coordination is obviously the transfer passengers themselves who will enjoy shorter waiting times. It must be stated that not all transfer passengers benefit from transfer coordination. In fact, only those transfer passengers that are eligible to ride a specific train, heading in a specific direction, and serving specific destinations benefit and save time when a particular train is held. This being said, for any transfer coordination system to be viable, there will need to be large numbers of transferring passengers benefiting from such a scheme.

Looking at overall directional transfer movements for both the Red Line and the Green Line, Table 2-1 showed that transfers to the Green Line Westbound are the greatest with over 20,500 transfers per day. The Green Line Westbound has over 4,000 and 8,000 more daily transfers than the second and third most utilized directional transfer movements, the Red Line Southbound and Northbound respectively. Thus, the Green Line Westbound has the potential to benefit the greatest number of transfer passengers from effective holding decisions.

2.5.2 Headway Variance

Variance of Green and Red Line train arrival headways into Park Street is another key factor in choosing a particular directional transfer movement to model. The average headway and the headway variance suggest the average and the minimum/maximum expected waiting times that transfer passengers might expect to wait if they arrive at the Green Line platform just as their connecting vehicle pulls out of the station. The longer the expected wait for a transfer is, the more benefit transfer coordination has. Tables 2-2 and 2-3 show the average and standard deviation of the headways for Red and Green Line trains entering Park Street. We choose to concentrate our findings on the average overall headways throughout the day instead of the peak ones because we assume that passengers are most likely to save time in off-peak periods due to reduced vehicle frequencies and longer expected waiting times if a train is missed.

Table 2-2 shows that over the entire day, Red Line trains enter Park Street on average of every 5 minutes, with standard deviations of about 2 and 2.5 minutes for Southbound and Northbound trains respectively. On average, transfer passenger from the Green to either of the Red Lines should expect to wait almost 3 minutes to make their connection.

Table 2-2: Average Headways and Standard Deviations for Red and Green Lines Entering Park Street (in minutes)[15]

	Red Line		Green Line[16]		
	SB	NB	WB	EB	EB - D and E Lines[17]
Overall Avg. Headway For Entire Day	5.1	5.0	1.9	1.8	3.8
STD	1.9	2.6	1.8	1.6	2.9
Avg. Headway During AM Peak	4.7	4.1	1.7	1.6	3.2
STD	1.8	2.6	1.4	1.3	2.8
Avg. Headway During PM Peak	4.1	4.1	1.6	1.5	3.3
STD	1.4	2.0	1.3	1.1	2.3

The Green Line arrival data in Table 2-2 for the WB and EB directions is somewhat misleading as it accounts for the arrival headways into Park Street for the combined headway of all arriving Green Line trains, without differentiating between trains heading to particular branches. These findings suggest that transfer passengers from the Red Line heading to common stops served by

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[15] AM and PM Peaks in Tables 2-2, 2-3 and 2-4 correspond to MBTA standards: 6:30-9:30AM and 3:30-6:30PM.
[16] Green Line headways reflect collective arrivals, regardless of destination.
[17] Eastbound D and E Lines serve the Haymarket-Lechmere Corridor.

all four branches in the Green Line WB direction, Boylston through Copley, wait an average of 2 minutes for the next train over the entire day. Serivce Eastbound to Government Center is similar.

On the Green Line, the transfer passengers most likely to benefit from transfer coordination are those heading to destinations served exclusively by a particular branch train. For instance passengers heading Westbound, to surface stops on the B Line after Kenmore, can only take B Line trains to these destinations. Passengers in the Eastbound direction can usually take either of two trains, D or E Line trains, to reach the stations between Haymarket and the terminus at Lechmere.

Table 2-2 suggests that over the entire day, transfer passengers in the Eastbound direction, headed to stations between Haymarket and Lechmere, may expect to wait about 3 minutes for the next D or E Line train.

Average headways and headway variations in Table 2-3 suggest that transfers heading to surface stops on the Green Line Westbound might save the most significant amounts of times out of all possible transfer movements. On average, such transfer passengers using the B or C Line might expect to wait about 5.5 and 5 minutes respectively. Transfers passengers headed to surface stops on the D or E Line might expect to wait about 5 and 6 minutes respectively. In terms of average headway and headway variance, the Green Line Westbound has the greatest potential to produce the most substantial time savings for impacted passengers if transfer coordination is implemented.

Table 2-3: Average Headways and Standard Deviations for Green Line Westbound Entering Park Street (in minutes)

	B Line	C Line	D Line	E Line
Avg. Headway Over Entire Day	7.7	7.6	6.8	9.1
STD	4.8	3.8	4.4	5.1
Avg. Headway During AM Peak	6.4	7.5	4.9	8.8
STD	4.3	3.0	3.5	4.5
Avg. Headway During PM Peak	6.3	6.8	5.1	9.1
STD	4.4	4.1	3.3	5.1

2.5.3 The Total Passengers Delayed

Service equity is another crucial factor in the success of transfer coordination. Passengers will rightly object if they feel that they are not being treated fairly. It is a given that transfer coordination benefits transfer passengers by shortening transfer waits, but at the same time it delays and inconveniences passengers aboard the train being held and also possibly those waiting at downstream locations and at the station where holding occurs. With limited knowledge of passenger arrival rates at Park Street and beyond, the group most affected by these delays may well be the "through-passengers": those who are already aboard the train coming into Park Street bound for stations past Park Street. In the overall scheme of coordination, we would want to find the transfer movement that is likely to negatively impact the fewest number of through-passengers.

The most likely statistic to indicate the level of delay and disruption to through-passengers is the average number of through-passengers on a given train as it passes through Park Street. Table 2-4 estimates the mean through-passengers per train for the Green and Red Line based upon the scheduled headways during peak, mid-day and late-evening periods from Table 1-2. (Note Green Line trains are the sum of B, C, D, and E trains in the Central Subway Area)

Table 2-4: Average Through-Passengers Per Train, Based on Scheduled Arrivals

Time Interval	Green Line West[a]	Green Line East	Red Line Northbound[b]	Red Line Southbound
7:00 - 8:00 a.m.	43	32	175	161
8:00 - 9:00 a.m.	47	54	177	266
9:00 – 10:00 a.m.	21	26	84	121
10:00 - 11:00 a.m.	18	23	122	82
11:00 a.m. - Noon	18	17	89	88
Noon - 1:00 p.m.	22	24	112	111
1:00 - 2:00 p.m.	16	7	117	107
2:00 - 3:00 p.m.	17	26	126	108
3:00 - 4:00 p.m.	33	50	116	125
4:00 - 5:00 p.m.	26	37	144	132
5:00 - 6:00 p.m.	56	36	255	186
6:00 - 7:00 p.m.	45	20	107	69
7:00 - 8:00 p.m.	27	22	114	92
8:00 - 9:00 p.m.	25	18	54	42
9:00 – 10:00 p.m.	20	14	45	41
10:00 - 11:00 p.m.	23	17	47	48
Hourly Average	29	26	118	111
Hourly STD	12	13	53	58

[a] Green Line Assumptions: 40 trains/hour during peak, 30 trains/hour in mid-day, 25 trains/hour in evening; found by combining the expected number of trains for each branch in one hour

[b] Red Line Assumptions: 16 trains/hour during peak, 10 trains/hour in mid-day, 10 trains/hour in evening

From Table 2-4, the hourly average of through-passengers per train on the Red Line in either direction is nearly four times as large as the average on the Green Line in either direction. Thus for a single train entering Park Street, Green Line through-passengers are considerably less than those on the Red Line, in no small part due to the Central Subway where trains of the four branches combine to lower the inter-arrival headway period and consequently the average load entering Park Street. Thus in terms of the number of through-passengers per train, considerably fewer riders on the Green Line would be negatively affected by a hold, when compared to those potentially delayed on the Red Line.

2.5.4 Park Street Location and Station Layout

The last factor to consider in the success of transfer coordination is the location and station layout of Park Street. Focusing on the Green Line WB, the dominant direction of transfers for the Green Line, Park Street is situated near the beginning of the line in the Westbound direction. For the Red Line, Park Street is situated halfway between the northern and southern termini. Thus, overall benefits should be significantly higher on the Green Line Westbound than those on the Red Line, because of the larger route length extending past Park Street to the west.

Lastly the branching structure of the Green Line is unique compared to the other rapid transit lines comprising the MBTA subway network. The dual tracks (G3 and G4) on the Green Line Westbound platform allow multiple trains to be in the station simultaneously, loading at different locations along either track depending upon the route. Furthermore, transfer and regular passengers using the Green Line Westbound can board one or more of four branch trains depending upon their final destination, making it more difficult to model passenger behavior precisely. Thus, the branching and the dual track situation on the Green Line Westbound at Park Street serve to complicate any attempts to simulate or to capture the operating and the passenger demand characteristics of the system. Therefore any successful implementation of a transfer coordination project on the Green Line could easily be simplified and applied to the less structurally-complex rapid transit lines in the MBTA such as the Red, Orange, or Blue Lines.

2.5.5 Selection of Green Line Westbound

In conclusion the Green Line Westbound appears to be the most promising candidate of all four Park Street directional transfer movements, to produce a successful implementation of a transfer coordination system. Considering the total number of passengers benefiting, the average and variance of the headway throughout the day, the number of through-passengers per train, as well as the location and the station layout of Park Street, the Green Line Westbound has the greatest potential for significant benefits, while at the same time minimizing the disbenefits to delayed passengers. Finally and more far-reaching however, implementing transfer coordination on the Green Line level will allow us to easily adapt the system to other transit lines in the MBTA and other transit systems, which have much simpler structures or travel patterns. From this point forward, we will focus solely upon transfers from the Red Line (in both directions) to the Green Line Westbound at Park Street.

2.6 Transfer Characteristics

Before jumping into the design of the transfer coordination system itself, transfer movements at Park Street to the Green Line Westbound must be analyzed to better understand the transfer process. The two main points of analysis for transfer passengers at Park Street are the manner in which they reach the Green Line level, and the time it takes for them to complete the movement.

2.6.1 Stairwell Usage

Transfers between the Red and Green Lines occur via a series of stairwells connecting the two levels. Each of the three platforms on the Red Line level has one stairwell leading to the Green Line Westbound and one to the Green Line Eastbound, with the Center Platform possessing one additional stairwell to the Green Line Eastbound platform.

Stairwell usage by transferring passengers from the Red Line to the Green Line Westbound, is not divided evenly. Based on the 1997 CTPS counts, transfers to the Green Line WB from the Red Line SB primarily funnel through the stairwell on the South Platform (92.5% of all transfers), while the great majority (75.9%) of Red Line NB transfers utilize the stairwell on the North Platform.

2.6.2 Transfer Times

The manner in which transferring passengers arrive on the Green Line platform is an important step in modeling the total transfer process. Maybe the most important factor though is the time characteristics of the transfer movement. By time we are referring to the amount of time that elapses for one transfer passenger to leave the Red Line train and arrive at the Green Line level, or possibly the vehicle itself. We define the duration of a transfer as the time window between the moment the doors of the Red Line train open, until all (or a large proportion of) the transferring passengers reach the Green Line boarding area.

Knowing the stairwell usage patterns of transferring passengers, we assume that all transfers from a given Red Line direction to the Green Line Westbound utilize the primary stairwell only. This assumption although unrealistic, especially for Red Line NB transfers to the Green Line WB is necessary to simplify the collection of approximate transfer times and durations. Table 2-8 shows the approximate minimum transfer time and duration of a transfer for a given movement during the afternoon peak on a typical weekday.

Table 2-5 shows the time it takes for transfer passengers to reach the top of the stairwell in each case. These transfer times however, do not include the time it takes to reach the Green Line train itself. The large number of queuing people on the Green Line platforms and line-of-sight difficulties make it difficult to measure accurately the time to reach the vehicle. Secondly, upon reaching the top of the stairwell and seeing their prospective train on the track, the passenger is more likely to walk quickly or to run to catch the train.

Table 2-5: Approximate Transfer Times and Durations

Originating Platform	Destination Platform	Stairwell	Minimum Transfer Time(in minutes)	Duration of Transfer (in minutes)
Red Line SB	Green Line WB	South Stairs	0:20	1:45
Red Line NB	Green Line WB	North Stairs	0:45	1:45

Although the observations lasted for slightly longer than an hour, we gain a good idea of the time it takes to complete a transfer (the minimum transfer time), as well as the approximate duration of the transferring period. The duration of the transferring period may be a subjective piece of data however, since the end of the period is based upon the opinion of the observer and not on any hard statistical evidence. There may be cases when remaining stragglers, such as young or elderly individuals will arrive long past the expected passing of the transfer duration. For now though, we will assume these values to be accurate.

2.7 Overall Feasibility of Transfer Coordination

It is vital that any transfer coordination system produces enough passenger benefits to justify implementation. Maybe just as important however, is the economic effectiveness of such a project. Sound ideas and initiatives may improve transit service significantly, yet if the incremental costs of the project are too high and system management does not foresee credible return on its investment, such projects will not be implemented. Figures 2-7 and 2-8 show approximate cost estimates for the transfer coordination project, divided into two phases.[18] Phase

[18] Cost estimates are courtesy of Bob Swirbalus of the MBTA, February 2000.

One of implementation would consist of the installation of a Green Line AVI terminal and of a Red Line CTC screen for the Park Street inspector on the Green Line Westbound platform. Phase Two would consist of the installation of a Programmable Logic Controller (PLC) to automatically assess transfer situations. Furthermore a control and indication box in the inspector's booth, as well as two hold signs on the platform, visible to train drivers from any of the four train berthing locations, would be installed. Altogether, the total cost of the transfer coordination project is estimated to be around $100,000.

The MBTA must decide what annual expected benefit in passenger-minutes saved would justify implementation given the initial investment cost. The MBTA might base this decision on the economic benefits accruing to riders from the reduced journey time. For instance, if passengers value an hour of waiting time to be equivalent to $10.00/hour and the transfer coordination system is expected to produce annual time savings benefits of about 9,000 passenger-hours saved, then the annual equivalent dollar savings for passengers from improved transfer performance would be approximately $90,000. These results would suggest that after one year in operation, the initial investment in the transfer coordination system would have essentially been recouped. It remains to be seen what level of return on the initial investment is sufficient to justify the final implementation decision by the MBTA. Various factors enter into the decision such as the availability of funding for the initial investment as well as the desire of the agency to divert funding to a project whose benefits may be clear on paper, but has yet to prove itself in actual operation. Overall however, if significant passenger benefits are produced over the long haul, it is likely that the transfer coordination system should eventually be able to pay for itself in terms of the equivalent passenger waiting time costs.

Figure 2-7: Cost Estimates for Phase One of Park Street Transfer Coordination Project

This Phase includes the following:

1 Installation of a Green Line AVI terminal at the Green Line Inspector's Booth
2 Installation of a Red Line CTC screen at the same location using CCTV feed from High Street

Assumptions:

1 The method for installation of the Green Line AVI terminal is fixed and known
2 The method for installation of the Red Line Display is not completely identified (It may not work in which case a second plan must be developed)
3 If additional computer hardware is necessary at the OCC, this estimate will require an update

Green Line AVI Terminal Installation:

Function	Engineers				Foreman			Maintainers/Wirepersons				Frank Feltes			Labor	Materials	
	Num.	Hrs.	Rate	Sub-Total	Hrs.	Rate	Sub-Total	Num.	Hrs.	Rate	Sub-Total	Hrs.	Rate	Sub-Total	Sub-Total		Estimate
Initial Survey	2	4	$ 46.33	$ 370.64	4	$49.71	$ 198.84			$46.86	$ -		$ 100.00	$ -	$ 569.48		
OCC Modem Installation	2	4	$ 46.33	$ 370.64	4	$49.71	$ 198.84	2	4	$46.86	$ 374.88		$ 100.00	$ -	$ 944.36	Modem & Cable	$ 750.00
Park Street Modem Installation	2	8	$ 46.33	$ 741.28	8	$49.71	$ 397.68	2	16	$46.86	$ 1,499.52		$ 100.00	$ -	$ 2,638.48	Modem & Cable	$ 750.00
Terminal Setup and Installation	2	8	$ 46.33	$ 741.28		$49.71	$ -			$46.86	$ -		$ 100.00	$ -	$ 741.28	Terminal	$ 950.00
Training	1	4	$ 46.33	$ 185.32		$49.71	$ -			$46.86	$ -		$ 100.00	$ -	$ 185.32	Misc.	$ 250.00
Sub-Totals				$ 2,409.16			$ 795.36				$ 1,874.40			$ -	$ 5,078.92		
Totals	Grand Total:			$ 7,778.92									Labor Total:		$ 5,078.92	Materials Total:	$ 2,700.00

Red Line CTC Display Screen:

Function	Engineers				Foreman			Maintainers/Wirepersons				Frank Feltes			Labor	Materials	
	Num.	Hrs.	Rate	Sub-Total	Hrs.	Rate	Sub-Total	Num.	Hrs.	Rate	Sub-Total	Hrs.	Rate	Sub-Total	Sub-Total		Estimate
Initial Survey	2	4	$ 46.33	$ 370.64	4	$49.71	$ 198.84			$46.86	$ -	2	$ 100.00	$ 200.00	$ 769.48		
OCC Computer Setup	2	8	$ 46.33	$ 741.28		$49.71	$ -	2	4	$46.86	$ 374.88	8	$ 100.00	$ 800.00	$ 1,916.16	Modem & Cable	$ 600.00
OCC Software Setup			$ 46.33	$ -		$49.71	$ -	2	8	$46.86	$ 749.76	8	$ 100.00	$ 800.00	$ 1,549.76	Jupiter Display	$ 3,000.00
OCC Modem & Comm.	2	8	$ 46.33	$ 741.28	8	$49.71	$ 397.68	2	8	$46.86	$ 749.76		$ 100.00	$ -	$ 1,888.72	Modem & Cable	$ 600.00
Park St. Modem & Comm.	2	8	$ 46.33	$ 741.28	8	$49.71	$ 397.68	2	8	$46.86	$ 749.76		$ 100.00	$ -	$ 1,888.72	Modem & Cable	$ 1,000.00
Video Screen Installation	2	4	$ 46.33	$ 370.64	4	$49.71	$ 198.84	2	4	$46.86	$ 374.88		$ 100.00	$ -	$ 944.36	Video Screen	$ 400.00
Training	1	4	$ 46.33	$ 185.32		$49.71	$ -			$46.86	$ -	1	$ 100.00	$ 100.00	$ 285.32	Misc.	$ 100.00
Sub-Totals				$ 3,150.44			$ 1,193.04				$ 2,999.04			$ 1,900.00	$ 9,242.52		
Totals	Grand Total:			$ 14,942.52									Labor Total:		$ 9,242.52	Materials Total:	$ 5,700.00

Totals:	**Grand Total:**	**$ 22,721.44**	**Labor Total:**	**$ 14,321.44**	**Materials Total:**	**$ 8,400.00**

Figure 2-8: Cost Estimates for Phase Two of Park Street Transfer Coordination Project

This Phase includes the following:

1. Installation of a PLC with appropriate programming to automatically hold trains
2. Installation of appropriate control and indication box for the inspector's booth
3. Installation of two hold signs on the platforms

Assumptions:

1. This is a budgetary estimate
2. The methods used to develop this estimate may require modification depending on field conditions (The price could go up or down)
3. It is assumed that all new equipment will be used.
4. No interface to the OCC

Function	Engineers				Foreman			Maintainers				Labor	Materials	
	Num.	Hrs.	Rate	Sub-Total	Hrs.	Rate	Sub-Total	Num.	Hrs.	Rate	Sub-Total	Sub-Total		Estimate
Initial Survey	2	4	$ 46.33	$ 370.64	4	$49.71	$ 198.84	1	4	$46.86	$ 187.44	$ 756.92		
Design	2	24	$ 46.33	$ 2,223.84	0	$49.71	$ -	0	0	$46.86	$ -	$ 2,411.28		
PLC Parts	1	4	$ 46.33	$ 185.32	0	$49.71	$ -	0	0	$46.86	$ -	$ 185.32	PLC Parts, etc.	$ 18,000.00
PLC Installation	1	8	$ 46.33	$ 370.64	8	$49.71	$ 397.68	2	8	$46.86	$ 749.76	$ 1,518.08	Misc. Parts	$ 100.00
Red Line PLC Interface Inst.	2	8	$ 46.33	$ 741.28	8	$49.71	$ 397.68	2	8	$46.86	$ 749.76	$ 1,888.72	Wire	$ 100.00
Green Line PLC Interface Inst.	2	24	$ 69.50	$ 3,336.00	24	$74.57	$ 1,789.68	4	24	$70.29	$ 6,747.84	$ 11,873.52	Cable	$ 4,000.00
Green Line AVI Modifications	2	8	$ 69.50	$ 1,112.00	8	$74.57	$ 596.56	1	8	$70.29	$ 562.32	$ 2,270.88	PD-2 Cards	$ 2,000.00
Control Box Build	1	8	$ 46.33	$ 370.64	16	$49.71	$ 795.36	1	16	$46.86	$ 749.76	$ 1,915.76	Misc. Parts	$ 2,000.00
Control Box Installation	1	16	$ 69.50	$ 1,112.00	16	$74.57	$ 1,193.12	2	16	$70.29	$ 2,249.28	$ 4,554.40	Misc. Parts/Conduit	$ 1,000.00
Hold Sign Build	1	16	$ 69.50	$ 1,112.00	24	$49.71	$ 1,193.04	1	24	$46.86	$ 1,124.64	$ 3,429.68	Misc. Parts	$ 10,000.00
Hold Sign Installation	1	16	$ 69.50	$ 1,112.00	16	$74.57	$ 1,193.12	2	16	$70.29	$ 2,249.28	$ 4,554.40	Misc. Parts/Conduit	$ 1,500.00
PLC Programming & Testing	2	48	$ 46.33	$ 4,447.68	0	$49.71	$ -	0	0	$46.86	$ -	$ 4,447.68		
Training	1	8	$ 46.33	$ 370.64	0	$49.71	$ -	0	0	$46.86	$ -	$ 370.64		
Sub-Totals				$ 16,864.68			$ 7,755.08				$15,370.08	$ 40,177.28		
Totals	Grand Total:			$ 78,689.84						Labor Total:		$ 39,989.84	Materials Total:	$ 38,700.00

Chapter 3: The Analytical Model

This chapter covers the development of a model for evaluating holding decisions and making holding recommendations based upon net passenger-minutes saved in the course of improving transfer coordination. First, the basic underlying principles and elements comprising the analytical model are explained. Second, the application of the model to the Park Street case study is described. Lastly the results of the analysis presented and analyzed.

3.1 The Basic Elements

Before delving into the issue of transfer coordination at Park Street, we must first identify and explain some of the basic elements of the analytical model used to evaluate holding decisions at a transfer station. These basic elements are common to all transfer locations and all transit agencies contemplating transfer coordination systems:

a) The basis behind any holding decision.
b) The impacts of holds.

More complicated aspects of the analytical model are covered in the examination of the Park Street case study. This approach is taken for one major reason: ease of comprehension. Many of the assumptions and principles behind the analytical model are easier to illustrate and to understand if a concrete example is presented with a specific set of operating characteristics and physical layout.

3.1.1 Basis for Holding Decisions

Holding decisions improving transfer connections and coordination may be looked at in several manners. Several key benefits of coordination include the minimization of missed transfers, the shortening of transfer waiting time, and improved service reliability. The reduction in total transfer waiting time however, is the most important benefit of transfer coordination for the transit agency and transfer passengers. At the same time however, the transit agency needs to assure that the level-of-service is not so drastically reduced for non-transferring passengers, that they now become dissatisfied.

Passengers impacted by coordination consist of those saving time and those being delayed. Regardless of whether they transfer or not, passengers on the whole do judge the quality of their journey in terms of the total time spent within the system, consisting of waiting time and in-vehicle time. It is true that trip times in the vehicle vary according to the time of day and the passenger demand at stations along the way as well as the initial wait. It is also true that for transferring passengers, the waiting time for connecting trains is the major source of variability in their journeys. Thus it makes sense to base any transfer coordination system on the potential effects holding has upon the net waiting time for passengers, whether it is in-vehicle or out-of-vehicle.

Net passenger-minutes (pax-mins) saved, or the total net benefit, from a hold is an appropriate measure of the total change in waiting time and thus the effectiveness of a potential hold. The total net benefit measures the difference in waiting times for passengers benefiting from the hold and those being delayed by it. The total net benefit, measured in passenger-minutes saved, is relatively easy to understand conceptually not only for transit agency personnel, but also for the main beneficiaries of transfer coordination, the general public and the riders. Net passengers-minutes saved is easily calculated and quantifiable.

Net passenger-minutes saved is not the only criterion that a hold can be based upon. For instance the number of passenger benefiting, the number of passengers being delayed, or a ratio of the two (the passenger-benefit ratio) are just as plausible measures of effectiveness as net passenger-minutes saved is. Total net benefits however is the best all-around evaluation measure as it gives an idea of the overall effect of a hold upon all passengers. It is true that if a hold results in a total net benefit of 100 passenger-minutes saved, it is unclear as to whether fifty passengers saved two minutes a piece, or twenty-five passengers saved four minutes a piece. But basing a model on such a statistic is clearly more meaningful than if it is based solely upon the number of passengers benefiting or the ratio of benefited passengers to delayed ones.

For instance, an estimate of 100 passengers saving time is ambiguous as we have no indication how these 100 passengers benefit and how other passengers are delayed. Furthermore, a passenger-benefit ratio of two signifies that for every passenger delayed by a hold, two subsequently save time. It is unclear however, how passengers are delayed and how they benefit. Solely utilizing a passenger benefit ratio could conceivably result in a hold producing a negative total net benefit, ultimately creating an overall deleterious effect on all passenger groups considered. Although a passenger benefit ratio has its shortcomings, it may nonetheless be a useful tool to assess the level of service equity provided to passengers for a potential hold. A potential hold yielding benefits surpassing the minimum-benefit criterion, may save substantial amounts of time for a small number of passengers, while delaying large numbers of passengers a relatively shorter amount of time.

In summary, the initial feasibility of holding a train is solely determined by the net overall change in waiting time, measured in net passenger-minutes saved. Any potential train hold producing positive net benefits is a viable candidate. Secondary evaluation measures such as passenger benefit ratios may play a factor in the final holding decision as they can be used by the inspector to assess service equity for all impacted passengers.

3.1.2 The Impacts of a Hold

Transfer coordination is primarily meant to benefit passengers transferring from one rail line, the origin line, to another line, the destination line. Holding actions, which occur only on the destination line, can also benefit and delay transit riders on the destination line, who are not transferring. There are generally six separate classes of potentially affected passengers for a held train on the destination line.

- **P1 Passengers**

  Also known as through-passengers, P1 are those already onboard the train when it passes through the transfer station. P1 passengers originate at stations upstream of the transfer station and proceed past the transfer station to downstream destinations. P1 passengers are negatively affected by a hold since they are delayed by the holding period.

- **P2 Passengers**

  P2 passengers board at the transfer station regardless of a hold. P2 passengers are essentially boarding during the time period before any holding occurs. They are headed to destinations downstream of the transfer station and are also negatively affected by a holding decision, by the duration of the hold.

- **P3 Passengers**

  P3 passengers are composed entirely of transfers from the origin line to the destination line. P3 passengers board the destination line train only as a result of holding. P3 passengers benefit the most from a hold. Instead of waiting for the next incoming train, P3 passengers experience no waiting time if a hold is instituted on the current destination line train. P3 passengers save time amounting to the following headway of the current train entering the transfer station.

- **P4 Passengers**

  P4 passengers board trains on the destination line at the transfer station during the hold. The arrival rates for P2 and P4 passengers are the same. P4 passengers save time amounting to the following headway of the current destination line train.[19]

- **P5 Passengers**

  P5 passengers board at stations downstream from the transfer station on the destination line. P5 passengers, similar to P2 passengers, arrive and board the train regardless of a hold. P5 riders are negatively affected by a hold by the duration of the holding period at the transfer station.

- **P6 Passengers**

  P6 passengers, similar in nature to P4 passengers, board during the holding period but at downstream stations along the destination line. P6 passengers save time amounting to the following headway of the current train at the specific downstream station analyzed.

The cumulative passenger impacts of a hold are summed for the six passengers groups. The resulting net passenger impact determines the desirability of a hold for a destination line train approaching the transfer station. Table 3-1 summarizes the affected passengers and the extent of the impact.

Table 3-1: Summary of Affected Passengers Classes

Passenger Type	Originating Location	Passenger Accumulation Time	Impact of a Hold
P1	Upstream Stations	Prior Arriving Headway	Delayed by the holding time
P2	Transfer Station	Prior Arriving Headway	Delayed by the holding time
P3	Transfer Station	Holding Time	Savings of following departing headway
P4	Transfer Station	Holding Time	Savings of following departing headway
P5	Downstream Stations	Prior Arriving Headway	Delayed by the holding time
P6	Downstream Stations	Holding Time	Savings of following departing headway

3.2 Park Street Case Study Model Assumptions

This section presents the assumptions and issues included in the Park Street model without mentioning how these assumptions are connected to form a cohesive model: this will be the focus of Section 3.3.

[19] Boarding for P3 and P4 passengers occurs simultaneously at the transfer station and occurs in six stages. We will defer this explanation until later in the Park Street case study discussion.

The analytical model is meant as a way to assess the validity of assumptions and of data for the transfer coordination system. The results for Park Street will be approximate figures rather than exact benefits as we are testing the appropriateness of our model under different circumstances. The simulation model (to be presented in Chapter 4) will be a more precise representation of the Park Street situation. The analytical model will show whether, when, and how a transfer coordination system can benefit the MBTA. Furthermore, the results will suggest ways to alter assumptions or the model structure itself to better account for unique operating or physical characteristics of Park Street in the simulation model.

The critical assumptions of the analytical model as applied to the Park Street case study are grouped into the following six categories:

1) Holding Characteristics and Assumptions
2) Vehicle Location, Preceding Headway and Passenger Arrival Assumptions
3) Train Operating Issues and Assumptions
4) Impacted Passenger Definition
5) Eligible, Actual and Leftover Passenger Definition
6) Transfer Passenger Assumptions

3.2.1 Holding Characteristics and Assumptions

This section presents some of the issues, which need to be considered in terms of holding Green Line trains at Park Street.

- **Initial Holding Considerations**

There are times when a Green Line train approaching Park Street is deemed ineligible for holding from the outset. Being considered for a hold means that a hold is possible whether or not it turns out to be beneficial. This is based on the arrival time of the initial Green Line train into Park Street, the expected number of transferring passengers from the Red Line, and finally the expected arrival times of following Green Line trains. We make the assumption that an incoming Green Line train is eligible to be considered for a hold only if:

1. The required holding period for Red Line transfer passengers from a specific Red Line train ends AFTER the arrival of the current Green Line train,

   AND

2. The same required holding period ends BEFORE the expected arrival of the following Green Line train.

The first condition requires that the transfer period for passengers from a specific Red Line train must conclude after a Green Line train arrives at Park Street. This condition essentially assures that a hold results in at least some of the Red Line transfer passengers benefiting from a held Green Line train.

The second condition means that a Green Line train will never be held so long that it delays the arrival of the next Green Line train. The next train, regardless of what track it arrives on and regardless of what branch the train is heading for (or originating from), will never be delayed by a holding decision. This stipulation prevents blocking from occurring. Blocking defeats the whole purpose of the transfer coordination system to reduce delays and waits for passengers in the system, since additional passengers on the following train will also be delayed, resulting in increased congestion, confusion and frustration on the Green Line, on each side of the platform.

The configuration at the Park Street Westbound platform, is unique because of the dual tracks on each side of the platform. Thus if the current train were a Westbound B Line train, it is physically possible that a C, or a D Line train could enter Park Street without being inhibited by the current train (See Figure 2-4 showing the Park Street Green Line Platform). Suppose that a C Line train enters the station and leaves the station on Track G4 while a B Line train is being held for transferring Red Line passengers. Although the holding action on the B Line train may appear to be advantageous in terms of a positive net benefit, these time savings are meaningless to passengers in the face of the departing C Line train.

Many of the riders on the B Line train could have waited for the C Line train and arrived at their destinations earlier. Those passengers supposedly benefiting from a held B Line train are actually forced to wait longer because of the hold, since the later arriving C Line train departs the station earlier. Rider dissatisfaction with this sort of behavior would rightly result in frustration and anger with the service. To maintain a customer-oriented operation, holding will not be permitted when the following trains would have arrived at the station.

- **Holding Duration**

Transfer passengers benefit the most from coordination efforts. To assure that the vast majority of transfer passengers successfully complete the connection, in general we assume that any potential hold shall last until the conclusion of the transferring period defined previously in

Chapter 2 for a single Red Line train arrival. The holding period begins only after the conclusion of the initial dwell time after the Green Line train has first arrived at Park Street. Suppose that a Green Line WB train arrives at 8:00:00AM and has an initial dwell time of 30 seconds. Red Line transfer passengers begin arriving on the platform at 8:00:20AM and have all arrived by 8:01:45AM. Thus the current Green Line train could potentially be held for up to 1:15 to allow most of the transferring passengers to board the Green Line train. If capacity becomes an issue for a held train, we assume that the train will be dispatched as soon as it is full.

- **Holding Decision**

A hold is deemed plausible if and only if the expected total net benefit is positive. While there is no argument with this statement, some transit agencies may want to see more significant benefits to justify any given hold, to prove the value of a transfer coordination system. A minimum-benefit criterion eliminates borderline holds that may possibly, due to variable factors such as variable arrival rates and early-arriving trains, impact passengers negatively.

In the formulation of the analytical model, we utilize a minimum-benefit criterion (minimum holding threshold) as the basis for holding decisions. We make the initial assumption of a minimum-benefit criterion of 50 passenger-minutes of waiting time saved. This value can easily be changed in the model. We will assess the model sensitivity in terms of total number of potential holds and the average benefit of a hold when this threshold is raised.

Secondary information such as passenger-benefit ratios measuring the ratio of passengers benefiting to those being delayed should also be considered. Some holds resulting in positive net benefits, may have small passenger-benefit ratios for instance, under .25. Such a result suggests that for every passenger saving time, there are four being delayed by a hold. The issue of service equity once again becomes important here. If the majority of impacted passengers are delayed, these riders may be annoyed and feel as if their concerns are not being addressed, an attitude that runs contrary to the goals and objectives of a transit agency. It is assumed that given this information, the Park Street platform inspectors can make more informed decisions about holds and their impacts on riders than just basing a hold on the total net benefit. In the analytical model however, we base all holding decision upon the total net benefit of a potential hold.

Some instances may arise when there are several possible holding scenarios for the same Green Line train all resulting in total net benefits surpassing the minimum criterion spelled out above.

Suppose Southbound and Northbound Red Line trains enter Park Street two minutes apart. A Westbound Green Line train enters Park Street at 9:00:00AM and is followed by another Green Line train at 9:05:00AM. Transfers from the Southbound Red Line train commence boarding at 9:00:20AM and conclude boarding at 9:01:45AM. Transfers from the Northbound Red Line train commence boarding at 9:02:45AM and conclude at 9:03:45AM. The Green Line train could possibly be held until 9:01:45AM for the first Red Line train, or until 9:03:45AM for the second one. In this scenario, we assume that the hold producing the largest total net benefit, exceeding the minimum criterion, is the hold that is chosen.

Another situation may occur when transferring periods for Red Line trains operating in different directions overlap. Suppose that in the previous example, transfers from the NB Red Line begin to arrive at 9:01:40AM. Although holding for the SB Red Line train may result in larger benefits than if the Northbound train were held for, it does not make sense to close the doors on the Northbound transferring passengers just as they arrive on the Green Line level. Thus we assume in cases of overlapping transfer periods each resulting in benefits surpassing the minimum level, the Green Line train is held to allow transfers from the initial and the second train to board.

Table 3-2 below outlines the four possible arrival scenarios and the corresponding basis for holding the Green Line train.

Table 3-2: Red Line Train Arrival Scenarios and Corresponding Holding Decisions

Arrival Scenario	Green Line Train Holds If:	Green Line Train Holds Until:
One Red Line trains arrives	Net benefit of the possible hold surpasses the minimum-benefit criterion	The end of the transferring period for Red Line passengers
Two Red Line trains arrive separately without overlapping transfer periods	Either of the possible holds produces net benefits surpassing min. benefit criterion	The end of the transferring period for the Red Line train with the largest holding benefit
Two Red Line trains arrive simultaneously with overlapping arrival periods	The possible hold on the 1st Red Line train produces net benefits surpassing min. benefit criterion	The end of the transferring period for passengers from the 1st Red Line train.
Two Red Line trains arrive simultaneously with overlapping arrival periods	The possible holds on both Red Line trains produce net benefits surpassing min. benefit criterion	The end of the transferring period for passengers from the 2nd Red Line train.

- **Holding Summary**

A feasible hold is governed by the following criteria:

a) A hold only occurs when it benefits transfer passengers.
b) The holding time resulting in the maximum net passenger benefit is chosen, subject to the following conditions:

1) There is capacity on the Green Line train to take the additional passengers.
2) The following Green Line train is not blocked in any manner by the hold.
3) The passenger benefits surpass the minimum criterion set by the transit agency.

c) There may be instances when a hold results in sub-optimal passenger benefits. This occurs when the previous three conditions are satisfied AND the following two conditions are also satisfied:

1) Transfers from two Red Line trains arrive simultaneously.
2) Holding for transfers from the second Red Line train results in fewer total benefits than only holding for transfers from the first Red Line.

3.2.2 Vehicle Location, Preceding Headway and Passenger Arrival Assumptions

This section discusses the estimation of vehicle location, preceding headway and passenger arrivals in the Park Street Model.

- **Vehicle Location**

A real-time information system such as AVI gives the approximate location of any Green Line train within the system. Although the exact location of the train is unknown between two detector locations, it nonetheless provides the approximate whereabouts of the train. With approximate vehicle location, preceding headways, train branch, and historical running times, a run time model can be estimated to predict the arrival time of any train into Park Street.

The OCS on the Red Line is akin to the AVI system on the Green Line but utilizes a series of blocks. The location is known to the block level, but the exact train location is not known in general just as for the Green Line. Red Line train location is a factor in determining when the train will arrive at Park Street and when transfers to the Green Line ultimately begin and end.

- **Preceding Headways**

Preceding headways are deterministic and based upon the AVI and OCS detection times at any given station for the current and the preceding Green and Red Line trains, respectively. Preceding headways are used to estimate the potential passenger load entering Park Street or the potential number of boarders at any given station. Long headways allow more passengers to accumulate on the platform and board the train whereas smaller than normal loads should result from lower than average headways.

Preceding headways at stations upstream of Park Street on the Green Line are assumed to be the same as the headway of the same train entering Park Street. However, preceding headways on the Red Line are taken from the scheduled arrivals at Park Street for a typical weekday. Assuredly, arrival times and headways entering Park Street will change from the scheduled assumptions on any given day. However scheduled arrivals should give a good approximation of when a train typically arrives at Park Street and the typical headway.

There is one caveat for Red Line trains heading Northbound towards Alewife. The southern end of the Red Line is separated into two branches south of JFK/UMASS, one terminating at Braintree and the other at Ashmont. We now assume that there are different branch headways for Braintree and Ashmont, as well as a separate headway on the trunk portion between JFK/UMASS and Park Street in the Northbound direction of travel. For the Braintree and Ashmont cases, the headway entering all stations on these branches is assumed to be equal to the headway of the branch train prior to merging at JFK/UMASS. All headways entering upstream stations between JFK/UMASS and Park Street are still taken from the scheduled arrivals. Therefore, if the headway entering JFK/UMASS for the Northbound Braintree train is four minutes, then the headway entering all stations between JFK/UMASS and Braintree is also assumed to be four minutes.

- **Passenger Arrival Rates**

Passengers accumulate at stations during the preceding headway period. Passenger arrival rates at any station are assumed to be deterministic and time-dependent and are derived from the 1997 CTPS data. The CTPS passenger counts took place between 7:00AM and 11:00PM during which time total boardings and alightings along with departing passenger flows were collected at all Green Line stations within the Central Subway as well as on the Red Line. The 1997 CTPS data is assumed to represent typical current operating conditions and boarding behavior accurately.

Without additional information on the exact station-to-station demand rates in the system, an assumption must be made to transform the CTPS passenger counts into origin-destination demand rates. Utilizing the approach developed by Machi(1989) and Deckoff(1990), we know from the alighting counts and the remaining passenger loads, the proportion of passengers aboard trains alighting at any given Green Line station. What we do not know is the boarding location of each alighting passenger. We assume as did Machi and Deckoff, that passengers will alight independent of their boarding location. If the CTPS data shows that 5% of the total arriving passengers alight at North Station, then 5% of the current train load entering North Station is assumed to alight.

An origin/destination (O/D) matrix can be developed which traces the alighting of passengers from a single origin throughout the course of the line. For instance assume 100 passengers board a short-turned train at Park Street headed towards the westbound B Line surface stations. At the next stop, Boylston, 10% of passengers, based on the CTPS passenger counts, alight leaving 90% of Park Street boarders still riding the train. At the next stop Arlington, 5% of the total on-board passengers alight. Regardless of the number of passengers boarding at Boylston, 5% of the remaining 90 Park Street boarders alight to remain consistent with the CTPS data counts. After leaving Arlington, there are still 85 passengers originally boarding at Park Street that will alight at downstream locations. This process continues on down the line until the terminus of the B Line at Boston College. Thus by aggregating the data over the entire day, we can estimate the approximate station-to-station passenger demand rates over a certain time period. CTPS data for the Red Line is similar to that for the Green Line. The procedure to convert CTPS data to an origin/destination matrix at different times of the day is also similar to that used for the Green Line.

We measure passenger demand rates in passengers per minute. Again, there are certain data limitations involved with this assumption. There would be no data problems if the data were actually gathered on a minute-by-minute basis. However this is impractical and passenger counts were aggregated at the fifteen-minute level leading to some intrinsic error when estimating an average passenger per minute arrival rate. Fluctuations occur throughout this fifteen-minute period and average demand rates reveal nothing about the minimum and maximum peak arrival rates witnessed throughout a period. To simplify matters and in the absence of other data, we assume that riders arrive at a constant rate over the observed fifteen-minute intervals. Thus the average demand rate is assumed to hold steady throughout any fifteen-minute time period. In most cases outside the peak time periods, it may also be a safe assumption that demand rates over the entire hour observed remain fairly constant and can be modeled as such.

3.2.3 Train Operating Issues and Assumptions

This section presents some of the operating issues and assumptions about Green Line train operations such as train consist, train capacity, expected arrival time of following trains into Park Street, dwell time at Park Street and downstream headways after Park Street.

- **Train Consist**

The AVI system on the Green Line records not only vehicle detection time at keypoints, but also the route designation, the consist (the number of cars) comprising a train, and the car identification numbers. Most trains on the Green Line consist of one or two cars each.

- **Train Capacity**

The train capacity is a product of the consist and the capacity of an individual car. Although there are several models of Green Line cars currently in service, we assume that the passenger capacity is 150 passengers per car according to Lin and Wilson (1993). The seating capacity is assumed to be 52 seats per car. The initial train capacity constrains the number of passengers boarding a given train and the number of passengers benefiting from transfer coordination. The seating capacity allows us to determine the standees at any given time, a major element comprising the dwell time at Park Street as discussed below.

It is possible that during rush hour, passengers stand closer and cram together to create additional space, above the assumed capacity. A very crowded train, with passengers standing in the doorways leaving little space for boarding, may persuade passengers to wait for the next train to ride more comfortably. Thus, crowded car conditions effectively establish a ceiling on the number of riders in a transit car, close to the stated value. If we assume that the maximum consist of any train is two cars, then the maximum capacity for any given Green Line train is 300 passengers.

From the derived origin/destination matrix, passenger demand rates for stations past Park Street are much lighter than those at Government Center and at Park Street. Therefore, we assume that train capacity is not an issue when estimating the number of downstream boarders.

- **Expected Arrival Times of Following Trains into Park Street**

The expected arrival times of following trains into Park Street limits the time a Green Line train may potentially be held for. To prevent blocking, Green line trains are never held past the expected arrival time of a following Green Line train. The expected arrival times of Red Line trains are important in ascertaining the number of transfer passengers that will benefit from a hold. In the analytical model, we assume perfect prediction capabilities. Arrivals at Park Street are deterministic and are already known from the AVI and OCS data. Without perfect prediction capabilities, run time models would need to be estimated as is the case with the simulation model (see Chapter 4).

- **Dwell Time**

The dwell time for a train is the amount of time the train will spend at Park Street to accommodate the flow of boarding and alighting passengers. As mentioned previously, holds are initiated after the initial dwell time elapses. Thus all passengers that arrive before a hold is initiated, board during the dwell time and are delayed by a hold. Conversely, passengers arriving during the holding period immediately following the initial dwell time benefit from a hold.

The estimation of initial dwell time is based on models derived by Lin and Wilson (1993). Lin and Wilson found that dwell time on the Green Line is a function of four parameters, namely the number of arriving standees into a station, the number of boarding passengers, the number of alighting passengers, and the number of departing standees. The dwell time models are based on the premise that passenger interactions occur between standees, alighters and boarders, similar to vehicles travelling through a bottleneck on a freeway, and these can be a significant component of dwell time under congested conditions.

For the analytical model, we simplify the dwell time model and assume a deterministic value of thirty seconds for all time periods and situations. Thirty seconds is a good estimate of an average dwell time period at Park Street. It is however just an assumption that is used to simplify calculations. It may be the case that thirty seconds, particularly in the peak periods is a poor estimate of the dwell time and may lead to over-estimated net benefits. Later in the simulation model however, a more realistic interpretation of the Park Street situation, will attempt to portray the dwell time situation at Park Street more accurately by utilizing the models and assumptions proposed by Lin and Wilson.

- **Headway Propagation**

The headways at downstream locations past Park Street such as Kenmore and the B Line Surface stations are important in estimating the number of downstream boarders affected by a holding decision as passengers accumulate during this inter-arrival period. We assume that headways departing from Park Street are maintained throughout the rest of the journey to the terminal. Thus if a train leaves Park Street with a headway of four minutes, we assume that this same train pulls into Kenmore with the same headway of four minutes. The departing headway is based on the preceding headway coming into Park Street, the dwell time at Park Street and the actual holding time for the Green Line train at Park Street.

Each of the three time periods represents a separate boarding period during which different passenger types identified previously may board. The combined period spanning the initial preceding headway into Park Street and the dwell time at Park Street allows boarding to take place for all passengers arriving at a station regardless of whether a hold occurs. These passengers are delayed by any holding action. The holding period itself benefits any passenger arriving within the holding period. Thus at downstream locations, P5 passengers board during the combined initial preceding headway and dwell time period at Park Street, and P6 passengers board during the holding period.

3.2.4 Impacted Passenger Definition

The six passenger categories defined previously in Section 3.1.2 are affected by a hold at Park Street Westbound as follows:

- **P1 Passengers**

  P1 passengers are those that board a Green Line train between Lechmere and Government Center, and alight after Park Street. P1 passengers are delayed by a hold.

- **P2 Passengers**

  P2 passengers are those boarding at Park Street during the arrival headway interval entering Park Street and the dwell time at Park Street. They are delayed by any holding action.

- **P3 Passengers**

  P3 passengers are transfer passengers from the Red Line to the Green Line, able to board during the holding time. P3 passengers save time amounting to the following departing headway.

- **P4 Passengers**

  P4 passengers are those boarding at Park Street during the holding time. They experience time savings of the following departing headway.

- **P5 Passengers**

  P5 passengers board and alight at stations between Boylston and one of the four Western branch termini. P5 passengers are delayed by a hold.

- **P6 Passengers**

  P6 passengers are similar to P5 passengers in all respects except that they board during the holding period at Park Street, and thus save time with a hold.

Table 3-3 summarizes the six passenger type categories.

Table 3-3: Passenger Types for Park Street Model

Passenger Type	Origins	Destinations
P1	Lechmere-Gov. Center	Boylston – Surface Lines
P2	Park Street	Boylston – Surface Lines
P3	Red Line	Boylston – Surface Lines
P4	Park Street	Boylston – Surface Lines
P5	Boylston – Surface Lines	Boylston – Surface Lines
P6	Boylston – Surface Lines	Boylston – Surface Lines

3.2.5 Eligible, Actual and Leftover Passenger Definition

This section divides the impacted passengers into three categories: Eligible, Actual and Leftover passengers.

- **Eligible Passengers**

Only those passengers heading to locations directly served by the incoming Green Line train, will board it. Thus at Park Street, a rider heading to Kenmore is eligible to take either a B, C, or D Line train, but not an E Line train which does not serve Kenmore. Table 3-4 shows the passenger eligibility on the Green Line Westbound. It should be noted that for passengers originating at stations between Lechmere and Haymarket in the Westbound direction, only D and E Line trains regularly serve these stations. We assume that passengers headed to the B Line (for instance) from Lechmere will transfer at their first opportunity, in this case at Government Center.

Passengers alighting prior to Park Street are of no concern for the transfer coordination system because they are not affected by a hold at Park. Only those passengers heading to destinations beyond Park Street experience are impacted by a hold.

Table 3-4: Passenger Eligibility for Green Line Trains

Destinations:	B Line	C Line	D Line	E Line
Boylston-Copley	X	X	X	X
Hynes Convention Center – Kenmore	X	X	X	
B Line Surface Section	X			
C Line Surface Section		X		
D Line Surface Section			X	
E Line Surface Section				X

From Table 3-4, it is evident that six separate classes of Westbound destinations exist: the Boylston-Copley Corridor, the Hynes Convention Center(Auditorium for short)-Kenmore Corridor, and the surface portion of the B, C, D and E Lines.

We designate the six classes of passengers in the Westbound direction as shown in Table 3-5.

Table 3-5: Green Line Passenger Classes

Destinations	Passenger Class
Boylston-Copley	BCDE
Hynes Convention Center – Kenmore	BCD
B Line Surface Section	B
C Line Surface Section	C
D Line Surface Section	D
E Line Surface Section	E

Thus P2-BCDE passengers refer to those passengers who board at Park Street prior to a hold, heading to destinations between Boylston and Copley.

Segregating boarders into separate classes allows us to keep track of those passengers ineligible to board and those forced to wait for the next eligible Green Line train. These passengers become leftover passengers as discussed later in this section. Primarily though, for a given Green Line train, the passenger classes boarding the train may experience differing amounts of time savings depending upon the sequence of following trains and their headways.

For instance assume that there is a C Line train at Park Street which is a candidate for holding, with a B Line train following it at a headway of four minutes, and a C Line train following it at a headway of five minutes. P3-BCDE and P3-BCD passengers who can board the train if it is held, would otherwise have had to take the next train four minutes after the current train. P3-C passengers, only eligible to take the C Line train, would have had to wait nine minutes for their train. Thus, each passenger class experiences different time savings, even though they may all board the same Green Line train.

- **Actual Passengers**

Actual passengers are those that are able to successfully board a given Green Line train. They are also the only passengers impacted by a hold. On occasion, all eligible passengers may be able to board a Green Line train, but sometimes capacity may prevent this. We assume that if the total eligible passengers exceeds the train capacity, then the proportion of eligible passengers able to board is equal to the ratio of the available capacity to the total eligible passengers.

For instance suppose there are 150 eligible passengers for an E Line train with a remaining capacity of 75 passengers after alighting occurs at Park Street. 100 of the 150 eligible passengers are headed towards the Boylston-Copley Corridor, while the remaining 50 will terminate their journeys on the E Line Surface Line. Thus only half of the total eligible passengers can board due to the capacity constraint. We assume that the proportion of actual boarders is split evenly among the passenger groups vying to board. Thus half of the actual boarders are taken from the pool of 100 eligible passengers headed to the Boylston-Copley Corridor, and half of the actual boarders are taken from the 50 eligible passengers going to the surface portion of the E Line.

- **Leftover Passengers**

Leftover passengers consist of two groups of passengers, those ineligible to board from the outset, and those eligible to board, but unable to do so because of capacity constraints. From the previously cited example of an incoming E Line train at Park Street, all passengers deemed ineligible to board become leftover passengers. Furthermore, of the passengers eligible to board, only half of them actually board because of capacity limitations. Eligible passengers unable to board are also deemed leftover passengers. Lastly, passengers transferring from the Red Line can become leftover passengers for either of the reasons described above.

Leftover passengers in effect are "carried over" and become potential passengers for the following Green Line train. For now, assume an E Line train pulls into Park Street. Only those passengers going to the Boylston-Copley Corridor or to the surface portion of the E Line are eligible to board the train. All other passengers that have accumulated during the previous headway period are ineligible to board and can now be considered leftover passengers. The leftover passengers remain on the platform to wait for the next Green Line train. When the next train enters Park Street, the determination of eligibility begins anew and passengers are separated according to whether or not they are eligible to board the train.

In the Green Line model, leftover P2, P3 and P4 passengers from the previous Green Line train are grouped together to augment the arriving P2 passengers for the next Green Line train. This distinction is made because essentially, P3 and P4 passengers that do not board the train mix with the leftover and newly-arrived P2 passengers on the platform at Park Street. Being indistinguishable from each other, they will all experience the same delay or time savings from a hold on the next train. Similarly, leftover passengers from the P5 and P6 groups from preceding trains are combined to augment the P5 passengers for the next train at downstream stations.

• P3 and P4 Joint Boarding Situation

As previously mentioned P3 and P4 passengers board jointly at Park Street whenever a hold occurs. Boarding for P3 and P4 passengers can occur in six stages, depending on whether or not the Northbound and Southbound Red Line trains arrive and unload passengers simultaneously.

The following example outlines the different possible stages of boarding and the approximate duration of each for P3 and P4 passengers. There are two situations to consider for P3 and P4 boarding, when two Red Line trains arrive simultaneously, and when a single Red Line train arrives. Figure 3-1 sets up the initial conditions around Park Street for this example.

Figure 3-1: Typical Green and Red Line Arrivals

Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7
Green Line Train Arrival	Time After Normal Dwell	NB Red Line Transfers Begin	SB Red Line Transfers Begin	NB Transfers Completed	SB Transfers Completed	Green Line Train Departure
7:59:30	8:00:00	8:00:20	8:00:45	8:01:45	8:02:05	8:02:05

♦ Case 1: Overlapping Red Line train arrivals

The following is a description of the different stages for boarding during a hold when overlapping transfers occur from two Red Line train arrivals.

- Stage 1 – The time period before the normal dwell time of the Green Line train elapses in which transfer passengers from the Red Line arrive on the platform. This may only take place if the time after the normal dwell time (Column 2) of the Green Line train is later than the arrival times of the transfer passengers from the Red Line (Column 3 or 4). Stage 1 passengers are not considered benefited transfer passengers and are re-classified as P2 passengers since they are essentially indistinguishable and experience the same amount of delay from a hold as do the normally-arriving P2 passengers. It is important to estimate the number of Stage 1 boarders because the remaining transfer passengers that do not reach the

Green Line platform during Stage 1 boarding are considered to be the pool of potential P3 transfer passengers that ultimately benefit from a hold. In Figure 3-1, there are no Stage 1 boarders.

- Stage 2 – All Park Street boarders during a hold at Park Street may board a Green Line train without considering transfer passengers if a window exists between the end of the normal dwell time period for the Green Line train and the time when the first transfer passengers arrive. In Figure 3-1, Stage 2 boarding lasts for approximately 20 seconds (Column 3 – Column 2).

- Stage 3 – The time before transfer passengers from both the NB and the SB Red Line trains board jointly. Since the NB train arrives earlier, the NB transfer passengers board simultaneously with the P4 Park Street boarders arriving during this portion of the hold. Stage 3 boarding lasts for exactly 25 seconds in Figure 3-1 (Column 4 - Column 3).

- Stage 4 – The time period where NB and SB transfers, as well as P4 passengers board simultaneously. Stage 4 boarding lasts exactly 1 minute in Figure 3-1 (Column 5 – Column 4).

- Stage 5 – The time period after all transfers from the first Red Line train (NB) are completed, in which there are still some transfers occurring from the second Red Line train. Therefore in the Figure 3-1 example, Stage 5 is a combined arrival period for the SB transfers, P3 transfers, and the P4 passengers, lasting 20 seconds (Column 6 – Column 5).

- Stage 6 – The time period between either the last completed transfer and the departure time of the vehicle, or the time period between the last competed transfer and the next arrival of transfer passengers. Since we already assumed that the Green Line train only holds until the last transfer from the particular Red Line train is completed, the completion of the transferring period coincides with the departure of the Green Line train. If it does wait for the next arriving Red Line train, only P4 passengers are considered to board during Stage 6. In Figure 3-1, there is no Stage 6 boarding.

♦ Case 2: Single Red Line train arrivals

Single Red Line train arrivals at Park Street are easier to analyze. Separate arrivals require simplified versions of Stages 1, 2, 4, and 6 since the complicating factor of an additional Red Line train and its arriving transfers is not present. Figure 3-2 presents the scenario for Case 2.

Figure 3-2: Green and Red Line Arrivals for Case 2

Column 1	Column 2	Column 3	Column 4	Column 5
Green Line Train Arrival	Time After Normal Dwell	NB Red Line Transfers Arrive	NB Transfers Completed	Green Line Train Departure
7:59:30	8:00:00	8:00:20	8:01:45	8:01:45

For Case 2, assuming that there is only an incoming Northbound Red Line train, there is no Stage 1 boarding time. Stage 2 boarding time would be 20 seconds (Column 3 – Column 2) since the Red Line train arrives after the Green Line train does. Stage 4 boarding where P3 and P4 passengers jointly board lasts for the duration of the transfer period which is 1:25 (Column 4 –

Column 3). Since there is no other incoming Red Line train which is being waiting for, the Green Line train departs Park Street as soon as transferring is completed at 8:01:45, thus there is no Stage 6 boarding time.

- **Waiting Time Valuation**

Every rider perceives time in the system differently. One minute to one rider may seem like five to another. In the model is it plausible that some passengers regard in-vehicle time differently from out-of-vehicle time and consequently in-vehicle and out-of-vehicle waiting times differently. One study conducted by CTPS for the Federal Transit Administration attempts to tackle this issue.[20]

First, the study found that transfer waiting times are more onerous than initial waiting times by a factor of 1.5 to 1.8. Such findings make sense since transfer locations are situated closer to the destinations of the riders, who are more anxious to reach their destination, knowing it is so near. Second, the study reveals transfer waiting time is nearly twice as burdensome as in-vehicle time. Thus one passenger spending two minutes of in-vehicle time, whether the train is moving or not, perceives the same wait as four minutes if the waiting time is outside the vehicle.

If these findings are to believed, it is easy to conclude that passengers may similarly regard in-vehicle waiting time differently than out-of-vehicle waiting time. Such an assumption gives priority to transferring passengers since they are able to board the vehicle instead of waiting at the platform for the next incoming train. While this may appear inequitable to those already aboard the train, the whole tenet of a transfer coordination system is to improve transfer reliability and reduce the associated waiting time. The assumption of different waiting time perceptions is just another step in improving the ability of the analytical model to best represent the actual field conditions. We have thus assumed that there is indeed a difference in perception between in-vehicle time and out-of-vehicle time. From the results of the CTPS study, we have assumed the ratio of out-of-vehicle time to in-vehicle time, or α, as 1.5. Thus 10 minutes of in-vehicle time would be valued the same as 15 minutes of time at a station. This assumes that passengers feel more comfortable and less anxious once they board the train than they are waiting for it. It places more importance upon minimizing the waiting time, thus making such a transfer coordination system even more attractive. Thus the benefits and disbenefits of the hold are measured in

[20] Central Transportation Planning Staff. "Transfer Penalties in Urban Mode Choice Modeling", 1997.

equivalent in-vehicle waiting minutes, accounting for the perceived difference between out-of-vehicle and in-vehicle waiting times.

The assumption of a certain value for α is not meant as a standard to use, but simply as a starting assumption that may be altered in the course of the analysis to better reflect actual passenger behavior. Different values of α will be tested in the simulation model to analyze the sensitivity of the model to different passenger behavior and perceptions. For the analytical model though, we assume that α is deterministic and equal to 1.50.

3.2.6 Transfer Passenger Assumptions

This section discusses the minimum transfer times, the duration of a transfer, the transferring percentage to the Red Line as well as the transferring rate to the Green Line Westbound.

- **Minimum Transfer Times and the Duration of the Transferring Period**

The transfer times and the overall duration of the transferring period are based on the observed data gathered at the transfer station as described in Chapter 2. We will assume that all passengers will utilize the main stairwell for each transfer direction and will do so under the conditions outlined in Table 2-8.

- **Transferring Percentage from Red Line**

Previously, we have determined the number of passengers alighting at Park Street from the Red Line. The CTPS counts tell us the proportion of total transfer passengers from a given Red Line direction that connects with the Green Line Westbound. They also tell us the proportion of Park Street alighters actually transferring.

With this knowledge, the proportion of the total Red Line alighters that transfer to the Green Line Westbound can be estimated. Suppose that between 8:15AM and 8:30AM, 80% of all transfers from the Red Line SB go to the Green Line WB. From the CTPS data, of all alighting passengers at Park Street from the Red Line SB, 60% transfer to the Green Line. Therefore of the total alightings at Park Street, approximately 48% go to the Green Line WB. These transfer proportions are assumed to be deterministic and constant over a short period of time, i.e. fifteen minutes, for the analytical model.

- **Transferring Rates to Green Line Platform**

We now know the proportion of transfers out of all alighting passengers from the Red Line. To model the transfer arrival rate at the Green Line level, we assume that transfers arrive at a constant rate over a short period of time. Transfers however must take place within the given transfer period mentioned previously. For transfers to the Westbound Green Line from the Southbound Red Line, there is a 1:45 transfer period for passengers. Since the first transfer arrives on the Green Line Level twenty seconds after the Red Line train arrives, transfer passengers will arrive at a constant rate for the next 1:25. Thus if it is estimated that if 50 passengers transfer from the Red Line SB to the Green Line WB, they arrive over that 1:25 span at a rate of about 35 passengers/minute.

3.2.7 Summary of Assumptions for the Park Street Model

Table 3-6 summarizes the assumptions for the Park Street case study.

Table 3-6: Summary of Assumptions for the Park Street Model

Holding Characteristics and Assumptions		
1)	**Holding Eligibility**	Hold is feasible for Green Line train IF and ONLY IF A) The proposed holding period starts AFTER the expected arrival of the incoming Green Line train. AND B) The proposed holding period ends BEFORE the expected arrival of the next Green Line train
2)	**Holding Duration**	Generally, Green Line train is held until end of the transferring period.
3)	**Holding Decision**	See Table 3-2
Vehicle Location, Preceding Headway and Passenger Arrival Assumptions		
1)	**Vehicle Location**	AVI and OCS give locations to the closest detector or block location
2)	**Preceding Headways**	A) Deterministic and calculated from AVI and OCS data. B) For Green Line: Preceding headways entering upstream stations are assumed to be the same as headway entering Park Street. C) For Red Line: Assumed to be the same as the scheduled headways. There are also separate Ashmont and Braintree headways in the Northbound direction.
3)	**Passenger Arrival Rates**	Based on CTPS passenger counts transformed into O/D matrix; assumed to occur at a constant, steady rate over a short period of time.
Train Operating Issues and Assumptions		
1)	**Train Consist**	Green Line trains have at most two cars in the consist.
2)	**Train Capacity**	Green Line train capacity does not exceed 150 passenger/car. Cars have only 52 seats/car. Capacity is not an issue after Park Street.
3)	**Approximate Arrival Times**	A) For Green Line: Deterministic and assumed to be equal to the actual arrival times given in the AVI data. B) For Red Line: Assumed to be equal to the scheduled arrival times.
4)	**Dwell Time**	Assumed to be 30 seconds.
5)	**Headway Propagation**	Headways leaving Park Street are maintained downstream.

Impacted Passenger Definition		
1)	**Passenger Definition**	See Table 3-3.
Eligible, Actual and Leftover Passenger Definition		
1)	**Eligible Passengers**	All passengers whose ultimate destination is served by the current Green Line train at Park Street and are potentially affected by a holding decision. See Table 3-4.
2)	**Actual Passengers**	Eligible passengers actually boarding a train, subject to capacity constraints.
3)	**Leftover Passengers**	A) All passengers ineligible or eligible but unable to board a given Green Line train. B) They "carry-over" to the next Green Line train where the entire process of eligible, actual, and leftover passengers are recalculated C) Leftover P2, P3 and P4 passengers become potential P2 passengers for next Green Line train. D) Leftover P5 and P6 passengers become potential P5 passengers for next Green Line train
4a)	**Joint P3 and P4 Boarding Case 1: Simultaneous Red Line Arrivals**	
1)	Stage 1 Boarding	a) Time period before Green Line Train arrives where transferring P3 passengers accumulate on the Green Line Platform level. b) Reclassified as P2 passengers since they are basically indistinguishable as both wait on platform for next train. c) They do not benefit from a hold since they would have been able to board the Green Line train regardless of coordination.
2)	Stage 2 Boarding	a) Time period before Red Line transfers first begin arriving on Green Line level. b) Only P4 passengers board during Stage 2 boarding.
3)	Stage 3 Boarding	a) Time period before BOTH transfer passengers from NB and SB Red Line arrive. b) Assuming NB transfers arrive earlier, Stage 3 consists of joint boarding between the NB Red Line transfers and the P4 passengers
4)	Stage 4 Boarding	Joint boarding period between both P3 and P4 passengers.
5)	Stage 5 Boarding	Joint boarding period between the P4 passengers and the later arriving transfer passengers, in this case the SB transfers.
6)	Stage 6 Boarding	Time period between either: a) The last completed transfer and the departure time of the Green Line train OR b) The last completed transfer and the next arrival of transfer passengers from the Red Line.
4b)	**Joint P3 and P4 Boarding Case 2: Separate Red Line Arrivals**	
1)	Stage 1 Boarding	Same as above.
2)	Stage 2 Boarding	Same as above.
3)	Stage 4 Boarding	Same as above except there is only one Red Line train not two.
4)	Stage 6 Boarding	Same as above.
5)	**Waiting Time Valuation**	A) Passengers perceive out-of-vehicle time differently from in-vehicle time. B) Assumed that $\alpha = 1.5$; subject to change for sensitivity analysis.
Transfer Passenger Assumptions		
1)	**Minimum Transfer Times and the Duration of the Transferring Period**	Transfer times and durations follow historical patterns found in Table 2-8.
2)	**Transferring Percentage from Red Line**	Transfer percentages are found from CTPS data in fifteen-minute intervals.
3)	**Transfer Rates to Green Line Platform**	Transfers are assumed to arrive at a constant rate during throughout the duration of the transferring period.

3.3 Analytic Model Framework

This section will briefly present the structure and framework of the analytical model for evaluating holding actions on Green Line trains. The framework describes how the analytical model is triggered to begin the process of evaluating a Green Line train for a potential hold. It also outlines the process for estimating net passenger benefits and finally determining the ultimate feasibility of a hold.

A more detailed step-by-step methodology explaining the process of evaluation and the calculation of impacted passengers and their expected benefits/disbenefits is presented in Appendix A. Thus, we will keep the description of the model structure as simple and brief as possible in this section for the sake of comprehension and omit mathematical equations and formulas.

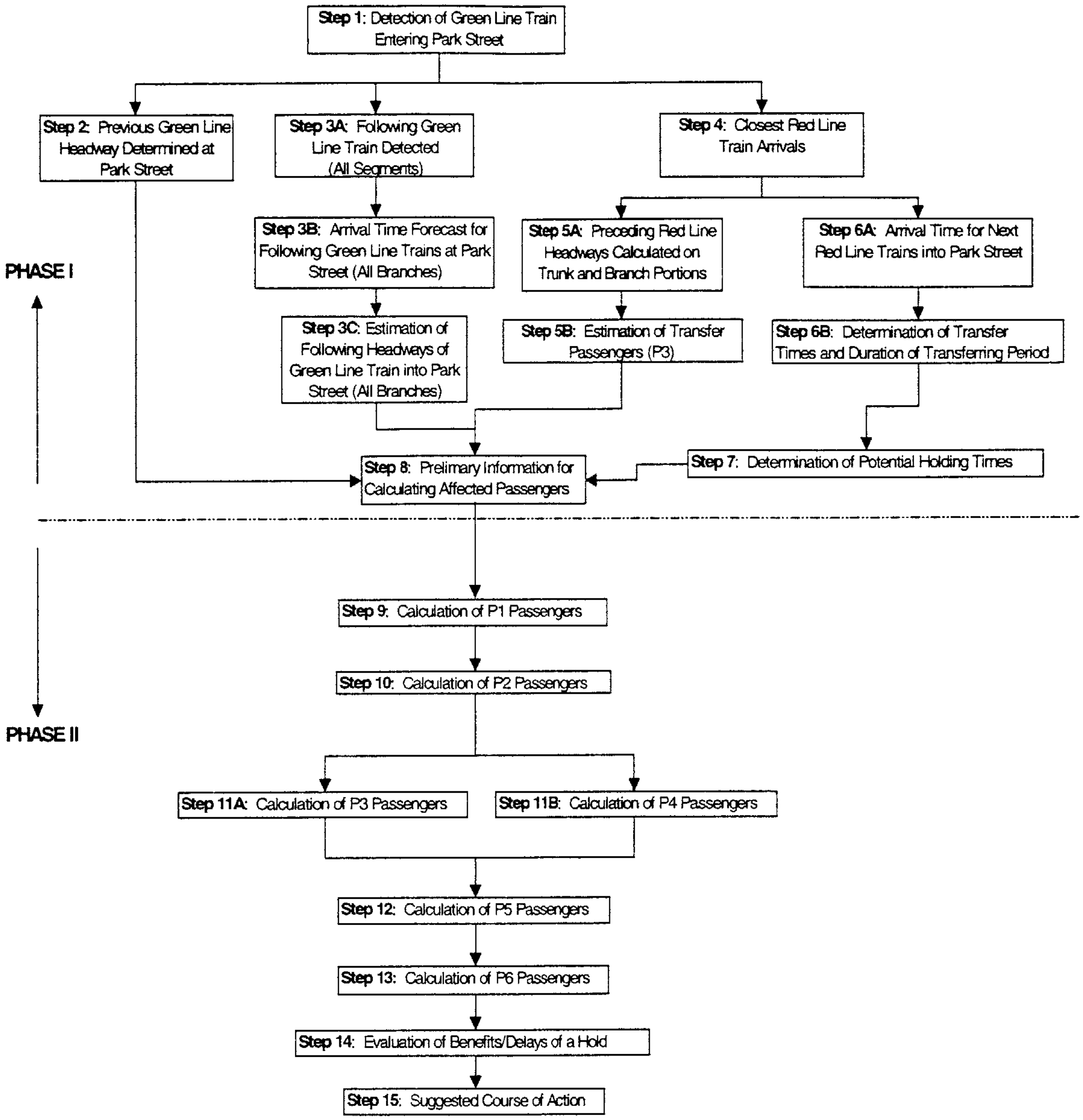
Figure 3-4 shows the structure of the analytical model and the step-by-step process to evaluate holding Green Line trains. The analytical model is split into two distinct phases.

3.3.1 Phase I

Phase I of the analytical model includes Steps 1-8. It essentially estimates the number of potential P3 transfer passengers based on the expected arrival times of Red Line trains into Park Street, as well as the expected arrival times of following Green Line trains into Park Street. Phase I also calculates the potential holding times for the current Green Line train to allow all P3 transfers to complete their transfer movement. The process is triggered by a Green Line train (i) entering Park Street. The preceding Green Line train is train (i-1) and the following Green Line train is train (i+1). There is also a Red Line train (m) approaching Park Street.

Green Line trains entering Park Street are evaluated on an hour-by-hour basis. Thus the analytical model evaluates all trains in an hourly block from say 7:00-8:00PM, but does not continue to evaluate trains from 8:00-9:00PM. While this does not affect the estimation of preceding headways into Park Street for Green Line train (i), it does affect the estimation of potential passengers for this train. It is possible that leftover passengers from the previous Green Line train (i-1) which entered Park Street at the end of the 7:00-8:00PM period, do not carry-over and become potential passengers for Green Line train (i), the initial train entering Park Street in the 8:00-9:00PM time period. We assume that all leftover passengers that have accumulated and have yet to board, take the last train in that hour, train (i-1). Furthermore, we

Figure 3-3: Analytical Model Framework



assume that the only passengers that have accumulated for the first train in the new time period, train (i) are P2 passengers arriving during the preceding headway. As a result, it is possible that the benefits estimated by the analytical model may be over-estimated, especially for trains entering Park Street at the beginning of an hour.

- ***Step 1: Detection of Green Line Train Entering Park Street*** – The triggering event for the entire transfer coordination system is the detection of an incoming Green Line train (i) into Park Street at the K04 detector in the Westbound direction. The wayside detector records the train consist (and hence the capacity), and the train route.

- ***Step 2: Previous Green Line Headway Determined at Park Street*** – Once Green Line train (i) is detected, the most recent Green Line train, regardless of destination, entering Park Street, Green Line train (i-1) is identified from the AVI arrival data. Thus the preceding headway of train (i) at Park Street is calculated.

- ***Step 3A: Following Green Line Trains Detected (All Segments)*** – To estimate the potential time savings from a hold, the next incoming Green Line trains serving the following three track segments are identified from the AVI data: Boylston-Copley (served by the B, C, D and E Lines), Auditorium-Kenmore (served by the B, C and D Lines) and the surface portions (served by trains of the same branch as Green Line train (i)). Passengers to any of the three track segments may experience differing amounts of time savings.

- ***Step 3B: Arrival Time Forecast for Following Green Line Trains at Park Street*** – The arrival time forecast for following Green Line trains is important as it limits the possible length of the holding period. The forecast arrival times are also important in estimating how much time certain passengers save from holding. With the assumption of perfect prediction capabilities, we track the closest Green Line trains, serving the three track segments and note their arrival times into Park Street (the K04 detector).

- ***Step 3C: Estimation of Following Headways of Green Line Train into Park Street*** – Once the arrival times are estimated, the following headways of trains entering Park Street are calculated. The following headways for Green Line train (i) into Park Street determine the amount of time saved by the different passengers during a holding situation.

- ***Step 4: Closest Red Line Train Arrivals*** – Transfers originate from the Red Line. Once the Green Line train (i) is detected entering Park Street, the next three incoming Red Line trains in each direction are identified in the scheduled arrival data. After potential Red Line trains are identified, the block location, train number, and detection time are recorded.

- ***Step 5A: Preceding Red Line Headways Calculated on Trunk and Branch Portions*** – The preceding headways on the Red Line are necessary to calculate the expected load entering Park Street from upstream stations and therefore the number of passengers transferring to the Green Line Westbound. Trunk headways are calculated from the scheduled arrival data. In the Northbound direction, trains originate from one of two branches, Ashmont or Braintree. The train number is used to track a potential Red Line train back to the block prior to JFK/UMASS, where trains from the two southern branch termini converge onto a single track. Thus the preceding branch headway is assumed to be the same as the headway entering the block prior to JFK/UMASS.

- ***Step 5B: Estimation of Transfer Passengers*** – The number of transfer passengers is a product of the load entering Park Street on a Red Line train and the historical alighting ratios derived from CTPS data.[21]

[21] Mathematical equations and formulas are again presented in Appendix A.

- *Step 6A: Arrival Time for Next Red Line Trains into Park Street* – The expected arrival time of Red Line trains into Park Street is an important factor in determining how long a Green Line train should be held to allow transfer passengers to board. In the analytical model, we assume perfect prediction capabilities. Arrival times are based on scheduled arrivals.

- *Step 6B: Determination of Transfer Times and Duration of Transferring Period* – The direction of the Red Line train determines how quickly transferring occurs to the Green Line Westbound as well as the overall transfer period. Transfer times are based on empirical data presented in Table 2-8.

- *Step 7: Determination of Potential Holding Times* – The expected arrival time of Red Line train (m) along with the estimate of the transfer time and the overall transfer period result in the time in which transfers first arrive on the Green Line platform and the time in which transferring concludes. Generally, potential holds are assumed to last only as long as it takes for the last transfer passenger to complete the movement from a particular Red Line train. Holding time begins only after the conclusion of the initial dwell time estimation (dealt with later). Thus, any potential hold is eligible for consideration if the hold begins AFTER the current Green Line train is detected entering Park Street AND the hold concludes BEFORE the following Green Line train is expected to enter Park Street to prevent blocking.

- *Step 8: Preliminary Information for Calculating Affected Passengers* – Step 8 collects all the data from the previous steps. Information such as the preceding headways on the Red and Green Lines, the following headways entering Park Street for the Green Line, the estimated number of transfers from the Red Line to the Green Line, the estimated transfer period, and the potential holding times are used in Phase II.

3.3.2 Phase II

Phase II of the analytical model calculates the expected number of impacted passengers (P1 through P6) and estimates the time savings/delay experienced by each group. The estimation of impacted passengers is a cyclical process that requires the estimation of the number of eligible, actual and leftover passengers for any train. The estimation of all impacted passengers requires this process, but only outputs the actual number of boarding passengers. Lastly, Phase II makes the final holding decision based on the overall net benefit to impacted passengers.

- *Step 9: Calculation of P1 Passengers* – P1 passengers are those passing through Park Street. They accumulate during the preceding headway period at upstream stations according to CTPS on/off counts.

- *Step 10: Calculation of P2 Passengers* – P2 passengers arrive at Park Street and are delayed by a hold. There are three types of P2 passengers: normal arriving passengers accumulating during the preceding headway, leftover passengers from previous Green Line trains and transfer (P3) passengers that arrive before the Green Line train arrives, accumulating in the Stage 1 Boarding Time. P2 passengers arrive during the previous headway time and the dwell time.

- ***Step 11A and 11B: Joint-Calculation of P3 and P4 Passengers*** – We will assume at this time that the Green Line train (i) will be held for only one Red Line train (m). Transfers from non-overlapping Red Line arrivals will potentially board Green Line trains and save time during Stage 2, Stage 4 and Stage 6 boarding periods. Stage 1 transfer boarders were already counted as P2 passengers since they arrived at the Green Line platform before the Green Line train arrives. Transfers from overlapping Red Line trains arrive during the three stages mentioned above, and possibly in two additional stages, Stage 3 and Stage 5. P4 passengers arrive simultaneously during a hold with the transfer passengers in Stages 2-6.

- ***Step 12: Calculation of P5 Passengers*** – P5 passengers accumulate at downstream stations during the previous headway. We assume that at all stations past Park Street, boarding is not constrained in any manner by the capacity of the Green Line trains. Thus all passengers eligible to board become actual passengers. Only those passenger ineligible to board a given Green Line train from the outset become leftover passengers. P5 passengers also consist of any leftover P6 passengers ineligible from the last Green Line train.

- ***Step 13: Calculation of P6 Passengers*** – P6 passengers arrive at downstream stations during the hold time. Any leftover P6 passengers become potential P5 passengers for the next Green Line train.

- ***Step 14: Evaluation of Benefits/Delays of a Hold*** – The expected delay and benefit of a hold vary across passenger types. We assume that passengers perceive out-of-vehicle waiting time to be generally more burdensome than in-vehicle waiting time by a factor α. The total benefit/delay to each passenger group is estimated based on the number of impacted passengers in each group, the holding time, the initial dwell time, the following headway on the Green Line for the three track segments and α.

- ***Step 15: Suggested Course of Action*** – A Green Line train (i) will or will not be held for a Red Line train (m) based on the total net benefits of a hold. A potential hold is considered feasible if the total net benefits equal or surpass the minimum benefit criterion set by the transit agency. If the Green Line train (i) is held for transfers from the Red Line train (m), the holding period will last only up to the time of the last transfer from the Red Line to the Green Line train.

3.4 Park Street Case Study

In this section, we present the results from applying the analytical model to Green Line train arrival data for an entire day.

3.4.1 Park Street Case Study Data

The following data are used for the evaluation of Park Street transfer coordination.

- *Green Line Arrival Data* – Green Line arrival data is based upon AVI data collected on Monday, April 26, 1999. The data includes detection location, time, car number, and route at three detector locations surrounding Park Street in the Westbound Direction, specifically detector K07 entering Boylston, detector K04 entering Park Street, and detector K06 entering

Government Center. We assume that April 26th is a representative day of service in the MBTA, without significant incidents.

- *Red Line Arrival Data* – We utilize scheduled Red Line arrival data, as of November 1999, to approximate the arrival times of Red Line trains throughout the day. Trains are scheduled to arrive every three to four minutes for instance during the peak periods and every five minutes during the base periods without variation. Although they do not reflect the actual daily arrival patterns on the Red Line, they do approximate Red Line arrivals which should be adequate for our purposes here.

- *Green Line Passenger Arrival Rates* – The arrival rates for Green Line passengers are taken from the 1997 CTPS counts. As described in prior sections, the CTPS on/off counts are transformed into station-to-station demand rates. We assume that the Green Line arrival rates in 1997 are similar to the current time.

- *Red Line Passenger Arrival Rates* – Similar to the Green Line demand rates, the Red Line rates originate from the 1997 CTPS counts. It is also assumed that the 1997 CTPS passenger counts are representative of the April 26th test date.

- *Transferring Proportions from Red Line to Green Line* – Transfer proportions from the Red Line to the Green Line WB are also calculated from the 1997 CTPS passenger counts.

It must be noted that the data availability restricts the scope of the analytical model. The shortcomings of the data and its consequences are explained below:

a) Since the WB Green Line AVI data is limited to three detectors, the analytical model utilizes the known arrival times of following trains into Park Street to determine the amount of time savings. The preceding headway is assumed to be the same at upstream stations as it is for the same Green Line train entering Park Street.

b) The preceding and following headways on the Red Line are based on scheduled, deterministic arrivals.

c) CTPS passenger counts are aggregated at the fifteen-minute level. If the counts were collected down to the closest minute, perhaps per-minute variations could be observed and included in the model, to be more consistent with the actual arrival of passengers within the system. Since this is not the case, the best we can do is assume that the average arrival rate is constant over the fifteen minutes.

3.4.2 Initial Hypotheses

Several hypotheses were made about the expected results of applying the analytical model to the Park Street case study:

1) Of all time periods in the day, it is hypothesized that the off-peak period will show the largest benefits from a transfer coordination system. Although passenger loads and transfers during the off-peak period are smaller, larger incoming passenger loads on Green Line trains entering Park Street make for greater through-passengers delays in the

peak than in other times. Second, with closer following trains in the peak and near-peak periods, fewer and shorter holds are allowed in order to prevent blocking. Thirdly, the Green Line trains operate closer to capacity during the peak, constraining the potential benefits. Lastly, passengers benefit more in the off-peak period from holding as trains arrive less frequently, resulting in longer average waiting times and more substantial time savings.

2) A hold is most likely on a Green Line train if it closely follows the previous train into Park Street, and if it has a long following headway. Thus the current train will have fewer Park Street boarders (P2) that will have accumulated during the previous headway period. Second, transfer passengers boarding during a hold save more time given the long following headway into Park Street for the next Green Line train.

3) The minimum-benefit criterion specified, 50 passenger-minutes saved, may result in a large number of marginally beneficial holds throughout the day. If so, then perhaps the holding benefit threshold will need to be raised.

3.4.3 Case Study Results

In this section, we present the results from applying the analytical model in discrete hourly blocks from 7AM to 11PM.

Table 3-7 shows the hourly results of the analytical model for the entire day with a minimum holding threshold of 50 passenger-minutes saved and a perceived waiting time ratio of $\alpha = 1.50$. Figure 3-5 shows the total benefit for each held train throughout the day.

- **Total Net Passenger Benefits**

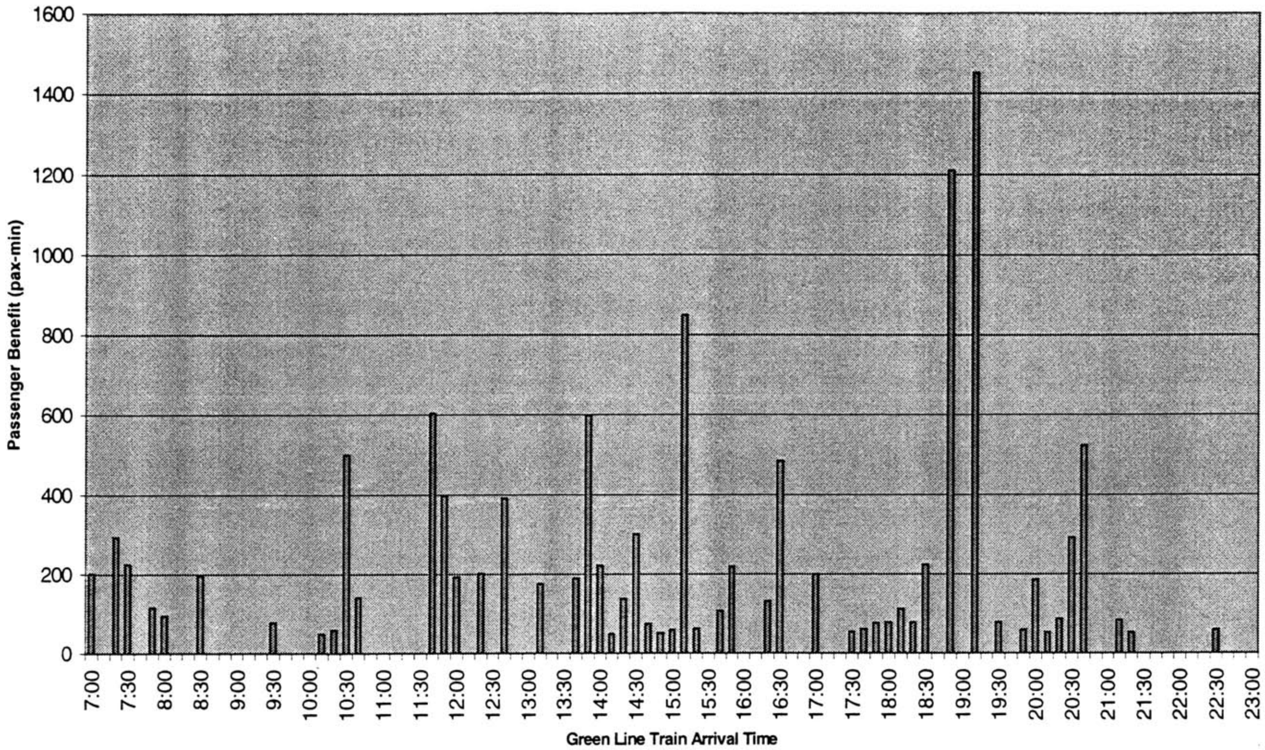
Transfer coordination produces total net benefits around 12,500 passenger-minutes saved. The largest benefits occur during the early-evening period (specifically between 6:00-9:00PM) where total benefits range from 1,100-1,600 passenger-minutes per hour. Although the benefits are not as robust, another time period where holding actions result in sizeable benefits is the mid-day period between 11:00-4:00PM where total benefits range from 750-1,400 passenger-minutes saved per hour. Holding produces the smallest benefits during the peak and the late evening periods (9:00-10:00PM) ranging from 60-500 passenger-minutes saved per hour.

Table 3-7: Green Line WB Benefit and Hold Summary for Analytical Model: Minimum Passenger Benefit = 50 pax-mins, a = 1.50

Time Period	Trains Held	Green Ln. Trains	HOLD DURATION(MIN:SEC) Avg. Hold Duration	Shortest Hold	Longest Hold	PASSENGER BENEFITS(PAX-MIN) Average Benefit	Largest Benefit	Smallest Benefit	Total Benefit
7:00-8:00AM	4	40	1:09	0:24	1:48	209	294	116	837
8:00-9:00AM	2	33	0:16	0:12	0:19	146	196	96	292
9:00-10:00AM	1	35	0:12	0:12	0:12	79	79	79	79
10:00-11:00AM	4	37	2:24	1:12	3:42	188	499	50	751
11:00-12:00PM	2	26	1:54	0:48	3:00	500	603	397	999
12:00-1:00PM	3	29	1:50	0:42	3:36	261	390	192	783
1:00-2:00PM	3	27	1:49	1:18	2:14	321	599	175	964
2:00-3:00PM	5	31	1:57	0:54	3:36	157	300	50	785
3:00-4:00PM	6	30	1:47	0:18	3:54	227	849	52	1361
4:00-5:00PM	2	37	0:42	0:24	1:00	308	485	131	615
5:00-6:00PM	5	39	0:41	0:24	1:00	94	199	55	470
6:00-7:00PM	4	38	2:16	0:48	3:34	406	1210	78	1624
7:00-8:00PM	3	36	2:54	1:24	5:30	530	1452	59	1590
8:00-9:00PM	5	25	1:56	0:30	3:06	230	534	53	1151
9:00-10:00PM	2	27	3:44	1:50	5:37	68	83	53	136
10:00-11:00PM	1	26	0:39	0:39	0:39	60	60	60	60
Average Per Held Train			1:44			240.0			
TOTALS:	52	516							12497

Time Period	Delayed/Time Savings Breakdown: Total Passengers Savings 0-2 mins	2-4 mins	4-6 mins	6 + mins	Total Pax	Total Passengers Delayed 0-2 mins	2-4 mins	4-6 mins	6 + mins	Total Pax	Pax-Ben %
7:00-8:00AM	101	117	34	40	292	652	0	0	0	652	45%
8:00-9:00AM	0	22	28	7	57	447	0	0	0	447	13%
9:00-10:00AM	0	0	0	11	11	171	0	0	0	171	6%
10:00-11:00AM	208	27	20	47	302	121	119	0	0	240	126%
11:00-12:00PM	0	89	8	54	151	51	56	0	0	107	141%
12:00-1:00PM	48	31	29	62	170	230	56	0	0	286	59%
1:00-2:00PM	0	0	0	202	202	223	92	0	0	315	64%
2:00-3:00PM	212	22	27	56	317	253	189	0	0	442	72%
3:00-4:00PM	263	68	36	97	464	262	374	0	0	636	73%
4:00-5:00PM	12	0	0	61	73	478	0	0	0	478	15%
5:00-6:00PM	179	26	0	64	269	1045	0	0	0	1045	26%
6:00-7:00PM	115	130	86	102	433	323	184	0	0	507	85%
7:00-8:00PM	88	20	89	125	322	231	0	89	0	320	101%
8:00-9:00PM	47	40	45	72	204	161	169	0	0	330	62%
9:00-10:00PM	12	63	63	0	138	83	0	86	0	169	82%
10:00-11:00PM	0	0	2	9	11	72	0	0	0	72	15%
Average Per Held Train	24.7	12.6	9.0	19.4	65.7	92.4	23.8	3.4	0.0	119.6	55%
TOTALS:					3416					6217	

Figure 3-4: Passenger Benefits Accrued for Each Held Train from 7:00AM to 11:00PM, with Minimum Benefit = 50 Pax-Mins Saved



- **Average Passenger Benefits Per Held Train**

Over the day, a hold is expected to produce average net benefits of about 240 passenger-minutes. The largest average benefits occur during the early-evening period where average benefits per hold range from 230-530 passenger-minutes saved/hold per hour. The mid-day afternoon period also produces sizeable average benefits per hold, ranging from 250-500 passenger-minutes saved/hold per hour. The smallest average benefits per hold occur during the peak and late evening periods, ranging from 60-150 passenger-minutes saved/hold per hour.

- **Holds with Insignificant Benefits**

A large number of the overall holds produced benefits slightly exceeding the minimum holding threshold of 50 pax-mins. The average benefit during the 9:00-10:00PM period was only about 70 pax-mins saved per train. Small benefits barely surpassing the minimum holding threshold may not significantly improve the transfer journey. Thus it may be wise to raise the minimum holding threshold so that holds produce more substantial benefits.

- **Distribution of Passenger Impacts**

Overall there are almost twice as many passengers delayed as passengers benefiting. Total delayed passengers are close to 6,300 passengers and total benefited passengers amount to nearly 3,400 passengers. However, the great majority of passengers delayed are impacted by less than 2 minutes whereas almost 30% of benefiting passengers enjoy time savings of greater than 6 minutes. The largest number of benefiting passengers occurs during the mid-afternoon and early-evening period, ranging from 170-450 passengers. The largest number of delayed passengers is produced during the PM peak, with over 1,000 passengers negatively impacted by a hold.

The overall passenger-benefit ratio for the day was around 55%. Passenger-benefit ratios are the highest between 10:00-12:00PM, ranging from 120-140%. The mid-afternoon period has passenger-benefit ratios between 55-75%. Early evening passenger-benefit ratios range from 60-100%.

- **Holding Frequency**

Throughout the day, we might expect to hold about 10% of Green Line trains. Out of 516 Green Line train arrivals at Park Street, 52 trains are held. The mid-afternoon and the early-evening periods produce the greatest number of holds, between 3 and 6 per hour. The fewest holds are produced during the AM Peak and the late evening period where between 1 and 2 trains are held per hour.

- **Holding Times**

Average hold periods, are typically between 1-2 minutes with holds as great as five minutes. The shortest hold time for twelve of the time periods is under 1 minute in duration. Additionally, the shortest hold period for half of these twelve is under 30 seconds in duration as well. The longest hold time produced for nine of the time periods is over 3 minutes in duration, with two of these time periods producing holds of over 5 minutes.

- **Early Evening Period**

The early evening has extremely large passenger benefits for some holds, generating passenger benefits surpassing 1,200 pax-mins with passenger-benefit ratios around 85 and 100% respectively. Although these benefits may seem high, one must first remember that these hours represent the shoulder period with high arrival rates at Park Street and transfers from the Red

Line. Both of these trains have specific characteristics that result in large benefits. Specifically both trains are preceded into Park Street by trains arriving less than one minute earlier and following trains due to arrive at Park Street over ten minutes later. Both Green Line trains are held to allow transfers from three different Red Line trains to board.

3.4.4 Discussion of Results

This section discusses some of the results of the analytical model and their possible implications.

- **Most Advantageous Time Periods for Transfer Coordination**

The analysis found that transfer coordination is most beneficial during the base period between 11:00AM-4:00PM and the early evening period from 6:00PM-9:00PM. These findings are generally supportive of the initial hypothesis, that the off-peak periods would produce the largest benefits. In the late evening however, although there may be fewer through-passengers on the train delayed by a hold, there are also fewer transferring passengers that benefit. As it turns out, the far few passengers that did benefit from transfer coordination in the late evening are not sufficient to offset the delay caused to other passengers.

However as expected, the two off-peak periods specified above produce larger benefits than the peak-periods because of blocking and capacity issues. Peak periods have the highest service frequencies throughout the day and consequently Green Line trains running during the peak are generally able to hold much shorter times to preclude blocking following train from entering Park Street. Furthermore the peak periods have the least available capacity on Green Line trains at Park Street. Boarders at Park Street may be so numerous during the peak periods that a hold may be inconceivable from the outset because there is so little capacity left for boarding. In the off-peak periods there are fewer people aboard the train when holding is desirable. Thus due to blocking and capacity constraints, it is less likely for a train to be held during the peak than it is during other times of the day.

- **Possible Under-Estimation of Leftover Passengers**

As noted in the description of the analytical model framework, trains are only evaluated on an hourly basis. That is, only trains within discrete hourly blocks are analyzed. Thus there may be leftover passengers from the last train in an hour block. These leftover passengers do not carry-over to the next train, the first train in the next hourly block. Thus it is possible that especially near the beginning of the hour, leftover passengers may be under-estimated depending on the previous arrival sequence of trains and arrival headways. If the number of leftover passengers has been under-estimated, then the total delay to all impacted passengers has also been under-estimated as well as the overall net benefit from holding. It is possible several holds deemed feasible in the analytical model, may actually produce expected benefits failing to meet the minimum benefit threshold if leftover passengers are properly accounted for with a continuous evaluation of train arrivals. The simulation model will correct this problem by evaluating trains on a continuous basis.

- **The Selection of a Minimum Benefit Threshold**

The choice of a minimum benefit threshold factors prominently in the resulting holds and their benefits. Some holds from Table 3-7 barely satisfy the minimum requirement of 50 passenger-minutes saved. A higher criterion of 100 pax-mins for instance, should reduce the number of holds and optimize the process so as not to delay trains that ultimately produce only marginal benefits (close to 50 passenger-minutes) to the system. A threshold of 75 passenger-minutes should result in passenger benefits somewhere in between. Tables 3-8 and 3-9 summarize the model results if the minimum passenger benefit threshold is changed to 75 and 100 passengers-minutes respectively.

From Table 3-8, increasing the minimum passenger benefit criterion from 50 to 75 passengers-minutes decreases total benefits from about 12,500 to 11,850 passengers-minutes, a decrease of about 5%. The average benefit per held train increases by nearly 25% to 296 passengers-minutes per hold. The total number of passengers saving time is reduced by about 14%, but the total number of delayed passengers is reduced by 20%. The result is a slightly higher passenger-benefit ratio of 59% compared to 55% for the 50 pax-min threshold. There is practically no change in the distribution of benefits as a majority of delayed passengers are still impacted by less than 2 minutes and slightly less than 30% of benefiting passengers enjoy time savings of greater than 6 minutes. Overall, the number of holds is reduced by 12 trains and the average holding time is increased by about twelve seconds to 1:56.

In Table 3-9, the minimum passenger benefit is further augmented to 100 passengers-minutes saved per hold. Overall total hold benefits are reduced by another 5% to about 11,200 passengers-minutes. The average benefit per held train increases by a further 20% to 351 passengers-minutes saved. The total number of passengers saving time is reduced by nearly 21%,

Table 3-8: Green Line WB Benefit and Hold Summary for Analytical Model: Minimum Passenger Benefit = 75 pax-mins, a = 1.50

Time Period	Trains Held	Green Ln. Trains	HOLD DURATION(MIN:SEC) Avg. Hold Duration	Shortest Hold	Longest Hold	PASSENGER BENEFITS(PAX-MIN) Average Benefit	Largest Benefit	Smallest Benefit	Total Benefit
7:00-8:00AM	4	40	1:09	0:24	1:48	209	294	116	837
8:00-9:00AM	2	33	0:16	0:12	0:19	146	196	96	292
9:00-10:00AM	1	35	0:12	0:12	0:12	79	79	79	79
10:00-11:00AM	2	37	3:33	3:24	3:42	320	499	142	641
11:00-12:00PM	2	26	1:54	0:48	3:00	500	603	397	999
12:00-1:00PM	3	29	1:50	0:42	3:36	261	390	192	783
1:00-2:00PM	3	27	1:49	1:18	2:14	321	599	175	964
2:00-3:00PM	4	31	1:45	0:54	3:36	184	300	75	735
3:00-4:00PM	3	30	2:50	2:06	3:54	397	864	108	1190
4:00-5:00PM	2	37	0:42	0:24	1:00	308	485	131	615
5:00-6:00PM	3	39	0:44	0:30	1:00	121	199	78	362
6:00-7:00PM	4	38	2:16	0:48	3:34	406	1210	78	1624
7:00-8:00PM	2	36	3:27	1:24	5:30	766	1462	79	1631
8:00-9:00PM	4	25	2:17	0:42	3:06	277	534	95	1107
9:00-10:00PM	1	27	5:37	5:37	5:37	83	83	83	83
10:00-11:00PM	0	26	0:00	0:00	0:00	0	0	0	0
Average Per Held Train			1:56			296.0			
TOTALS:	40	516							11842

Time Period	Delayed/Time Savings Breakdown: Total Passengers Savings 0-2 mins	2-4 mins	4-6 mins	6 + mins	Total Pax	Total Passengers Delayed 0-2 mins	2-4 mins	4-6 mins	6 + mins	Total Pax	Pax-Bens %
7:00-8:00AM	101	117	34	40	292	652	0	0	0	652	45%
8:00-9:00AM	0	22	28	7	57	447	0	0	0	447	13%
9:00-10:00AM	0	0	0	11	11	171	0	0	0	171	6%
10:00-11:00AM	124	27	20	32	203	0	119	0	0	119	171%
11:00-12:00PM	0	89	0	54	143	51	56	0	0	107	134%
12:00-1:00PM	48	31	29	62	170	230	56	0	0	286	59%
1:00-2:00PM	0	0	0	202	202	223	92	0	0	315	64%
2:00-3:00PM	178	22	0	56	256	253	101	0	0	354	72%
3:00-4:00PM	182	68	25	93	368	0	374	0	0	374	98%
4:00-5:00PM	12	0	0	61	73	478	0	0	0	478	15%
5:00-6:00PM	120	26	0	34	180	594	0	0	0	594	30%
6:00-7:00PM	115	130	86	102	433	323	184	0	0	507	85%
7:00-8:00PM	44	0	89	125	258	145	0	89	0	234	110%
8:00-9:00PM	39	40	45	67	191	89	169	0	0	258	74%
9:00-10:00PM	0	63	33	0	96	0	0	86	0	86	112%
10:00-11:00PM	0	0	0	0	0	0	0	0	0	0	0%
Average Per Held Train	24.1	15.9	9.7	23.7	73.3	91.4	28.8	4.4	0.0	124.6	59%
TOTALS:					2933					4982	

Table 3-9: Green Line WB Benefit and Hold Summary for Analytical Model: Minimum Passenger Benefit = 100 pax-mins, a = 1.50

Time Period	Trains Held	Green Line Trains	HOLD DURATION(MIN:SEC) Avg. Hold Duration	Shortest Hold	Longest Hold	PASSENGER BENEFITS(PAX-MIN) Average Benefit	Largest Benefit	Smallest Benefit	Total Benefit
7:00-8:00AM	4	40	1:09	0:24	1:48	209	294	116	837
8:00-9:00AM	1	33	0:12	0:12	0:12	196	196	196	196
9:00-10:00AM	0	35	0:00	0:00	0:00	0	0	0	0
10:00-11:00AM	2	37	3:33	3:24	3:42	320	499	142	641
11:00-12:00PM	2	26	1:54	0:48	3:00	500	603	397	999
12:00-1:00PM	3	29	1:50	0:42	3:36	261	390	192	783
1:00-2:00PM	3	27	1:49	1:18	2:14	321	599	175	964
2:00-3:00PM	3	31	1:58	0:54	3:36	220	300	138	660
3:00-4:00PM	3	30	2:50	2:06	3:54	397	864	106	1190
4:00-5:00PM	2	37	0:42	0:24	1:00	308	485	131	615
5:00-6:00PM	1	39	0:42	0:42	0:42	199	199	199	199
6:00-7:00PM	3	38	1:55	0:48	3:34	515	1210	112	1545
7:00-8:00PM	1	36	5:30	5:30	5:30	1452	1452	1452	1452
8:00-9:00PM	3	25	2:11	0:42	3:06	337	634	186	1011
9:00-10:00PM	1	27	0:37	0:37	0:37	124	124	124	124
10:00-11:00PM	0	26	0:00	0:00	0:00	0	0	0	0
Average Per Held Train			1:55			351.0			
TOTALS:	32	516							11216

Time Period	Delayed/Time Savings Breakdown: Total Passengers Savings 0-2 mins	2-4 mins	4-6 mins	6 + mins	Total Pax	Total Passengers Delayed 0-2 mins	2-4 mins	4-6 mins	6 + mins	Total Pax	Pax-Benefit %
7:00-8:00AM	101	117	34	40	292	652	0	0	0	662	46%
8:00-9:00AM	0	0	22	5	27	231	0	0	0	231	12%
9:00-10:00AM	0	0	0	0	0	0	0	0	0	0	0%
10:00-11:00AM	124	27	20	32	203	0	119	0	0	119	171%
11:00-12:00PM	0	89	0	54	143	51	56	0	0	107	134%
12:00-1:00PM	48	31	29	62	170	230	56	0	0	286	59%
1:00-2:00PM	0	0	0	202	202	223	92	0	0	315	64%
2:00-3:00PM	136	22	0	56	214	221	101	0	0	322	66%
3:00-4:00PM	182	68	25	93	368	0	374	0	0	374	98%
4:00-5:00PM	12	0	0	61	73	478	0	0	0	478	15%
5:00-6:00PM	42	0	0	19	61	212	0	0	0	212	29%
6:00-7:00PM	23	130	31	102	286	323	64	0	0	387	74%
7:00-8:00PM	0	0	61	125	186	0	0	89	0	89	209%
8:00-9:00PM	39	0	19	67	125	89	83	0	0	172	73%
9:00-10:00PM	0	0	0	0	0	0	0	0	0	0	0%
10:00-11:00PM	0	0	0	0	0	0	0	0	0	0	0%
Average Per Held Train	22.1	15.1	7.5	28.7	73.4	84.7	29.5	2.8	0.0	117.0	63%
TOTALS:					2350					3744	

with delayed passengers reduced by about 23%. Producing a slightly higher passenger-benefit ratio of 63%. The distribution of benefits changes slightly as almost 40% of benefiting passengers save over six minutes. Total holds are reduced by another 8 trains to 32 trains throughout the day with an average holding time of 1:55 per train.

The results of the sensitivity analysis in Tables 3-8 and 3-9, show that increasing the minimum holding threshold from 50 to 100 passengers-minutes produces holds which are more substantial and delay fewer passengers overall. The increase in minimum net benefit from 50 to 100 passenger-minutes saved, decreased total benefits by only about 10%. Most importantly however, average benefits increase by close to 45% from 240 to nearly 350 passenger-minutes saved per held train. This substantial increase in average benefit per held train indicates that holds produce more significant benefits with increased minimum holding thresholds.

The total number of passengers negatively affected by a held train is reduced by about 40%, while the number of passengers saving time is reduced by only 30%. Consequently, the number of passengers benefiting from holding, averaged nearly 75 passengers per held train, up some 15% from the 65 passengers per hold estimated from the 50 passenger-minute benefit criterion.

Furthermore, 40% of benefiting passengers enjoy time savings over 6 minutes whereas with minimum net benefits of 50 and 75 passengers-minutes, only about 30% of benefiting passengers save over 6 minutes. The passenger-benefit ratio increases from .55 to nearly .63 after the minimum benefit threshold was increased to 100 passenger-minutes saved. Thus, a 100 pax-min minimum benefit criterion results in fewer holds which in turn delay fewer people. In addition, the reduced frequency of holding results in a large increase in the proportion of benefiting passengers enjoying substantial time savings of at least 6 minutes. Overall, the increase in hold threshold produces twenty fewer holds over the day.

From the results of the sensitivity analysis, it is apparent that a threshold of 100 passenger minutes is more appropriate given the reduced number of holds combined with increased average benefits per held train, the reduced number of delayed passengers and the improved passenger-benefit ratio.

3.5 Limitations of the Analytical Model

This section identifies the most important limitations in the analytical model.

- **Prediction Capabilities**

The assumption of perfect prediction capabilities in terms of the arrival times of trains into Park Street (both Red and Green Lines) is not realistic. It is likely that some trains deemed feasible for holding, could actually produce more overall delay than expected if prediction capabilities were imperfect. It is possible that time savings have been over-estimated with the assumption of perfect prediction capabilities for arrival times. In any transfer coordination model, estimated train arrival times should be based on some sort of run time model which accounts for factors that could explain the variation in running times such as time-of-day as well as preceding headway. Run time models based on these two factors will be included in the simulation model.

- **The Assumption of Different Perceived Waiting Time Ratios**

The assumption that riders value waiting time differently depending on whether they are in-vehicle or out-of-vehicle greatly affects the outcome of the model. While this concept is generally agreed upon by most in the transit industry, it remains to be seen whether the choice of $\alpha=1.5$, accurately represents passenger perception and behavior towards waiting time. Without the assumption that passengers find out-of-vehicle waiting time more burdensome than in-vehicle waiting time, it is plausible that significantly fewer trains over the day will be selected for holding. If the transit agency assumes that passengers strongly dislike out-of-vehicle waiting time compared to in-vehicle waiting time, for instance assigning a value of $\alpha = 2.0$, perhaps the benefits of transfer coordination may be over-estimated. The selection of α should be based on the perceptions of the passengers as well as the service policies and operating philosophy of the transit agency in question. The effects of different values of α will be tested in the simulation model.

- **The Assumption of a Fixed Dwell-Time**

To simplify the analytical model, we assumed a fixed dwell-time of thirty seconds, regardless of the time of day, the train type, and the number of passengers aboard the train, or boarding and alighting, etc. While thirty seconds may seem like a reasonable approximation to the real situation, applying the dwell-time findings of Lin and Wilson, leads us to conclude that in the peak especially, dwell times may surpass one minute or even two minutes in rare cases. Therefore, the time savings for the peak periods may be over-estimated. As dwell time becomes longer, more passengers board the train before the holding period begins. Thus the number of delayed passengers aboard the train increases. In addition, there is less capacity remaining for boarding by passengers that save time from holds such as the transfer passengers and the P4 passengers. The simulation model also addresses the issue of dwell-time more thoroughly.

Chapter 4: The Simulation Model

This chapter describes the development of a simulation model developed to analyze the Park Street case study. First, the need for a simulation is discussed. Second, the differences between the underlying assumptions for the analytical and the simulation models are explained. Third, the structure of the simulation model is described. Lastly, the results of the simulation model are presented and analyzed.

4.1 Reasons for Simulation

Briefly, the simulation model attempts to account for the stochasticity inherent in the application of transfer coordination at Park Street. While the analytical model has shown that transfer coordination can result in sizeable benefits, several questions remain about the ultimate suitability of the analytical model to the actual field conditions. Many of the assumptions made in the analytical model, while simplifying the initial calculations, may not accurately represent the actual operating conditions in the field, thereby affecting the potential viability of the system.

For instance, the analytical model assumes perfect prediction capabilities for arrival times into Park Street for both Green Line and Red Line trains. In the field however, operating characteristics such as variable passenger arrival rates, heavy or light train loads, as well as unforeseen events, affecting train movement, may lengthen trip times into Park Street from the detection location. Furthermore the assumption of a constant dwell time of thirty seconds is likely not an adequate approximation of the dwell time at Park Street particularly under peak period conditions.

The simulation model allows us to account for minute-to-minute and day-to-day variability in the system in such variables as train running times and passenger arrivals. We are able to test the sensitivity of the model to different assumptions or operating plans. For instance the assumption that waiting time for passengers is 50% more burdensome when it occurs outside the vehicle rather than inside the vehicle may be regarded as inappropriate by some transit agencies. The simulation allows such assumptions as the out-of-vehicle to in-vehicle waiting time ratio to be altered, thereby helping to determine the robustness of the transfer coordination system benefits.

Lastly, the simulation model represents the most accurate depiction of the field conditions at Park Street. As a result, any findings or conclusions based upon the simulation model are more relevant to the MBTA than the conclusions drawn from the analytical model and give a better sense of what may actually occur if such a system is implemented. Thus it allows a more realistic assessment of the likely benefits of this coordination system.

4.2 Simulation Model Assumptions

A majority of the principles and assumptions behind the analytical model also hold true for the simulation model. This section discusses the assumptions or issues that are treated differently in the simulation model than in the analytical model. Any issues not explicitly mentioned in this section, are defined and treated in precisely the same manner as within the analytical model. The structural differences between the analytical model and the simulation model are described in Section 4.3.

4.2.1 Holding Threshold Value

It is essential that the MBTA use some threshold value for the expected net benefit of a potential hold so that holds which are unlikely to result in significant benefits are not implemented. The results of the analytical model, as shown in Tables 3-7, 3-8 and 3-9, found that increasing the minimum net benefit from 50 to 100 passenger-minutes saved, resulted in twenty fewer trains being held over the day. More importantly however, the average benefits rose from nearly 240 to 350 passenger-minutes saved, or about 45%. The total number of passengers affected negatively and delayed by a held train was reduced by about 40%, while the number of passengers saving time was reduced by only 30%. Consequently, the average number of passengers benefiting per held train, rose some 15% from 65 to 75 passengers. Lastly, the ratio of benefited to delayed passengers increased from .55 to nearly .63.

Therefore since the higher net benefit criterion of 100 passenger-minutes results in more significant average per held train benefits from transfer coordination along with an improved ratio of benefited to delayed passengers, we adopted 100 passenger-minutes as the minimum benefit criterion and therefore the base case for all simulation experiments.

4.2.2 Preceding Headways and Passenger Arrivals

This section discusses the estimation of preceding headways as well as the estimation of passenger arrivals in the simulation model.

- **Preceding Headways**

With perfect knowledge of preceding headways at upstream stations, the simulation model should be capable of more accurately predicting the volume of through-passengers passing Park Street on the Green Line, as well as the loads on Red Line trains entering Park Street.

The analytical model was constrained in many ways and assumed that on the Green Line, preceding headways entering stations prior to Park Street are the same as the headways entering Park Street. Preceding upstream headways are important in calculating the passenger load on the train entering Park Street as well as the expected arrival time of following trains into Park Street. It is possible to relax this assumption for the simulation model. Thus, the preceding headways of any Green Line train are estimated based upon the actual AVI detection times at a particular detector location.

Similar to the analytical model for the Green Line, the analytical model for the Red Line assumes that trains entering stations on the trunk line prior to Park Street possess the same preceding headway as when entering Park Street. This assumption is also relaxed so that headways at any block location on the Red Line are calculated from the OCS block occupancy data. Northbound branch headways are still assumed to be the same as the headway entering the block prior to JFK/UMASS where the branch line tracks converge into the trunk line

- **Passenger Arrivals**

Potentially impacted passengers accumulate during the preceding arrival headway time. Thus, the manner in which passengers arrive at a station is important in estimating the number of potential riders accumulating on the platform to board a Green Line train. The analytical model assumes that passengers arrive at a station at a uniform, constant rate. Since the CTPS data is aggregated into fifteen-minute periods, it is likely that minute-to-minute fluctuations exist in passenger arrival rates, which may vary significantly from the average in a single headway. The average arrival rates do not reveal anything about the minimum or maximum arrival rates within the fifteen-minute observation period. The analytical model thus does not account for variation in passenger demand observed not only on a daily basis, but also on a minute-by-minute basis.

Consistent with the simulation models of Seneviratne (1990) and Dessouky & Hall (1999), in the simulation model we assume that the actual number of passengers that arrive between departures for the Green and Red Lines is Poisson distributed. With mean, μ, and variance, σ^2, both equal to the product of the historical passenger arrival rates multiplied by the preceding headway, the approximation best accounts for randomness in passenger arrivals. We assume that arriving passengers are unaware of the train schedule, hence arriving randomly throughout the inter-arrival period. In addition to arriving randomly, we assume that passenger arrivals are independent of the arrival of any other passenger.

4.2.3 Train Arrival Time Estimation

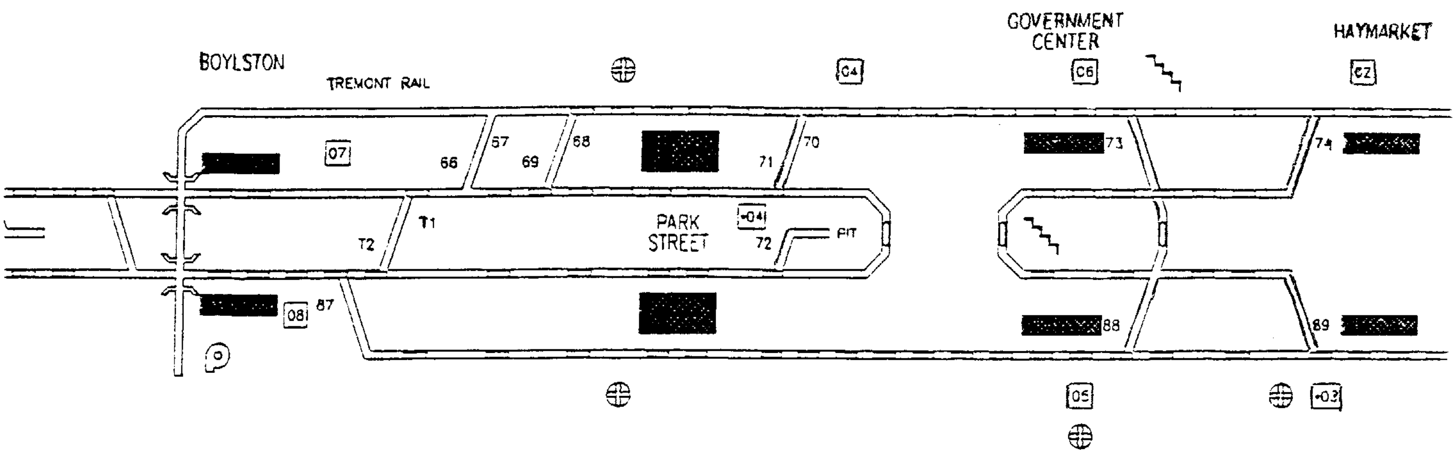
This section discusses changes in the estimation of train arrival time into Park Street.

- **Actual Arrival Time on Green Line WB Boarding Platform**

The arrival time of Green Line trains into Park Street is an important factor that limits how long a hold may last and therefore the feasibility of a potential hold. Closely following trains make holding less likely due to the possibility of blocking. In the analytical model, it is assumed that the K04 AVI detection time is the actual arrival time of Green Line trains into Park Street. The K04 detector is actually situated some distance from the Park Street platforms where passengers board the Green Line trains. It lies prior to the track switch allowing a train of a given route to proceed into Park Street on either Track G3 or G4. Figure 4-1 shows a schematic of the AVI system around Park Street.

It is difficult to estimate precisely the travel time from the K04 detector to the particular berthing location for any of the four branch trains (See Figure 2-4 for platform layout). One of the most important factors in determining the travel time from detector to platform location is the prior train that passes the detector. As noted previously, the B and E Line trains board on Track G3 and the C and D Line trains on Track G4, with E and D Line trains situated at the western end of the platform towards Boylston. Therefore any B or E Line train following a B Line train that is still at Park Street, is blocked from entering. Analogously, a C Line train at Park Street will block any incoming C or D Line train. Therefore the travel time is subject to blocking from the dwell (or hold time) of a B or C Line train on a particular track.

Figure 4-1: Green Line AVI Detector Schematic Around Park Street



Second, any train using Track G3 that follows a train using Track G4 or vice versa, must wait for the track switch to be reset. This process requires proper identification of the train route by the K04 AVI detector, which then relays this information to a central processor that sets the switch for either the G3 or G4 track. In some cases, manual operation of the switch is required if the detector is unable to read the route destination successfully, or if the AVI system is malfunctioning for any reason.

Due to the various contingencies that factor into the travel time into Park Street, we assume an average travel time from the detector to the berthing location, devoid of these aforementioned elements. A series of observations were made to estimate the average travel time from the detector to the B, C, D, or E berthing location on Tracks G3 and G4. The resulting average travel times are as follows:

1) B-Line Train: 45 seconds
2) C-Line Train: 45 seconds
3) D-Line Train: 55 seconds
4) E-Line Train: 55 seconds

It is assumed in the simulation model that these empirical travel times are the actual travel times from the K04 AVI detector entering Park Street into the appropriate berthing location.

- **Green Line Run Time Models to Park Street**

Although we just defined the average travel time from the K04 AVI detector to the Westbound Green Line platform, there still exists a need to predict the expected arrival time into Park Street of any incoming Green Line train to determine the sequence of following headways and therefore the expected benefits of a hold. To accomplish this, we need to have an estimate of when an approaching train will reach the K04 detector.

In the simulation model, we assume that with the AVI providing vehicle detection times at AVI detector locations, we can estimate the running time and hence the arrival time at Park Street for any Green Line train, detected upstream. Trains heading into Park Street are split into three distinct groups:

1) **Eastbound Group**

The Eastbound Group consists of all Green Line trains that are detected heading Eastbound, prior to Government Center, and are to turn at Government Center and head back towards Park Street. Trains in the Eastbound Group are primarily either B or C Line trains since they are normally scheduled to turn at Government Center. We assume that any Eastbound Group train of interest is detected no earlier than the Kenmore AVI detector.

Running times are difficult to predict before the Kenmore AVI detector for three reasons:

- Trains on the surface portion of the branch lines do not operate on exclusive "right-of-ways", thus they are subject to unexpected and random interference from surface traffic crossing the tracks.
- The considerable distance between successive AVI detectors on the surface portions of the branch lines makes it difficult to approximate vehicle location between two detectors. For instance, two detectors on the surface portion of the D-Line, K34 to K29 are separated by over 6.5 miles. With such large detector gaps, trains may have high variance in run times due to extenuating factors such as accumulated dwell times, interference from surface vehicles as noted previously, and bunching.
- Trains on the surface portions of the B, C and D Lines operate on separate tracks which converge into a single track just prior to the location of the Kenmore AVI detector (K14). Thus it is difficult to estimate the sequence of trains and the preceding headways of the combined three branches before the Kenmore AVI detector, one of the essential factors in estimating the running time.

Therefore, we only assess the arrival times of trains that are detected at Kenmore (K14), Copley (K10), Boylston (K08), and Government Center (K05 and K06). Eastbound Group trains must pass two Government Center AVI detectors, one in the Eastbound direction towards Lechmere (K05), and one in the westbound direction (K06) prior to the Government Center WB platform.

2) **Westbound Group**

The Westbound Group is made up of trains that originate from the Lechmere terminus and enter Park Street in the Westbound direction. Trains in the Eastbound Group, which do not start from Lechmere are excluded from this group. Trains in the Westbound Group are primarily D and E Line trains which are scheduled to originate from Lechmere, but may occasionally include a B or C Line train that is dispatched from Lechmere at the beginning or end of the day. In this group, we estimate the arrival times of trains at Park

Street based on detections at Lechmere (K01), Haymarket (K02), and Government Center (K06).

3) **Short-Turn Group**

The Short-Turn Group consists of those Green Line trains headed Eastbound which are short-turned on Track G2 at Park Street and do not proceed to Government Center. Prior to the Boylston detector, short-turned trains are indistinguishable from any other trains heading Eastbound. It is assumed that prior to the Boylston AVI detector, a short-turn if appropriate, is ordered by the Boylston inspector. The route number is altered, which is then read by the Boylston AVI detector and the train switches onto Track G2 entering Park Street instead of arriving on Track G1.

The short-turning procedure does have one interesting caveat. There is no means of detecting the short-turned train once it trips the Boylston (K08) detector, until it is detected again heading Westbound at the Westbound Boylston detector (K07). This situation presents an interesting dilemma in terms of modeling the arrival times of short-turned trains into Park Street since we have no arrival time data in the AVI records on which to base any run time models. We therefore assume that the historical running times, are exactly half of the total travel time found between the Boylston Eastbound (K08) detector and the Boylston Westbound (K07) detector, as recorded in the AVI data.

Predictions of running time are difficult on the Green Line for several reasons:

- The western branching network structure and the different northern termini cause inherent variation in passenger loads on successive trains.
- In a two-car train, car doors are opened and closed by the driver of the individual car, tending to lengthen dwell times.
- Different Green Line train types may experience different dwell times as new low-floor trains are introduced.

In theory however, the run time model for the Green Line should at least account for the following three major elements:

♦ **Short Preceding Headway**

A Green Line train (j) is slowed, and eventually blocked, by the previous train (j-1), if train (j) approaches the minimum safe following distance behind train (j-1). One instance where short preceding headways, relative to the average headways, cause significant blocking problems, occurs when train (j) approaches a station. Assume that train (j) is approaching Boylston. At the same time however, train (j-1) is still at Boylston boarding or unloading passengers. Train (j) then must wait for train (j-1) to depart, and is thereby blocked and its arrival into Boylston delayed.

- **Long Preceding Headway**

  Green Line train (j), with a longer than average preceding headway, may be slowed due to the dwell time at any station. Due to the longer preceding headway, there is more time for passengers to accumulate on the platform and board the train. Thus the dwell time is longer than normal increasing the running time.

- **Peak Hour Operations**

  With higher ridership during the morning and afternoon peaks, it seems obvious that dwell time during these time periods will be longer, thus contributing to longer running times than during the off-peak periods. In addition train congestion effects are more likely to increase running times during the peak periods.

To simplify the formulation of the run time models, we have assumed that these three factors are the primary explanatory variables. We separate the day into five periods 6:00-8:00AM, 8:00-9:30AM (AM Peak), 9:30-5:00PM, 5:00-6:00PM (PM Peak), and 6:00-11:00PM. The three non-peak periods are classified as off-peak based on the average running times throughout the day from a particular AVI detector to the one at Park Street. Some periods exhibited similar running times and hence were combined into a single model.

An example of the Green Line running time model from the Boylston Eastbound (K08) detector to the Park Street (K04) detector during the off-peak hours is as follows:

Run time from K08 to K04 (in seconds) During Off-Peak Periods $= 360.6 + 43.1X_1 + 18.8X_2$,

where:

$$X_1 = \begin{cases} 1, \text{if (Preceding Headway} < 1.0 \text{ minutes)} \\ 0, \text{otherwise} \end{cases}$$ and

$$X_2 = \begin{cases} 1, \text{if (}1.0 \text{ minutes} < \text{Preceding Headway} < 1.5 \text{ minutes)} \\ 0, \text{otherwise} \end{cases}.$$

This run time model suggests that the base travel time from the K08 to the K04 detector is about 360 seconds during the off-peak. The model also suggests that running time increases when the preceding headway of the train is short compared to the average headway. During the off-peak, headways on the WB Green Line in the Central Subway average around 2 minutes. Thus the model implies that an extremely short preceding headway, under 1 minute for instance, should result in more severe blocking and thus longer overall travel times, than would a moderately short preceding headway, between 1 and 1.5 minutes for instance. Thus when the preceding headway is under 1 minute, the travel time increases by about 43 seconds. If the headway is between 1 and 1.5 minutes, the travel time increases by close to 19 seconds. For example a Green Line train entering the K08 detector with a preceding headway of 1.2 minutes is estimated to arrive at the K04 detector nearly 380 seconds later.

Tables 4-1, 4-2 and 4-3 summarize the Green Line run time models from a particular AVI detector to the Park Street detector, K04, divided into the three train groups defined previously: Westbound, Eastbound and Short-Turn. Overall, Green Line running time models show that significant differences exist between the peak and off-peak periods. For instance the average running time from the K08 to the K04 detector in Table 4-2, is close to 360 seconds in off-peak periods. During peak periods however, the average running time is nearly 120 seconds higher than in the off-peak, amounting to almost 480 seconds.

Green Line run time models also suggest that the short headway effects are more significant in explaining run time variation than long headway effects. In nearly half the models estimated, the short headway effect is shown to lengthen the average running time significantly. None of the models however, found that the long headway effect significantly increased the total travel time. Hence it can be inferred that running time variability is more susceptible to blocking effects downstream than it is to potential delay from dwell time effects caused by the preceding train.

- **Red Line Run Time Models to Park Street**

With the OCS data, including vehicle location at specific times, we can develop Red Line run time models for use in the simulation model. The scope of our run time models for the Red Line is limited by the maximum holding times determined for Green Line trains in the analytical model. For instance only two trains out of over five-hundred Green Line trains analyzed throughout the day had holds exceeding five minutes. Thus it seems logical to narrow the focus

Table 4-1: Green Line Run-Time Models to Park Street: Westbound Group

Time Period Definition

Time Period	Beginning	End
Off-Peak 1	6:00AM	8:00AM
AM	8:00AM	9:30AM
Off-Peak 2	9:30AM	5:00PM
PM	5:00PM	6:00PM
Off-Peak 3	6:00PM	11:00PM

Variable Definition

H Headway of Current Green Line Train

Westbound Group of Trains: Lechmere - Park Street

		Time Periods	Model Variables		Model Measures			
Government Center	Model Name	Included		Intercept	Adjusted R2	Avg. Headway	STD Headway	RMSE
Direction: WB AVI Detector# K06	Government Center WB 1	All Off-Peak	Value:	93.8		2.0	1.4	15.5
	Model Name	Time Periods	Model Variables		Model Measures			
	Government Center WB 2	All Peak	Value:	114.8		1.6	0.9	31.5

		Time Periods	Model Variables		Model Measures			
Haymarket	Model Name	Included		Intercept	Adjusted R2	Avg. Headway	STD Headway	RMSE
Direction: WB AVI Detector# K02	Haymarket WB 1	All Off-Peak	Value	158.1		4.0	2.1	23.7
	Model Name	Time Periods		Intercept	Adjusted R2	Avg. Headway	STD Headway	RMSE
	Haymarket WB 2	All Peak	Value	196.0		3.0	1.0	45.7

		Time Periods	Model Variables				Model Measures			
Lechmere	Model Name	Included		Intercept	$H<2$	$H<2.5$	Adjusted R2	Avg. Headway	STD Headway	RMSE
Direction: WB AVI Detector# K01	Lechmere WB 1	Off-Peak 1 Off-Peak 2	Value	521.3		68.8	0.11	3.9	2.0	84.1
			t-stat	61.9		4.3				
	Model Name	Time Periods		Intercept	$H<2$	$H<2.5$	Adjusted R2	Avg. Headway	STD Headway	RMSE
	Lechmere WB 2	Off-Peak 3	Value	496.6		42.8	0.08	4.0	2.0	56.3
			t-stat	72.4		3.0				
	Model Name	Time Periods		Intercept	$H<2$	$H<2.5$	Adjusted R2	Avg. Headway	STD Headway	RMSE
	Lechmere WB 3	AM Peak	Value	725.8	124.3		0.20	3.0	1.4	100.4
			t-stat	32.8	2.9					
	Model Name	Time Periods		Intercept	$H<2$	$H<2.5$	Adjusted R2	Avg. Headway	STD Headway	RMSE
	Lechmere WB 4	PM Peak	Value	559.3		48.7	0.09	2.9	1.3	60.5
			t-stat	30.4		1.7				

Table 4-2: Green Line Run-Time Models to Park Street: Eastbound Group

		Time Periods	Model Variables		Model Measures			
Government Center	Model Name	Included		Intercept	Adjusted R2	Avg. Headway	STD Headway	RMSE
Direction: EB	Government Center EB 1	All Off-Peak	Value:	165.0		1.9	1.5	31.5
AVI Detector# K05								
	Model Name	Time Periods		Intercept	Adjusted R2	Avg. Headway	STD Headway	RMSE
	Government Center EB 2	All Peak	Value:	197.5		1.5	0.8	42.4

		Time Periods	Model Variables				Model Measures			
Boylston	Model Name	Included		Intercept	H<1	1<H<1.5	Adjusted R2	Avg. Headway	STD Headway	RMSE
Direction: EB	Boylston EB 1	All Off-Peak	Value	360.6	43.1	18.6	0.11	1.9	1.5	47.9
AVI Detector# K08			t-stat	65.2	5.5	2.4				
	Model Name	Time Periods		Intercept	H<1	1<H<1.5	Adjusted R2	Avg. Headway	STD Headway	RMSE
	Boylston EB 2	All Peak	Value	476.8				1.4	0.7	81.8

		Time Periods	Model Variables					Model Measures			
Copley	Model Name	Included		Intercept	H<1	1<H<1.5	H<1.5	Adjusted R2	Avg. Headway	STD Headway	RMSE
Direction: EB	Copley EB 1	All Off-Peak	Value:	554.7			61.2	0.17	1.9	1.4	65.6
AVI Detector# K10			t-stat	87.8			6.9				
	Model Name	Time Periods		Intercept	H<1	1<H<1.5	H<1.5	Adjusted R2	Avg. Headway	STD Headway	RMSE
	Copley EB 2	AM Peak	Value:	661.5	71.8	35.8		0.07	1.4	1.0	64.2
			t-stat	23.6	1.9	1.0					
	Model Name	Time Periods		Intercept	H<1	1<H<1.5	H<1.5	Adjusted R2	Avg. Headway	STD Headway	RMSE
	Copley EB 3	PM Peak	Value:	664.3	122.9			0.18	1.3	0.9	112.8
			t-stat	15.7	2.1						

		Time Periods	Model Variables				Model Measures			
Kenmore	Model Name	Included		Intercept	H<1	H<1.5	Adjusted R2	Avg. Headway	STD Headway	RMSE
Direction: EB	Kenmore EB 1	All Off-Peak	Value	793.9		84.0	0.20	2.4	1.9	80.2
AVI Detector# K14			t-stat	114.0		7.5				
	Model Name	Time Periods		Intercept	H<1	H<1.5	Adjusted R2	Avg. Headway	STD Headway	RMSE
	Kenmore EB 2	All Peak	Value	933.7	113.3		0.21	1.5	1.3	104.4
			t-stat	39.0	3.4					

Table 4-3: Green Line Run-Time Models to Park Street: Short-Turn Group

		Time Periods	Model Variables		Measures
Boylston	Model Name	Included		Intercept	RMSE
Direction: EB	Short-Turn EB 1	All Time Periods	Value	154.9	61.2
AVI Detector# K08					

of the Red Line run time model to account for only those trains that are within five minutes travel time of Park Street in either direction. Therefore Red Line trains are split into two distinct groups:

1) **Northbound Group**

From an initial analysis of the average travel times to Park Street from the OCS occupancy data, the five-minute travel time threshold occurs at a detector prior to South Station, Block # 1475T. Figure 4-2 shows a schematic representation of the block and station layout of the Red Line around Park Street (Note: Figures 2-6 and 4-2 are identical). The transfer coordination system only estimates the travel times of potential Red Line trains in the Northbound Group if they are detected within an eight-block segment starting from Block 1475T, passing through South Station and Downtown Crossing, and terminating at Block 146T, just prior to entering Park Street.

2) **Southbound Group**

The Southbound Group of Red Line trains consists of any Red Line train headed towards Ashmont or Braintree and detected within a nine-block segment starting from Block 2701T, the block immediately after a train departs Kendall, passing through Charles/MGH, and terminating at Block 7-2T, just prior to the entrance to Park Street.

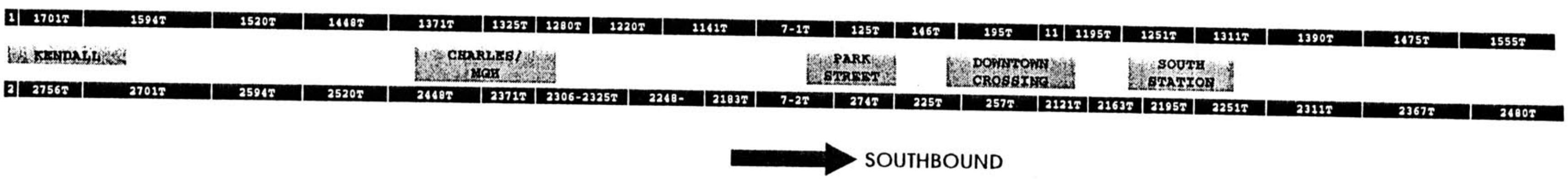
The run time models for the Red Line are similar in nature to those for the Green Line and in theory account for the effects of a short preceding headway, a long preceding headway, and peak period operations. The Red Line run time models use identical time periods as the Green Line. However, the Red Line has different operational characteristics from the Green Line that affect the running time models.

- The Red Line train control system is much more automated than for the Green Line. Thus, the human factors affecting running time such as the need for a manual track switch are eliminated, thus making our models much more precise.

- Branching on the southern end of the Red Line does not play a significant role in the trip time to Park Street from a given detection location.

- Train doors are controlled by one operator per train.

Figure 4-2: Red Line OCS Schematic Around Park Street



- From the data collected, the average headway on the Red Line is about five minutes in the off-peak periods, while in the peak it is between three and four minutes. The Green Line on the other hand, has off-peak headways close to two minutes, and peak headways close to a minute and a half.

With longer average headways on the Red Line, it is possible that a Red Line train may be delayed by the preceding train which itself may be delayed by its preceding train. For instance assume a Red Line train is headed from Kendall to Park Street. In this scenario, the train at Kendall is effectively delayed not only by the first preceding train that is at Charles/MGH, but also by the second preceding train that is still at Park Street. The necessity of maintaining safe following distances prevents the train at Charles/MGH from proceeding into Park since the second preceding train is already there. Consequently, the train at Kendall is unable to proceed due to blocking from the first preceding train at Charles/MGH. Therefore, we assume that the running time of a train may be affected not only by the headway of the first preceding train, but also by the headway of the second preceding train in the following manner:

- **Short Second Preceding Headway**

  We assume that if the second preceding headway is short relative to the average headway, then train (k-1) conceivably could catch up with train (k-2) and be forced either to slow down or to hold so that it does not violate the safe following distance. If this is the case, it is more likely that the run time of current train (k) may be increased as train (k-1) may block it and force it to slow down or hold to maintain a safe following distance.

- **Long Second Preceding Headway**

  We assume that if the second preceding headway is long relative to the average headway, then train (k-1) may experience longer dwell times, thereby allowing train (k) possibly to catch up with it and be forced to slow down to maintain a safe following distance.

An example of the Red Line running time model from near South Station (Block 1390T) to Park Street (Block 125T) in the Northbound direction during the AM Peak is as follows:

*Run time from Block 1390T to Block 125T During AM Peak (in seconds) = 293.5 + 103.2*X_1 *+ 69.5*X_2*,*

where:

$$X_1 = \begin{cases} 1, \text{if (First Preceding Headway} < 3.0 \text{ minutes)} \\ 0, \text{otherwise} \end{cases} \text{ and}$$

$$X_2 = \begin{cases} 1, \text{if (Second Preceding Headway} < 3.5 \text{ minutes)} \\ 0, \text{otherwise} \end{cases}.$$

This running time model suggests that the base travel time from Block 1390T to Block 125T in the AM Peak is approximately 294 seconds. Similar to the run time model estimated between AVI detectors K08 and K04, the run time model from Block 1390T to Block 125T suggests that running time increases when the preceding headway is shorter than the average headway. In the peak periods, the average headway on the Red Line is between 3 and 4 minutes. The model suggests that a short headway compared to the average one, under 3 minutes for instance, increases the average run time by nearly 100 seconds.

Furthermore, it suggests that trains are also affected by the second preceding headway. The model estimates the run time is increased by 70 seconds if the second preceding headway is under 3.5 minutes. Thus a Red Line train entering Block 1390T during the AM Peak with an initial preceding headway of 2.5 minutes and a second preceding headway of 5 minutes is estimated to arrive at Block 125T nearly 400 seconds later. If its second preceding headway were 2.5 minutes instead, then the estimated trip time would be close to 470 seconds.

Tables 4-4 and 4-5 summarize the Red Line run time models from a particular block to the Park Street Platform, Block 125T. Several of the run time models for the Red Line exhibit large variations in average running times over different time periods, most notably in the Northbound direction. Running time from blocks prior to Downtown Crossing show the greatest variation in average running times for the five different time periods. For instance, the average off-peak run time from Block 1311T (near South Station) to Block 125T is nearly 220 seconds in the early morning period, 195 seconds in the afternoon and close to 180 seconds in the early evening period. The average run time in the AM Peak is close to 260 seconds, while in the PM Peak it is almost 307 seconds. One possible explanation for the large disparity in running times is Northbound trains may be subject to long dwell times at Downtown Crossing, the transfer station

Table 4-4: Northbound Red Line Run Time Models to Park Street, Block 125T

Time Period Definition:

Time Period	Beginning	End
Off-Peak 1	5:00AM	8:00AM
AM	8:00AM	9:30AM
Off-Peak 2	9:30AM	5:00PM
PM	5:00PM	6:00PM
Off-Peak 3	6:00PM	12:00AM

Variable Definition:

H Headway of Current Red Line Train

P Headway of Preceding Red Line Train

		Time Periods	Model Variables					Model Measures	
Detection Block	Model Name	Included	Intercept	H<2.5	H<3	2.5<H<3	P > 7.5	Adjusted R:	RMSE
146T	1146T - 1	Off-Peak1	34.4	12.3				0.59	3.7
		(t-stat)	(38.2)	(5.7)					
Closest Station:	146T - 2	AM	35.4	18.1		9.1		0.53	5.1
Park Street		(t-stat)	(24.0)	(4.4)		(3.4)			
	146T - 3	Off-Peak2	34.0		29.0			0.70	10.9
		(t-stat)	(79.6)		(12.0)				
	146T - 4	PM	33.9	21.1			34.1	0.93	7.7
		(t-stat)	(31.6)	(8.4)			(10.1)		
	146T - 5	Off-Peak 3	32.7		12.3			0.40	4.5
		(t-stat)	(102.6)		(5.6)				

		Time Periods	Model Variables					Model Measures	
Detection Block	Model Name	Included	Intercept	H<3	3<H<3.5	P > 7.5	P < 3.5	Adjusted R:	RMSE
195T	195T - 1	Off-Peak1	115.7				44.2	0.80	7.3
		(t-stat)	(66.3)				(9.3)		
Closest Station:	195T - 2	AM	122.5	21.8	9.8		71.5	0.59	11.6
		(t-stat)	(22.9)	(3.1)	(1.2)		(5.1)		
Downtown Crossing	195T - 3	Off-Peak2	98.8	13.7				0.28	9.1
		(t-stat)	(65.0)	(4.5)					
	195T - 4	PM	129.7			16.3	91.3	0.76	12.4
		(t-stat)	(27.2)			(1.5)	(6.1)		
	195T - 5	Off-Peak 3	86.5	15.0	7.5			0.36	6.2
		(t-stat)	(69.4)	(4.3)	(2.2)				

		Time Periods	Model Variables					Model Measures	
Detection Block	Model Name	Included	Intercept	H<3	3<H<3.5	P > 7.5	P < 3.5	Adjusted R:	RMSE
1140T	1140T - 1	Off-Peak1	121.6				44.1	0.81	7.2
		(t-stat)	(70.2)				(9.4)		
Closest Station:	1140T - 2	AM	128.3	21.8	10.4		71.7	0.58	11.8
		(t-stat)	(23.6)	(3.0)	(1.2)		(5.0)		
Downtown Crossing	1140T - 3	Off-Peak2	104.7	7.3		12.6		0.32	9.7
		(t-stat)	(64.2)	(2.1)		(3.8)			
	1140T - 4	PM	137.3			14.7	88.7	0.74	12.8
		(t-stat)	(27.8)			(1.3)	(5.7)		
	1140T - 5	Off-Peak 3	92.4	16.2				0.70	5.8
		(t-stat)	(84.1)	(5.6)					

		Time Periods	Model Variables						Model Measures	
Detection Block	Model Name	Included	Intercept	H<2.5	H<3	2.5<H<3	P > 7.5	P < 3.5	Adjusted R:	RMSE
1195T	1195T - 1	Off-Peak1	135.3	22.2		12.9		44.7	0.60	11.1
		(t-stat)	(34.4)	(2.3)		(1.9)		(5.5)		
Closest Station:	1195T - 2	AM	148.5			28.8		65.5	0.63	12.8
		(t-stat)	(36.9)			(4.1)		(4.5)		
Downtown Crossing	1195T - 3	Off-Peak2	117.7		12.4		10.8		0.40	9.1
		(t-stat)	(75.3)		(3.6)		(3.3)			
	1195T - 4	PM	153.5	85.3			20.3	85.5	0.76	19.4
		(t-stat)	(17.6)	(5.2)			(1.1)	(24.0)		
	1195T - 5	Off-Peak 3	106.2	37.8		26.0			0.46	11.7
		(t-stat)	(49.2)	(4.2)		(4.4)				

		Time Periods	Model Variables						Model Measures	
Detection Block	Model Name	Included	Intercept	H<2.5	H<3	2.5<H<3	P > 7.5	P < 3.5	Adjusted R^2	RMSE
1251T	1251T - 1	Off-Peak1	206.8	22.3				44.6	0.72	9.9
		(t-stat)	(65.1)	(1.9)				(6.3)		
Closest Station:	1251T - 2	AM	231.4	49.1		51.1	89.6	56.5	0.62	21.8
		(t-stat)	(30.2)	(2.5)		(3.4)	(3.4)	(2.0)		
South Station	1251T - 3	Off-Peak2	176.7		24.4				0.33	13.1
		(t-stat)	(83.5)		(4.9)					
	1251T - 4	PM	273.2				105.8	116.8	0.56	30.9
		(t-stat)	(24.2)				(2.8)	(3.1)		
	1251T - 5	Off-Peak 3	159.5	64.5		23.5			0.60	21.6
		(t-stat)	(73.9)	(7.1)		(2.6)				

		Time Periods	Model Variables							Model Measures	
Detection Block	Model Name	Included	Intercept	H<2.5	H<3	2.5<H<3	3<H<3.5	P > 7.5	P < 3.5	Adjusted R^2	RMSE
1311T	1311T - 1	Off-Peak1	217.7	30.3		11.7	14.7		51.3	0.78	8.3
		(t-stat)	(53.5)	(2.8)		(1.7)	(2.1)		(7.3)		
Closest Station:	1311T - 2	AM	260.0		46.0			50.0	79.1	0.45	27.3
		(t-stat)	(31.6)		(2.4)			(1.4)	(2.5)		
South Station	1311T - 3	Off-Peak2	193.5		22.0			8.7		0.36	12.7
		(t-stat)	(91.1)		(4.2)			(1.5)			
	1311T - 4	PM	307.0		85.0			92.0	101.0	0.54	29.7
		(t-stat)	(17.9)		(3.0)			(2.2)	(2.4)		
	1311T - 5	Off-Peak 3	178.1		45.5					0.40	14.6
		(t-stat)	(69.0)		(5.0)						

		Time Periods	Model Variables						Model Measures	
Detection Block	Model Name	Included	Intercept	H<2.5	H<3	2.5<H<3	P > 7.5	P < 3.5	Adjusted R^2	RMSE
1390T	1390T - 1	Off-Peak1	245.0	25.0		6.0		48.0	0.70	10.3
		(t-stat)	(61.8)	(2.0)		(1.0)		(6.0)		
Closest Station:	1390T - 2	AM	293.5		103.2			69.5	0.38	44.4
		(t-stat)	(21.6)		(3.3)			(1.4)		
South Station	1390T - 3	Off-Peak2	215.6		24.1				0.34	13.2
		(t-stat)	(98.3)		(5.0)					
	1390T - 4	PM	344.7	153.3			75.3		0.59	34.1
		(t-stat)	(19.6)	(3.3)			(1.6)			
	1390T - 5	Off-Peak 3	198.9		43.1				0.28	11.0
		(t-stat)	(102.6)		(3.8)					

		Time Periods	Model Variables							Model Measures	
Detection Block	Model Name	Included	Intercept	H<2.5	H<3	2.5<H<3	3<H<3.5	P > 7.5	P < 3.5	Adjusted R^2	RMSE
1475T	1475T - 1	Off-Peak1	269.5						41.5	0.55	13.8
		(t-stat)	(65.7)						(4.4)		
Closest Station:	1475T - 2	AM	299.7	114.8		114.6			81.3	0.60	36.4
		(t-stat)	(23.9)	(3.6)		(4.2)			(1.9)		
South Station	1475T - 3	Off-Peak2	232.8		21.8			9.1		0.38	12.8
		(t-stat)	(106.4)		(4.3)			(1.6)			
	1475T - 4	PM	385.3		159.7					0.32	62.1
		(t-stat)	(14.2)		(2.1)						
	1475T - 5	Off-Peak 3	212.9		42.6		9.6			0.60	8.6
		(t-stat)	(112.4)		(6.4)		(1.4)				

Table 4-5: Southbound Red Line Run Time Models to Park Street, Block 274T

Time Period Definition:

	Beginning	End
Off-Peak 1	5:00AM	8:00AM
AM	8:00AM	9:30AM
Off-Peak 2	9:30AM	5:00PM
PM	5:00PM	6:00PM
Off-Peak 3	6:00PM	12:00AM

Variable Definition:

H Headway of Current Red Line Train
P Headway of Preceding Red Line Train

		Time Periods	Model Variables					Model Measures	
Detection Block	Model Name	Included	Intercept	H<2.5	H<3	2.5<H<3	3<H<3.5	Adjusted R²	RMSE
7-2T	7-2T - 1	Off-Peak1	41.2		24.3			0.78	3.6
		(t-stat)	(48.2)		(8.6)				
Closest Station:	7-2T - 2	AM	61.2						10.6
Park Street		(t-stat)							
	7-2T - 3	Off-Peak2	41.7		16.4		17.0	0.67	4.8
		(t-stat)	(69.3)		(8.4)		(11.0)		
	7-2T - 4	PM	54.4		13.6			0.29	9.1
		(t-stat)	(14.4)		(2.3)				
	7-2T - 5	Off-Peak 3	39.6	15.4		16.2	4.0	0.66	3.9
		(t-stat)	(65.7)	(3.8)		(10.5)	(2.6)		

		Time Periods	Model Variables			Model Measures	
Detection Block	Model Name	Included	Intercept	H<3	3<H<3.5	Adjusted R²	RMSE
2183T	2183T - 1	Off-Peak1	51.1	26.9		0.78	3.9
		(t-stat)	(57.7)	(8.9)			
Closest Station:	2183T - 2	AM	72.7				10.8
Park Street		(t-stat)					
	2183T - 3	Off-Peak2	51.7	16.0		0.62	4.2
		(t-stat)	(100.2)	(11.2)			
	2183T - 4	PM	75.6				10.6
		(t-stat)					
	2183T - 5	Off-Peak 3	49.3	15.1	3.1	0.75	2.8
		(t-stat)	(112.9)	(13.0)	(2.6)		

		Time Periods	Model Variables			Model Measures	
Detection Block	Model Name	Included	Intercept	H<3	3<H<3.5	Adjusted R²	RMSE
2248T	2248T - 1	Off-Peak1	64.7	27.8	4.3	0.80	3.7
		(t-stat)	(70.9)	(9.4)	(1.1)		
Closest Station:	2248T - 2	AM	87.6				11.1
Park Street		(t-stat)					
	2248T - 3	Off-Peak2	65.5	15.7		0.62	4.3
		(t-stat)	(123.1)	(11.2)			
	2248T - 4	PM	90.7				10.3
		(t-stat)					
	2248T - 5	Off-Peak 3	62.9	15.3	4.5	0.72	3.1
		(t-stat)	(130.9)	(11.9)	(3.3)		

		Time Periods	Model Variables						Model Measures	
Detection Block	Model Name	Included	Intercept	H<2.5	H<3	2.5<H<3.5	3<H<3.5	P>8	Adjusted R²	RMSE
2306T	2306T - 1	Off-Peak1	88.3	51.8				6.7	0.93	4.2
		(t-stat)	(79.5)	(15.2)				(2.9)		
Closest Station:	2306T - 2	AM	150.4							33.0
Charles/MGH		(t-stat)								
	2306T - 3	Off-Peak2	90.2		74.4		23.6		0.76	10.5
		(t-stat)	(69.4)		(15.1)		(5.6)			
	2306T - 4	PM	145.8							30.7
		(t-stat)								
	2306T - 5	Off-Peak 3	87.0	40.0		5.5			0.84	4.0
		(t-stat)	(138.6)	(16.1)		(2.5)				

Detection Block	Model Name	Time Periods Included	Intercept	H<2.5	H<3	2.5<H<3	3<H<3.5	P<3	Adjusted R^2	RMSE
2371T	2371T - 1	Off-Peak1	140.2	62.8		32.3			0.90	5.1
		(t-stat)	(107.7)	(11.1)		(7.4)				
Closest Station: Charles/MGH	2371T - 2	AM	211.6							31.3
		(t-stat)								
	2371T - 3	Off-Peak2	137.6		55.5		7.4	14.3	0.68	9.4
		(t-stat)	(111.1)		(12.4)		(1.3)	(3.7)		
	2371T - 4	PM	201.7		47.8				0.27	24.9
		(t-stat)	(23.3)		(2.3)					
	2371T - 5	Off-Peak 3	133.2	43.4		23.3			0.71	8.0
		(t-stat)	(113.1)	(11.2)		(3.9)				

Detection Block	Model Name	Time Periods Included	Intercept	H<2.5	H<3	2.5<H<3.5	3<H<3.5	P<3	Adjusted R^2	RMSE
2448T	2448T - 1	Off-Peak1	160.5	65.5		32.5			0.90	5.1
		(t-stat)	(123.3)	(11.5)		(7.9)				
Closest Station: Charles/MGH	2448T - 2	AM	222.4		22.3				0.07	28.3
		(t-stat)	(22.7)		(1.6)					
	2448T - 3	Off-Peak2	155.8	105.2		53.5			0.73	11.9
		(t-stat)	(100.6)	(8.6)		(11.0)				
	2448T - 4	PM	215.8		55.7		17.8	44.2	0.31	21.4
		(t-stat)	(20.1)		(2.6)		(1.0)	(1.6)		
	2448T - 5	Off-Peak 3	151.2	44.0		11.8			0.69	8.5
		(t-stat)	(114.8)	(10.7)		(2.6)				

Detection Block	Model Name	Time Periods Included	Intercept	H<2.5	H<3	2.5<H<3.5	3<H<3.5	P<3	Adjusted R^2	RMSE
2520T	2520T - 1	Off-Peak1	176.1	73.4		25.9			0.93	5.7
		(t-stat)	(121.9)	(16.1)		(4.1)				
	2520T - 2	AM	242.8		118.7		76.2		0.43	43.2
Closest Station:		(t-stat)	(10.9)		(2.9)		(2.4)			
Charles/MGH	2520T - 3	Off-Peak2	170.6	96.9		25.2		10.0	0.74	12.8
		(t-stat)	(100.4)	(14.3)		(4.5)		(2.0)		
	2520T - 4	PM	243.3		151.8		74.0		0.52	37.7
		(t-stat)	(10.5)		(2.9)		(2.3)			
	2520T - 5	Off-Peak 3	165.5	56.9		12.0			0.73	10.0
		(t-stat)	(107.0)	(11.8)		(2.2)				

Detection Block	Model Name	Time Periods Included	Intercept	H<2.5	H<3	2.5<H<3.5	3<H<3.5	P<3	Adjusted R^2	RMSE
2594T	2594T - 1	Off-Peak1	189.1	74.9		25.9			0.91	6.6
		(t-stat)	(113.6)	(14.2)		(3.6)				
Closest Station: Charles/MGH	2594T - 2	AM	280.5		76.2		72.5		0.25	44.9
		(t-stat)	(15.3)		(2.2)		(1.3)			
	2594T - 3	Off-Peak2	183.6	99.9		25.4		10.9	0.74	13.4
		(t-stat)	(103.3)	(14.1)		(4.3)		(2.1)		
	2594T - 4	PM	284.0		101.0		86.5		0.34	49.4
		(t-stat)	(10.8)		(2.3)		(1.8)			
	2594T - 5	Off-Peak 3	178.2	57.8		11.6			0.71	10.4
		(t-stat)	(110.5)	(11.5)		(2.1)				

Detection Block	Model Name	Time Periods Included	Intercept	H<2.5	2.5<H<3.5	P<3	Adjusted R^2	RMSE
2701T	2701T - 1	Off-Peak1	212.8	73.2	25.2		0.89	7.2
		(t-stat)	(116.1)	(12.6)	(3.2)			
Closest Station: Kendall/MIT	2701T - 2	AM	308.8	106.4	57.8		0.39	46.7
		(t-stat)	(14.2)	(3.1)	(1.5)			
	2701T - 3	Off-Peak2	208.7	103.8	40.0	11.8	0.68	16.8
		(t-stat)	(94.8)	(11.7)	(5.4)	(2.1)		
	2701T - 4	PM	277.9	161.1	134.9	75.9	0.68	36.6
		(t-stat)	(10.6)	(2.9)	(3.8)	(2.1)		
	2701T - 5	Off-Peak 3	201.6	57.0	14.4		0.71	10.4
		(t-stat)	(125.2)	(11.3)	(2.3)			

between the Orange and the Red Lines having the second-highest number of daily transfers after Park Street. Trains dwelling at Downtown Crossing may also block successive trains from entering the station and thereby lengthen the overall trip time to Park Street.

Overall, Red Line run time models suggest that the short headway effect is more significant in explaining run time variation than the long headway effect from the first preceding train. In a majority of the run time models, the short headway effect is shown to lengthen the average run time significantly. The long headway effect was found to be insignificant in terms of estimating running time and was not included in any of the run time models as an explanatory variable. Hence it can be inferred that run time variability is more susceptible to blocking effects downstream than it is to potential dwell time effects from the first preceding train.

Finally, the run time models suggest that a short second preceding headway and a long second preceding headway are factors in explaining run time variability. In the Southbound direction, the short second preceding headway effect is found to be significant in six of the models compared to just one for the long second preceding headway effect. In the Northbound direction, the short and long second preceding headway effects play much more prominent roles in the estimation of run times. The short second preceding headway effect is found to be significant in nearly half of the models estimated, while the long second preceding headway effect is significant in nearly a quarter of the models. These results suggest that blocking effects from the two most recent preceding trains play a prominent role in train run time into Park Street.

4.2.4 Dwell Time

The dwell time is an important factor in assessing the benefits of holding Green Line trains at Park Street since holding can only be initiated after the completion of the dwell time. The dwell time was assumed to be thirty seconds in the analytical model. In off-peak periods this may be a reasonable estimate, but the dwell time during the AM and PM peaks may well exceed this threshold value regularly from the heavy loads on incoming trains and the large volume of passengers wanting to board at Park Street. In the simulation model, we attempt to capture some of the elements that result in longer dwell times at Park Street in the peak periods. We base our dwell time model upon the models developed by Lin & Wilson (1993).

Lin & Wilson developed various dwell-time models specific to the Green Line, differentiating between one and two-car trains. These models are based largely upon three explanatory variables: the number of passengers boarding, the number of passengers alighting, and the number of passengers aboard the train. The models also show that the effect of passenger crowding and congestion is statistically significant and significantly improves the explanatory power of the models.

Lin & Wilson assume that the crowding on the train causes alighting passengers to be impeded by arriving standees. Similarly, the departing standees impede boarding passengers. We assume that the dwell time in seconds is well represented by the Lin & Wilson Green Line models:

1) **One-Car Green Line Train**

   Dwell Time = 12.50 + 0.55*Tons + 0.23*Toffs + 0.0078*SUMASLS

2) **Two-Car Green Line Train**

   Dwell Time = 13.93 + 0.27*Tons + 0.36*Toffs + 0.0008*SUMASLS

where:

Tons = The Total Boarding Passengers,
Toffs = The Total Departing Passengers,
AS = The Number of Arriving Standees,
LS = The Number of Departing Standees,
and
SUMASLS = *Tons*AS* + *Toffs*LS*.

4.2.5 Waiting Time Valuation

Research, most notably a study conducted by CTPS[22] in 1997, has shown that passengers regard in-vehicle time and transfer waiting time differently, with transfer waiting time being generally more onerous. The analytical model assumed that passengers view out-of-vehicle waiting time as being 1.5 times as burdensome as in-vehicle waiting time. The simulation model assumes that this proportion is uncertain and can be varied to test the sensitivity of the model to different passenger behavior and perceptions. We will assume $\alpha = 1.50$ represents the base case and will discuss the sensitivity of the model to a decrease in α to 1.25. Decreasing α can be viewed as the transit agency placing more emphasis on providing service equity to all passengers and minimizing the overall negative impact of a hold delaying passengers.

[22] Central Transportation Planning Staff (CTPS). "Transfer Penalties in Urban Mode Choice Modeling", 1997.

4.2.6 Transfer Passenger Assumptions

This section discusses the estimation of the number of passengers on a Red Line train that will transfer to the Green Line WB, as well as the manner in which they transfer.

- **Transferring Proportions from Red Line Train**

In the analytical model, we assume that the number of transferring passengers to the Green Line Westbound from either the Red Line NB or SB is a proportion of the total passengers on the Red Line train when it enters Park Street. One would expect that the proportion of transferring passengers would vary from train to train.

To better account for this real-world variation, we model the transfer process from the Red to the Green Line WB as a binomial process. We model each passenger on an incoming Red Line train, either as transferring to the Green Line WB or not. From the CTPS data, we have the historical proportion of all incoming Red Line passengers that transfer to the Green Line WB. Therefore, we assume that the probability, p, of any passenger transferring to the Green Line WB is equal to the rate found from the CTPS data, where q (1-p) is the probability of not transferring to the Green Line WB. If there are n passengers on the train, then the mean, μ=np, and the variance, σ^2 = npq.

- **Transfer Arrival Pattern**

In the analytical model, we also assumed that transfers arrive at Park Street at a uniform, constant rate. Figures 4-3 and 4-4 represent an hour and a half of data gathered during the evening peak, showing the manner in which Red Line transfer passengers arrive on the Green Line Platform. Arrival time on the platform is defined as the moment that either a Southbound Red Line passenger steps onto the Green Line platform from the South Stairs, or the moment a Northbound Red Line passengers walks past the opening of the South Stairs. Thus the first passenger up the stairs is recorded as arriving at time zero, but in actuality the transfer has been in progress for possibly 20 or 45 seconds already, the minimum time necessary to complete the transfer from the SB or the NB Red Lines.

Figures 4-3 and 4-4 confirm our initial assumption that cumulatively, transfers arrive in a manner closely approximating a uniform arrival pattern. It is conjectured that a uniform arrival pattern develops because all transfer passengers disembark the Red Line train at essentially the same time. The transfer movement to the Green Line level is not a “free-flowing” process in that it is limited in many ways by the station layout at Park Street and the transfer passengers themselves. The transfer process is limited by the capacity of the stairwells and the Red Line platforms to accommodate large numbers of transfer passengers, the level of crowding in the stairwells, as well as the physical abilities of the transferring passengers to walk quickly and their general familiarity with the transfer routine.

Figure 4-3: Cumulative Arrival Pattern from Red Line NB to Green Line WB Platform

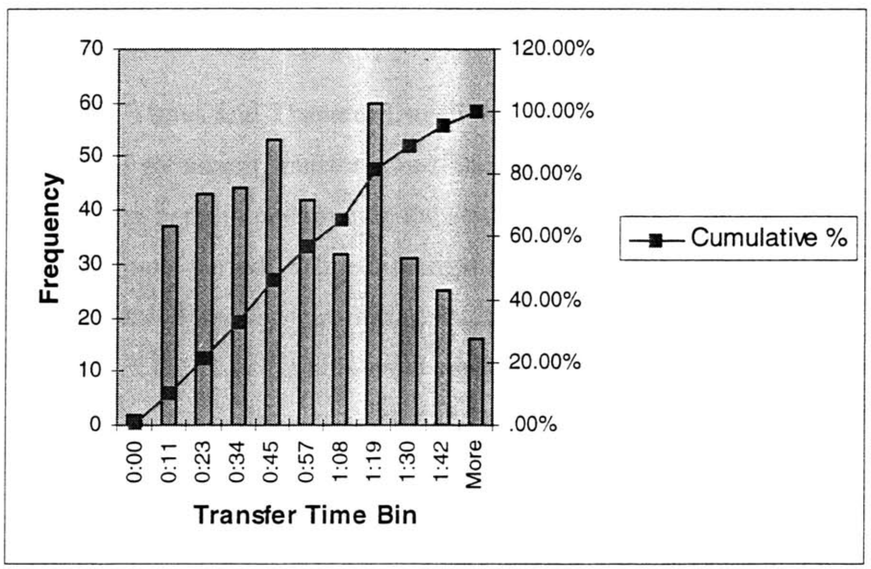
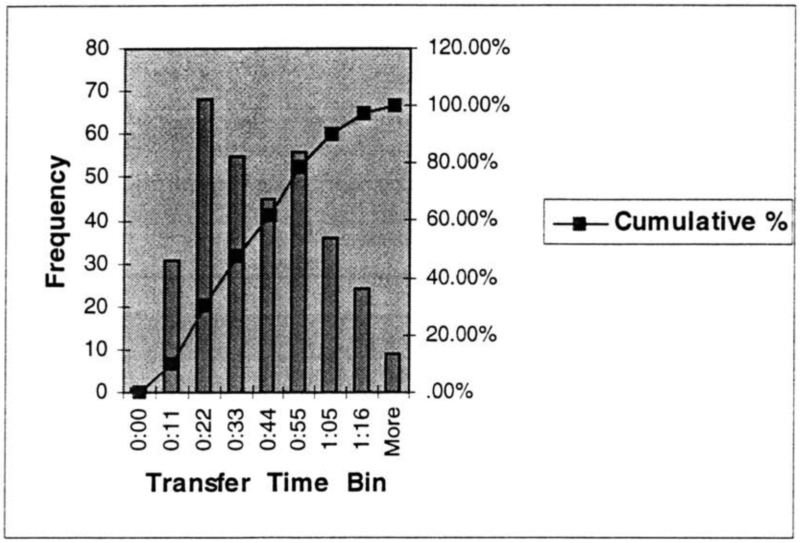


Figure 4-4: Cumulative Arrival Pattern from Red Line SB to Green Line WB Platform



- **Minimum Transfer Times and Transfer Duration**

The assumptions for the minimum transfer times and the transferring duration period in the analytical model, both key parts in determining the suitability of a hold, are based entirely upon data collected for a 30-minute period. While investigating the manner in which transfers arrive at Park Street, we also observed heavier transferring loads to the Green Line, and greater numbers of arriving Red Line trains than was first observed when the data was collected for the analytical model. Thus, Figures 4-3 and 4-4 allow us to (slightly) revise our initial transfer assumptions.

Figures 4-3 and 4-4 show that at least 95% of all passengers arrive within a transferring period of 1:45 and 1:15, which is above the minimum transfer times to the Green Line level from the Red Line NB and SB respectively. The analytical model assumes transfers from the Southbound Red Line take 1:25 to arrive, while those from the Northbound Red Line are assumed to take only 1:00 to arrive. With a larger data set collected during an evening peak period, we assume that the new observations on transferring duration periods are as given in Table 4-6, with the minimum transfer times assumed to remain the same.

Table 4-6: New Approximate Transfer Times and Durations for Simulation Model

Originating Platform	Destination Platform	Stairwell	Minimum Transfer Time(in minutes)	Duration of Transfer (in minutes)
Red Line SB	Green Line WB	South Stairs	0:20	1:35
Red Line NB	Green Line WB	North Stairs	0:45	2:30

4.2.7 Brief Summary of Simulation Model Assumptions

Table 4-7 recapitulates the simulation model assumptions that are different from those in the analytical model.

Table 4-7: Summary of Assumptions for Simulation Model

Holding Threshold Value		
	Holding Decision	A hold is plausible if it has a net benefit exceeding 100 passenger-minutes saved.
Preceding Headways and Passenger Arrivals		
1)	**Preceding Headways**	Preceding headways entering Green or Red Line station are calculated from AVI and OCS data.
2)	**Passenger Arrivals**	Passenger arrivals are assumed to be Poisson distributed with mean μ and variation σ^2, both equal to the previous headway multiplied by the historical passenger arrival rates from CTPS data.
Arrival Time Estimation		
	Approximate Arrival Times into Park Street	A) The travel time from the K04 AVI detector just outside of Park Street to The appropriate berthing location for Green Line trains are as follows: 1. B-Line and C–Line Trains– 45 seconds 2. D-Line and E-Line Trains – 55 seconds B) Green and Red Line arrival times are predicted by run time models summarized in Appendix 2.
Dwell Time		
	Dwell Time	Based on Lin & Wilson models for one and two-car Green Line trains.
Waiting Time Valuation		
	Waiting Time Valuation	A) Passengers perceive out-of-vehicle time differently from in-vehicle time. B) Simulation experiments based on α values of 1.25 and 1.50.
Transfer Assumptions		
1)	**Transferring Percentage from Red Line**	Transfers are modeled as a binomial process with each Red Line passenger having a probability of transferring, p, modeled upon the historical percentage of Red Line passengers transferring to Green Line.
2)	**Transfer Rates to Green Line Platform**	Transfers are assumed to arrive at a constant rate throughout the duration of the transferring period.
3)	**Minimum Transfer Times and the Duration of the Transferring Period**	Transfer times and durations are slightly different from the analytical model and follow the empirical transfer times found in Table 4-3.

4.3 Simulation Model Structure

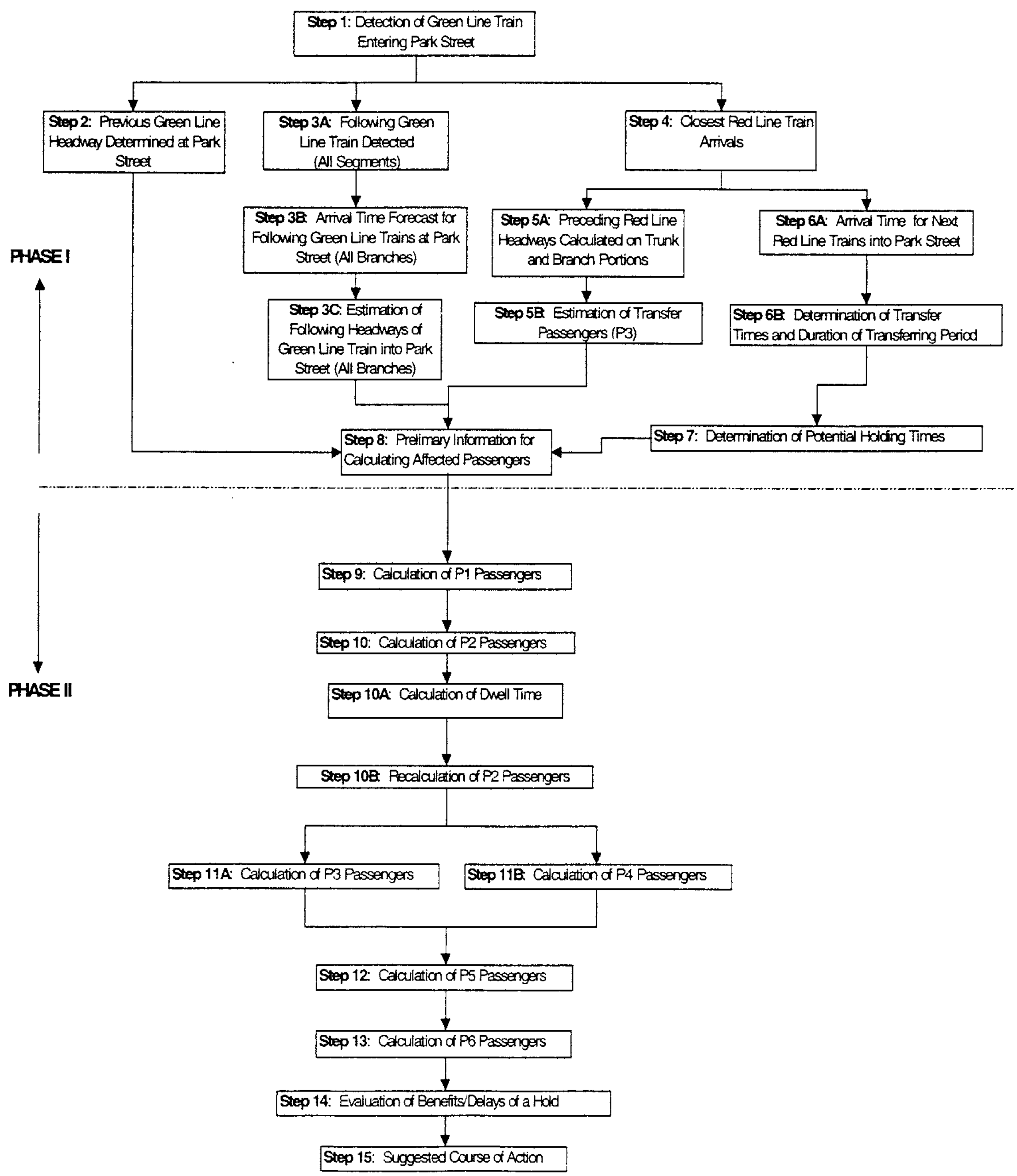
The general structure of the simulation model is similar to that of the analytical model as described in Section 3.3 and in Appendix A. However, the simulation model has several differences from the analytical model as noted below.

4.3.1 Simulation Model Framework

The holding evaluation process for Green Line trains in the simulation model is essentially the same as for the analytical model. The framework is basically unchanged, except for two notable additions (Steps 10A and 10B covered later) which calculate the dwell time and recalculate P2 passengers.

In this section, only the changes from the analytical model to the simulation model are discussed. Figure 4-5 shows the structure of the simulation model.

Figure 4-5: Simulation Model Framework



- *Step 3B: Arrival Time Forecast for Following Green Line Trains into Park Street* -Without perfect prediction capabilities, expected train arrival times are forecasted from run time models.

- *Step 4C: Closest Red Line Train Arrivals* – Incoming Red Line trains are identified from the OCS arrival data, not the scheduled arrivals.

- *Step 6A: Arrival Time for Next Red Line Trains into Park Street* – The expected arrival time of Red Line trains are predicted by run time models.

- *Step 10: Calculation of P2 Passengers* – P2 passengers are now calculated in two stages, Stage A and Stage B. Stage A P2 passengers arrive during the previous headway. Stage B P2 passengers arrive during the dwell time (Steps 10A and 10B).

- *Step 10A: Calculation of Dwell Time* – The simulation model utilizes the Lin & Wilson findings which bases the dwell time on the number of arriving standees, the number of alighters and boarders at Park Street, and the number of departing standees.

- *Step 10B: Recalculation of P2 Passengers* – P2 passengers are given an additional amount of time to board, equivalent to the duration of the dwell time estimated in Step 10A. The cumulative number of P2 passengers is the sum of P2 passengers estimated in Step 10 (Stage A boarders) and those arriving during the dwell time from Step 10A (Stage B boarders).

4.3.2 New Assumptions

Many of the assumptions in the analytical model have been changed in the simulation model as noted in Section 4.2 to better approximate the actual operating conditions. For instance we have attempted to better portray the actual boarding process at Park Street and on the Green Line by modeling arrivals as a Poisson process and transfers as a binomial process. Furthermore, preceding headways are now calculated from the AVI arrival data at a particular detector. Previously we had assumed preceding headways on the Green Line were the same as the headway of the train entering Park Street. Thus we gain a much better idea of the accumulation time during which upstream passengers and Park Street passengers arrive on the Green Line platform. The inclusion of added realism to approximate the actual operating conditions at Park Street makes the simulation model more valuable to as a tool to assess transfer coordination.

4.3.3 Evaluation Process

Another difference between the analytical and the simulation models is the evaluation process for potential holding candidates. The evaluation process for the simulation model has two distinct phases.

- **Phase A – Selection of Train for Potential Holding**

  The simulation model will first choose a train for potential holding based upon the expected passenger benefits that will result from the hold. The expected passenger benefits are calculated from the expected arrival time of the Red and Green Line trains into Park Street based upon the run time models noted previously, using preceding headway data from the OCS or AVI systems. Furthermore, the expected number of impacted passengers is estimated from the expected or mean arrival and transfer rates from the CTPS data. Therefore any hold decision is based on its expected benefits exceeding the minimum holding threshold. Phase A of the simulation model is similar in structure to the analytical model.

- **Phase B – Evaluation of Potential Hold**

  Phase B analyzes the trains that were chosen for holding based on the expected passenger benefits (in Phase I), and determines what actually happened and the resulting actual passenger benefit. The actual benefits from a hold are calculated based upon the actual, rather than the expected arrival times of Red and Green Line trains into Park Street. The actual arrival times are based upon OCS and AVI arrival data not the derived run time models. The actual number of impacted passengers is based on the mean arrival rates from the CTPS data, however these are now modeled as Poisson arrivals to better approximate actual boarding conditions. The total number of transfer passengers from the Red Line to the Green Line Westbound are also based upon the mean arrival rates from the CTPS data, however transferring is modeled as a binomial process, again to better approximate actual conditions. The model is run ten times to simulate stochasticity and randomness in passenger arrivals and represent a realistic range of conditions.

The major difference between the analytical model and the simulation model framework is that the analytical model essentially runs through the evaluation process once and identifies trains that are feasible to be held based on the expected benefits. The simulation model takes the process one step further and evaluates the actual benefits for those trains that are held in Phase A under the actual operating conditions with randomness and stochasticity included to simulate daily activity. There may be cases when the expected benefit of a train is less than the minimum holding threshold, yet its actual benefit may surpass the minimum threshold. Phase B of the simulation however, only analyzes the actual benefit for those trains that are deemed feasible for a hold, and thus surpass the minimum benefit, in Phase A. In summary, Phase A selects trains for holding based on expected benefits. Phase B evaluates these trains and determines the actual benefit resulting from the hold.

- **Continuous Evaluation of Trains**

The last major difference between the analytical and the simulation model is the analysis method for Green Line trains once they have passed the K04 AVI detector to trigger the evaluation process. The analytical model is constrained in that it is only able to evaluate trains in discrete hourly blocks. It is conjectured in Section 3.4.4 that leftover passengers may have been underestimated since the model does not carry these passengers over to the next incoming Green Line train at the beginning of a new hourly block. It is assumed that there are no leftover passengers for this initial train. In other words, even if there are leftover passengers from a train at 8:59AM, the analytical model assumes that there are no leftover passengers for the 9:02AM train since they are not carried over. However, the simulation model is structured so as to analyze trains on a continuous basis throughout the day. Thus the simulation model will have a more accurate estimate of the number of leftover passengers that are carried over to become potential passengers on the next incoming Green Line train.

4.4 Simulation Application

The simulation model is now applied to assess the benefits of a transfer coordination system at Park Street.

4.4.1 Simulation Model Data

The following data is used in the simulation model for evaluation of transfer coordination at Park Street.

- *Green Line Arrival Data* – Green Line train arrival data is based upon AVI data collected for the ten weekdays between April 3rd and April 14th, 2000. The data consists of detection location, time, car number, and route throughout the entire Green Line AVI system consisting of thirty-six detectors ranging from the northern terminus at Lechmere to the western termini for the four branch lines. We are only concerned however with trains detected in the Westbound direction at the Lechmere AVI detector (K01) to Park Street (K04), and in the Eastbound direction from Kenmore (K14), through Government Center (K05).

- *Red Line Arrival Data* – Instead of the scheduled Red Line arrival data used in the analytical model, the simulation model utilizes Red Line block occupancy data from the OCS for the same period as the Green Line data, from April 3rd to the 14th. Data consists solely of train number and block occupancy time. We are only interested in trains occupying blocks within a five-minute running time of Park Street.

- *Green Line and Red Line Passenger Arrival Rates and Transferring Proportions* – All the rates are taken from the 1997 CTPS counts, similar to the analytical model. Likewise, we assume that these rates are an accurate depiction of the current situation in April 2000.

4.4.2 Initial Hypotheses

Several hypotheses are made about the transfer coordination system which will be tested in the simulation model using the data described above:

1) From the analytical model, it is clear that the time periods where transfer coordination is expected to produce the largest passenger time savings are during the base period in the mid-afternoon as well as during the early-evening period after the evening rush has concluded. The combination of lower train frequencies and a sufficiently large enough passenger demand results in these time periods yielding the largest benefits.

2) It is hypothesized that with a more accurate estimation of dwell time at Park Street in the peak periods, holds will become even less likely in the peaks given the probability of longer dwell times than the thirty seconds assumed in the analytical model.

3) It is expected that altering the value of α, the ratio of out-of-vehicle to in-vehicle waiting time, will have significant effects upon the number of recommended holds as well as the total benefits throughout the day. Lowering the value of α would reduce the number of holds and the associated benefits.

4) It is expected that fewer holds and smaller total passenger benefits will result for the simulation experiments compared to the analytical model because we now lack perfect prediction capabilities for train arrival times. Instead we base train arrival time on run time models which have varying degrees of inherent imperfection in their prediction capabilities. Thus, it is likely that the overall benefits produced by holding in the analytical model are over-estimated given that the running time models used to predict train arrival times are imperfect.

   Furthermore, we would expect the number of holds and total passenger benefits to decrease in the simulation due to the method of train analysis in the simulation and analytical models. The analytical model analyzes trains in discrete hourly blocks, whereas the simulation analyzes trains on a continuous basis throughout the day. The result of this difference is that leftover passengers in the analytical model do not "carry-over" into the next hour of analysis. For instance if a Green Line train departs Park Street at 8:55AM, there are 100 leftover passengers left on the platform. The next train arrives at 9:01AM. The analytical model essentially assumes that there are no leftover passengers for the 9:01AM train. The simulation model however is able to analyze trains on a continuous basis throughout the day and account for the 100 leftover passengers for the 9:01AM train. With more leftover passengers eligible to board, but also eligible to be delayed by a hold, it is less likely that the overall net passenger benefit will surpass the minimum holding threshold. Furthermore with more leftover passengers boarding the next train, it is more likely that there will be less capacity for P3 and P4 passengers, who benefit from a hold, to board.

4.4.3 Simulation Model Results for Base Conditions

The simulation model was run with arrival data from eight of the ten weekdays between April 3rd and the 14th; two days (Wednesday April 12th and Thursday April 13th) are omitted from the data set because of missing AVI data. Trains are evaluated on a continuous basis throughout the day, between 7:00AM to 11:00PM for which ridership data exists. It is assumed that the eight days of data accurately represent typical operating conditions on the MBTA Red and Green Lines. A minimum holding threshold of 100 passenger-minutes as well as a perceived waiting time ratio of $\alpha = 1.5$ represent the base conditions for the simulation model.

Table 4-8 shows the averaged results of all simulation runs, as well as the largest/smallest benefit, and longest/shortest hold times for the eight days analyzed under the base conditions. The simulation results in Table 4-8 may be interpreted as the actual number of trains held, benefits accrued, and impacted passengers produced by holding trains based upon the expected benefits for any given day. For instance there are an average of 2.3 holds during the 1:00-2:00PM hour. Since these results are averages over eight days, individual days may have more holds, while other days may have fewer holds. The result may be interpreted however as over all eight days during the 1:00-2:00PM hour, on average between 2-3 holds occur.

Combining the eight days into average results as seen in Table 4-8 eliminates outlying hold results and extreme daily variation in terms of the number of holds, passenger benefits, etc. depending upon the operating conditions on that particular day. Table 4-8 gives us an idea of the

Table 4-8: Green Line WB Benefit and Hold Summary for Base Conditions: Minimum Passenger Benefit = 100 pax-mins, a = 1.50

Time Period	Trains Held	Green Ln. Trains	HOLD DURATION(MIN:SEC) Avg. Hold Duration	Longest Hold	Shortest Hold	Pax Benefits per Held Train Average Benefit	Largest Benefit	Smallest Benefit	Hourly Total Benefit
7:00-8:00AM	0.6	38	1:11	2:03	0:34	163.0	392	5	101.8
8:00-9:00AM	0.0	33	0:00	0:00	0:00	0.0	0	0	0.0
9:00-10:00AM	0.1	48	2:06	2:17	1:44	543.2	648	429	67.9
10:00-11:00AM	1.4	31	2:01	3:44	0:15	232.4	874	4	319.5
11:00-12:00PM	1.1	30	2:37	4:57	0:24	420.3	1091	20	472.9
12:00-1:00PM	2.4	28	2:36	5:47	0:30	399.4	1409	-224	948.6
1:00-2:00PM	2.3	27	2:11	4:37	0:54	277.2	796	3	623.7
2:00-3:00PM	2.6	27	2:29	4:17	0:07	433.6	1472	-209	1138.1
3:00-4:00PM	1.8	33	2:10	3:56	0:23	442.2	1332	2	773.8
4:00-5:00PM	1.5	40	1:29	4:11	0:08	243.7	1775	-154	365.5
5:00-6:00PM	0.3	39	0:25	0:42	0:06	77.7	229	15	19.4
6:00-7:00PM	0.0	42	0:00	0:00	0:00	0.0	0	0	0.0
7:00-8:00PM	0.4	31	1:29	2:36	0:35	317.8	929	-68	119.2
8:00-9:00PM	1.1	27	2:45	4:27	0:54	548.2	1347	86	616.7
9:00-10:00PM	0.8	22	3:21	4:35	2:03	332.4	909	3	249.3
10:00-11:00PM	1.9	25	2:39	4:50	0:42	184.2	550	7	345.3
Average Per Held Train			2:18			340.0			
TOTALS:	18.1	521							6161.7

Time Period	Delayed/Time Savings Breakdown — Total Passengers Savings 0-2 mins	2-4 mins	4-6 mins	6 + mins	Total Pax	Total Passengers Delayed 0-2 mins	2-4 mins	4-6 mins	6 + mins	Total Pax	Pax-Bens %
7:00-8:00AM	9.9	17.4	3.6	2.9	33.6	63.7	2.5	0.0	0.0	66.2	51%
8:00-9:00AM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0%
9:00-10:00AM	0.0	6.6	3.0	2.8	12.3	1.1	2.3	0.0	0.0	3.5	356%
10:00-11:00AM	4.7	37.3	37.1	7.2	86.2	46.5	57.2	0.0	0.0	103.7	83%
11:00-12:00PM	1.8	39.6	36.4	16.6	94.4	28.1	52.9	10.1	0.0	91.1	104%
12:00-1:00PM	2.7	72.4	54.2	67.1	196.4	68.1	203.5	10.7	0.0	282.3	70%
1:00-2:00PM	12.1	53.4	65.4	32.2	163.0	129.8	101.4	9.7	0.0	240.8	68%
2:00-3:00PM	2.1	61.8	84.0	84.1	232.0	113.8	210.4	19.7	0.0	343.9	67%
3:00-4:00PM	14.0	60.8	72.4	39.5	186.7	122.8	142.1	0.0	0.0	264.9	70%
4:00-5:00PM	6.6	50.8	10.0	48.6	115.9	87.3	105.4	16.8	0.0	209.5	55%
5:00-6:00PM	2.1	1.9	0.0	2.3	6.3	39.2	0.0	0.0	0.0	39.2	16%
6:00-7:00PM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0%
7:00-8:00PM	0.0	1.4	4.8	8.9	15.1	41.4	12.1	0.0	0.0	53.4	28%
8:00-9:00PM	2.5	23.1	17.1	38.3	81.0	45.5	40.5	20.4	0.0	106.4	76%
9:00-10:00PM	0.0	0.0	16.4	20.1	36.5	0.0	43.2	10.1	0.0	53.3	68%
10:00-11:00PM	3.6	3.3	8.9	45.1	60.9	33.1	90.3	19.9	0.0	143.4	42%
Average Per Held Train	3.4	23.7	22.8	22.9	72.8	45.3	58.7	6.5	0.0	110.4	66%
TOTALS:					1320.3					2001.4	

overall average performance of transfer coordination on an average day under normal operating conditions.

- **Total Net Passenger Benefits**

Under the base conditions, the simulation model produces total net benefits of around 6,200 passenger-minutes saved. The largest hourly benefits occur between 12:00-4:00PM where total benefits range from 600-1,150 passenger-minutes saved. The 11:00-12:00AM and 8:00-9:00PM periods also produce significant passenger benefits ranging from 450-625 passenger-minutes saved. As expected, the smallest benefits are produced during the peak periods when holds are rare.

- **Average Passenger Benefits Per Held Train**

Throughout the day, a hold is expected to produce average net benefits between 300-400 passenger-minutes. The largest average benefits per held train, for time periods with at least one expected hold, occur between 10:00AM-5:00PM and 8:00-9:00PM, with holds on average producing benefits between 200 and 600 passenger-minutes saved per held train.

For individual trains, the largest benefits per held train again occur between 11:00AM-5:00PM and 8:00-9:00PM with benefits surpassing 1,000 passenger minutes for most of these hours. It is particularly interesting to observe smallest benefit figures. During four hours there is at least one instance of negative benefits, which indicates that the hold actually produced more overall delay to impacted passengers than time savings. A negative overall benefit does not indicate that there are no passengers benefiting from a hold. On the contrary, transfer passengers will still save time from a holding decision. The negative value means that a hold results in a total net delay to all passengers. This issue will be discussed further in Section 4.5.

- **Distribution of Passenger Impacts**

Overall, for every two passengers benefiting from a hold, there are three other passengers who are delayed by a hold with an overall passenger-benefit ratio of 66%. The great majority of passengers benefiting from holding, close to 95%, save at least two minutes of equivalent in-vehicle waiting time with roughly an equal proportion of passengers save 2-4, 4-6 and 6 or more minutes from a hold. Overall the expected time saved per passenger benefiting is about 5 minutes. Different times of the day however may produce varying degrees of expected time savings due to the particular train arrival frequencies for a given time period.

The great majority of delayed passengers are negatively impacted by less than 4 minutes with nearly 45% being delayed by less than 2 minutes on average. Overall the expected time increase for passengers being delayed is about 2 minutes. This result should be intuitive as the average holding time for trains throughout the day was also about 2 minutes.

Overall the largest number of benefiting passengers per hour are produced in the noon-5PM period. During this time period, the number of passengers benefiting from holding is between 115 and 230 passengers/hour with a passenger-benefit ratio of around 70% throughout the base period.

- **Holding Frequency**

Throughout the day, we might expect to hold less than 5% of Green Line trains: out of 521 Green Line trains entering Park Street, only about 18 were held. During noon-3PM the most active holding period fewer than 10% of all trains are held, between 2 and 3 per hour. There are virtually no holds during the peak periods.

- **Holding Times**

Average hold periods, are typically between 2:00-3:00 minutes. It is very rare to hold a train as much as five minutes. The shortest holding time observed for twelve of the time periods is under 1 minute in duration, with seven of these time periods having a hold of under thirty seconds.

4.5 Discussion of Simulation Model Results

This section discusses the results of the simulation model and their ramifications upon the prospects for an effective transfer coordination system at Park Street.

4.5.1 Comparison of Results from Analytical and from Simulation Model

A comparison of the results for the analytical and the simulation models under the same base conditions, $\alpha = 1.50$, and a minimum benefit criterion of 100 passenger-minutes saved, exhibit several similarities (Table 3-9 and Table 4-8 respectively). In the analytical model, two periods are identified as most likely to produce substantial benefits from transfer coordination, a base, mid-afternoon period and an evening period. Similarly, the results for the simulation show that a mid-afternoon period between 12:00-4:00PM and an evening period from 8:00-10:00PM produce significant passenger benefits.

While the analytical model results show that under the base conditions, the evening period produces the most significant benefits over the entire day, the results for the simulation model show that the most advantageous time period for transfer coordination is during the mid-afternoon period between 12:00-4:00PM. The simulation model produced between 2 and 3 holds during this time with average passenger benefits per held train exceeding 400 passenger-minutes saved, and total hourly benefits exceeding 750 passenger-minutes saved in three of the four hours. In addition over the entire day, this base period produced the largest number of passengers saving time from a hold, totaling over 160 passengers in each hour. For three out of the four hours, more than 60% of the benefiting passengers save at least 4 minutes. Lastly, the overall passenger-benefit ratio during this four-hour period is nearly constant at 70%.

Benefits during the evening period from 8:00-10:00PM are less robust but still significant nonetheless. On average between 1-2 trains are held, with average passenger benefit per held train between 200-600 passenger-minutes saved. Total hourly benefits are very similar to the average benefit per held train, ranging from 250-650 passenger minutes. In addition, the total number of passengers saving time during this period ranged from about 40-80 per hour, resulting in passenger benefit ratios ranging from 45-75%.

Lastly, the results for both the analytical and the simulation model suggest that few if any trains should be held in the AM and the PM peak periods. The combination of high service frequencies into Park Street, longer dwell times calculated from the enhanced dwell time models and higher passenger demand limits the potential for Green Line trains to be held during the peak periods. First, short following headways prevent trains from holding for extended periods of time in the peak. Second, high passenger demand along with the longer dwell time results in greater numbers of passengers boarding Green Line trains and subsequently being delayed either as through (P1) passengers or normal boarders at Park Street (P2) and beyond (P5). Additionally the more passengers boarding the train, the more likely that a train is filled to capacity, which could prohibit P3 and P4 passengers that could save time from a hold from boarding.

Several important differences exist between the results of the analytical and the simulation model, most notably the frequency of holding and the overall net benefit produced. In the analytical model, we would expect to hold 6% of the total trains in the day, whereas in the simulation model we would expect to hold only 3% of the total trains, amounting to 14 fewer holds per day in the simulation model. With fewer total holds, the total benefits over the entire day are 45% lower in the simulation model than the analytical model predicted.

It is likely that the overall decreases in holding frequency and total benefits in the simulation model compared to the analytical model are due to four reasons:

1) In the analytical model, it is assumed that we possess perfect arrival prediction capabilities for both Red and Green Line trains. In the simulation model we predict the expected arrival time of trains into Park Street using run time models based on time of day and preceding headway. Run time models introduce error and variance into our estimations which are absent in the analytical model. The estimated arrival time is a key factor in determining how long a hold may last, as well as determining how passengers benefit from holding. Thus expected train arrival times which may be significantly less precise than those in the analytical model, and may result in shorter time periods for holding, thereby reducing the amount of time savings for P3, P4, or P6 passengers, resulting in benefits failing to meet the minimum benefit criterion.

2) The analytical model assumed that the dwell time under any condition at Park Street was thirty seconds. During peak periods, thirty seconds may be an inadequate estimate of the dwell time. Therefore, the simulation modeled utilized the Lin & Wilson models to more accurately model dwell time for one and two-car trains, by accounting for the effects of passengers crowding and congestion. Dwell time estimation is important because the holding period only begins after the conclusion of the initial dwell time. It is likely that longer estimates of the dwell time (greater than the assumed 30 seconds in the analytical model) will effectively reduce the time that a train can be held for, consequently reducing the number of passengers that benefit from a hold. With fewer passengers benefiting, it is possible that the hold will produce benefits below the minimum holding threshold, thus making it infeasible to hold.

3) In the analytical model, passenger demand is assumed to be constant over a short period of time. Furthermore, the passenger accumulation time in the analytical model at upstream stations is assumed to be equal to the headway of the train as it enters Park Street on the Green Lines. On the Red Line, preceding headways were deterministic and based on scheduled arrivals. Under actual conditions, passenger demand at stations can

vary significantly from one minute to the next. In addition, large differences in the inter-arrival headways at upstream stations compared to the headway entering Park Street may arise. The simulation model attempts to more accurately account for actual passenger behavior by modeling normal arrivals as a Poisson process and transfer arrivals as a Binomial process. The simulation further relaxes the assumption that preceding headways are equal to those entering Park Street, instead basing them on the actual OCS and AVI arrival data. With more accurate estimations of the number of impacted passengers, it is likely that the total number of benefiting passengers may be overestimated in the analytical model thus resulting in fewer holds and fewer associated benefits in the simulation model.

4) Lastly, the analytical and the simulation models assess holding differently. The analytical model analyzed trains in discrete hourly blocks. In the simulation model, trains are analyzed on a continuous basis throughout the day. So leftover passengers at the conclusion of an hour block in the analytical model are not "carried-over" to the next train if it arrives during the next hourly block. Thus the potential passenger pool eligible to board the next train does not include any leftover passengers. The simulation model however "carries-over" these leftover passenger to trains arriving in the subsequent hour block. Thus with more leftover passengers waiting on the platform at Park Street, more passengers will be delayed by a hold, as well as possibly less capacity being left on Green Line trains to accommodate passengers saving time from a hold such as P3 and P4 passengers to board. Thus the method of analysis for the analytical model may have over-estimated the benefits from holding.

The four major differences listed between the analytical model and the simulation model make holding less frequent and consequently reduce the total benefit from holding. The differences noted however make the simulation model more realistic and allows it to more completely capture actual passenger behavior and train operating conditions. Hence, the results of the simulation are much more meaningful and applicable to transfer coordination at Park Street than those from the analytical model.

4.5.2 Implications of Results

This section will discuss some of the implications of our findings from Table 4-8.

- **Surface Portion Passengers**

The bulk of the passenger benefits accrue from passengers saving 4 or more minutes from a hold. In most cases, this means that passengers heading to destinations outside of the Central Subway and on the surface portion of the four branch lines experience the greatest time savings from holding. It is likely that such passengers will be the primary benefactors from transfer coordination. This result should be intuitive. The surface portions of a line are served exclusively by one and only train line, thus passengers heading to these destinations would have to wait much longer periods of time to board than passengers heading to Boylston would, which is served by all four branches.

- **Train Holding Times**

Figure 4-5 shows the frequency of train holding times for all eight days, while Figure 4-6 shows the cumulative passenger benefit from different train holding times.

From Figure 4-5, it is clear that the great majority of trains are held for less than four minutes. Trains are most frequently held between 2:00 and 2:30 minutes, accounting for more than 20% of all held trains. Trains with very short holds (under 30 seconds) or very long holds (over 4 minutes in duration) account for less than 10% of all held trains.

From Figure 4-6, the majority of the passenger benefits accrue from holds lasting between 1:00-4:00 minutes with the largest cumulative benefits, almost 11,000 passenger-minutes saved, accruing for trains held between 2:00-2:30 minutes saved. Trains held for less than one minute, or longer than 4:30 minutes produce the smallest overall benefit.

The results from Figure 4-5 show that trains are most frequently held between 2:00-2:30 minutes, which agrees with the average holding time calculated in Table 4-8. Furthermore Figure 4-6 shows that these trains also produce the most significant passenger benefits over the day. This

Figure 4-5: Train Holding Time Frequency

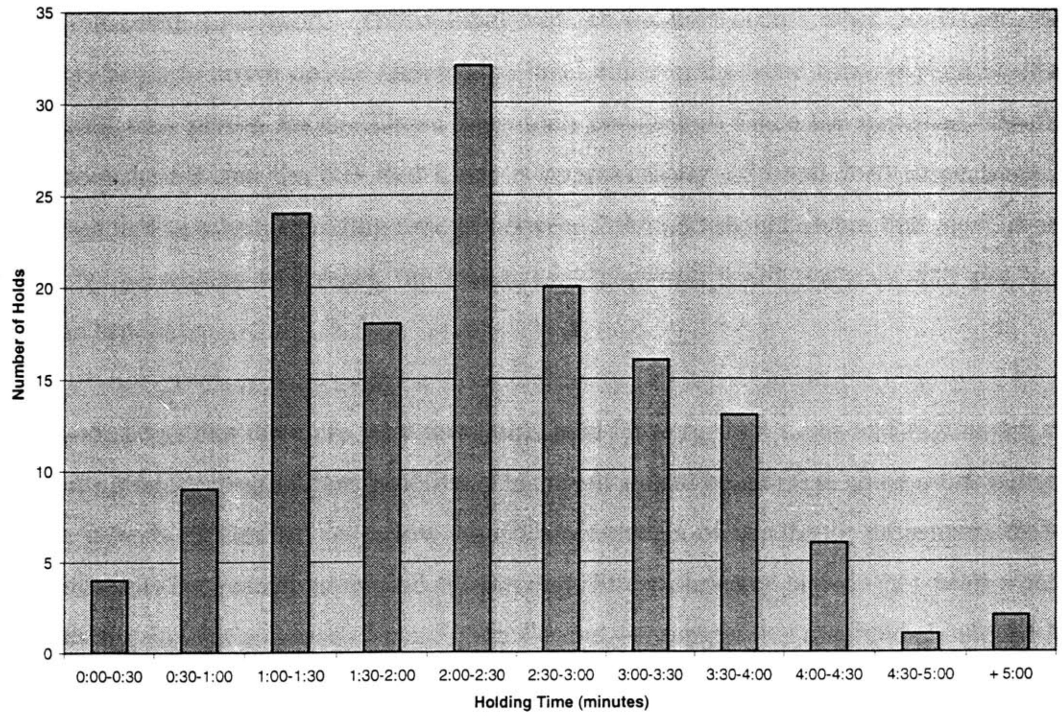
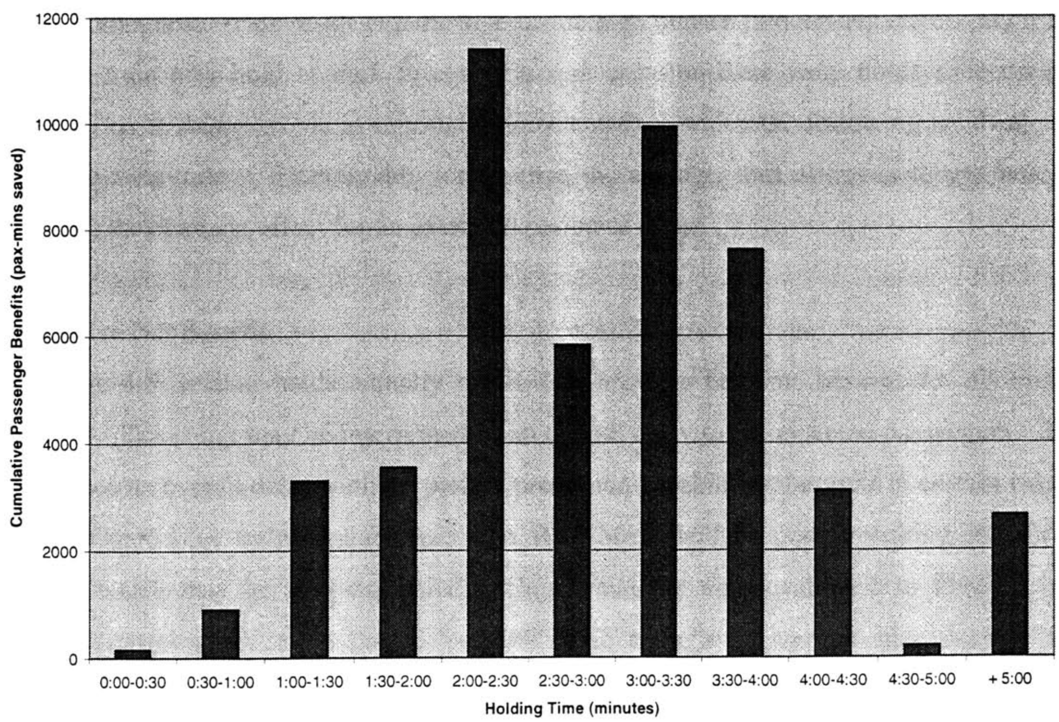


Figure 4-6: Cumulative Passenger Benefit vs. Train Holding Time



result seems logical because in order to maximize the benefits from transfer coordination, we would want to allow the maximum number of Red Line transfer passengers to successfully board the holding Green Line train. The optimal transfer situation occurs when Red Line transfer passengers begin to arrive on the Green Line level either at the same time or slightly after the initial dwell time period for the Green Line train concludes. Since the expected transferring period from the SB and the NB Red Lines is approximately 1:35 and 2:30 respectively, it is conjectured that an average holding time of between 2:00-2:30 should assure that most, if not all, the transfer passengers will reach the Green Line platform, board the train and produce the maximum benefit.

Figures 4-5 shows that there are very few trains held for very short times and Figure 4-6 shows these trains produce insignificant benefits. This result should be intuitive since trains being held for short periods of time do not allow significant numbers of benefiting passengers to board. These situations are readily identified by the Park Street inspector and do not need a transfer coordination system in any case. Thus Figure 4-5 and 4-6 suggest that any hold should last for at least one minute to produce significant benefits.

Figure 4-5 also shows that most trains are held for less than four minutes. This result indicates that the great majority of delayed passengers have their trip times lengthened by at most four minutes from a hold. This result is indicative of the high service frequencies effectively limiting the time a train may hold at Park Street. On rare occasion there were holds exceeding four minutes. This is only possible in unusual circumstances in which the following headway of the next Green Line train is considerably longer than the average, thus allowing longer holds and forestalling the blocking effect for an extended period of time.

- **Negative Net Benefit**

From Table 4-8, several holds actually resulted in negative net time savings for all impacted passengers. This result may be interpreted as an overall delay to all impacted passengers. A hold may produce an overall delay without perfect prediction capabilities, because in certain cases the predicted Green Line train arrival times into Park Street will be poor, resulting in following headways which may be over-estimated. Thus while the train evaluated in Phase I of the simulation model produced expected benefits large enough to warrant holding, the actual following headways for trains to the three track segments might have been significantly shorter than anticipated, thus resulting in an overall deleterious impact.

It is also possible "actual" passenger arrival rates for benefiting passengers were much lower than the expected, mean arrival rates. Thus they might have been over-estimated in Phase A. Similarly, passenger arrival rates for disbenefiting passengers may have exceeded the expected arrival rates. Thus the number of passengers delayed by a hold might have been under-estimated in Phase A.

- **Most Advantageous Time Periods for Transfer Coordination**

Lastly as found in the analytical model, the scenario under which transfer coordination produces the most significant benefits occurs when a Green Line train enters Park Street with a short preceding headway, and is followed by a long headway. At the same time, one or more Red Line trains arrivals coincide with the arrival of a Green Line train. For instance between the 4:00-5:00PM hour, a single hold produced over 1,500 passenger minutes saved. This particular train entered Park Street only 50 seconds after the last train had entered. Thus the number of P2 passengers is minimized. The following train entered Park Street nearly 6 minutes later. The long following headway allowed three Red Line train arrivals during the hold period. The long following headway also translated into significant time savings for all P3, P4 or P6 passengers, regardless of final destination.

4.5.3 Daily Variation

Table 4-8 summarized the average results over the eight days, however it does not give any information about the holding results for individual days. It is likely that the transfer coordination system will produce different results and benefits for different days. Tables 4-9 and 4-10 show the results for the days with the most (Monday April 10th) and the least (Tuesday April 4th) holds.

Tables 4-9 and 4-10 shows that under base conditions, $\alpha = 1.50$ and a minimum benefit criterion of 100 passenger-minutes, the holding results do indeed vary over days. For instance on April 10th, 21 trains are held compared to only 14 on the 4th. Meanwhile, total benefits produced on the 10th from a hold amount to nearly 6,200 passenger-minutes saved, while on the 4th benefits are close to 5,000 passenger-minutes saved. Finally, passenger-benefit ratios for each day are different with the 10th producing a ratio close to 60% while the 4th results in a ratio of about 65%.

Although both days had similar total train arrivals over the entire day, 521 trains in both cases, it is clear that operating conditions and passenger demand particular to a given day result in different holding outcomes. For instance hourly train arrivals vary in nearly all hours for the two

Table 4-9: Day with Most Holds: Monday April 10, 2000

Time Period	Trains Held	Green Ln. Trains	HOLD DURATION(MIN:SEC) Avg. Hold Duration	Longest Hold	Shortest Hold	Pax Benefits per Held Train Average Benefit	Largest Benefit	Smallest Benefit	Hourly Total Benefit
7:00-8:00AM	0	38	0:00	0:00	0:00	0.0	0	0	0.0
8:00-9:00AM	0	33	0:00	0:00	0:00	0.0	0	0	0.0
9:00-10:00AM	0	48	0:00	0:00	0:00	0.0	0	0	0.0
10:00-11:00AM	1	31	1:13	1:15	1:10	101.3	145	74	101.3
11:00-12:00PM	1	30	1:29	2:31	1:12	182.5	356	92	182.5
12:00-1:00PM	2	28	4:32	5:47	3:16	807.2	1409	368	1614.3
1:00-2:00PM	1	27	2:40	2:50	2:21	342.5	480	115	342.5
2:00-3:00PM	5	27	2:00	3:47	0:13	275.4	772	2	1376.9
3:00-4:00PM	2	33	1:05	1:17	0:52	98.8	175	13	197.6
4:00-5:00PM	3	40	1:32	2:17	0:08	159.8	397	-154	479.5
5:00-6:00PM	0	39	0:00	0:00	0:00	0.0	0	0	0.0
6:00-7:00PM	0	42	0:00	0:00	0:00	0.0	0	0	0.0
7:00-8:00PM	0	31	0:00	0:00	0:00	0.0	0	0	0.0
8:00-9:00PM	1	27	4:12	4:17	4:07	945.3	1347	485	945.3
9:00-10:00PM	0	22	0:00	0:00	0:00	0.0	0	0	0.0
10:00-11:00PM	5	25	1:55	3:12	0:42	188.5	464	9	942.7
Average Per Held Train			2:22			294.4			
TOTALS:	21	521							6182.6

Time Period	Delayed/Time Savings Breakdown — Total Passengers Savings 0-2 mins	2-4 mins	4-6 mins	6 + mins	Total Pax	Total Passengers Delayed 0-2 mins	2-4 mins	4-6 mins	6 + mins	Total Pax	Pax-Bens %
7:00-8:00AM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0%
8:00-9:00AM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0%
9:00-10:00AM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0%
10:00-11:00AM	26.2	0.0	0.0	5.8	32.0	40.2	0.0	0.0	0.0	40.2	80%
11:00-12:00PM	0.0	55.5	0.0	8.9	64.4	87.9	9.3	0.0	0.0	97.2	66%
12:00-1:00PM	0.0	0.0	145.3	77.8	223.1	0.0	33.8	69.6	0.0	103.4	216%
1:00-2:00PM	0.0	75.9	14.0	0.0	89.9	0.0	67.3	0.0	0.0	67.3	134%
2:00-3:00PM	12.7	121.5	132.9	93.5	360.6	334.0	390.7	0.0	0.0	724.7	50%
3:00-4:00PM	36.3	13.7	36.4	15.0	101.4	358.3	0.0	0.0	0.0	358.3	28%
4:00-5:00PM	7.5	120.6	38.5	55.0	221.6	98.1	308.6	0.0	0.0	406.7	54%
5:00-6:00PM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0%
6:00-7:00PM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0%
7:00-8:00PM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0%
8:00-9:00PM	0.0	0.0	50.9	41.0	91.9	0.0	0.0	66.7	0.0	66.7	138%
9:00-10:00PM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0%
10:00-11:00PM	19.0	0.0	15.7	117.5	152.2	81.9	279.0	0.0	0.0	360.9	42%
Average Per Held Train	4.8	18.4	20.7	19.7	63.7	47.6	51.8	6.5	0.0	106.0	60%
TOTALS:					1337.1					2225.4	

Table 4-10: Day with Fewest Holds: Tuesday April 4, 2000

Time Period	Trains Held	Green Ln. Trains	HOLD DURATION(MIN:SEC) Avg. Hold Duration	Longest Hold	Shortest Hold	Pax Benefits per Held Train Average Benefit	Largest Benefit	Smallest Benefit	Hourly Total Benefit
7:00-8:00AM	0	38	0:00	0:00	0:00	0.0	0	0	0.0
8:00-9:00AM	0	33	0:00	0:00	0:00	0.0	0	0	0.0
9:00-10:00AM	0	48	0:00	0:00	0:00	0.0	0	0	0.0
10:00-11:00AM	1	31	3:31	3:44	3:00	520.3	874	307	520.3
11:00-12:00PM	1	30	2:40	2:53	2:01	308.8	407	168	308.8
12:00-1:00PM	2	28	2:33	2:58	1:18	274.5	667	-224	549.0
1:00-2:00PM	2	27	1:16	2:15	0:56	109.0	338	3	218.0
2:00-3:00PM	2	27	1:33	2:16	0:56	139.2	353	5	278.3
3:00-4:00PM	3	33	2:25	3:56	0:23	676.9	1332	32	2030.8
4:00-5:00PM	0	40	0:00	0:00	0:00	0.0	0	0	0.0
5:00-6:00PM	0	39	0:00	0:00	0:00	0.0	0	0	0.0
6:00-7:00PM	0	42	0:00	0:00	0:00	0.0	0	0	0.0
7:00-8:00PM	1	31	0:56	2:32	0:37	146.7	389	41	146.7
8:00-9:00PM	1	27	1:59	2:51	0:59	364.2	661	110	364.2
9:00-10:00PM	0	22	0:00	0:00	0:00	0.0	0	0	0.0
10:00-11:00PM	1	25	2:50	2:56	2:36	338.9	445	151	338.9
Average Per Held Train			2:08			339.6			
TOTALS:	14	521							4755.0

Time Period	Delayed/Time Savings Breakdown: Total Passengers Savings 0-2 mins	2-4 mins	4-6 mins	6 + mins	Total Pax	Total Passengers Delayed 0-2 mins	2-4 mins	4-6 mins	6 + mins	Total Pax	Pax-Bens %
7:00-8:00AM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0%
8:00-9:00AM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0%
9:00-10:00AM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0%
10:00-11:00AM	0.0	0.0	80.6	21.2	101.8	0.0	106.8	0.0	0.0	106.8	95%
11:00-12:00PM	0.0	37.8	27.2	0.0	65.0	0.0	22.7	0.0	0.0	22.7	286%
12:00-1:00PM	0.0	34.1	63.5	34.0	131.6	14.6	226.1	0.0	0.0	240.7	55%
1:00-2:00PM	57.1	23.5	0.0	21.0	101.6	243.8	2.7	0.0	0.0	246.5	41%
2:00-3:00PM	1.1	89.2	6.6	24.1	121.0	218.4	55.4	0.0	0.0	273.8	44%
3:00-4:00PM	63.4	22.9	218.0	118.8	423.1	203.8	180.3	0.0	0.0	384.1	110%
4:00-5:00PM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0%
5:00-6:00PM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0%
6:00-7:00PM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0%
7:00-8:00PM	0.0	8.5	10.7	15.9	35.1	155.7	15.2	0.0	0.0	170.9	21%
8:00-9:00PM	0.0	18.9	2.9	36.8	58.6	43.7	69.4	0.0	0.0	113.1	52%
9:00-10:00PM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0%
10:00-11:00PM	0.8	0.0	29.0	27.6	57.4	0.0	120.1	0.0	0.0	120.1	48%
Average Per Held Train	8.7	16.8	31.3	21.4	78.2	62.9	57.1	0.0	0.0	119.9	65%
TOTALS:					1095.2					1678.7	

days, consequently the arrival sequence of trains and the preceding/following headways of trains may be drastically different from one day to the next. Thus we should expect that benefits and resulting holds produced by transfer coordination on different days should differ to some degree depending on the unique circumstances for that day.

4.5.4 Sensitivity Analysis

Table 4-8 shows the simulation results under base conditions, α = 1.50 and minimum holding threshold of 100 passenger-minutes. The base conditions represent values determined by the transit agency that affects the transfer coordination system. For instance, a perceived waiting time ratio of α = 1.50 could be considered too liberal. A smaller waiting time ratio such as α = 1.25, indicates that the transit agency places more importance upon providing service equity to all passengers, rather than significantly improving transfer reliability at the expense of some other passengers. A smaller value of α should result in fewer overall holds, but goes further in assuring that holds result in genuine passenger benefits for transfer and any other passengers saving time as well as reducing passenger delay. The downside to this approach is that fewer passengers benefit from a hold and the overall transfer reliability of the system may not rise significantly in the opinion of passengers.

Additionally, the minimum benefit criterion may be too high for a transit agency wishing to drastically improve transfer reliability. Lowering the minimum criterion should result in more holds being generated while at the same time increasing the number of passengers benefiting, the total overall benefits and the transfer performance in general. At the same time however the number of passengers being delayed will rise and overall service equity will deteriorate.

Tables 4-11 through 4-13 show the average results of the simulation under alternative scenarios with varying benefit threshold criterion and perceived waiting time ratios, α, compared to the base case for the eight days. The results of these simulation experiments indicate the sensitivity of the simulation model and thus the transfer coordination system itself to changes in holding criterion as well as passenger perceptions and behavior. The conclusions from the sensitivity analysis can be used to better calibrate the transfer coordination model to produce holds resulting in more robust overall benefits.

♦ **Results of Sensitivity Analysis#1: Minimum Benefit = 100 pax-mins, α = 1.25**

Table 4-11 shows the average results for all simulation runs assuming a minimum benefit criterion of 100 passenger-minutes saved and a perceived waiting time ratio, α = 1.25. Sensitivity Analysis#1 tests how the results of the model change under the assumption of a different perceived waiting time. We expect that the number of holds and the associated benefits to be lower as transfer passengers are given less priority in order to improve overall service equity to all passengers.

In summary from Table 4-11, by reducing the waiting time ratio from 1.50 to 1.25:

- Total benefits over the entire day decrease by over 35% from nearly 6,200 to less than 4,000 passenger minutes saved.
- Average benefits per held train decrease from nearly 340 passenger-minutes saved, to almost 280 passenger-minutes saved or 18%.
- Total passengers benefiting decrease by about 20% from nearly 1,300 to nearly 1,050 passengers. Total delayed passengers decrease slightly more by about 25% from nearly 2,000 passengers to 1,500 passengers. Due to the greater decrease in delayed passenger compared to benefited ones, the passenger-benefit ratio rises slightly from 66% to 71%.
- The overall number of holds decreases by nearly four a day or about 25%.
- Average holding time increases by about 5 seconds

♦ **Results of Sensitivity Analysis#2: Minimum Benefit = 75 pax-mins, α = 1.50**

Table 4-12 shows the average results for all simulation runs assuming a minimum benefit criterion of 75 passenger-minutes saved and a perceived waiting time ratio of α = 1.50. Sensitivity Analysis#2 tests how the simulation results change under the assumption of a lower benefit threshold. We would expect that the number of holds should increase, as should the overall benefits but the delayed passengers should also increase.

In summary from Table 4-12, by reducing the minimum benefit threshold from 100 to 75 passenger-minutes saved:

- Total benefits increase by about 500 passenger-minutes or 9% more than the total benefits produced in the base case.
- Average benefits per held train decrease by about 40 passenger-minutes per held train or nearly 12%.

Table 4-11: Sensitivity Analysis#1: Minimum Passenger Benefit = 100 pax-mins, α=1.25

Time Period	Trains Held	Green Ln. Trains	HOLD DURATION(MIN:SEC) Avg. Hold Duration	Longest Hold	Shortest Hold	Pax Benefits per Held Train Average Benefit	Largest Benefit	Smallest Benefit	Hourly Total Benefit
7:00-8:00AM	0.3	38	1:05	1:32	0:34	110.8	282	2	27.7
8:00-9:00AM	0.0	33	0:00	0:00	0:00	0.0	0	0	0.0
9:00-10:00AM	0.1	48	2:06	2:20	1:44	430.0	513	350	53.8
10:00-11:00AM	0.8	31	2:35	3:47	1:08	201.6	575	15	151.2
11:00-12:00PM	1.0	30	2:23	4:35	1:14	289.1	839	11	289.1
12:00-1:00PM	2.1	28	2:37	5:46	0:47	288.3	1032	-476	612.6
1:00-2:00PM	1.5	27	2:02	4:03	0:54	213.2	696	-52	319.7
2:00-3:00PM	2.4	27	2:32	4:13	0:14	344.3	1287	-322	817.7
3:00-4:00PM	1.5	33	2:19	3:56	0:23	367.9	1040	3	551.8
4:00-5:00PM	1.3	40	1:39	4:10	0:06	226.3	1360	-38	282.9
5:00-6:00PM	0.3	39	0:23	0:45	0:03	46.9	118	13	11.7
6:00-7:00PM	0.0	42	0:00	0:00	0:00	0.0	0	0	0.0
7:00-8:00PM	0.3	31	1:44	2:38	0:45	336.5	720	42	84.1
8:00-9:00PM	0.9	27	2:56	4:29	0:59	429.4	1001	23	375.8
9:00-10:00PM	0.6	22	3:24	4:34	1:47	278.0	788	-28	173.8
10:00-11:00PM	1.3	25	2:40	4:51	0:43	158.4	481	2	198.0
Average Per Held Train			2:23			279.6			
TOTALS:	14.1	521							3949.8

Time Period	Delayed/Time Savings Breakdown: Total Passengers Savings 0-2 mins	2-4 mins	4-6 mins	6 + mins	Total Pax	Total Passengers Delayed 0-2 mins	2-4 mins	4-6 mins	6 + mins	Total Pax	Pax-Bens %
7:00-8:00AM	3.6	7.2	2.7	3.0	16.6	42.8	0.0	0.0	0.0	42.8	39%
8:00-9:00AM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0%
9:00-10:00AM	0.0	6.6	2.7	2.9	12.2	1.1	2.5	0.0	0.0	3.7	333%
10:00-11:00AM	2.9	14.3	29.3	5.9	52.3	11.9	45.1	0.0	0.0	57.0	92%
11:00-12:00PM	3.2	37.4	12.6	18.8	72.0	27.7	49.0	3.1	0.0	79.8	90%
12:00-1:00PM	2.7	69.4	51.4	61.1	184.6	58.6	177.9	13.8	0.0	250.3	74%
1:00-2:00PM	6.8	23.0	42.8	24.3	96.9	89.7	56.9	2.5	0.0	149.2	65%
2:00-3:00PM	2.5	47.1	79.2	82.3	211.1	81.4	194.3	14.5	0.0	290.2	73%
3:00-4:00PM	11.0	50.8	65.8	34.5	162.0	74.0	125.1	1.6	0.0	200.8	81%
4:00-5:00PM	3.1	34.7	15.1	40.0	93.0	47.8	69.1	16.3	0.0	133.2	70%
5:00-6:00PM	1.9	2.0	0.0	2.2	6.1	40.7	0.0	0.0	0.0	40.7	15%
6:00-7:00PM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0%
7:00-8:00PM	0.0	1.0	1.4	9.7	12.1	19.3	13.1	0.0	0.0	32.4	37%
8:00-9:00PM	1.3	7.1	15.0	31.0	54.4	26.2	20.0	20.6	0.0	66.7	81%
9:00-10:00PM	0.0	1.0	14.8	20.0	35.7	2.0	36.3	9.5	0.0	47.9	75%
10:00-11:00PM	1.7	1.9	5.1	33.8	42.5	13.1	76.3	3.9	0.0	93.3	46%
Average Per Held Train	2.9	21.5	23.9	26.2	74.4	38.0	61.3	6.1	0.0	105.3	71%
TOTALS:					1051.3					1487.8	

Table 4-12: Sensitivity Analysis#2: Minimum Passenger Benefit = 75 pax-mins, α=1.50

Time Period	Trains Held	Green Ln. Trains	HOLD DURATION(MIN:SEC) Avg. Hold Duration	Longest Hold	Shortest Hold	Pax Benefits per Held Train Average Benefit	Largest Benefit	Smallest Benefit	Hourly Total Benefit
7:00-8:00AM	0.6	38	1:12	2:03	0:34	160.6	392	5	100.4
8:00-9:00AM	0.0	33	0:00	0:00	0:00	0.0	0	0	0.0
9:00-10:00AM	0.1	48	2:06	2:17	1:44	543.2	648	429	67.9
10:00-11:00AM	1.6	31	2:02	3:44	0:15	208.4	874	4	338.7
11:00-12:00PM	2.0	30	2:11	4:57	0:02	297.2	1091	2	594.4
12:00-1:00PM	2.5	28	2:31	5:47	0:02	372.0	1409	-224	929.9
1:00-2:00PM	2.3	27	2:11	4:37	0:54	277.2	796	3	623.7
2:00-3:00PM	3.1	27	2:23	4:17	0:07	383.7	1472	-209	1199.2
3:00-4:00PM	2.3	33	1:56	3:56	0:06	335.6	1332	2	765.0
4:00-5:00PM	2.5	40	1:11	4:11	0:06	212.3	1775	-154	530.8
5:00-6:00PM	0.3	39	0:25	0:42	0:06	77.7	229	15	19.4
6:00-7:00PM	0.0	42	0:00	0:00	0:00	0.0	0	0	0.0
7:00-8:00PM	0.4	31	1:29	2:36	0:35	317.8	929	-68	119.2
8:00-9:00PM	1.4	27	2:42	4:27	0:54	473.0	1347	-63	650.4
9:00-10:00PM	0.9	22	3:12	4:35	2:03	290.4	909	3	254.1
10:00-11:00PM	2.5	25	2:39	4:50	0:42	210.8	550	7	527.1
Average Per Held Train			2:10			299.9			
TOTALS:	22.4	521							6710.3

Time Period	Delayed/Time Savings Breakdown: Total Passengers Savings 0-2 mins	2-4 mins	4-6 mins	6 + mins	Total Pax	Total Passengers Delayed 0-2 mins	2-4 mins	4-6 mins	6 + mins	Total Pax	Pax-Bens %
7:00-8:00AM	11.1	17.4	3.9	3.0	35.3	66.8	2.5	0.0	0.0	69.2	51%
8:00-9:00AM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0%
9:00-10:00AM	0.0	6.6	3.0	2.8	12.3	1.1	2.3	0.0	0.0	3.5	356%
10:00-11:00AM	9.3	46.2	38.8	7.7	101.9	53.5	72.0	0.0	0.0	125.4	81%
11:00-12:00PM	7.5	61.9	36.9	24.7	130.9	75.1	83.2	10.1	0.0	168.4	78%
12:00-1:00PM	2.9	80.4	55.5	68.0	206.8	81.4	211.8	10.7	0.0	303.9	68%
1:00-2:00PM	12.5	53.4	65.4	32.3	163.5	131.0	101.4	9.7	0.0	242.1	68%
2:00-3:00PM	2.6	64.6	84.0	87.0	238.3	116.4	225.4	19.7	0.0	361.5	66%
3:00-4:00PM	17.1	78.6	72.4	41.5	209.6	173.0	161.0	0.0	0.0	334.0	63%
4:00-5:00PM	10.5	61.8	21.0	56.2	149.5	127.9	123.7	16.8	0.0	268.4	56%
5:00-6:00PM	2.1	1.9	0.0	2.3	6.3	39.2	0.0	0.0	0.0	39.2	16%
6:00-7:00PM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0%
7:00-8:00PM	0.0	1.4	4.8	8.9	15.1	41.4	12.1	0.0	0.0	53.4	28%
8:00-9:00PM	3.3	27.3	18.6	42.2	91.3	53.8	55.9	20.4	0.0	130.1	70%
9:00-10:00PM	0.0	3.7	16.4	20.1	40.2	0.0	47.8	10.1	0.0	58.0	69%
10:00-11:00PM	3.9	3.3	10.5	47.7	65.3	42.5	92.4	19.9	0.0	154.9	42%
Average Per Held Train	3.7	22.7	19.3	19.9	65.5	44.8	53.3	5.2	0.0	103.3	63%
TOTALS:					1466.6					2312.0	

- Total passengers benefiting increases by over 10% from 1,300 passengers to over 1,450 passengers. However, delayed passengers increase by a greater amount, nearly 15% from nearly 2,000 delayed passengers to around 2,300. Due to the greater increase in delayed passengers, the passenger-benefit ratio decreases slightly from 66% to 63%.

- The overall number of holds increases by four, amounting to an increase of about 25%.

- Average holding time decreases slightly by nearly 8 seconds.

♦ **Results of Sensitivity Analysis#3: Minimum Benefit = 75 pax-mins, $\alpha = 1.25$**

Table 4-13 shows the average results for all simulation runs assuming a minimum benefit criterion of 75 passenger-minutes saved and a perceived waiting time ratio of $\alpha = 1.25$. Sensitivity Analysis#3 tests how the simulation results change under the assumption of a lower benefit threshold as well as a lower perceived waiting time ratio. Sensitivity Analysis#3 should give us a rough idea which variable is more important in determining holding and the associated benefits. For instance from Sensitivity Analysis#1, it appears that a lowered perceived waiting time reduces the overall holds and benefits, whereas in Sensitivity Analysis#2, a lowered minimum benefit criterion results in increased holds and benefits. Results from Sensitivity Analysis#3 yielding increased numbers of holds and larger benefits from the base case, suggest that perhaps the minimum benefit criterion is the more important of the two variables. On the other hand if the analysis yields fewer holds and smaller overall benefits, then it is likely that the perceived waiting time ratio is a more important factor.

In summary from Table 4-13, by reducing the minimum benefit threshold from 100 to 75 passenger-minutes saved and the perceived waiting time ratio from $\alpha = 1.50$ to $\alpha = 1.25$:

- Total benefits over the entire day decrease by about 33% from 6,200 passenger-minutes saved to nearly 4,200.

- Average benefits per held train decrease by about 80 passenger-minutes per held train or about 23% under the new conditions.

- Total passengers benefiting decrease by over 10% from 1,300 passengers to 1,150 passengers. Delayed passengers decrease by a greater amount, nearly 20% from about 2,000 delayed passengers to around 1,600. Due to the larger decrease in delayed passengers, the passenger-benefit ratio increases slightly from 67% to 72%.

- The overal number of holds decreases by two or about 13%.

- Average holding time increases slightly by nearly 3 seconds.

Table 4-13: Sensitivity Analysis#3: Minimum Passenger Benefit = 75 pax-mins, α=1.25

Time Period	Trains Held	Green Ln. Trains	HOLD DURATION(MIN:SEC) Avg. Hold Duration	Longest Hold	Shortest Hold	Pax Benefits per Held Train Average Benefit	Largest Benefit	Smallest Benefit	Hourly Total Benefit
7:00-8:00AM	0.4	38	1:10	1:32	0:34	110.4	282	2	41.4
8:00-9:00AM	0.0	33	0:00	0:00	0:00	0.0	0	0	0.0
9:00-10:00AM	0.1	48	2:06	2:20	1:44	430.0	513	350	53.8
10:00-11:00AM	1.1	31	2:27	3:47	1:08	172.4	575	4	193.9
11:00-12:00PM	1.1	30	2:24	4:35	1:14	283.9	839	11	319.4
12:00-1:00PM	2.1	28	2:37	5:46	0:47	288.3	1032	-476	612.6
1:00-2:00PM	1.9	27	2:07	4:37	0:54	203.1	696	-52	380.9
2:00-3:00PM	2.4	27	2:31	4:13	0:14	341.0	1287	-322	809.9
3:00-4:00PM	1.8	33	2:10	3:56	0:21	343.9	1040	3	601.8
4:00-5:00PM	1.3	40	1:39	4:10	0:06	226.3	1360	-38	282.9
5:00-6:00PM	0.3	39	0:23	0:45	0:03	46.9	118	13	11.7
6:00-7:00PM	0.0	42	0:00	0:00	0:00	0.0	0	0	0.0
7:00-8:00PM	0.3	31	1:44	2:38	0:45	336.5	720	42	84.1
8:00-9:00PM	0.9	27	2:54	4:29	0:59	391.9	1001	23	343.0
9:00-10:00PM	0.6	22	3:24	4:34	1:47	278.0	788	-28	173.8
10:00-11:00PM	1.6	25	2:40	4:51	0:43	139.6	481	2	226.9
Average Per Held Train			2:21			262.6			
TOTALS:	15.8	521							4136.0

Time Period	Delayed/Time Savings Breakdown: Total Passengers Savings 0-2 mins	2-4 mins	4-6 mins	6 + mins	Total Pax	Total Passengers Delayed 0-2 mins	2-4 mins	4-6 mins	6 + mins	Total Pax	Pax-Bens %
7:00-8:00AM	8.1	9.1	2.7	3.0	22.9	48.5	0.0	0.0	0.0	48.5	47%
8:00-9:00AM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0%
9:00-10:00AM	0.0	6.6	2.7	2.9	12.2	1.1	2.5	0.0	0.0	3.7	333%
10:00-11:00AM	2.9	32.4	33.2	6.8	75.3	23.3	62.0	0.0	0.0	85.2	88%
11:00-12:00PM	3.2	42.5	16.3	18.8	80.8	28.9	51.9	3.1	0.0	83.9	96%
12:00-1:00PM	2.7	69.4	51.4	61.1	184.6	58.6	177.9	13.8	0.0	250.3	74%
1:00-2:00PM	11.8	30.2	60.6	26.6	129.2	112.6	61.4	9.7	0.0	183.7	70%
2:00-3:00PM	2.5	48.8	79.2	82.3	212.8	85.3	194.3	14.5	0.0	294.1	72%
3:00-4:00PM	12.2	59.2	65.8	40.5	177.7	96.8	133.5	1.6	0.0	231.9	77%
4:00-5:00PM	3.1	34.7	15.1	40.0	93.0	47.8	69.1	16.3	0.0	133.2	70%
5:00-6:00PM	1.9	2.0	0.0	2.2	6.1	40.7	0.0	0.0	0.0	40.7	15%
6:00-7:00PM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0%
7:00-8:00PM	0.0	1.0	1.4	9.7	12.1	19.3	13.1	0.0	0.0	32.4	37%
8:00-9:00PM	1.3	16.1	15.0	31.0	63.3	27.9	25.7	20.6	0.0	74.2	85%
9:00-10:00PM	0.0	1.0	14.8	20.0	35.7	2.0	36.3	9.5	0.0	47.9	75%
10:00-11:00PM	3.3	1.9	7.9	39.0	52.0	17.1	79.6	12.3	0.0	109.0	48%
Average Per Held Train	3.4	22.5	23.2	24.4	73.5	38.7	57.6	6.4	0.0	102.8	72%
TOTALS:					1157.9					1618.5	

- **Conclusions from Sensitivity Analysis**

Table 4-14 summarizes the simulation results when the base conditions for the simulation model are altered to reflect different passenger behavior assumptions or transit agency operating philosophy. The percentage changes from the base condition, α = 1.50 and minimum holding threshold = 100 pax-mins are also noted.

Table 4-14: Summary of Sensitivity Analyses

Sensitivity Analysis	α	Min. Holding Criterion	Total Holds	Avg. Benefit Per Held Train	Total Benefits	Total Benefited Passengers	Total Delayed Passengers	Pax-Benefit Ratio
Base Case	1.50	100	18.1	340.0	6161.7	1320.3	2001.4	66%
Relative % Change from Base			-	-	-	-	-	
#1	1.25	100	14.1	279.6	3949.8	1051.3	1487.8	71%
Relative % Change from Base			-22%	-18%	-36%	-20%	-26%	
#2	1.50	75	22.4	298.9	6710.3	1466.6	2312.6	63%
Relative % Change from Base			24%	-12%	9%	11%	16%	
#3	1.25	75	15.8	262.6	4136.0	1157.9	1618.5	72%
Relative % Change from Base			-13%	-23%	-33%	-12%	-19%	

From the results of the sensitivity tests in Table 4-14, it is apparent that different α and minimum holding threshold values do indeed produce different holding results. The objective of a lower α value is to reduce the number of total holds and to improve service equity by reducing the number of delayed passengers significantly. The objective of a lower minimum benefit criterion is to increase the number of holds, the total passengers benefiting as well as the total benefit. With these goals in mind, Table 4-14 suggests that the simulation model and hence transfer coordination at Park Street, is most sensitive to changes in the perceived waiting time ratio α.

Looking first at Sensitivity Test#1, the reduction in α produces significantly fewer holds, total benefits and benefited/delayed passengers than compared to the base scenario. On the whole, the relative magnitude of the decrease is on the order of about 20-30% for the four measures. The results are clear-cut, a reduction in α produces fewer holds, benefits and benefited passengers, but also delays fewer passengers.

The results for Sensitivity Test#2 are less obvious than they are for Sensitivity Test#1. Decreasing the minimum benefit threshold results in more frequent holds, larger total benefits and increased benefited/delayed passengers. However, while holds increase by nearly 25%, total benefits and total benefited passengers increase only by about 10%. This suggests that although holds may be more frequent, more numerous holds do not directly translate into equivalent and more substantial time-savings. Thus a lowered minimum holding criterion adds holds of very little value.

It may be more useful to test the model with an increased minimum holding threshold instead. The results from Table 4-8 indicate that several holds produced negative benefits. With a higher threshold, the frequency of holding will decrease. Most importantly though, borderline holds producing small or negative benefits will be eliminated. The increased minimum holding threshold should also improve the average benefits per held train and the overall passenger-benefit ratio.

Sensitivity Analysis#3 looks at the combined effect of a decreased α and a lowered minimum holding threshold. From the first sensitivity tests, we conclude that changes in α reduce the number of holds, the total benefits as well as the number of benefited/delayed passengers. The results of the second sensitivity test are less clear, but indicate that a slight increase in total benefits may be produced, while holds and benefited/delayed passengers increase significantly when the minimum holding threshold is lowered. A moderate to significant decrease in the holding results for Sensitivity Analysis#3 may indicate that the model and transfer coordination at Park Street is most sensitive to changes in α. On the other hand, slight to moderate increases in the holding results might indicate that the model is more sensitive to changes in the minimum benefit threshold.

The results of Sensitivity Analysis#3 show a moderate reduction in the number of holds and the number of benefited/delayed passengers, which both decrease between 10-20%. The total benefits however sharply decrease by more than 25%. Although the overall decrease is smaller in magnitude than the changes witnessed in Sensitivity Analysis#1, they are significant enough to conclude that transfer coordination at Park Street is more sensitive to changes in α. This conclusion seems logical given the fact that the premise of the whole transfer coordination system is built around the assumption that transfer passengers perceive out-of-vehicle waiting time differently than in-vehicle waiting time. Thus it would make sense that α is a major determining factor in the potential benefits from a hold and in the final decision whether to hold a train or allow it proceed.

Another interesting experiment that could provide additional insight into transfer coordination is the adoption of a minimum holding time. For instance, the results from Tables 4-5 and 4-6 indicate that very short holds (under 1 minute) do not produce significant benefits. Thus it would be interesting to see the increase in average hold benefits and passenger-benefit ratios if holding is only limited to trains that hold longer than one minute.

4.6 Final Recommendations for Implementation

This section discusses the ramifications of the results upon implementation of a transfer coordination system at Park Street.

- **Selection of α**

The most vital element that affects the results of transfer coordination besides the arrival times and sequences of trains and the volumes of impacted passengers is the selection of α, the perceived waiting time ratio. The transfer coordination system is built on the premise that passengers find out-of-vehicle waiting time more burdensome than in-vehicle time.

The assumption of α should be based fundamentally upon passenger perceptions but also upon the service requirements and operating characteristics of the individual transit system. We have chosen $\alpha = 1.50$ because it is a more conservative value than suggested by some of the prior research, most notably the CTPS study on transfer penalties for transit riders in the Boston Metropolitan Area, so as to assure that holds produce significant passenger benefits. The choice of α however, is an important decision for any transit agency considering this type of transfer coordination.

It is likely that a transit agency that is particularly concerned about the reliability of transfers may assume higher values of α to give preferential treatment to transfer passengers so as to greatly improve their transfer experience by shortening their transfer waiting times. A transit agency that is concerned about transfer reliability, but also concerned about service equity may choose a more conservative value. As the results from the sensitivity analysis suggest, a more conservative value of α such as $\alpha = 1.25$ results in fewer holds and consequently fewer delayed passengers. At the same time however, benefited passengers still enjoy significant time savings.

It is recommended that the MBTA either adopt the assumption of $\alpha = 1.5$ or assume a more conservative value of α. The vast majority of passengers using Park Street as a transfer point have become accustomed to the transfer situation at Park Street. Any enhancement of their journeys,' however slight, should be sufficient to satisfy the majority of their concerns about the quality of the transfer at Park Street. Frequent or long holds are likely to annoy delayed passengers, unaccustomed to having their trains held at Park Street. Thus the deleterious effects on delayed passengers may be lessened with relatively conservative estimates of α.

- **AVI Improvements**

The AVI system as it is currently configured, consists of more than thirty detectors throughout the Green Line but it does not include a detector on the short-turn track at Park Street. Thus, trains turning here are undetected until triggering the detector again at Boylston in the Westbound direction. The lack of an AVI detector on this track prevents the estimation of a run time model based on historical arrival times into Park Street. Instead we estimate the run times based on the assumption that half the travel time from the Boylston Eastbound (K08) to the Boylston Westbound (K07) detector represents the arrival time into Park Street. The installation of another AVI detector would allow the transfer coordination system to more precisely estimate the arrival time of short-turned trains into the Green Line WB platform at Park Street. Hence the assessment of overall net benefits of a hold should be more precise.

- **Travel Time into Park Street Berthing Location**

The travel time from the K04 AVI detector to the appropriate Park Street berthing location may be longer than the average trip times recorded throughout the one-hour observation period because of complications noted previously, such as AVI scanning malfunctions as well as track switching and blocking. A better estimate of the travel time from detector to boarding location should improve the accuracy of the arrival time predictions into Park Street and therefore the overall net benefit assessment for any potential holds.

- **Run Time Models**

Running time is an important element in predicting the expected arrival time of a train into Park Street as well as the expected changes in waiting time for impacted passengers. The incorporation of improved run time models should enhance the effectiveness of transfer coordination. For instance special events such as basketball or baseball games produce higher than normal ridership. It is possible that the increased loads along the line may result in higher dwell times at stations, prior to the start and after the conclusion of the event, which serves to increase the running time well beyond the expected run time for an average day. Thus improved run time models when special events occur could produce better transfer coordination results during these times. Lastly, it is likely that internal run time estimations undertaken and validated by the transit agency could improve the robustness of the transfer coordination system.

- **Real-Time Information**

As it stands, Park Street has no form of automated passenger information on any of its platforms. Signs directing passengers to the correct stairwell to reach the Green Line level immediately after disembarkation from the Red Line train, could conceivably shorten average transfer times and the overall duration of the transfer period by helping disoriented passengers navigate their way through the system. In this way, holding times could be shortened and the negative effect upon delayed passengers lessened somewhat.

- **Cost-Effectiveness**

While it is important to prove the actual passenger benefits from transfer coordination, maybe the most important factor in the implementation process is the economic cost-effectiveness of the system. Previous cost estimates by the MBTA (see Figures 2-6 and 2–7), for a planned transfer coordination system at Park Street estimate that the overall cost at about $100,000. This sum estimates the total costs of labor and parts to install communication links, terminal screens, Programmable Logic Controllers (PLC) and visible Hold Signs on the Green Line to enhance efficiency of transfers at Park Street. The MBTA and any transit system considering implementing transfer coordination must weigh the initial investment in terms of manpower and capital, against the expected benefits produced.

From Table 4-8 we find that under base conditions, the total benefit over a typical weekday averages over 6,000 passenger-minutes saved. Therefore on any given weekday the average total benefit should be about 100 passenger-hours saved. Projected over the entire year, assuming a year has 250 weekdays (discounting holidays), then total passenger benefits amount to nearly 25,000 annual passenger-hours saved. If we assume that passengers value in-vehicle time at only $4.00/hour, then it is clear that the benefits from transfer coordination nearly cover the initial investment in the system in just the first year of operation. It is likely passengers value in-vehicle time at higher equivalent values, however a conservative assumption produces an estimate of the minimum potential benefits from coordination. It is possible that the value of annual time savings may be much more substantial. There is no doubt that over the long haul, the transfer coordination system should more than recoup the investment through passenger time-savings, improved rider satisfaction and potentially increased ridership.

Besides the potential cost savings for passengers, transfer coordination will result in a much better level of information in the field. Previously station inspectors, accustomed to having little or no real-time information, would base decisions on second-hand information or upon first-hand experience. The inspector might have no idea how a holding decision at one station would affect passengers and trains at other stations. With the transfer coordination system, inspectors will have access to AVI and OCS train arrival data on the platform itself. The inspector can quickly assess the following train sequence and headways to determine the potential impacts that holding a Green Line train will have on impacted passengers. Thus, the level of information accessible in the field to station inspectors will be much better, which should translate into improved real-time decisions.

It is also foreseeable that the implementation of transfer coordination at Park Street could be the impetus driving improved provision of passenger information. Passenger information systems relaying expected arrival time into a station or the following headways of a train, relying upon the detection capabilities of either the AVI system or the OCS and are a logical compliment to transfer coordination. Passenger would then know how long they would need to wait for the next train and do not need to worry over when the next train will come. Not only would transfer passengers benefit, but passengers throughout the system would also benefit.

Chapter 5: Conclusion

The two sections that comprise this concluding chapter summarize the results and impacts of this research, and suggest future extensions.

5.1 Summary

Transfers and the waiting time associated with transfers is a major factor determining the overall trip reliability. One means of improving transfers is to hold selected trains to allow transferring passengers to board trains on their destination line. Previous applications of holding at transfer stations have had a very narrow focus. That is, holds were deemed feasible if and only if they appeared to benefit the transfer passengers at the connection location. However, passengers that might have been delayed by a holding action were not accounted for. Thus it was possible that the overall effect of the hold would be to introduce more delay to impacted passengers. The lack of train information, including train headways and train sequences, were a major reason why many control decisions made at the local level might actually result in poor holding decisions.

With improved real-time information capabilities, we formulated a transfer coordination system that applied real-time holding strategies to a key transfer point, with holds based on the expected impacts on all passengers. Holding guidelines were designed to identify the circumstances in which a holding action would be feasible. For instance trains would only be held as long as there are transferring passengers from the origin line boarding the train.

Six passenger types were identified as being impacted by holding. Three of these passenger types experience delays due to holding: the through-passengers boarding prior at upstream stations (P2), and the destination line boarders that accumulate at the transfer station (P2) and at downstream stations (P5) during the preceding headway. These passengers are delayed by the duration of the hold. Three passenger types benefit from holding: the transfer passengers (P3), and the destination line boarders arriving during the holding period at the transfer station (P4) and at downstream stations (P6). These passengers experience different time savings depending on the following arrival headway of the next train they are eligible to board.

The transfer system was based on the premise that passengers perceive out-of-vehicle waiting time as more burdensome than in-vehicle waiting time. Thus greater priority would be placed on improving overall transfer performance for transfer passengers by shortening their expected waiting times.

Our focus was upon the Massachusetts Bay Transit Authority. Park Street, the transfer point between the Green and the Red Lines was an ideal location to assess the benefits and impacts of transfer coordination as it was the busiest transfer station between the two most heavily-used lines in the system. Transfers from the Red Line to the Green Line Westbound showed the greatest potential for significant benefits from coordination. Holds on the Green Line Westbound would delay the fewest number of through-passengers on incoming trains. Equally important, holds were expected to produce the largest time savings, based on the expected waiting times for passengers heading to the surface portions of the B, C, D or E lines.

An analytical model was developed to assess the benefits of transfer coordination from the Red Line to the Green Line Westbound at Park Street. The analytical model estimated the impact of a hold in terms of the net in-vehicle time saved, measured in passenger-minutes. Several simplifying assumptions are made in the analytical model such as perfect prediction capabilities for expected arrival times at Park Street, a fixed dwell time and preceding headways at upstream stations are the same as the headway entering Park Street.

Several factors limit the potential benefits produced by the transfer coordination system most notably the capacity of Green Line trains, the expected arrival times of following Green Line trains as well as the minimum holding threshold.

The results of the analytical model suggested that there could be substantial passenger benefits from transfer coordination: over 12,000 daily passenger-minutes saved with a minimum holding threshold of 50 passenger-minutes. Furthermore, results indicated that transfer coordination produces the largest benefit when Green Line trains have short preceding headways but long following headways, thus minimizing the delay to impacted passengers and maximizing the benefits.

Sensitivity analyses found that a higher minimum holding threshold increases the average passenger benefits per hold and eliminated borderline holds which due to variable factors in the system such as train running times and passenger arrivals, may actually produce benefits significantly lower than expected.

It is hypothesized that the overall net benefits produced by the analytical model may have been over-estimated because of the assumptions of a fixed dwell time and of perfect prediction capabilities. Furthermore, trains are analyzed in discrete hourly blocks which may have resulted in under-estimated numbers of leftover passengers potentially boarding trains at the beginning of the new hourly period.

Transfer coordination is then analyzed with a simulation model to better account for the stochasticity and variance inherent in daily operations, which the analytical model did not deal with. For instance passenger arrivals are now modeled as a Poisson process to represent the minute-to-minute variations in passenger arrivals throughout the day. Transfers from the Red Line are now modeled with a binomial distribution.

The simulation is more complex than the analytical model but follows the same general structure. The analytical model based the holding decision upon the expected benefits of a hold, whereas the simulation model looks at the expected benefits to select a train for holding, but then evaluates the actual benefits produced by the holding decision. The expected benefits of the simulation model are based on expected passenger arrivals as well as expected train arrival times. The actual benefits are based on the actual passenger arrivals and the actual train arrival time. Thus it is likely that some holds, deemed feasible from the expected benefits, might actually produce negative time savings which can be interpreted as an overall delay to impacted passengers.

The simulation experiments used eight days of AVI and OCS arrival data from early April 2000. Under the base conditions, a minimum holding threshold of 100 pax-mins and a perceived waiting time ratio of 1.50, the simulation experiments indicate that under more realistic operating conditions, transfer coordination could produce significant benefits, about 6,000 daily passenger-minutes saved resulting from about 18 holds per day of about 2 minutes duration. The expected time savings for each passenger benefiting is about 5 minutes, while the expected time increase for each passenger being delayed is about 2 minutes. In addition, the results suggest that the most advantageous time period for transfer coordination occurs in the base, mid-afternoon period from 12:00-4:00PM with hourly benefits exceeding 1,000 passenger-minutes saved.

A comparison of the results for the analytical and simulation models shows a significant difference in total hold benefits as well as the overall frequency of holding. It is hypothesized that this disparity results from the additional realism incorporated into the simulation model primarily from the run time model predictions and the passenger arrival assumptions.

Sensitivity analysis reveals that a decrease in the perceived waiting time ratio to assure service equity results in a significant decrease in the number of passengers being delayed and the total frequency of holds. Decreasing the minimum holding threshold in order to significantly improve transfer performance increases the number of holds and benefiting passengers significantly. Surprisingly however, total hold benefits grew only marginally. This result indicates that more frequent holds do not directly translate into significant increases in overall benefits, instead it adds holds of little value. Overall the simulation model is most sensitive to changes in the perceived waiting time ratio. It may prove worthwhile to investigate the effects of increased minimum holding thresholds which eliminate borderline holds and should produce more significant benefits. Furthermore, the elimination of very short holds should produce improved average benefit per held train and improved passenger-benefit ratios.

Several recommendations are made to improve the transfer coordination system at Park Street. For instance a conservative value for the perceived waiting time ratio should be adopted so as to cause the least disturbance to the daily routine of passengers. More accurate run time models would also increase the accuracy of arrival time predictions and therefore the estimation of expected benefits.

Finally, transfer coordination has definite potential to produce significant cost savings for passengers in terms of equivalent in-vehicle time. If as predicted, the transfer coordination system under the base conditions produces annual savings of 25,000 passenger-hours and assuming passengers value in-vehicle waiting time at only $4.00/hour, then the system should more than pay for itself within just its first year in operation. Furthermore, the transfer coordination system provides inspectors with better overall real-time information about trains location and headways, assisting them in making better and more sound control decisions.

5.2 Further Research

As previously recommended, enhanced run time models and better passenger information may result in improved system performance. It may be interesting to see how much better the results for transfer coordination can if the arrival time into the transfer station can be predicted to a higher degree of accuracy. The provision of passenger information and its effect upon transfer times and ultimately holding is an interesting issue that has not yet been investigated. It may well be worth considering the initiatives taken by many transit agencies to improve the provision of real-time information to passengers.

In terms of model sensitivity, it is obvious that the value of the perceived waiting time ratio plays a large part in determining the number of holds, the total benefits, as well as the benefited/delayed passengers. A better understanding of this aspect of passenger perception will make for a better transfer coordination system.

Lastly, it may also be interesting to observe and analyze the results that the application of transfer coordination have upon ridership within the system over the long haul. While the benefits of transfer coordination are clear, it remains to be seen whether these benefits and improvements to the travel journey are sufficient to attract a larger ridership base and to increase revenue for the transit agency.

The choice of Park Street as the test scenario for transfer coordination should be the impetus driving enhancement studies at the other three major downtown transfer stations within the MBTA. Although not as complicated as Park Street, application of transfer coordination to these locations may suggest means to improve the Park Street model itself and the transfer coordination scheme in general.

On a broader scope, instead of applying transfer coordination only to Park Street, in the context of transfers between the Red and Green Lines, it may be even more valuable to apply transfer coordination to the network as a whole and assess net benefits on a system-wide basis instead of on a single line. If transfer coordination were applied to Park Street as well as Government Center, for transfers between the Blue and Green Lines, then we could gain a better understanding and idea of how transfer coordination affects passengers in the network context. This would require a transfer coordination system that simultaneously analyzes multiple trains on different lines, approaching different stations. While the complexity of the model would be greatly increased, it is likely that a successful implementation of a network-wide coordination system would produce significant passenger benefits and have important application to transit operations on the whole.

Lastly, this research mentioned some of the important factors that determine whether or not a train should be held. The research did not however make clear-cut guidelines for when transfer coordination is most likely to be worth implementing. Such an endeavor would require testing transfer coordination at multiple transfer points for extended periods of time. Nonetheless, potential coordination guidelines would be a very useful tool for transit agencies seeking to improve transfer performance through coordination.

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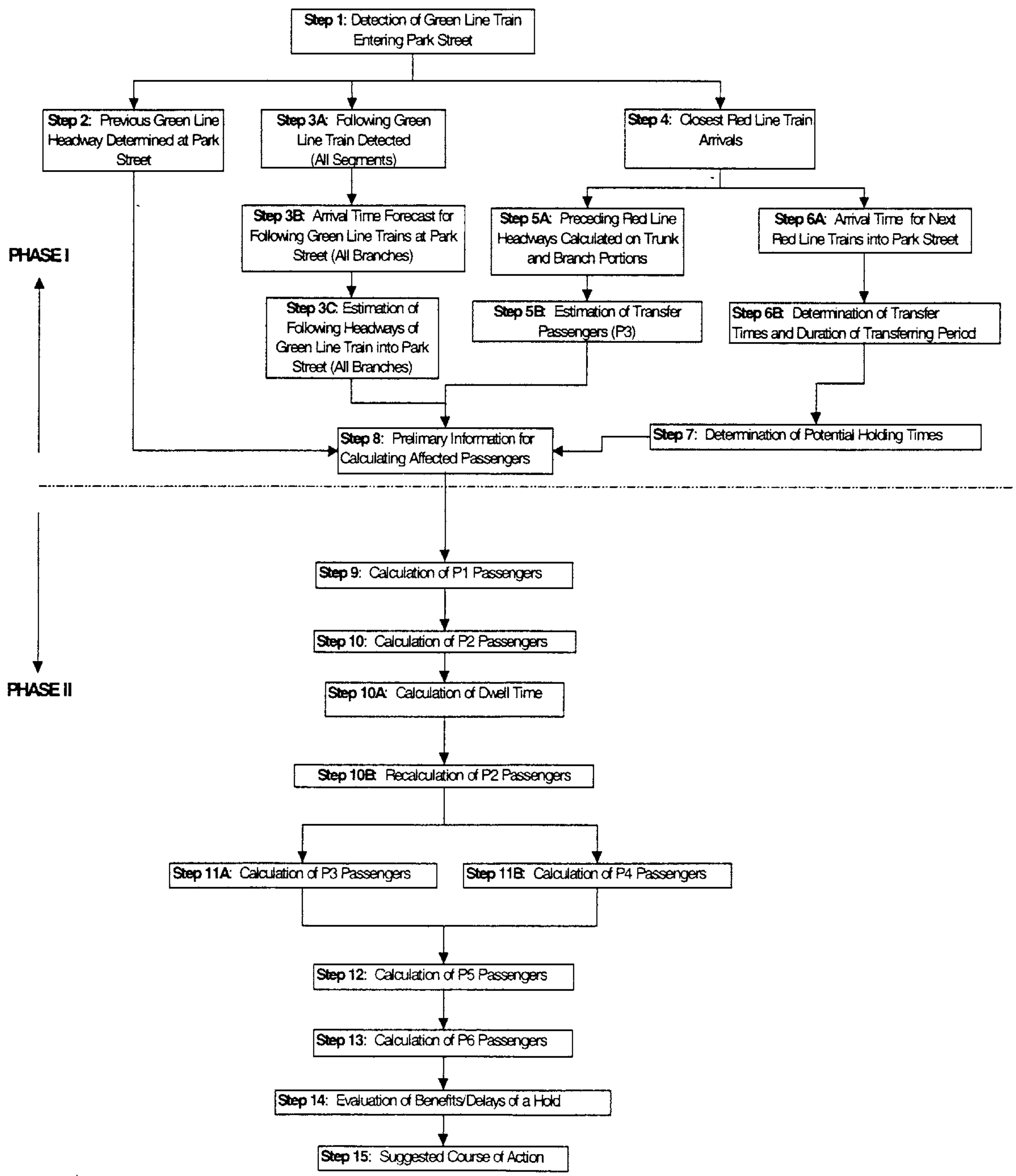
Appendix A: Formulation and Structure of Park Street Model

Appendix A describes the structure and framework of the transfer coordination model. It includes model notation and mathematical equations omitted from Section 3.3 which gives a simplified version of the model framework. Figure A-1 shows the sequence of events occurring in the analytical model. The model is divided into two phases: Phase I consists of Stages 1-8 and Phase II consists of Stages 9-17.

Figure A-1: Framework for Park Street Case Study



Model Notation

The model notation is as follows:

1) *Green Line train(i) = current Green Line train(i) at (entering) Park Street.*
2) *Red Line train (m) = current Red Line train (m) at (entering) Park Street.*
3) *Green Line train(i +1) = following train after Green Line train(i).*
4) *Green Line train(i –1) = preceding train before Green Line train(i).*
5) λ_S^T *= Passenger Arrival Rates (per minute) from Station S to Station T.*
6) $\beta(i)(m)$ *= Arrival Rate for Transferring Passengers for Green Line train (i), Red Line train (m).*
7) *Preceding_Headway(i)(k) = Preceding headway of Green Line train (i) at station(k).*
8) *Following_Headway(i)(k) = Following headway of Green Line train (i) at station (k).*
9) *P2-BCDE(i) = The number of P2 passengers heading to common track segment served by B, C, D and E Line trains, between Boylston and Copley, on train (i).*
10) *P5-BCD(i) = The number of P5 passengers heading to common track segment served by B, C and D Line trains, between Auditorium and Kenmore on train (i).*
11) *P6-C(i) = The number of P6 passengers heading to the surface portion of Line C on train (i);*
12) *Sum of Eligibles (i) = Sum of All Eligible Passengers for train (i).*
13) *Sum of Actuals (i) = Sum of All Actual Passengers for train (i).*
14) *Transfer % from Red Line NB to Green Line WB (i)(m) = Proportion of Total Riders from Red Line NB train (m) that transfer to Green Line WB train (i).*
15) *Proportion of Transfers, BCDE (i) = Ratio of Transfer Passengers going to common track segment served by B, C, D and E Lines for train (i) =* $\sum_{k=Boylston}^{Copley} \lambda_{Park\ Street}^{k} / \left[\sum_{n=Boylston}^{All-Surface\ Termini} \lambda_{Park\ Street}^{n} \right]$.
16) *Proportion of Transfers, BCD (i) = Ratio of Transfer Passengers going to common track segment served by B, C and D Lines for train (i) =* $\sum_{k=Hynes}^{Kenmore} \lambda_{Park\ Street}^{k} / \left[\sum_{n=Boylston}^{All-Surface\ Termini} \lambda_{Park\ Street}^{n} \right]$
17) *.Proportion of Transfers, C (i) = Ratio of Transfer Passengers going to surface portion of C Line for train (i) =* $\sum_{k=Surface\ Portion\ of\ C\ Line}^{Cleveland\ Circle} \lambda_{Park\ Street}^{k} / \left[\sum_{n=Boylston}^{All-Surface\ Termini} \lambda_{Park\ Street}^{n} \right]$.
18) *Stage1_Time(i)(m) = Stage 1 Boarding Time for Passengers from Red Line train (m) to Green Line train(i).*
19) *Holding_Time(i)(m) = Holding Time at Park Street for Green Line train (i) for transfers passengers from Red Line train (m).*
20) *Following_Headway_BCDE(i) = The following headway for Green Line train (i) for the next Green Line train heading to common track segment served by B, C, D and E Lines (Boylston-Copley).*
21) α *= Out-of-Vehicle/In-Vehicle Waiting Time Proportion.*

We assume that any variables not explicitly mentioned above, but are used in the following model description, are self-explanatory give the context in which they are used.

Model Phase I: Steps 1-8[23]

The analytical model is separated into two phases. Phase I, covering Steps 1-8, essentially estimates the number of potential P3 transfer passengers based on the expected arrival times of Red Line trains into Park Street, as well as the expected arrival times of following Green Line trains into Park Street. Phase I also estimates the potential holding times for current Green Line trains to allow Red Line transfer passengers to complete the transfer movement.

We assume that an incoming WB Green Line train, train (i) approaches Park Street and a NB Red Line train (m) approaches as well. A brief description of Steps 1-8 in Phase I of the model follows:

Step 1: Detection of Green Line Train Entering Park Street – The triggering event for the entire transfer coordination system is the detection of an incoming Green Line train into Park Street at the K04 detector in the Westbound direction. The wayside detector detects the trigger time at the sensor, the train consist (and therefore indirect the capacity), and the train route.

Step 2: Previous Green Line Headway Determined at Park Street – Once Green Line train (i) is detected, the most recent Green Line train entering Park Street, Green Line train (i-1) is identified from the AVI arrival data. Thus the preceding headway of train(i) is calculated. The preceding headway of train (i) is important because P2 passengers accumulate on the Park Street platform during this time.

Step 3A: Following Green Line Trains Detected (All Segments) – To estimate the potential time savings from a hold, the next incoming Green Line trains serving the three following three track segments are identified from the AVI data: Boylston-Copley (served by the B, C, D and E Lines), Auditorium-Kenmore (served by the B, C and D Lines) and the surface portion (served by trains of the same branch as Green Line train (i)). Passengers to any of the three track segments may experience differing amounts of time savings.

Step 3B: Arrival Time Forecast for Following Green Line Trains at Park Street – The arrival time forecast for following Green Line trains is important as it limits the possible length of the holding period. The forecasted arrival times are also important in estimating how much time certain passengers heading to a track segment save from holding. With the assumption of perfect prediction capabilities, we track the closest Green Line trains, serving the three track segments and note their arrival times into Park Street (K04).

Without perfect prediction capabilities, run time models from the last detected location estimate the expected arrival time into Park Street.

Step 3C: Estimation of Following Headways of Green Line Train into Park Street – Once arrival times are estimated, the following headways of trains entering Park Street are calculated. The following headways for Green Line train (i) into Park Street determine the amount of time saved by the different passengers during a holding situation.

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[23] Analytic model has slightly different versions of Step 3B, 4C and 6A.

Step 4: Closest Red Line Trains Detected – Transfers originate from the Red Line. Once the Green Line train (i) is detected entering Park Street, the following three incoming Red Line trains in each direction are identified in the OCS arrival data. After potential Red Line trains are identified, the block location, train number, and detection time are recorded.

Step 5A: Preceding Red Line Headways Calculated on Trunk and Branch Portions – The preceding headways on the Red Line are necessary to calculate the expected load entering Park Street from upstream stations and therefore the number of passengers transferring to the Green Line Westbound. Trunk headways are calculated from OCS arrival data. In the Northbound direction, trains originate from one of two branches, Ashmont or Braintree. The train number is used to track a potential Red Line back to the block prior to JFK/UMASS, where trains from the two southern branch termini converge onto a single track. Thus the preceding branch headway is assumed to be the same as the headway entering the block prior to JFK/UMASS.

Step 5B: Estimation of Potential Transfer Passengers – The number of potential transfer passengers is a product of the load on a Red Line train entering the transfer station and the historical alighting ratios found derived from CTPS data. The potential number of passengers from the Red Line NB train (m) transferring to a Green Line WB train (i) at Park Street is broken into two steps:

$$\text{a) Red\_Line\_Load\_Entering\_Park\_Street(i)(m)} = \sum_{h = Park\ Street}^{Alewife} \left[\left(\sum_{j = Braintree}^{Quincy} \left(\lambda_j^h * (Preceding\_Headway(m)(j)) \right) \right) + \left(\sum_{k = JFK\ /\ UMASS}^{South\ Station} \left(\lambda_k^h * (Preceding\_Headway(m)(k)) \right) \right) \right]$$

$$\text{b) Potential\_P3\_Transfers (i)(m)} = \left[(Red\_Line\_Load\_Entering\_Park\_Street(i)(m)) * (Transfer\ \%\ from\ Red\ Line\ NB\ to\ Green\ Line\ WB(i)) \right]$$

The formulation for a SB Red Line train is the same as above sans the Braintree-Quincy spur. The transfer percentages vary according to time of day.

Step 6A: Arrival Time Forecast for Next Red Line Trains into Park Street – The expected arrival time of Red Line trains into Park Street is an important factor in determining how long a Green Line train should be held for to allow transfer passengers to board. In the analytical model, we assume perfect prediction capabilities. Arrival times are based on scheduled arrivals. Without perfect prediction capabilities, run time models will be used to estimate the arrival times.

Step 6B: Determination of Transfer Times and Duration of Transferring Period – The branch of the Red Line train determines how quickly transferring occurs to the Green Line Westbound as well as the overall transfer period. Transfer times are based on empirical data presented in Table 2-8.

Step 7: Determination of Potential Holding Times – The expected arrival time of Red Line train (m) along with the estimate of the transfer time and the overall transfer period result in the time in which transfers first arrive on the Green Line platform and the time in which transferring concludes. Generally, potential holds are assumed to last only as long as it takes for the last transfer passenger to complete the movement from a particular Red Line train. Holding time begins only after the conclusion of the initial dwell time estimation (dealt with later). Thus, any potential hold is eligible for consideration if the hold begins AFTER the current Green Line train is detected entering Park Street AND the hold concludes BEFORE the following Green Line train enters Park Street to prevent blocking. We only record the time that the transfer period concludes.

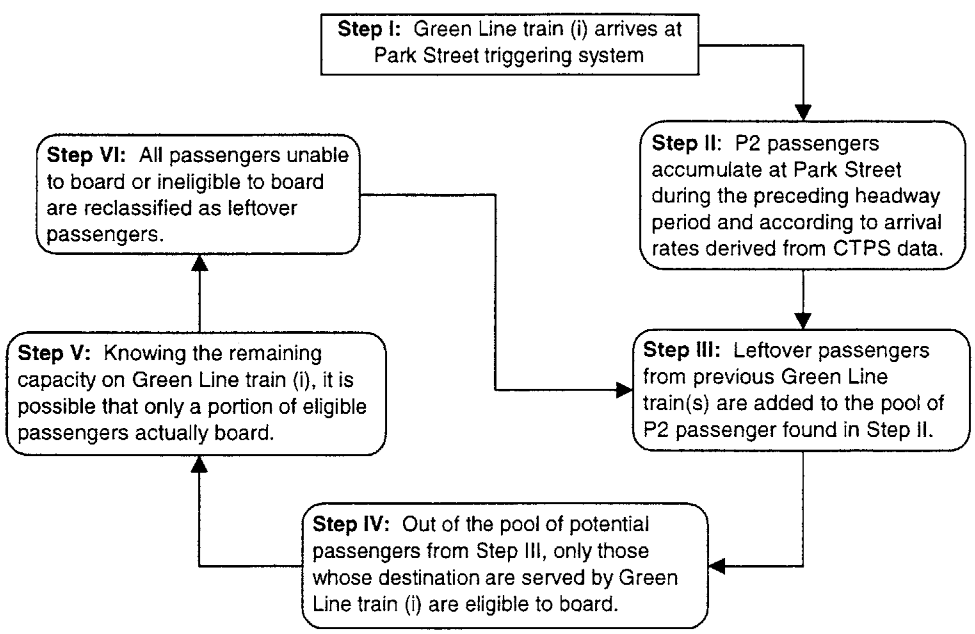
Step 8: Preliminary Information for Calculating Affected Passengers – Step 8 collects all the data that is previously processed. Information such as the previous headways on the Red and Green Lines, the following headways entering Park Street for the Green Line, the estimated number of transfers from the Red Line to the Green Line, the estimated transfer period, and the potential holding times is used in the next steps.

Model Phase II: Steps 9-17[24]

Phase II of the model calculates the expected number of impacted passengers (P1 through P6), as well as estimating the time savings/delay experienced by all affected passengers. Finally, the ultimate holding decision is based on the overall net benefits considering the impact on all passengers from a hold.

Steps 9 through 15 calculate the different groups of impacted passengers. Generally, the passenger types identified in Step 9 through Step 15 involve the same cyclical process to estimate the potential, the eligible, the actual, and finally the leftover passengers for a given Green Line train entering Park Street as seen in Figure A-2. The process begins with a detected Green Line train entering Park Street and triggering the transfer coordination system.

Figure A-2: Determination of Actual and Leftover Passengers



It is important to keep track of the leftover passengers because as Figure A-2 shows, there are potentially large numbers of leftover passengers from either passengers ineligible to board a train due to its ultimate destination, or from capacity constraints preventing eligible passengers from actually boarding. Leftover passengers are important since they carry-over to the next train and

[24] Steps 10A and 10B are only applicable to the simulation model.

could conceivably constitute a majority of the actual P2 boarders for the following Green Line train and consequently result in more passenger delays arising if holding occurs.

For Steps 9-15, we assume that the arriving Green Line train (i) is a C-Line train. Thus we will show how to calculate the eligible and actual passengers boarding this C-Line train, given the capacity of the train during the different boarding periods and the preceding headway. The six passenger types are also broken down into the three track segments in the Westbound direction.

Step 9: Calculation of P1 Passengers – P1 passengers are the through-passenger passing through Park Street. They accumulate during the preceding headway period at upstream stations according to CTPS on/off counts.

$$\text{a) Eligible\_P1 - BCDE}(i) = \sum_{j=\text{Lechmere}}^{\text{Gov Center}} \sum_{k=\text{Boylston}}^{\text{Copley}} [\lambda_j^k\,(Preceding\_Headway(i)(j))] + Leftover\_P1 - BCDE(i-1)$$

$$\text{b) Eligible\_P1 - BCD}(i) = \sum_{j=\text{Lechmere}}^{\text{Gov Center}} \sum_{k=Hynes}^{\text{Kenmore}} [\lambda_j^k\,(Preceding\_Headway(i)(j))] + Leftover\_P1 - BCD(i-1)$$

$$\text{c) Eligible\_P1 - C}(i) = \sum_{j=\text{Lechmere}}^{\text{Gov Center}} \sum_{k=\text{C-Surface Stops}}^{\text{C-Line Terminus}} [\lambda_j^k\,(Preceding\_Headway(i)(j))] + Leftover\_P1 - C(i-1)$$

$$\text{d) If Sum of Eligibles}(i) \leq \text{Capacity}(i) = \begin{cases} then,\ Capacity\_Ratio(i) = 1 \\ else,\ Capacity\_Ratio(i) = Sum\ of\ Eligibles(i)/Capacity(i) \end{cases}$$

e) Actual_P1 - BCDE(i) = *Eligible_P1-BCDE(i) *(Capacity_Ratio(i));*

Leftover_P1_BCDE(i) = *Eligible_P1-BCDE(i) - Actual_P1-BCDE(i)*

f) Actual_P1 - BCD(i) = *Eligible_P1-BCD(i) *(Capacity_Ratio(i));*

Leftover_P1_BCD(i) = *Eligible_P1-BCD(i) - Actual_P1-BCD(i)*

g) Actual_P1 - C(i) = *Eligible_P1-C(i) *(Capacity_Ratio(i));*

Leftover_P1_C(i) = *Eligible_P1-C(i) - Actual_P1-C(i)*

h) Capacity_After_P1(i) = *Capacity(i) - Sum of Actual P1's(i)*

Step 10: Calculation of P2 Passengers – P2 passengers arrive at Park Street and are delayed by a hold. There are three types of P2 passengers: normal arriving passengers accumulating during the preceding headway time, leftover passengers from previous Green Line trains and transfer (P3) passengers that arrive before the Green Line train arrives, accumulating in the Stage 1 Boarding Time. P2 passengers are calculated in two stages, Stage A and Stage B. Stage A P2 passengers arrive during the previous headway time and are calculated in order to make an estimated of the dwell time (Step 10). Once the dwell time is estimated (Step 11), additional P2 passengers are assumed to arrive during this dwell time period (Step 12). Since holding does not commence until after the dwell time period has concluded, any passengers arriving during the dwell time are considered to be delayed and hence P2 passengers. Stage B P2 passengers are those P2 passengers arriving during the dwell time.

$$\text{a) Eligible\_P2\_StageA - BCDE(i)} = \sum_{j=\text{Park Street}} \sum_{k=\text{Boylston}}^{\text{Copley}} [\lambda_j^k (Preceding\_Headway(i)(j))] + Leftover\_P1 - BCDE(i-1)$$

$$+ \sum_{m=\text{1st Red Line Train}}^{\text{Last Red Line Train}} [\beta(i)(m) * Stage1\_Time(i)(m) * (Proportion\ of\ Transfers,\ BCDE(i))]$$

$$\text{b) Eligible\_P2\_StageA - BCD(i)} = \sum_{j=\text{Park Street}} \sum_{k=Hynes}^{\text{Kenmore}} [\lambda_j^k (Preceding\_Headway(i)(j))] + Leftover\_P1 - BCD(i-1)$$

$$+ \sum_{m=\text{1st Red Line Train}}^{\text{Last Red Line Train}} [\beta(i)(m) * Stage1\_Time(i)(m) * (Proportion\ of\ Transfers,\ BCD(i))]$$

$$\text{c) Eligible\_P2\_StageA - C(i)} = \sum_{j=\text{Park Street}} \sum_{k=\text{C-Surface Stops}}^{\text{C-Line Terminus}} [\lambda_j^k (Preceding\_Headway(i)(j))] + Leftover\_P1 - C(i-1)$$

$$+ \sum_{m=\text{1st Red Line Train}}^{\text{Last Red Line Train}} [\beta(i)(m) * Stage1\_Time(i)(m) * (Proportion\ of\ Transfers,\ C(i))]$$

$$\text{d) If Sum of Eligibles(i)} \le \text{Capacity\_After\_P1(i)} = \begin{cases} then,\ Capacity\_Ratio(i) = 1 \\ else,\ Capacity\_Ratio(i) = Sum\ of\ Eligibles(i)/Capacity\_After\_P1(i) \end{cases}$$

$$\text{e) Actual\_P2\_StageA - BCDE(i)} = Eligible\_P2\_StageA\text{-}BCDE(i) * (Capacity\_Ratio(i));$$

$$\text{f) Actual\_P2\_StageA - BCD(i)} = Eligible\_P2\_StageA\text{-}BCD(i) * (Capacity\_Ratio(i));$$

$$\text{g) Actual\_P2\_StageA - C(i)} = Eligible\_P2\_StageA\text{-}C(i) * (Capacity\_Ratio(i));$$

Step 11: Calculation of Dwell Time – In the analytical model, the dwell time is a deterministic value. The simulation model utilizes the Lin & Wilson findings which bases the dwell time on the number of standing arrivees, the number of alighters and boarders at Park Street, and the number of standing departees leaving Park Street. Dwell time boarders are given the designation P2-StageB.

Step 12: Recalculation of P2 Passengers – P2 passengers are given an additional amount of time to board, equivalent to the duration of the dwell time estimated in Step 11. The estimate of the actual P2 Stage B boarders is similar to that outlined in Step 10 for Stage A P2 passenger except the dwell time would replace the "Preceding_Headway" term in the formulation. Furthermore the formulation would have no term for leftover P1 passengers. The combined P2 boarders are as follows:

$$\text{a) Actual\_P2 - BCDE(i)} = Actual\_P2\_StageA\text{-}BCDE(i) + Actual\_P2\_StageB\_BCDE(i);$$

$$\text{Leftover\_P2 - BCDE(i)} = [Eligible\_P2\_StageA - BCDE(i) + Eligible\_P2\_StageB\_BCDE) -$$

$$(Actual\_P2\_StageA - BCDE(i) + Actual\_P2\_StageB - BCDE(i))]$$

b) Actual_P2 - B(i) = $Actual\_P2\_StageA\text{-}BCD(i) + Actual\_P2\_StageB\_BCD(i);$

Leftover_P2 - BCD(i) = $[Eligible\_P2\_StageA - BCD(i) + Eligible\_P2\_StageB\_BCD) -$

$(Actual\_P2\_StageA - BCD(i) + Actual\_P2\_StageB - BCD(i))]$

c) Actual_P2 - C(i) = $Actual\_P2\_StageA\text{-}C(i) + Actual\_P2\_StageB\_C(i);$

Leftover_P2_C(i) = $[Eligible\_P2\_StageA - C(i) + Eligible\_P2\_StageB\_C) -$

$(Actual\_P2\_StageA - C(i) + Actual\_P2\_StageB - C(i))]$

d) Capacity_After_P2(i) = $Capacity\_After\_P1(i)$ - *Sum of Actual_P2's(i)*

Step 13A and 13B: Joint-Calculation of P3 and P4 Passengers – We will assume that at this time only one Red Line train (m) is eligible to be held for by the Green Line train (i). Transfers from non-overlapping Red Line arrivals will potentially board Green Line trains and save time during Stage 2, Stage 4 and Stage 6 boarding periods. Stage 1 transfer boarders were already counted as P2 passengers since they arrived at the Green Line platform before the Green Line train arrives. Transfers from overlapping Red Line trains arrive during the three stages mentioned above, and possibly in two additional stages, Stage 3 and Stage 5. P4 passengers arrive simultaneously during a hold with the transfer passengers in Stages 2-6, depending on of course whether Red Line trains overlap.

a) Eligible_P 3 - BCDE(i)(m) = $$\sum_{l=\text{1st Red Line Train}}^{m} [\beta(i)(l) * (Stage2\_Time(i)(l) + Stage3\_Time(i)(l) + Stage4\_Time(i)(l))] * (Prop.\ of\ Transfers,\ BCDE(i))$$

b) Eligible_P 3 - BCD(i)(m) = $$\sum_{l=\text{1st Red Line Train}}^{m} [(\beta(i)(l) * (Stage2\_Time(i)(l) + Stage3\_Time(i)(l) + Stage4\_Time(i)(l))] * (Proportion\ of\ Transfers.\ BCD(i))$$

c) Eligible_P 3 - C(i)(m) = $$\sum_{l=\text{1st Red Line Train}}^{m} [\beta(i)(l) * (Stage2\_Time(i)(l) + Stage3\_Time(i)(l) + Stage4\_Time(i)(l))] * (Proportion\ of\ Transfers, C(i))$$

If Red Line arrivals are simultaneous, each equation has two additional terms in the first sum. For instance, if there is another Red Line train (n) that arrives in the SB direction:

c) Eligible_P 3 - C(i)(m) = $$\sum_{l=\text{1st Red Line Train}}^{n} \begin{bmatrix} \beta(i)(l) * [Stage2\_Time(i)(l) + Stage3\_Time(i)(l) + Stage4\_Time(i)(l)] \\ + \beta(i)(l) * [Stage4\_Time(i)(l) + Stage5\_Time(i)(l)] \end{bmatrix} X\,(Proportion\ of\ Transfers, C(i))$$

The estimation of the P4 passengers is as follows:

d) Eligible_P4 - BCDE(i)(m) = $$\sum_{j=\text{Park Street}} \sum_{k=\text{Boylston}}^{\text{Copley}} [\lambda_j^k (Hold\_Time(i)(m))]$$

e) Eligible_P4 - BCD(i)(m) = $$\sum_{j=\text{Park Street}} \sum_{k=Hynes}^{\text{Kenmore}} [\lambda_j^k (Hold\_Time(i)(m))]$$

f) Eligible_P4 - C(i)(m) = $$\sum_{j=\text{Park Street}} \sum_{k=\text{C-Surface Stops}}^{\text{C-Line Terminus}} [\lambda_j^k (Hold\_Time(i)(m))]$$

The estimation of actual passengers for the P3 and P4 classes is as follows:

g) If Sum of Eligibles(i) ≤ Capacity_After_P2(i) = $\begin{cases} \textit{then, Capacity\_Ratio(i)} = 1 \\ \textit{else, Capacity\_Ratio(i)} = \textit{Sum of Eligibles(i)/Capacity\_After\_P2(i)} \end{cases}$

h) Actual_P3 - BCDE(i)(m) = *Capacity_Ratio(i) * (Eligible_P3-BCDE(i)(m));*

Actual_P4 - BCDE(i)(m)= *Capacity_Ratio(i) *(Eligible_P4-BCDE(i)(m));*

Leftover_P3 - BCDE(i)(m) = $\sum_{l = \text{All Red Line Trains}}$ *[Potential_P3_ Transfers(i)(l)*Proportion of Transfers, BCDEi)] - Actual_P3-BCDE(i)(m);*

Leftover_P4 - BCDE(i)(m) = *Eligible_P4-BCDE(i)(m)- Actual_P4-BCDE(i)(m);*

i) Actual_P3 - BCD(i)(m) = *Capacity_Ratio(i) * (Eligible_P3-BCD(i)(m));*

Actual_P4 - BCD(i)(m) = *Capacity_Ratio(i) *(Eligible_P4-BCD(i)(m));*

Leftover_P3 - BCD(i)(m) = $\sum_{l = \text{All Red Line Trains}}$ *[Potential_P3_ Transfers(i)(l)*Proportion of Transfers, BCD(i)] - Actual_P3-BCD(i)(m);*

Leftover_P4 - BCD(i)(m) = *Eligible_P4-BCD(i)(m)- Actual_P4-BCD(i)(m);*

j) Actual_P3 - C(i)(m) = *Capacity_Ratio(i) * (Eligible_P3-C(i)(m));*

Actual_P4 - C(i)(m) = *Capacity_Ratio(i) *(Eligible_P4-C(i)(m));*

Leftover_P3 - C(i)(m) = $\sum_{l = \text{All Red Line Trains}}$ *[Potential_P3_ Transfers(i)(l)*Proportion of Transfers C(i)] - Actual_P3-C(i)(m);*

Leftover_P4 - C(i)(m) = *Eligible_P4-A(i)- Actual_P4-C(i)(m);*

Step 14: Calculation of P5 Passengers – P5 passengers accumulate at downstream stations during the previous headway time. We assume that at all stations past Park Street, boarding is not constrained in any manner by the capacity of the Green Line trains. Thus all eligible passengers to board become actual passengers. The only leftover passengers in the P5 category are those ineligible to board the train from the outset. P5 passengers also consist of any leftover P6 passengers ineligible from the last Green Line train.

a) $\text{Eligible\_P5 - BCDE(i)} = \sum_{j=\text{Boylston}}^{\text{Arlington}} \sum_{k=\text{Arlington}}^{\text{Copley}} [\lambda_j^k (Preceding\_Headway(i)(j))] + (Leftover\_P5 - BCDE(i-1)) + (Leftover\_P6 - BCDE(i-1$

b) $\text{Eligible\_P5 - BCD(i)} = \sum_{j=Boylston}^{\text{Hynes}} \sum_{k=Hynes}^{\text{Kenmore}} [\lambda_j^k (Preceding\_Headway(i)(j))] + (Leftover\_P5 - BCD(i-1)) + (Leftover\_P6 - BCD(i-1))$

c) $\text{Eligible\_P5 - C(i)} = \sum_{j=Boylston}^{\text{C-Surface Stops}} \sum_{k=\text{C-Surface Stops}}^{\text{C-Line Terminus}} [\lambda_j^k (Preceding\_Headway(i)(j))] + (Leftover\_P5 - C(i-1)) + (Leftover\_P6 - C(i-1))$

Step 15: Calculation of P6 Passengers – P6 passengers board at downstream stations during the hold time. Any leftover P6 passengers become potential P5 passengers for the next Green Line train.

$$\text{a) Eligible\_P6 - BCDE(i)(m)} = \sum_{j=\text{Boylston}}^{\text{Arlington}} \sum_{k=\text{Arlington}}^{\text{Copley}} [\lambda_j^k (Holding\_Time(i)(m))]$$

$$\text{b) Eligible\_P6 - BCD(i)(m)} = \sum_{j=Boylston}^{\text{Hynes}} \sum_{k=Hynes}^{\text{Kenmore}} [\lambda_j^k (Holding\_Time(i)(m))]$$

$$\text{c) Eligible\_P6 - C(i)(m)} = \sum_{j=Boylston}^{\text{C-Surface Stops}} \sum_{k=\text{C-Surface Stops}}^{\text{C-Line Terminus}} [\lambda_j^k (Holding\_Time(i)(m))]$$

Step 16: Evaluation of Benefits/Delays of a Hold – The expected delay and benefit of a hold vary across passenger types. We assume that passengers perceived out-of-vehicle waiting time to be generally more burdensome than in-vehicle waiting time. α represents this ratio. The total benefit/delay to each passenger group is estimated based on the number of impacted passengers in each group, the holding time, the initial dwell time, the following headway on the Green Line for the three track segments and α.

a) Total Delay(i)(m) = $Holding\_Time(i)(m) * [Sum\ of\ All\ P1, P2, and\ P4\ Passengers]$

b) Total Time Savings(i)(m) =

$$\alpha \begin{bmatrix} [Following\_Headway\_BCDE(i) - Holding\_Time(i)(m) - Dwell(i)] * [P3 - BCDE(i)(m) + P4 - BCDE(i)(m) + P6 - BCDE(i)(m)] + \\ [Following\_Headway\_BCD(i) - Holding\_Time(i)(m) - Dwell(i)] * [P3 - BCD(i)(m) + P4 - BCD(i)(m) + P6 - BCD(i)(m)] + \\ [Following\_Headway\_C(i) - Holding\_Time(i)(m) - Dwell(i)] * [P3 - C(i)(m) + P4 - C(i)(m) + P6 - C(i)(m)] \end{bmatrix}$$

Step 17: Suggested Course of Action – A Green Line train (i) will be held for a Red Line train (m) based on the total net benefits of a hold. A potential hold is considered feasible if the total net benefits equal or surpass the minimum benefit criterion set by the transit agency. If transfers from the Red Line train (m) are held for by the Green Line train (i), the holding period will last only up to the time of the last transfer from the Red Line to the Green Line train.