Analysis of the Short-Turning Strategy on High-Frequency Transit Lines

by

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Abstract

Short-turning is a real-time control intervention in which a transit vehicle is removed from service at some point short of its destination and returned to service in the opposite direction. By skipping a section of its route in this way, the transit vehicle can recover lost time and fill a gap in service. In this thesis, a model is developed to simulate short-turning on a rail transit line with high-frequency service. In this model train dwell times, and hence headways, vary as a function of total passenger boardings and alightings. Passenger loads are dependent on vehicle headways. Inputs to this model include passenger arrival rates and passenger alighting proportions for each station on the line, average interstation running times, and initial sequences of train headways. Headways departing the terminal which is skipped when a train is short-turned are randomly generated. The principal output of the model is the change in total passenger waiting time for the system from short-turning. This model was set up to simulate short-turning at the outer end of the Blue Line of the Massachusetts Bay Transportation Authority. The analysis focused on short-turning in the a.m. peak period. The random generation of headways departing the skipped terminal was verified by comparing generated sequences of vehicles with records of actual train sequences.

Short-turns in which the short-turned train overtakes 0, 1, and 2 trains were simulated. In addition, a version of the model was tested in which the short-turning train was given slightly longer interstation running times. An additional effort to validate the model was then made by manually analyzing individual runs of the model. This analysis suggested several modifications to the simulation to make it more realistic. Additional trials were run with this modified simulation. The sets of simulation results from the base, 'slow train', and modified model were combined to prepare manual guidelines for short-turning. Alternative short-turn performance measures besides total passenger waiting time were also considered. Finally, a number of documented short-turns on the Blue Line were analyzed in an effort to understand actual short-turning practice on the line.

This research concluded that many of the short-turns currently made on the Blue Line are likely to increase, rather than decrease, total passenger waiting time and that short-turns are only likely to be beneficial in fairly severe delay incidents. Short-turning is apparently being used to compensate for insufficient allowed round-trip running time. The results of this research and previous work on short-turning were combined to reach a set of general conclusions about short-turning. In addition, the possibility of developing a decision support system based on some of this research for a central supervision center was explored.

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Chapter 1

Introduction

Over the last 15 years, public transit systems in North America have made considerable progress in renewing and modernizing their facilities and equipment. The reliability, safety, and public image of their services have steadily improved as a result, in many cases leading to expanded ridership, especially for rail transit systems. While these physical improvements have reduced serious disruptions caused by system failures, transit services continue to be affected by minor delays that cause overcrowding and frustration for transit users. Supervisors can correct such minor disruptions by redirecting vehicles to close gaps in service. Unfortunately, these efforts are often hampered by inadequate information and conflicting objectives. During the same 15 year period, information technologies have made enormous advances. Some of these technical innovations could provide supervisors with the information and tools needed to make more effective control interventions.

One frequently used type of real-time service intervention is known as short-turning or short-lining. Short-turning involves removing a transit vehicle from service before it has reached the end of its route and returning it to service in the reverse direction. Because part of the route is skipped, running time can be saved and delays recovered. The objective of this thesis is to evaluate short-turning as a real-time service intervention. In the process, a model for simulating high-frequency transit lines will be developed, applied to an actual rail transit line, and evaluated for accuracy. This research will attempt to answer the following three questions:

1) How can real-time control strategies, particularly short-turning, be evaluated both on one specific line and in general?

2) When is short-turning an effective strategy?

3) How might the findings of 1 and 2 above be applied to assist transit supervisors with real-time control decisions?

1.1 Characteristics of High-Frequency Transit Lines

This research applies primarily to "high-frequency" transit operations. “High-frequency” is used to describe transit services for which the scheduled headways over a given route during a given time period are no more than 10 minutes. It is generally accepted that under these conditions, passengers arrive at stops or stations in a Poisson, or random, manner[1]. In other words, passengers can be assumed not to time their arrival to that of a particular scheduled vehicle trip. Though the average passenger arrival rate at any station may vary widely over the course of a day, a constant rate may be assumed in a given headway interval.

This characteristic has a number of important operational implications. The most important result is that the expected number of passengers waiting to board a particular vehicle at a station will be directly proportional to the preceding headway of that vehicle. The passenger load of that vehicle will therefore also depend on its preceding headway. The result of this is that a vehicle with a longer than average preceding headway will grow more and more crowded, while a vehicle with a shorter than average headway will be lightly loaded. It is also an unfortunate fact that under such uneven loading conditions, the majority of passengers will experience the crowed vehicle. Vehicle dwell time at each stop is generally dependent on the number of boarding and alighting passengers[2]. In addition, as vehicles become more and more crowded, the boarding and alighting process usually becomes slower due to congestion within the vehicle. The extreme case is a packed

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[1] J. K. Joliffe and T. D. Hutchinson, “A Behavioral Explanation of the Associations Between Bus and Passenger Arrivals at a Bus Stop,” *Transportation Science*, Vol. 9, No. 3, 248-281.

[2] Nigel. H. M. Wilson and Tyh-Ming Lin, “Dwell Time Relationships for Light Rail Systems,” *Transportation Research Record 1361*, (1993) 296-304.

subway train spending over a minute at a crowded platform with almost no one able to board, while the train operator struggles to close the doors. The vehicle directly following one with an excess headway and running at average speed will begin to 'catch up'. As its headway gets shorter, it will encounter smaller numbers of boarding passengers and thus have shorter dwell times, causing it to gain on the preceding vehicle even more rapidly. The result of all this is the 'bunching' effect. These characteristics result in a strong positive feedback effect for late-running vehicles. Without regulation, headways are inherently unstable in high-frequency transit operations. (Empirical evidence of bunching behavior is discussed in Potts and Tamlin (1964)[3] and Vuchic (1969)[4]. Bunching is modeled in Newell and Potts (1964)[5] and Chapman and Michel (1978)[6]).

Under such conditions, on-time performance is secondary in importance to maintaining uniform headways. On-time performance generally involves defining threshold values for 'early' and 'late'; a trip is only considered 'early' or 'late' if its deviation from the schedule exceeds these threshold values. The range within these limits will likely be large enough to cause significant overcrowding, and may even be larger than the scheduled headway. Vehicles must reach their termini in time to begin their next trip on-time so that scheduled headways can be maintained. However, schedules normally include recovery time that ensures this is possible a high percentage of the time.

A large number of service reliability performance measures are used by U.S. transit agencies (indeed, the appropriateness of different indicators for different types of transit service is only now being carefully investigated). To individual transit users, service reliability might reflect on-time arrivals at their origin or destination, predictable travel times, or absence of delays en route. For services with headways greater than 10 minutes or so, passengers will tend to time their arrival at stops to meet scheduled departure times. Under these conditions, on-time performance clearly becomes more important. With high-

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[3] R. B. Potts and E. A. Tamlin, "Pairing of Busses," *Australian Road Research* 2 (2) (1964): 3-9.

[4] Vukan. R. Vuchic, "Propagation of Schedule Disturbances in Line-Haul Passenger Transportation," *UITP Revue* 18, (1969): 281-284.

[5] G. F. Newell and R. B. Potts, "Maintaining a Bus Schedule," *Proc. Australian Road Research Board Conf.* 2 (1) (1964): 388-393.

[6] R. A. Chapman and J. F. Michel, "Modeling the Tendency of Busses to Form Pairs," *Transportation Science*, Vol. 12, No. 2, (1978): 165-167.

frequency service, however, passengers really do not care what the scheduled arrival times are but simply go to the stop when they are ready to leave. While such passengers undoubtedly do want predictable overall travel times (so they reach their destination on time), they will be much more concerned with not having to wait an excessive amount of time than with whether the vehicle in on schedule. In addition, discrete choice analysis indicates that transit users perceive waiting time as more inconvenient that in-vehicle travel time[7]. Passenger waiting time will therefore be the principal performance measure used in this research. The pros and cons of using passenger waiting time will be discussed in Chapter 2.

Within the constraints of a given schedule, supervisors may take various actions to regulate headways and recover from disruptions. Such interventions may also be needed because it is not possible to schedule sufficient recovery time on busy sections of transit lines without lowering the capacity of the system. Recovery time also tends to reduce the utilization of equipment and operators. Most control interventions can be broadly categorized into holding strategies and station skipping strategies. Holding strategies are generally the easiest to implement and usually involve having a vehicle wait an extra amount of time at a station so that its preceding headway is increased, and its following headway decreased. Holding is constrained primarily by the need to avoid delaying a vehicle to the point that it can not begin its next trip on time - causing an additional gap in service later.

Station skipping procedures, by contrast, enable a vehicle to recover lost time but generally involve inconveniencing some passengers in order to benefit others. They thus tend to be more difficult to implement than holding, where the passenger inconvenience is only in terms of increased in-vehicle time for passengers on the vehicle being held. Station skipping actions include deadheading, expressing, and short-turning. Deadheading involves having a vehicle leave a terminus and run empty over the first segment of its return trip to avoid deceleration, acceleration and dwell time. Passengers at the skipped

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[7] P. Mayworm, A. M. Lago, and J. M. McEnroe, *Patronage Impacts of Changes in Transit Fares and Services,* Executive Summary, U.S. DOT, UMTA, RR 135-1, September 1980, 7-18.

stops who would have boarded this vehicle must wait for the next one, but may not even be aware of any intervention. Expressing involves directing a vehicle already in service to skip a succession of stops on its route. Short-turning involves removing a vehicle from service short of its planned destination and returning it to service in the opposite direction, possibly overtaking other vehicles in the headway sequence. Expressing and short-turning force passengers destined for the skipped segment to alight and wait for a suitable following vehicle. This is an inconvenience above and beyond the additional waiting time involved, since it is an unexpected delay and these passengers are forced to give up their seats. One additional class of service interventions sometimes used are run-as-directed (RAD) or "gap" vehicles. These are vehicles, with operators, that are routinely scheduled to stand by to be placed into service when needed to fill gaps in scheduled service. While this is a very effective way to recover from disruptions, it is not necessarily an efficient use of resources.

1.2 Motivation

Service interventions are generally made either by field supervisors such as inspectors positioned on station platforms or in radio cars, by operators in interlocking towers, or on more modern systems, by dispatchers located in control centers. While field supervisors have an "eye-witness" view of operating conditions at their location and can communicate directly with vehicle operators and customers, they usually have very limited information on the overall system state.

Centralized control, by contrast, should enable much more information to be channeled to the decision makers. Technological improvements such as video monitors, Automatic Vehicle Identification (AVI), Automatic Vehicle Location (AVL), and Automatic Passenger Counters (APC) can provide unprecedented levels of information to controllers. Supervisors have traditionally relied on judgment developed through years of experience. With additional information, they should be able to make much better control decisions. A potential challenge, however, is to provide systems enabling controllers to process the sheer volume of data presented to them. High-frequency transit operations tend to be too fast-paced to do this manually in the available time horizons. In addition, many control actions, particularly station skipping strategies, have complex consequences. This is because control actions result in both inconvenienced and benefited passengers. Automatically collected data, however, could easily be fed to an automated system to assist the decision process by performing the analysis.

1.3 Introduction to the Short-Turning Problem

Short-turning is carried out at some intermediate point on a transit route. On rail lines, it can only be done at a location where a train can reverse direction and cross over to the opposite track. Ideally, a siding or loop track should be available so that reversing the train will not delay other traffic. When a vehicle is short-turned, a segment of its route is skipped altogether. Passengers on board the short-turned vehicle traveling to points beyond the short-turn point must alight and wait for the next suitable vehicle. Passengers waiting at stops on the skipped segment who would have boarded the short-turned vehicle must also wait for the next suitable vehicle, but at least they are not unexpectedly "dumped". Hopefully, however, if the short-turn decision is sound a larger number of persons will experience a shorter wait in the reverse direction, and are also less likely to be denied boarding the first vehicle to arrive due to overcrowding.

An important difference between short-turning and other station-skipping strategies is that short-turned vehicles can overtake vehicles ahead of them in the sequence of vehicles. This has important implications for modeling short-turning.

This research will first develop a general short-turning simulation model. The model will then be adapted to simulate short-turning on the Blue Line of the Massachusetts Bay Transportation Authority (MBTA). Short-turning on this line will be analyzed using this model. The results of this analysis and other research will be used to examine the general conditions under which short-turning should be an effective strategy.

1.4 Prior Research

A considerable amount of work relevant to this project has already been done. Barnett (1974)[8] examined headway variation on transit lines and considered a holding strategy at a selected stop on a transit line. The paper developed an algorithm to determine an optimal threshold headway. Vehicles with headways less than this threshold would be held to this headway. The objective function was to minimize the sum of passenger waiting time downstream from the control point and the average delay for passengers on board that would be delayed by holding. Service on the MBTA Red Line was used as a case study, with Washington St. (Downtown Crossing) northbound selected as the control point. The model indicated that average waiting time could be reduced with holding and that average holds would be less than 1 minute. A later work by Barnett (1978)[9] considered a similar problem but tried to optimize holding for both the users and the transit operator. Rather than trying to minimize passenger waiting time, the model considered costs to passengers in terms of individual departure times, arrival times and waiting times. However, the transit system modeled consisted of a single vehicle and it was concluded that an analytic solution would probably not be possible for a system with multiple vehicles.

Tunquist and Blume (1980)[10] again examined holding strategies. The goal of this research was to develop a set of guidelines to identify conditions in which holding would potentially be helpful. A model was developed for screening routes and holding point locations. As in Barnett (1974), the objective of this model was to minimize the sum of aggregate passenger waiting time and delay time to riders on the vehicles held. Two extremes of this model were considered to estimate the upper and lower bounds on the

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[8] A. Barnett, "On Controlling Randomness in Transit Operations," *Transportation Science*, Vol. 8, No. 2, (1974): 102-106.

[9] A. Barnett, "Control Strategies for Transport Systems with Nonlinear Waiting Costs," *Transportation Science*, Vol. 12, No. 2, (1978): 102-116.

[10] Mark A. Turnquist and Steven W. Blume, "Evaluating Potential Effectiveness of Headway Control Strategies for Transit Systems," *Transportation Reasearch Record* 746 (1980): 25-29.

effectiveness of holding. The route screening process was based only on the coefficient of variation (COV) of the headway distribution and the proportion of passengers delayed as a result of holding. No knowledge of the covariance between successive vehicle arrivals was required.

Abkowitz and Engelstein (1984)[11] described a method for improving service reliability through improved scheduling combined with holding in real-time. The objective of the model was to minimize passenger waiting time by choosing the optimal holding point and threshold minimum holding headway. This model was based on empirical running time variation and headway variation models which were validated using empirical data from actual bus routes in Los Angeles. The authors concluded that holding is generally an effective strategy and also that the optimal holding point would be where loads are relatively light and stops downstream have high demand.

The main weakness of the above research projects is that dwell time effects and the positive feedback of these effects on headway variation were not explicitly modeled, if they were considered at all. In addition, these models depended on distributions of headways rather than on actual headway data. For the most part, it was assumed that only limited data would be available to the supervisor making the holding decision, specifically that the headways of following vehicles would be unknown. An exception to this was Koffman (1978)[12], who developed a simulation model of a bus route and used it to test several real-time control strategies. Bus dwell times were modeled as a linear function of passenger boardings and alightings, with passengers arriving at each stop at a constant rate. Running times were randomly generated. The controls tested were holding, allowing only alightings at stops , and signal preemption. At any stop at which the headway of a bus was less than some threshold value, it was held to that headway. If a bus load exceeded some level, it would skip loading. The simulation indicated that holding caused little or no decrease in passenger waiting time and an increase in travel

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[11] Mark Abkowitz, and Israel Engelstein, "Methods for Maintaining Transit Service Regularity," *Transportation Research Record* 961 (1984): 1-8.
[12] D. Koffman, "A Simulation Study of Alternative Real-Time Bus Headway Control Strategies," *Transportation Research Record* 663 (1978): 41-46.

time, while skipping loading increased passenger waiting time by more than it reduced travel times. Signal preemption, however, reduced both waiting and travel times.

Macchi (1989)[13] made the first effort to examine expressing as a real-time control strategy. He developed a model to evaluate the waiting time impacts of expressing trains on the MBTA Green Line. This spreadsheet-based model was used in a simulation program using real and randomly generated input data. This model was used to analyze expressing on two different segments of the Green Line. Selection of an express segment was also discussed, but was not directly incorporated into the model. Several important simplifying assumptions were made in the simulation: train capacity was not constrained; trains maintained their relative headways downstream from the expressing point (except, of course, for the time savings from expressing); all passenger waiting time was weighted equally; and the impact of expressing a train on that train's next trip was not considered. Nevertheless, this model provided many valuable insights into the real-world expressing problem. Manual expressing decision guidelines were developed, and it was concluded that an Automatic Vehicle Identification system could significantly improve the effectiveness of expressing on the Green Line if it were carefully integrated into the control structure.

Deckoff (1990)[14] modeled the impact of short-turning as a real-time control measure. Short-turning was examined at just one location, also on the MBTA Green Line. This project also developed a spreadsheet model. The most significant simplification was that constant headways were assumed. Each train retained its initial headway for its entire round trip. The only exception to this was the short-turned train. On the other hand, train capacity constraints and overtaking by short-turned trains *were* modeled in this project. As with Macchi, it was concluded that given good AVI data, the success-rate of short-turning could be substantially improved. Manual guidelines were also developed. The

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[13] Richard A. Macchi, "Expressing Vehicles on the MBTA Green Line," M.S. thesis, Civil Engineering, MIT, 1990.

[14] Anthony A. Deckoff, "The Short-Turn as a Real Time Transit Operating Strategy," M.S. thesis, Civil Engineering, MIT, 1990.

basic structure of Deckoff's short-turning model was taken as the starting point for this research.

Soeldner (1993)[15] continued this line of research with a comparison of expressing and short-turning in the Central Subway of the MBTA Green Line. Models were developed for expressing and short-turning using a similar set of assumptions as the previous two projects. In this case, however, an effort was made to develop an optimal strategy by considering two control strategies in combination. Once again, manual guidelines were developed. This is an important step, because in the real-world a number of strategies are often available.

Eberlein (1995)[16] represents the definitive work to date on the real-time control problem. This project developed generalized models for deadheading, expressing, and holding, both independently and in combination. However, short-turning was not included in this project because of the degree of added complexity created by overtaking. Optimization procedures were devised to minimize "passenger cost" in terms of waiting time. Data from the AVI system recently installed on the MBTA Green Line was used for much of the input for these models. Two different idealized forms of transit system were modeled. The first system assumed constant passenger arrival rates across stations and fixed vehicle dwell times. The second system allowed variable passenger arrival rates and dwell times which were dependent on the number of boardings and alightings. The optimization problem for this second system was found to be intractable. However, insights from the first model were used to develop a search algorithm to analyze the second model. This research concluded that holding is the best *individual* strategy but that combined control measures are even more effective and have fewer negative side effects. Combined control is particularly effective when scheduling constraints exist.

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[15] David W. Soeldner, "A Comparison of Control Options on the MBTA Green Line," M.S. thesis, Civil Engineering, MIT, 1990.

[16] Xu Jun Eberlein, "Real-Time Control Strategies in Transit Operations: Models and Analysis," Ph.D. dissertation, Civil Engineering, MIT, 1995.

Li (1994)[17] examined "real-time scheduling" for a single extremely high frequency transit line in Shanghai, China. The problem was described as assigning dispatching times, express segments, and short-turn points on a route with highly variable running times. The objective was nevertheless to minimize waiting time. The general characteristics of this problem were therefore very similar to those in the projects discussed above. Two models were developed, each with a different set of simplifying assumptions needed to make the problem tractable. Heuristic methods to optimize each of these problems were also developed. Unfortunately, the short-turning model did not allow for a short-turned vehicle to overtake others in the sequence. This severely limits the relevance of this work to general transit line applications.

Fellows (1990)[18] examined whether the AVI system installed on the MBTA Green Line could be used as a tool for centralized real-time control. Enhancements to the system, including models to evaluate the waiting time impacts of control actions, were proposed. In addition, an AVI workstation for central controllers was designed, and changes to the organizational structure of the Green Line were recommended to facilitate centralization. Fellows' research is relevant to this project because it lays the groundwork for the decision support systems that could be incorporated into a modern operations control center.

Major areas of research missing from this set of projects include the development of a generalized simulation model and models featuring variable dwell times and headways.

1.5 Thesis Outline

Chapter 2 describes a model developed to simulate a single transit line. This model will be set up to simulate short-turning on a rail line, but could also be used to model other control actions. The primary objective function in this model will be the net passenger

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[17] Yihua Li, "Real-Time Scheduling on a Transit Bus Route," Ph.D. dissertation draft, Ecole des Hautes Etudes Commerciales, Affiliee a l'Universite de Montreal, Canada, 1994.

[18] Robert E. Fellows, "Using and Enhancing Automatic Vehicle Identification to Improve Service Control on the MBTA Green Line," M.S. thesis, Civil Engineering, MIT, 1990.

waiting time saved by short-turning. Actual train sequences and passenger demand data will be inputs to the model. Vehicle capacity constraints, block signaling and station dwell time behavior will be modeled. Dwell times will be dependent on total passenger boardings and alightings at each platform. Thus, headways will also be variable. The headway of each train departing the skipped terminal will depend on its headway on arrival there and will also vary randomly. Time required for short-turning at the short turn point will be randomly generated, but other interstation times will be constants.

Chapter 3 will first introduce the case study of this project, which is the MBTA Blue Line. The characteristics and operations of this line will be outlined, including where and when short-turning is used in actual practice. A simulation of this line will then be prepared to evaluate short-turning using the model developed in Chapter 2. Constant and randomly generated inputs to this model, including passenger demand data, dwell time functions, and headway sequences, will be explained in detail. The simulation will then be checked against the actual behavior of the line.

Chapter 4 will describe how the simulation model was used and how the output was analyzed. Several types of short-turns will be considered. In addition, the impact of having the train with the long headway move slightly slower than the other trains will be examined. Then, potential errors in the simulation will be discussed and the sensitivity to changes in the initial assumptions analyzed. The validity of the model with then again be tested. The results of the simulations will then be used to derive proposed guidelines for short-turning on the Blue Line. Next, alternative measures to passenger waiting time will be considered. Finally, actual short-turning practice on the Blue Line will be examined.

Chapter 5 will begin by discussing the a priori conditions under which short-turning is likely to be an effective strategy. The findings of Deckoff's prior research on short-turning on the MBTA Green Line, and of this research project will then be reviewed. Finally, a general set of conclusions about short-turning will be presented.

Chapter 6 will outline the operations control and supervision structure currently in place for the MBTA's rail rapid transit system. A new operations control system (OCS) now under development will then be introduced. Opportunities presented by the new OCS for improving the effectiveness of supervision will then be considered. Finally, a conceptual proposal will be presented for a decision support system to be incorporated into the new OCS.

Chapter 7 will summarize the findings and conclusions of this research. Directions for future research will also be recommended.

Chapter 2

General Model Development

In order to evaluate short-turning in a realistic and efficient manner, a computer simulation model was developed. This model was implemented in a program written in the C++ programming language. Some references will be made to the structure of this program. However, the purpose of this chapter is to describe how the general short-turning model was developed and why the approach used was taken. The purpose is not to explain the program itself in detail.

2.1 Modeling Objectives

Studies of real-time control strategies have used both passenger waiting time and total travel time as principal decision variables. The objective of the control strategy is to minimize either or both of these quantities - usually subject to various constraints including vehicle capacities, minimum safe headways, and scheduling requirements. It will be seen, however, that although overall average travel times are impacted by the control actions taken, change in waiting time accounts for most of the change in travel time. Changes in dwell time caused as second-order effects of the real-time intervention impact the actual trip time of the train. This affects the on-train time of the passengers on board as well as the waiting time of passengers who are going to board this train. However, these effects are generally small in comparison to changes in waiting time. In addition, passenger waiting time is much more generally comparable across passengers, since dividing total passenger waiting time by the total number of passengers will give an average wait time that is representative of all these passengers. It seems less appropriate to think in terms of average travel time given the wide range of travel times for passengers traveling between different origin-destination pairs. Moreover, the significance of the benefit of a real-time intervention will diminish as the overall travel time of a particular passenger increases (e.g. a short-turn that saves two minutes will mean more to a commuter who's usual trip takes 5 minutes than it will to one who's usual trip takes 20 minutes). Expected waiting time is not directly dependent on the length of a trip over an individual line with a constant level of service. On the other hand, if one wanted to use total travel time for the entire system (in this case one line) as an objective variable, then these concerns would be moot. In addition, however, discrete choice analysis indicates that passengers typically perceive waiting time as more "costly" to them than in-vehicle travel time[19]. This is probably because of the uncertainty of when the transit vehicle will arrive; once a transit user is on the vehicle an expeditious arrival seems more certain. One additional incentive for using exclusively passenger waiting time as the objective variable for this model was for consistency with other studies on real-time control actions. The principal objective variable in this model will be total passenger waiting time for the system. With some additional effort, this model could be modified to calculate total travel time as well.

2.2 Model Structure

The models developed by Macchi, Eberlein, Li, and others dealt with real-time control strategies which did not involve overtaking or the removal or addition of vehicles to the system. Short-turning strategies, however, frequently involve re-inserting the vehicle that has been short-turned ahead of its original position in the sequence of vehicles. In other words, before the short-turn, one might have the sequence of trains 1, 2, 3, and 4 on a transit line. If train 3 is short-turned, it could be placed back in service in front of train 2, so that the sequence would now be 1, 3, 2, 4.

Because overtaking is allowed, it is not possible to model short-turning in strictly analytical terms; one can not express short-turning as a function to minimize subject to a set of constraints. It was therefore decided to write a model simulating the workings of the actual transit line. A period of operation of a transit line is simulated twice - once with

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[19] Mayworm, et. al., 7-18.

and once without a train being short-turned. The outcomes of the two cases can then be directly compared; specifically the total passenger waiting time for the two cases is compared. If the short-turn results in a significant saving in total passenger waiting time, then it might be deemed a successful intervention. Of course, this is ignoring any additional inconvenience incurred by those passengers forced off the short-turned train, or the effect of the short-turn on subsequent trips.

One approach to analyzing short-turning strategies would be to simulate the operation of a transit line for a time period such as the a.m. peak or even an entire day. Operations for the period could be simulated once with some short-turning policy in place, and then again without any short-turns allowed. Alternately, one could model an entire time period both with and without one individual short-turn intervention. This arrangement would allow all of the impacts of the short-turn on all operations for the remainder of the time period to be evaluated. Such impacts might include placing two trains scheduled to leave service at the end of the a.m. peak in adjacent positions in the sequence so that an excessive gap in service would result following the pull-backs. By taking the difference in total waiting time between the two cases, a comparison could then be made of the total waiting time accumulated with each strategy in place.

A somewhat different method is to look at an isolated set of trips preceding and following a disruption in service. The impact of a particular strategy on only this set of trips and their riders can then be evaluated. The impact of this intervention on trips after the last in the sequence can be assumed to be negligible. As before, the difference in total passenger waiting time would be taken as the principal performance indicator. The advantage of this arrangement is that far fewer trips must be simulated. Thus, the calculation time will be much shorter.

This later approach is the one taken in this project. One of the objectives of this thesis was to develop a model suitable for use in real-time. The limited computation time required by this model is thus very beneficial. In addition, the influence of external processes on the system are sufficient to limit the value of projecting outcomes far into the future. Therefore, modeling only the vehicles immediately adjacent to the vehicle actually short-turned is probably quite sufficient.

The model developed here is intended to be a general model that could be adapted for any non-branching transit line. While the program into which the model was incorporated is tailored to a specific system, modifying it for any other rail system should be straightforward. Somewhat more extensive changes would be required to use this model for a branching system, or for a bus system where overtaking is possible at any point along the route.

2.3 Model Assumptions and Generalizations

In the operation of real transit systems, a great many random processes are taking place simultaneously. Many are dependent on other events, often external to the system itself. In order to keep this modeling project manageable, many simplifications were made.

In planning this model, careful thought was given to what processes were essential to simulate, and which could be ignored. Many of the decisions made were guided by the particular characteristics of the line being modeled for this project. Since the model took the form of a simulation, rather than a set of mathematical relationships, there was considerable latitude to simulate various aspects of system behavior.

Each trains' trip over the line consists of travel time between stations, turning time between trips, and dwell time at stations. Interstation time is the time required for a train to move from one station platform to the next, including acceleration and deceleration time, but not including any time spent standing at platforms. In this model, with a few important exceptions, these times were treated as constants. As will be explained in Chapters 3 and 4, on the line actually modeled for this research, interstation times for a given station pair in fact do vary significantly and this appears to be an important cause of train bunching. Interstation times first of all show considerable random variation. In addition, however, the average time for a particular train over a particular segment may be largely dependent on the operator - some train operators tend to run slower and more cautiously than others throughout each trip. Unfortunately, there simply was not sufficient data available to model this systematic variation in interstation time, or even the random variation in times for individual segments, though the program could easily have accommodated it. Instead, average values were used.

The implications of this simplification are significant. A slow-running operator may be the initial cause of an excessively long headway, while a fast operator might be counted on to recover time and close a gap without intervention by supervisors. It might also be valuable to include this source of random variation in the simulation. Provision *was* made in the program for increasing or decreasing all of the interstation times of individual trains by a constant scaling factor. In this way, the sensitivity of the model to hypothetical systematic variation in train speeds could be tested.

Interstation time for a given train is also influenced by the preceding train, since a slow-moving train will delay its follower. The following train will encounter yellow or red signals and so will have to slow down. The effect of the signal system was easily simulated by imposing a minimum preceding headway constraint on each train. This will be discussed further later on.

Dwell time at each platform, on the other hand, was treated as a deterministic function of the total number of boarders and alighters. In order to simplify the dwell time calculation, a decision was made to partition dwell time into separate boarding and alighting processes. This implies that no passengers board the train until the alighting process has been completed. While this may extend the expected dwell time slightly, passenger flows on the line being modeled are such that either boarding or alighting generally dominates at any given stop. A dwell time function that captured simultaneous boardings and alightings could be used, but it would probably give only slightly shorter overall dwell times.

Alighting time is calculated simply by dividing the total number of alighters by an alighting rate in passengers/sec. Such a linear function is also used to calculate boarding time. However, there is a discontinuity in the boarding time function at the point at which the train becomes so full that passengers will be left behind on the platform. If the train is full but there are still a significant number of passengers waiting on the platform, an additional "excess_dwell_time" is imposed. The excess dwell time represents the time due to passengers crowding around the train doors, trying unsuccessfully to board, while the operator struggles to close the doors. Excess_dwell_time in only assigned a non-zero value when more than some threshold number of would-be boarders will be left behind.

The final component of dwell time is a constant which is simply the intercept term from the linear dwell time function. It was assumed that this represents the time taken by the train guard to look to see that the doors are not obstructed and close them. Setting this aside as a separate term has several advantages. The most important was the following: A few stops on the line simulated for this project were given constant dwell times to simplify some of the calculations. At these stops, alighting, boarding, and excess time were all constrained to equal 0 and a much longer constant dwell time is used to represent the entire dwell time at these stops.

This arrangement captures the essence of dwell time behavior on high-frequency transit operation. However, it is not completely realistic. Significant omissions include:

- The effect of increasing vehicle load slowing the boarding and alighting rates. For example, a completely full train stopping at a platform to allow only a few passengers off will still probably require extra dwell time.

- A realistic dwell-time function should also capture random variation in dwell time. There are several causes of this random variation. For one thing, dwell time is influenced by the *distribution* of boarders along the platform, and the distribution of alighters between cars and doors. If a disproportionate number of passengers try to board through one door, a longer dwell time will result than if they are uniformly distributed. The boarding rate estimation used in this project probably reflects the typical distribution of passengers at the platform where the data was collected.

- Discretion of the operator in holding the doors for running boarders is also a source of variation. The operator of a late-running train is less likely to wait for running passengers. This would introduce random variation to the constant term in the dwell time model.

Given a much larger data collection effort, it would be possible to develop a more accurate, non-linear dwell-time model. What is important is that the positive feedback effect of dwell time on a vehicle's preceding headway has been simulated realistically. This is essential to modeling high-frequency transit systems.

While this model reflects the effect of dwell time on the relative headways and overall travel times of trains, the preceding headway of the first train in the sequence must be assumed to remain constant, since the model knows nothing about the behavior of the train which preceded this first train (though an exception to this was later made). In addition, as mentioned above, dwell times for the first few platforms in the run were treated as constants. The initial state of the system for each short-turn trial is based on the times at which trains pass a specific platform defined as TIME_POINT. Since this point is several stations downstream from the first stop on the line, all trains are initialized with the headways recorded at TIME_POINT. Since all of the variation in headway in this application is due to variations in dwell time, constant dwell times are used at all platforms prior to this point.

An additional characteristic of most rail transit systems is that some minimum headway between the departure of one train from each stop and the arrival of the next train is effectively imposed by the signal system. This minimum might be near zero for a streetcar or light rail system (where enforcing non-negative headways would prevent vehicles from passing through each other like ghosts). For a fully signal protected line, this minimum would likely be different for each platform due to variations in signal spacing, gradients, and visibility. There would also undoubtedly be a stochastic component reflecting variations in operator and vehicle response. Data was available on the Blue Line track and signal system and on vehicle performance. However, modeling this level of detail seemed to introduce an excessive degree of detail for a constraint which is anyway stochastic. Therefore, a constant minimum headway value was used across all platforms except for one which was treated differently for reasons which will be explained in Chapter 3. This constraint was also needed because trains can not overtake one another except when they are being short-turned. If this model were being applied to a bus system in which overtaking is allowed at any point, the minimum headway constraint would be omitted.

Vehicle headways can change substantially at terminals. Schedules include recovery time at least at one end of a route to allow for variation in running time. Thus, up to a point, vehicles that arrive late or with excessive preceding headways can begin their next trip on the scheduled headway. The actual amount of time recovered will depend on a number of factors, including the time needed to turn around and the amount of recovery time available. The headways with which trains depart this terminal are also dependent on their headways on arrival at the terminal, their scheduled departure times, the individual operator, and other factors. There is therefore also considerable random variation. Specific characteristics are dependent on the specific terminal and line. In Chapters 3 and 4, the processes developed for modeling the headway sequences departing the terminal on the line modeled will be explained in detail.

As will be shown in the next section, the structure of the model requires the short-turned train to re-enter service in a specified location in the sequence of trains. The train can be re-inserted anywhere in the sequence, including its old location, but its place is predetermined as part of the short-turning strategy being tested. This arrangement allows the train's new position to be set as an element of a particular short-turn strategy.

Another significant component of a short-turning strategy is the manner in which the short-turned train is dispatched from the short-turn point S'. This component of the short-turning problem *could* be treated as an optimization problem. For this project, however, a simple procedure was employed: provided that it can be turned in sufficient time, the short-turned train is held at S' after all waiting passengers have boarded. The train is held long enough that its preceding headway on departure will be approximately half the preceding headway that the train that will follow the short-turned train had on departure from S'-1 (before the short-turned train was re-inserted into the sequence of trains). For example, if train 3 is overtaking train 2 in the short-turn, and train 2 had an 8-minute preceding headway departing S'-1, then train 3 will be held until its preceding and following headways are each 4 minutes. If the process of turning the candidate train (moving it from departure from S to arrival at S') takes up too much time to permit this, the short-turned train is dispatched immediately after boarding. The time spent by passengers waiting on board the train is not counted as waiting time or recorded in any other way. The train will also not be held if it is loaded to capacity or if it will become filled during the hold. Since the minimum headway constraint is still imposed at S', if the short-turned train takes too long to turn, or if the preceding headway of the following train is small enough, the following train will be delayed on approach to S'. This delay is recorded as an additional performance measure. This arrangement seemed to be a reasonable one that might represent a good policy for short-turning.

High-frequency operation assumes that passengers arrive on each platform roughly in a Poisson manner. The actual rate of arrivals depends on many factors external to the system being modeled. Obviously, the expected arrival rate varies over time depending on work schedules, etc. For example, there are major peaks inbound in the a.m., outbound in the p.m., as well as sub-peaks for people who start work at 8:00 am, 8:30 am, etc. The program allows passenger arrival rates to vary over time.

In this model passengers arrive on each platform according to a Poisson distribution. The expected number of arrivals is determined from an observed passenger arrival rate (pax) multiplied by the elapsed time. This expected number is the mean parameter (μ) of the Poisson distribution. Alighting passengers are also calculated in a random manner using the binomial distribution. In this case, the parameter P used by the binomial is simply the expected proportion of the passenger stream arriving at that platform that alights there. At terminal stations, where all remaining passengers must leave the train, P is unity. Thus, the number of alighters must equal the entire train load. Because these quantities are random, the dwell times also have some random variation.

The train capacity constraint is also represented in the model. Train capacity is probably in reality a stochastic quantity, even for a given transit vehicle design. Effective capacity is most likely influenced by the willingness of boarders in different situations to pass up a crowded train and wait for the next one. For this project, however, a constant capacity value was used for expediency. Again, there was not sufficient data available to get a sense of the distribution of practical train capacities. In any case, the train capacity should generally only be a binding constraint for one or two of the trains in the sequence and then only at a few of the stops approaching the peak load segment.

This capacity constraint required several important assumptions. First of all, because only a limited set of trips are being modeled, it is not possible to represent the possibility of passengers left behind on each platform by the train preceding the first train in the sequence. Therefore, it is assumed that this "0^{th}" train has sufficient capacity to "clear" all of the platforms. For this reason, the passenger loads on all platforms are initialized to zero at the beginning of each run of the simulation. Thus, passengers boarding the first train in the sequence have accumulated only over that train's preceding headway. Another group of passengers is the small number who arrive at platforms as the last train in each sequence closes its doors and are therefore "left behind" at the end of the period modeled. However, since the *expected* number of passengers accumulating on both the short-turn and non-short-turn runs of the simulation are the same, and the total numbers are in any case quite small relative to the total number in the system, this difference is assumed to be negligible.

What is not generally negligible, however, are passengers left behind on platforms due to overcrowding. A particular short-turning intervention could either increase or decrease significantly the number of denied boardings in a given scenario. A successful short-turn should reduce denied boardings. An inappropriate short-turn, however, simply reduces the level of service on one section of the route and could cause (or increase) overcrowding on the following train. In order to monitor this accurately, the set of trains modeled must include enough following trains to accommodate any overflow caused by short-turning a train. The total number of denied boardings (defined simply as the number of passengers who were unable to board a train in a given run of the model) was used as a secondary performance measure. No effort was made to separately record passengers who might be unable to board two or more successive trains. These passengers were simply recorded as additional denied boardings.

2.4 Model Inputs

The primary set of inputs for the model are records of the times of trains passing a single point on the line (this data is collected by the MBTA as a measure of subway service reliability). This point is defined as TIME_POINT. No train identification is included with this data, so trains are identified in the model simply by the time at which they passed this point. The headways of these trains at this point can be calculated directly. A more accurate application of this model could be set up if a full automatic vehicle identification (AVI) system were available. Records of vehicle passing times, together with vehicle identification, from several points along the route would allow the simulation to be recalibrated as it ran. This would have reduced the reliance on "forecasting" vehicle trajectories through modeling dwell times.

When the program is run, the user enters a date which is included in the data set. This entire day's worth of times is then read to an array in the program. The constant NUM_TRAINS is defined as the number of trains in each sequence of trains being modeled. A pair of times defined as constants specify the time period to be studied. Starting with the first time that falls within this period of interest, the first NUM_TRAINS + 1 times are read into another array. The set of headways between these times are then tested to determine whether a pre-determined set of conditions for short-turning are met. If these conditions are met, the last NUM_TRAINS trains in this sequence becomes the next sequence of trains on which a short-turn is tested. Once the trial is complete, the full set of times is advanced by one, and the procedure is repeated for the next NUM_TRAINS + 1 times. If the conditions are *not* met, then the sequence is advanced without the trial being run. In other words, if NUM_TRAINS = 4 and the first set of times to be looked at is

"7:08:23",
"7:12:10",
"7:23:17",
"7:27:45",
"7:29:56"

and this sequence meets the criteria for short-turning[20], this first sequence of trains simulated would be as follows:

Train	**Passed TIME_POINT at**	**Headway**
1	7:12:10	0:03:47
2	7:23:17	0:11:07
3	7:27:45	0:04:28
4	7:29:56	0:02:11

In this research, the headway preceding train 2 was always the headway to be filled by short-turning. If the next time after "7:29:56" is "7:32:13", the second set of times to be considered would be

---

[20] The headway sequence criteria for short-turning will be explained in detail in Chapter 3.

"7:12:10",
"7:23:17",
"7:27:45",
"7:29:56",
"7:32:13"

and so on.

The data structures which represent the trains are then initialized with these times minus the fixed amount of time that would be required to travel to TIME_POINT from the N^{th} stop on the line (which is the 0^{th} stop for all trains), given the constant dwell times imposed over this segment. The trains therefore also start their trips with the same preceding headways which they had at TIME_POINT. It was decided not to try to predict dwell time effects backward through time.

There are several other sets of inputs to this model. The passenger arrival rates (pax) and passenger alighting proportions (pap) for each platform on the line are used to randomly generate boarding and alighting passengers. The program allows for a different passenger arrival rate and alighting proportion at each platform for each quarter-hour interval of the day (00:00:00 to 00:14:59, 00:15:00 to 00:29:59, etc.). As indicated above, passenger arrivals are generated in a Poisson manner. In order that both runs of each trial of the model use the same set of passengers, an array of passenger arrivals was generated for each trial. At the beginning of each run of the model, passengers are generated for each 1 minute interval for each platform for a 90 minute envelope beginning just before the first stop for the first train in the sequence. Thus, an N+1 by 90 matrix (where N is the number of platforms on the line) of passengers is generated. In this way, the same set of passenger arrivals are used for both runs of the model. In deterministic terms, the expected number of passenger arrivals in one minute at a given platform would be

$$60 * \text{pax}$$

where pax is in passenger arrivals per second. This value is also the expected number of passenger arrivals if passengers arrive at random in a Poisson manner. This, in turn, is the parameter μ (the mean) of the Poisson distribution, where $\mu = \Delta t \cdot \lambda$, and $\lambda = \text{pax}$. μ is the only parameter needed to randomly generate Poisson distributed integers with a mean of μ. Before each pair of runs of the model, each matrix element is initialized with a randomly generated integer number of passengers using the correct pax value for each platform and time period. During the operation of the model, passenger arrivals on each platform are then calculated from this matrix as will be discussed in Section 2.5.2.

Other inputs to the model include the interstation times, turnaround times at S', boarding and alighting rates, and eastbound headways departing the outer terminal N/2 + 1. The procedures used to collect, prepare and generate these inputs will be explained in detail in Chapter 3.

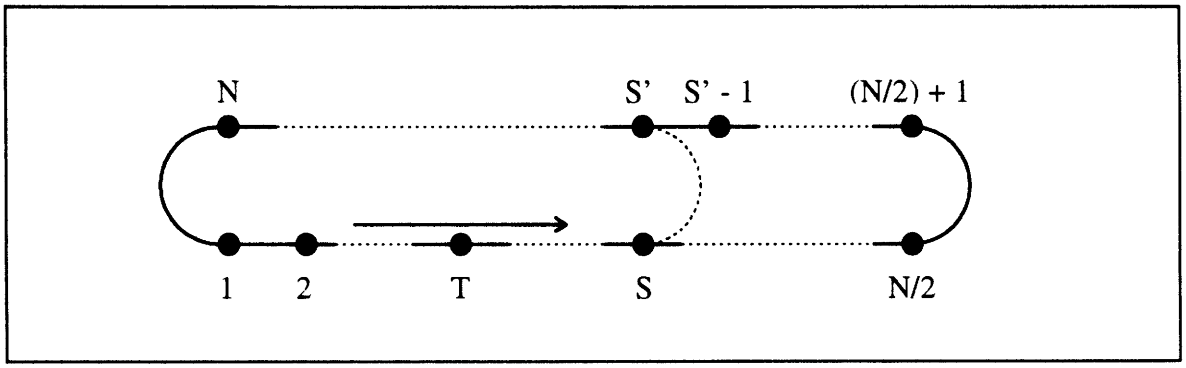
2.5 Model Structure

As explained above, the short-turn evaluation procedure involves running a simulation of the trips of a limited set of successive trains over the line being modeled. The run is done first with, and then without a particular short-turn being executed. During the short-turn run of the simulation, the specified train is removed from the sequence of trains at platform S. This train is then re-inserted into the sequence in the opposite direction, either in the same or a different position in the sequence. Waiting time is accumulated at each platform as passengers arrive, wait for the train arrival, and board when it does arrive. Additional waiting time is accrued by the passengers forced to alight from the short-turned train at S and wait for the following train. Following each run, total waiting time is summed over all platforms in the system. After both runs, the difference between the total waiting times for the two runs is taken to calculate the "delta_wt" for the short-turn.

2.5.1 Representation of Trains and Platforms

The transit line is represented simply by an array of records representing each platform (thus there will generally be two platforms for each station on the route, one for each direction). The position of each structure in this array corresponds to the position of each platform in sequence. The platforms are numbered in sequence from 1 to N. Platforms N / 2 and N / 2 + 1 are the terminal skipped by the short-turn, while 1 and N are the platforms at the terminal at the opposite end of the route. Platform S is the last stop made before short-turning. S' is the first stop following the short-turn. Figure 2.1 graphically shows the relative positions of each of these platforms. TIME_POINT is indicated by T.

Figure 2.1: Schematic Depiction of Transit Line with Short-Turn Point



Each platform record has variables for total accumulated passengers ("load"), total time waited by all passengers who used that platform ("total_pass_sec"), and the time of the most recent departure from that platform ("time_last_dep"). This later value is used to constrain the minimum headway.

The sequence of trains being modeled is also represented by an array of structures. Each train record has variables for "time", preceding headway ("prev_headway"), and passenger load ("load"). In this case, however, the order of the trains in this array does not necessarily correspond to the actual train sequence. A separate array of integers is used as a mapping function to keep track of the order of the trains. The integers in the array are the indices of the train records, and their place in this array corresponds to the place of these trains in the sequence. By calling the elements of the mapping array in ascending order, the trains can be called in their correct sequence. This arrangement allows overtaking to be accommodated. It could also just as easily allow for insertion of an extra train, re-insertion of a different train, or permanent removal of a train.

2.5.2 Representation of System Operation

Perhaps the most significant simplification in this model is that distance is not represented. Rather than modeling explicitly the laws of motion of the trains accelerating, braking, observing signals, etc., only time is represented. Since waiting time is the principal performance measure, and all of the other measures are based on passenger disposition, time is really all that is required. The behavior of the signal system in maintaining safe separation is easily simulated by the minimum headway constraint. One drawback of this arrangement, however, is that it is rather abstract and difficult to visualize.

At any given point in time, each train in the system is either dwelling at a platform or traveling between platforms. A train which has just departed S to be short-turned, essentially leaves the system until it re-appears at station S'. This train is temporarily removed from the mapping function, and the number of trains in the system is reduced to NUM_TRAINS - 1. On reentering service, the train is re-inserted in the mapping function in its new position. All passengers go through the following process: they first enter the system as they arrive on a platform. Then they wait to board, accumulating waiting time until boarding a train. In the case of the train which gets short-turned at S, however, all passengers on the train traveling to points between S + 1 and N / 2 must leave the train, join other passengers waiting on the platform, and resume waiting. This is the only special group of passengers in the model. They might formally be termed "skipped segment alighters". However, I have adopted the term "dumpees" from earlier researchers to describe this group. Passengers finally leave the system when they alight from the train at their destination.

The "time" stamp used by the trains is a particularly abstract concept. This variable is required to keep track of time for each train, since the model does not work in chronological order. Time is needed to recalculate headways and to index the correct elements of the passenger array, among other things. Since the dwell times in the segment of the route between the 0th stop and TIME_POINT are fixed, and the interstation times are all constants, the time required to cover this segment is itself a constant value over all trains. Thus, the time stamp of each train is initialized with the time at which that train passed TIME_POINT minus this fixed time. In other words, the time stamp's initial value is the estimated time at which that train departed the 0th platform. The time stamp is then updated at each step of that train's run over the line. For example as each train arrives at the second platform, the time stamp is augmented by the interstation time from the first platform to the second. The "prev_headway" variable is also recalculated on arrival and departure at each platform using the time variable minus the departure time of the previous train to depart that platform.

To explain the operation of the simulation model, it is necessary to describe some of the code used. At the highest level of the simulation there is a nested 'for' structure:

```
for(p = 1; p <= NUM_PLATFORMS; p++)
{
        for(s = 1; s <= num_t_this_p; s++)
        {
                Train_Handler(p, T[s], stop_mode);
        }
}
```

Where p runs over all of the platforms on the route, and s runs over num_t_this_p. Variable num_t_this_p is simply the number of trains in the sequence at the given time - either NUM_TRAINS or NUM_TRAINS - 1. T[s] is the mapping function which indexes the correct train record for each location in the sequence of trains. The subroutine called - Train_Handler() - is what controls virtually everything that happens to each train at each stop along its trip. Various 'if' statements within the inner 'for' loop call Train_Handler() in its various different modes.

2.5.2.1 Regular Dwells

The trains make several types of 'stops'. Each stop corresponds to a different stage of the trip. The majority of stops take place in the NORMAL mode and consist of the following steps, in order:

```
Arrive(p, t);
Alight(p, t);
Board(p, t);
Excess_Dwell(p, t);
Constant_Dwell(p, t);
Depart(p, t);
```

Each of these steps represents a different part of the dwell time, and a distinct operation for the train and passengers. Parameter p in each function is used to index the correct platform record, while parameter t is used to index the correct train record.

Arrive():

As each train arrives at each platform, the value of that train's time stamp is augmented by the interstation time from the previous. The only exception to this is for a short-turning train on arrival at S' from S where a randomly generated time for short-turning is added instead.

At this point, for all trains except the first one in the sequence, the minimum headway constraint is now imposed (recall that the first train is assumed to maintain a constant headway). The value of the train's time element is compared to the time at which the previous train departed that platform, plus the minimum headway. The following arrangement is used:

```
earliest_pos_arrival = platforms[p].time_last_dep + MIN_HEADWAY;
trains[t].time = max( earliest_pos_arrival, trains[t].time );
```

Where earliest_pos_arrival is the earliest possible arrival time for the train given the headway constraint and trains[t].time is the time element of the t^{th} train. Since the first train is not subject to this constraint, the model needs to know nothing about the train that preceded the first train. At this point, trains other than the first have their preceding headways recalculated:

trains[t].prev_headway = trains[t].time - platforms[p].time_last_dep;

Where trains[t].prev_headway is the preceding headway of the t^{th} train. A record of each train's arrival time at each platform is also made for later analysis.

Once the headway has been updated, the next important operation in Arrive() is to update the total accumulation of passengers on the platform since the previous train departed. The deterministic calculation for this would simply be

new_passengers = trains[t].prev_headway * pax

where pax is the passenger arrival rate in passengers per second (assuming the rate is constant over the elapsed time represented by prev_headway).

In this model, however, a matrix of random passenger arrivals is generated before the two runs of the model begin. Passenger arrivals over each time interval are then calculated from this array. If the time interval Δt (in this case prev_headway) spans two or more of the 1-minute periods, passenger arrivals from each minute are summed (note that a sum of Poisson distributed random variables is also a Poisson distributed random variable). Passengers from the fractions of minutes at the beginning and end of each interval are calculated proportionally. Thus, if an interval runs from 7:41:16 to 7:43:20, the number of passengers arriving on a particular platform will be 16/60 times the number of passengers in the 7:41:00 to 7:41:59 element of the matrix for that platform, all of the passengers from the 7:42:00 to 7:42:59 element, and 20/60 (or 1/3) of the passengers form the 7:41:00 to 7:41:59 element. All of these terms are rounded to the nearest integer. This process in used in each stage of the model to determine passenger arrivals.

After the number of newly arrived passengers has been determined and added to the total number of passengers waiting on the platform, the additional passenger waiting time accumulated is calculated. At each step of the model, additional passenger waiting time is determined in this way. This involves integrating the passenger accumulation over the elapsed time. To simplify this calculation, it is assumed that the passenger arrival rate during the interval was constant. The total additional passenger waiting time then equals

$(p_0 * \Delta t) + (\Delta p * \Delta t * 0.5)$

where p_0 is the number of passengers on the platform when the previous train departed, Δt is the total elapsed time (trains[t].prev_headway in the case of Arrive()), and Δp is the number of new passengers to appear during Δt. All of the initial passengers must wait the full Δt, while the expected waiting time for each subsequent passenger arrivals is one-half of Δt. The new passenger waiting time is added to the total passenger waiting time element for that platform.

Alight():

The next process undergone by every train at a normal stop is alighting. Alight() encompasses everything that happens to train t at platform p during the period of time it takes for all alighting passengers to leave the train. The number of passengers that will alight from the train is determined from the overall proportion of the passenger stream arriving at that platform that alights at that platform during a particular period of the day (pap). This proportion is equivalent to the probability that any given passenger on the train arriving at that platform will alight. This probability is used to randomly generate in a Binomial manner the number of alighters. Once the number of alighters has been generated, this number is subtracted from the train load. The alighters have left the system at this point.

This done, the next step is to calculate the time required for all alighters to exit the train. This is a very straightforward calculation:

alighting_time = alighters / ALIGHTING_RATE

The alighting time is then added to the time element of the train. During this time, additional passengers may have arrived on the platform. The alighting_time is used as the Δt to calculate the additional new passengers. The additional passengers are added to the platform load. Then, passenger waiting time is integrated over alighting_time using the same formula as in Arrive(). In this case, the constant portion of the passenger accumulation is likely to be much larger than the total number of new passengers. As in Arrive(), the additional passenger waiting time is added to the total wait time record of the platform record.

Board():

As with Alight(), Board() encompasses everything that happens to train t at platform p during the time required for all boarding passengers to board the train. Calculating boarding time in an accurate manner, however, is rather more difficult than calculating alighting time. This is because passengers continue to arrive on the platform and contribute to the boarding time. Thus, the boarding time and the number of boarders must be determined simultaneously. In addition, however, the train capacity constraint comes into play with boarding. Once the train reaches capacity, boarding stops. While this is not difficult to model in a deterministic manner, incorporating Poisson passenger arrivals into the boarding time calculation would have been excessively complex. Therefore, a deterministic boarding time was calculated and then used to calculate the number of boarders from the passenger arrival matrix.

To keep these calculations manageable, the following procedure is used. First, the expected number of passengers who *would* board the train, given sufficient capacity, is calculated. This is the number who could board during the time it takes for the accumulation of passengers on the platform to reach 0. The calculation used is

unconstr_boarders = load_0 * BOARDING_RATE / platform_empty_rate

where load_0 is the total number of passengers on the platform at the *beginning* of boarding, and

platform_empty_rate = BOARDING_RATE - pax where pax is the passenger arrival rate at the beginning of the boarding period. Next, the deterministic maximum number who *could* board the train given the capacity constraint is calculated with the expression

constr_boarders = TRAIN_CAPACITY - trains[t].load

where TRAIN_CAPACITY is the train capacity. Then, the *deterministic* number of boarders is determined as

boarders = min(unconstr_boarders, constr_boarders)

Next, the *actual* boarding time is calculated in exactly the same way that the alighting time was calculated

boarding_time = boarders / BOARDING_RATE.

The boarding_time, in turn, is used to calculate the *actual* number of new passenger *arrivals* from the matrix of passengers, which is added to the load variable of the platform. Once this is done, the *actual* number of *boarders* is calculated:

act_boarders = min(boarders, platforms[p].load)

act_boarders then added to the load variable of the train record and subtracted from the load variable of the platform record (the min. function ensures that the platform will not end up with a negative load) , and boarding_time is added to the time element of the train record. The additional passenger waiting time is also calculated at this time, again using the same formula as before. In this case, however, Δp is the actual number of boarders, and the constant p is the number of passengers (if any) left on the platform after boarding. The additional waiting time is again added to the total waiting time variable of the platform record.

Excess_Dwell():

The next stage of dwell time covers any excess dwell time incurred due to overcrowding. If more than a certain threshold number of passengers remain on the platform following boarding, an excess_dwell_time is randomly generated and added to the .time element of the train record. If all passengers were able to board, excess_dwell_time equals 0 and effectively nothing happens in this step. Any additional new passenger arrivals on the platform, and any new waiting time incurred, are calculated and added to the respective elements of the platform record. No additional passengers actually board the train during this period, however.

Constant_Dwell()

In terms of the processes that take place, this stage of train dwell time is quite similar to Excess_Dwell(), except that it is always invoked. At most platforms, the constant dwell time is the intercept term from the linear dwell time function. Additional new passengers accumulate on the platform, additional waiting time accrues, and the time stamp is augmented. All of the constant dwell time was assumed to all occur the end of the dwell period. This was done because the constant appeared to be most closely associated with the time spent by the train guard looking to see that all boarding and alighting had ended and closing the doors.

The constant dwell time had a different role at stops prior to TIME_POINT. At these stops, constant dwell times are maintained and therefore *all* of the dwell time is lumped into this period. All of the passenger calculations in Alight() and Board() take place, but all of the times are set to zero. Instead, all dwell time occurs in Constant_Dwell(). By making this dwell time constant across all trains at these platforms, a constant headway can be maintained.

Depart():

Once the constant dwell time has been added to the train's time stamp, and the additional new waiting time tallied, the train departs platform p. No operations are actually done on the train or passengers in this step, and no time actually elapses for the train. This operation allows the departure time of the train to be assigned to the time_last_dep element of the platform structure. The value time_last_dep is used to enforce the minimum headway on the following train. A record of the departure time of each train from each platform is also made for later analysis.

2.5.2.2 Special Types of Dwell for Short-Turns

Trains which are to be short-turned undergo a slightly different sequence of events at both S and S'. At S, any passengers traveling to points beyond S (the "dumpees") are forced to leave the train and wait for the next one. Train_Handler is called in mode LEAVE_SERV, in which the sequence of steps undergone by the train is:

```
Arrive(p, t);
Alight(p, t);
Dump(p, t);
Constant_Dwell(p, t);
Depart(p, t);
```

No one boards this train at this stop, so there is no Board() or Excess_Dwell(). Instead, Dump() is added to the procedure.

Dump():

Once all the passengers who would have alighted form the train anyway have left the system in Alight(), all passengers remaining on the train must get off. Dump() therefore is quite similar to Alight(), except that the passengers are added to the load variable of platform S, and the train load is set to zero. All these passengers then wait together, along with additional new boarders arriving during this time. Therefore, the additional passenger waiting time generated during this period includes waiting time for the passengers who were already on the platform (would-be boarders), the dumpees, and the new arrivals. In addition, separate records of the number of dumpees, and the additional waiting time imposed on the dumpees, are recorded as secondary performance measures.

As the short-turning train leaves platform S, its array index number is removed from the mapping function. If train 3 is being short-turned and initially T[] = {0, 1, 2, 3, 4}, now T[] = {0, 1, 2, 4}. Later, when s = S' and t equals train 3's new position, map function T is again re-ordered to {0, 1, 3, 2, 4}.

At S', when the short-turned train is returned to service, Train_Handler is called in mode RE_ENTER_SERV. The stop sequence here is:

```
Arrive_From_ST(p, t);
Board(p, t);
Hold(p, t);
Excess_Dwell(p, t);
Constant_Dwell(p, t);
Depart(p, t);
```

A different Arrive() routine is needed only because the train is arriving from S and not from S' - 1, and so the short-turning time in stead of the interstation time from S' - 1 to S' must be used. The train is empty, so Alight() is not included.

Hold()

The most significant change here is the use of Hold(). As explained above, an effort is made to dispatch the short-turned train form S' at such a time that its preceding and following headways are similar, provided the short-turned train arrives and boards its passengers in sufficient time to make this possible. If the short-turn takes too long, both the minimum headway constraint and the mapping function prevent a "collision" or the insertion of the short-turned train into the wrong location in the sequence of trains. However, a record is made of any delay to the following train as an additional performance measure.

The length of the hold is determined in the following way. The short-turned train's current preceding headway is found using

```
present_h = trains[t].time - platforms[p].time_last_dep
```

The desired headway (ideal_h) is one-half of what the preceding headway of the *following* train was when it departed S' - 1, this train's last previous stop before the short-turned train was re-inserted. Since the structure of the simulation means that all of the trains have already made their stop at the previous platform, this value is still stored in the prev_headway element of the following train at this point. The length of the hold (hold_t) is then calculated using the following expression:

```
hold_t = max(0, (ideal_h - present_h) - fixed_dwell_time
```

Note that if the short-turned train's preceding headway is already greater than the desired headway (i.e. holding any amount of time will not help), hold_t will be zero. Hold_t is then used to generate the number of new_passengers who would board during this interval of time. If and only if the train load plus new_passengers is still less than TRAIN_CAPACITY, the train's time stamp is augmented by hold_t, and its load by new_passengers. Since all of these passengers board the train immediately and because waiting time in the train is not counted, no waiting time is generated in this operation and no passengers accumulate on the platform. A separate subroutine later uses the records of the following train's departure time from S'-1, its actual arrival at S', and the interstation time from S'-1 to S' to determine whether the following train was delayed by the short-turn. This method of establishing delay would not always give an absolute answer if stochastic interstation times were being used. Were that the case, it would be necessary to make some modifications to Board() so that cases in which the minimum headway constraint was binding for the following train at S' would be recorded.

The processes carried out in the routines described above were for the most part tailored to the particular application for which this simulation was being used. Depending on the characteristics of the system being modeled, and on the quality of input data available, the user of this model could change any of the routines called from Train_Handler(). If a single, non-linear dwell time function were available, Alight(), Board(), Excess_Dwell(), and Constant_Dwell() should be collapsed into a single routine. The framework of this model could readily be used with any other control strategy. No optimization procedures were incorporated into this model, but they could undoubtedly be added.

2.6 Model Outputs

As mentioned above, passenger waiting time is the principal performance measure used in this study. At each platform, total passenger waiting time for each train in the sequence is calculated at each step of the simulation. At the conclusion of each run of the model, with and without the short turn, the total waiting time accumulated on all of the platforms is summed. Thus, the total waiting time for the entire system for this limited set of trains has been determined. By then taking the difference between these values, a measure of the benefit of the short-turn may be calculated. A negative delta PWT indicates that the short-turn resulted in a net reduction in total passenger waiting time, while a positive value would indicate a net "dis-benefit".

Passenger waiting time by itself is a straightforward measure of success. It is a quantity that captures several features of performance, including regularity, crowding, and reliability. By itself, however, it fails to capture some important outcomes of short-turning. First of all, the relative dis-benefit to the individual skipped segment alighters (the dumpees) is much greater than the average benefit to the other passengers in the system. Dumpees must unexpectedly leave the train which they have already waited to board (possibly for an excessive amount of time if this is the delayed train), give up their seat, and wait again. Most passengers understandably are quite annoyed by such treatment. As a result of this, a separate count of dumpees is recorded, and the additional waiting time for each dumpee calculated as additional indicators of the result of each short-turn.

Excess headways can result in overcrowding and denied boardings for the train with the long headway. Removing a poorly selected train from a section of a route will exacerbate this problem. In order to monitor this, during each run of the model a separate running total of remaining passengers at the end of each call to Board() is kept. At the end of each run, the total number of denied boardings for each platform are summed in two groups: the skipped segment S through S' - 1, and the downstream segment S' through N. A greater number of denied boardings in the skipped segment for the short-turn run should by itself be an indicator of a bad short-turn decision. Indeed, it may indicate that overcrowding is so severe that some "spillover passengers" may not be able to board the last train in the sequence. In this case the total passenger waiting time calculation for this run would fail to account for all of the waiting time impacted by the short-turn. In practice, this rarely proved to be a problem; the sequence selection criteria and the number of trains in the sequence meant that if there were any such "spillover passengers" they were primarily due to other factors which meant that the short-turn would not be recommended. On the other hand, a beneficial short-turn should reduce denied boardings in the downstream segment. This will be explained in greater detail in Chapters 3 and 4.

Denied boardings are also an indicator of inefficiently used capacity. If passengers are left standing on platforms by overcrowded trains while closely following trains are only partially loaded, capacity is under-utilized and the peak carrying capacity of the system is, in a sense, reduced. The same number of passengers may be transported in a given peak period, but since the overall commuting time for each user is increased by extra waiting, the peak flow over the line is reduced. An effort was therefore made to measure flow. This is done by summing the passenger loads on each train departing the platform at the beginning of the peak load segment.

As mentioned above, any delay caused to the train which is to end up following the short-turned train at S' is recorded. Such a delay indicates that there was not sufficient time to short-turn the train and fit it neatly into the excess headway gap. This would, in turn, suggest that the particular short-turn strategy might not have been optimal.

A record is also kept of the arrival and departure times of each train at each platform. These are written as an array with a column for each train and alternating rows of arrival and departure times at each platform. String-line diagram trajectories of the trains on each run can be generated using this data. These trajectories are useful for analysis.

2.7 Model Limitations

As will be discussed in Chapter 3, simulating the train headways departing N/2 + 1 was difficult because the actual process is not clearly understood. The biggest problem is that each train's actual departure from that terminal is partially determined by that train's scheduled departure time. However, no information was available to correlate the time point data with the schedule. Therefore, this relationship could not be modeled. The omission of variable interstation times is also a potential problem, especially since interstation times may largely be dependent on the operator of the train, and will therefore tend to show a pattern across all segments of the line for a given train. Thus, some trains will tend to move more slowly than others even without dwell time effects. (In actual practice, this is a significant factor in decisions to short-turn a train on the line studied in this project). This is not being considered in this analysis. With much more data, probability distributions of interstation time as a function of the time required for one or more previous segments (but not counting signal system effects) could be prepared. One could even prepare separate distributions for each train operator on the line, though this would require a fairly elaborate AVI system with an up-to-date record of operator assignments.

The way in which this model was used in this research is explained in the next chapter.

Chapter 3

Simulation and Analysis

The purpose of this chapter is to introduce the transit line used as the case study of this project, to explain how the general model was adapted to simulate the Blue Line, to explain how the model inputs were generated, and to show how the validity of the model was checked.

3.1 Blue Line Characteristics

3.1.1 System Characteristics

The MBTA Blue Line is a heavy rail transit line running 6.2 miles from Downtown Boston, under Boston Harbor, and through East Boston to Wonderland Station at Revere Beach. Downtown, the line intersects with the Green Line at Government Center Station, and with the Orange Line at State (Devonshire) Station. Figure 3.1 is a diagram of the MBTA rail transit network. Figure 3.2 and Figure 3.3 are track diagrams of the Blue Line itself[21]. Because the route originates downtown, the line has only one peak direction passenger flow during each peak period. This, together with the lack of branches, simplifies the real-time decision process. The route runs along the shore for much of its length, and parking facilities are limited at all of the route's stations except Wonderland. However a number of feeder bus routes, particularly at Wonderland and Maverick, provide heavy peak hour ridership. The line also serves Logan Airport via a shuttle bus connection. Thus, the Blue Line carries very heavy traffic inbound in the a.m. peak, and very heavy outbound traffic in the p.m. peak. Off-peak ridership is rather light by comparison.

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[21] *Boston Track Map,* Cambridge, Massachusetts: Boston Street Railway Association, Inc., July, 1986.

Figure 3.1: MBTA Rail Transit System

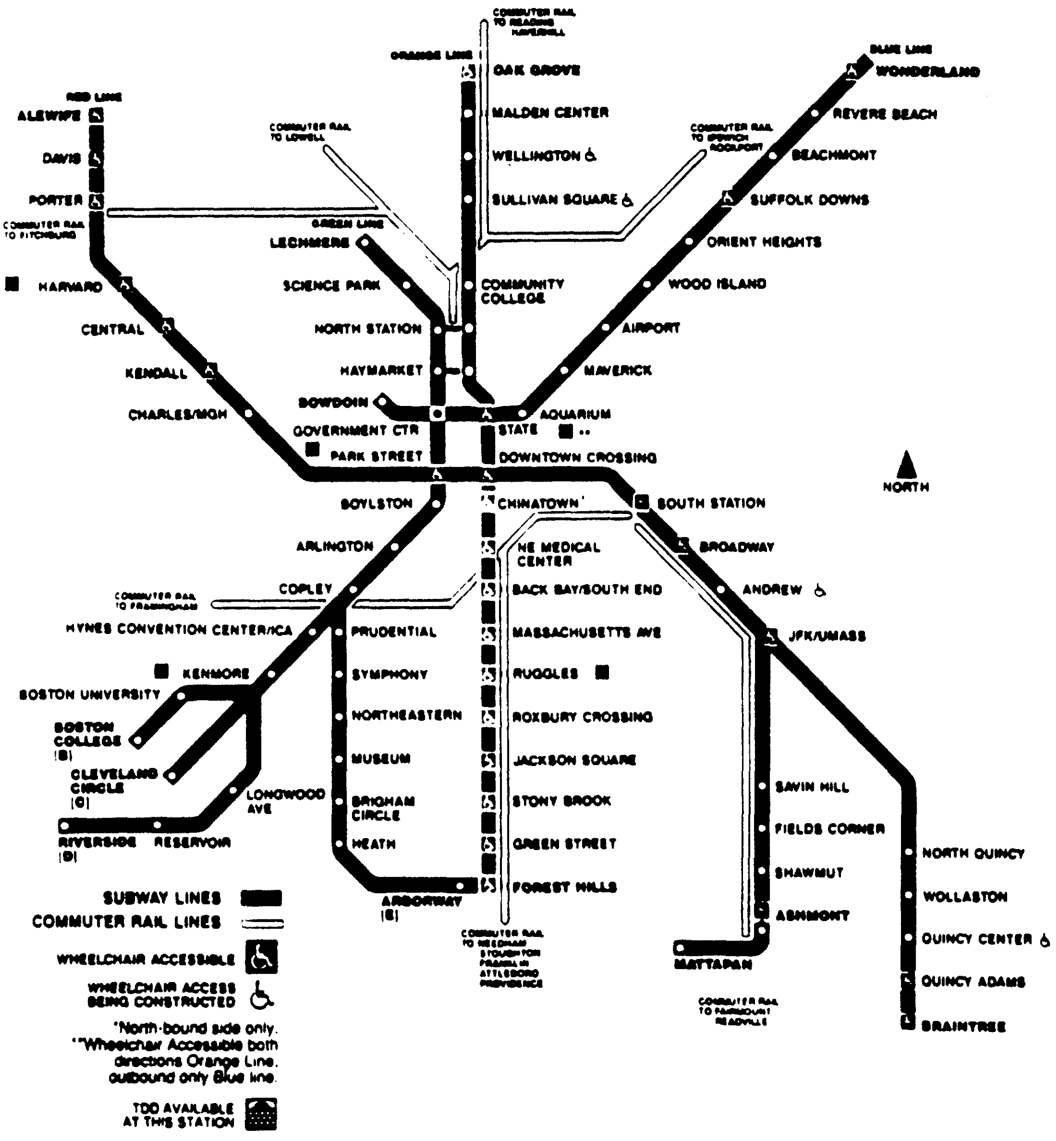


Figure 3.2: MBTA Blue Line Track Diagram

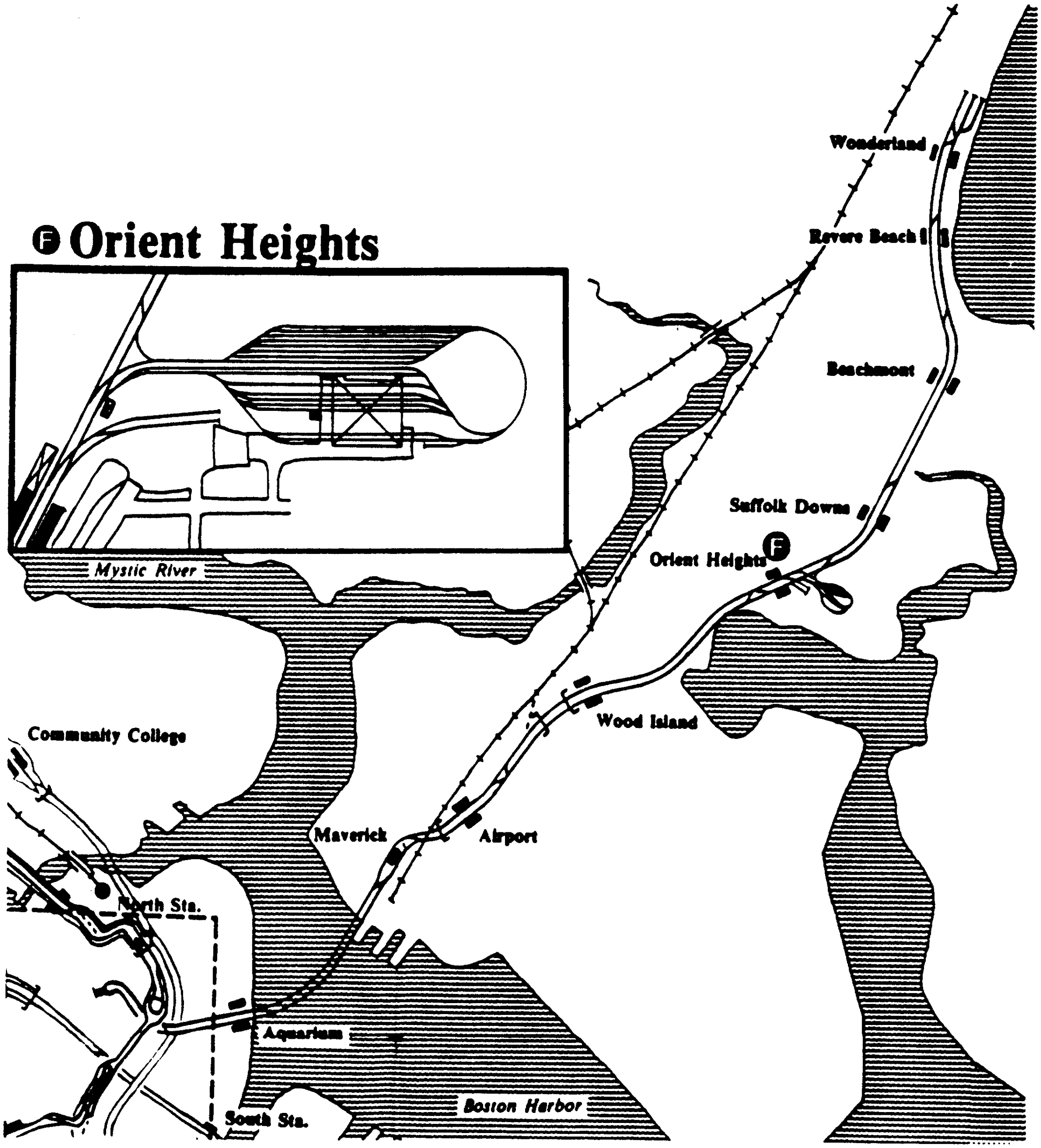
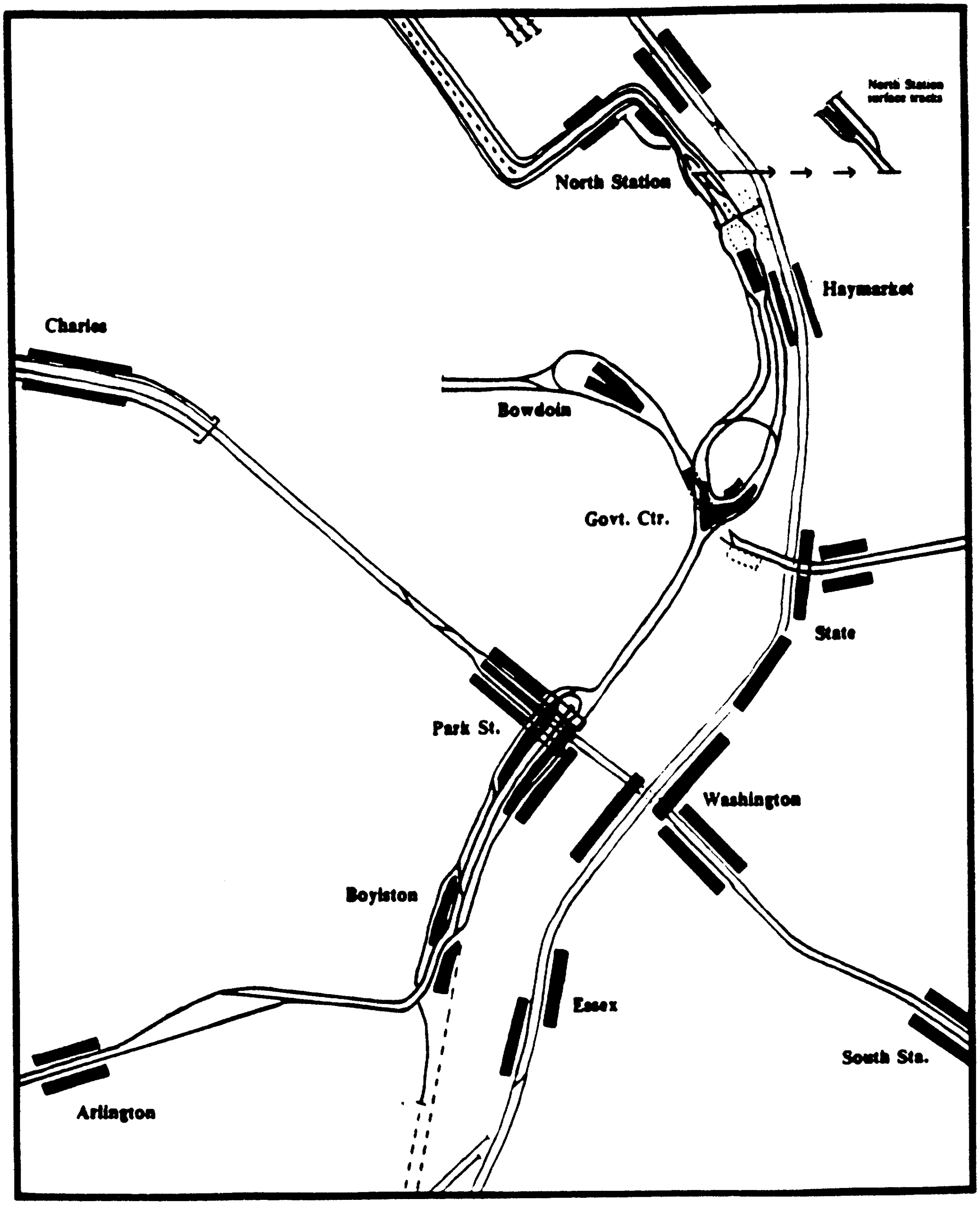


Figure 3.3: Blue Line Track Diagram (Downtown Boston Detail)



The underground section of the Blue Line from Bowdoin to Maverick was originally constructed as a streetcar tunnel similar to the present-day MBTA Green Line. Most of the remainder of the route, from near Airport Station to Wonderland, follows the right-of-way formerly used by the narrow-gauge Boston, Revere Beach and Lynn Railroad. The tight clearances resulting from this legacy forces the Blue Line to use some of the smallest heavy rail transit vehicles in North America. Four - car trains are used for all services on weekdays, although platforms are now being extended to permit the future operation of six - car trains. Each car seats 42 passengers and for the peak periods a loading standard of 225% of seating capacity, or 380 passengers, has been adopted as a performance threshold for passenger comfort. However, a maximum loading of 440 passengers per train in peak periods has been used for schedule planning purposes. Observations suggest a maximum crush capacity approaching 500 persons per train. A somewhat more conservative value of 470 was selected as the maximum train capacity for this project. The objective in choosing this value was to find a point at which additional passengers would find it difficult to board, causing excess dwell, as well as a level at which many passengers would voluntarily pass up the train in hope of finding a closely following train.

It was decided early on to consider short-turning only in the a.m. peak period in this research. Short-turning at other times would clearly benefit far fewer passengers, since passenger demand from stations downstream from the short-turn section is only particularly heavy in the a.m. peak. Short-turning in the p.m. peak would be especially detrimental because large numbers of passengers would be forced to alight from the short-turning train.

At the time that the data used for this project was collected, the a.m. peak period schedule on the line had 14 trains departing Wonderland on 3 1/2 minute headways from 7:00 a.m. until 9:20 a.m.. This provides a theoretical carrying capacity of 7540 passengers per hour. After 9:20, service fell off first to 6, and then, after 9:32, to 8 minute headways. (Recently, however, the Blue Line schedules were revised with the span of 3 1/2 minute headways modified).

The Blue Line is controlled by an automatic block signal system with wayside color-light signals and mechanical trip-arm automatic train-stop (ATS). Although the Red and Orange Lines have been equipped with continuous automatic train control (ATC) in recent years, when the Blue Line's signal system was renewed over the last several years, this less sophisticated was retained. While it is therefore up to the train operators to regulate the speed of the trains manually, speed control signals have been installed at a number of locations along the route that have permanent speed restrictions. Speed control signals display the red 'stop' indication, with the trip-arm raised, until the track circuit preceeding them has been occupied by an approaching train for a specified period of time. This time delay is calculated to force the approaching train to slow to the posted speed limit for that section of track. Once this time period has elapsed, the signal is allowed to 'clear' provided that none of the downstream track circuits controlling that signal are occupied. Trains failing to regulate their speed will over-run the stop signal, causing an automatic emergency stop. Differences in how different train operators respond to the speed control signals may be a significant source of variation in average running times between operators. Many train operators seem to have learned to approach these signals at speed, arriving at them just as the trip arm retracts. This is not necessarily a good practice, since it is entirely possible that a speed signal will remain at 'stop' due to the presence of a train ahead and resulting in over-running and an emergency stop. Motorpersons are instructed to regulate their train's speed so as to remain in full control at all times. Trains should thus approach time signals prepared to stop in case they fail to clear. Running at red time signals at a speed too great to stop without overrunning is technically a serious rules violation. On the other hand one would expect the operators who faithfully observe this rule to have a somewhat longer average running time. Moreover, the fact that Blue line operators manually control their speed will itself allow for significant running-time variation.

MBTA signal engineers have determined that the current Blue Line signal system will allow a minimum free flow headway of approximately 3 minutes, 20 seconds. In other words, although much closer headways are possible at most points along the route, a train with a preceding headway of less than 200 seconds is likely to encounter restrictive signal indications at some point during its run. Thus, the signal system should have a natural tendency to keep trains spaced apart near the scheduled peak headway of 3 1/2 minutes. However, since the signal system was not included in the model used in this project, no effort was made to simulate this effect. Nevertheless, absolute minimum headways were imposed at each platform as explained in Chapter 2. Inspection of headway data from both directions at Maverick and Orient Heights suggested minimum headways at these locations in the range of 60 to 90 seconds. At the westbound platform at Wonderland, however, as little as 15 sec. could elapse between the departure of one train and the arrival of the next. Therefore, while 60 sec. was adopted as the standard minimum headway value for the simulation, for reasons which will be explained a minimum headway of 15 sec. was permitted at Wonderland westbound. The actual minimum headway undoubtedly varies considerably over the length of line depending on signal spacing and other factors. However, 60 sec. seemed to be a reasonable approximation.

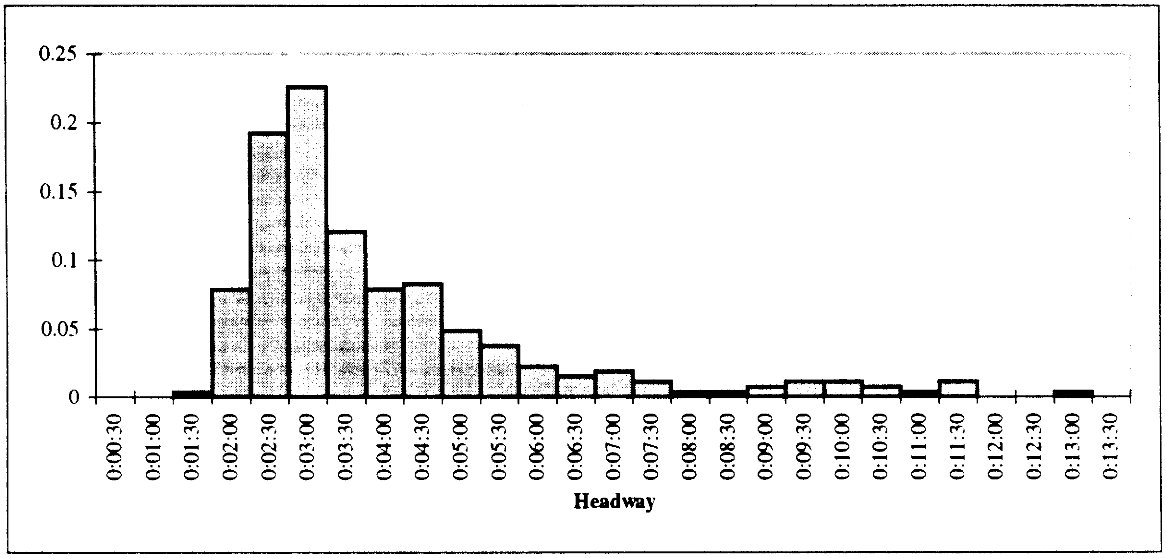
The Blue Line has a system which automatically records the times at which trains pass a point near Maverick Station in each direction. This data is used for performance measurement but unfortunately is not available in real-time to the field supervisors who are responsible for regulating headways. Table 3.1 presents some statistics for eastbound headways recorded between 7:15 and 9:00 a.m. over 10 consecutive weekdays in January, 1994.

Table 3.1: Statistics for Eastbound Headways at Maverick, a.m. Peak

Average	0:03:44
Std. Dev.	0:02:01
Min.	0:01:26
Max.	0:12:31
% > 8 Minutes	6%
Total Points	266

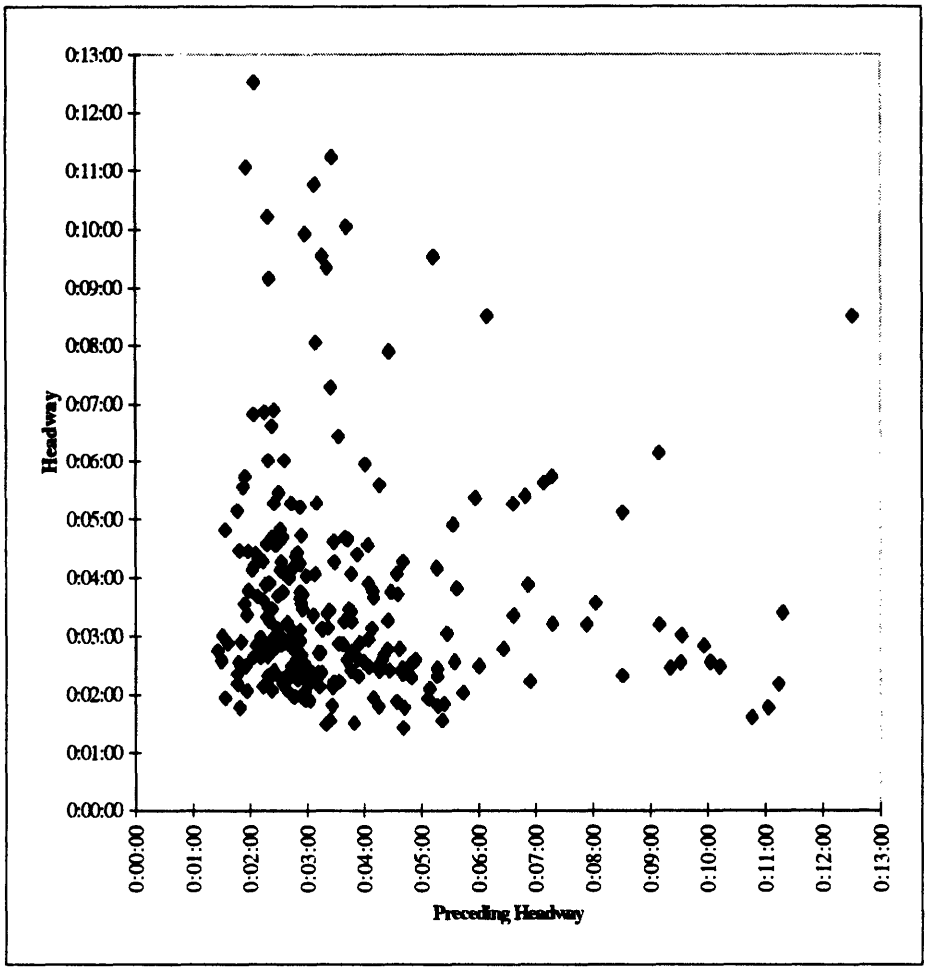
The scheduled headway between these times is a constant 3 ½ minutes. Note that the average headway is actually greater than this. The standard deviation is 54.1% of the average. Figure 3.4 shows a probability distribution for this data. The scale on the horizontal axis indicates the upper boundary of each bin.

Figure 3.4: Probability Distribution of Eastbound Headways at Maverick, a.m. Peak



Note the asymmetrical shape of the distribution. The minimum and the mean are less than 2 ½ minutes apart, with a sharply truncated left tail. The right tail, on the other hand, is virtually unlimited and a relatively small number of outliers pull the average up to 3:44 from the scheduled 3:30. This figure does not show the dependence between consecutive headways. Figure 3.5 attempts to illustrate this dependence by plotting each headway as a function of its immediately preceding headway. The points in the lower right hand quadrant of the plot are short headways following long headways. Many of the points in the extreme lower left-hand corner are probably *second and even third* headways following very long headways. In other words, the headways of the trains immediately preceding these trains were also short because the second train ahead had a long headway.

Figure 3.5: Dependence of Headways on Preceding Headways



Observations suggest that the currently scheduled round trip time of 49 minutes does not provide sufficient recovery time for trains to remain on schedule with high reliability. The new signal system has apparently slowed the average running speed considerably. Temporary speed restrictions further exacerbate this problem. Recovery time should be sufficient to allow for headway adjustment to a precision of less than 30 seconds, as well as to allow for "on-time" departures a high proportion of the time. Following disruptions on the Blue Line, supervisors try to restore trains to their schedules so that train crews can end their runs on time. However, the need to do this means that efforts to regulate headways are abandoned. Trains arriving at Wonderland are turned and reloaded as quickly as possible. Even under normal circumstances, supervisors are reluctant to pressure train crews to observe schedules to high accuracy. The track layout at the Bowdoin terminal consists of a simple loop. Trains therefore can not layover here for a significant period of time without delaying following trains. Eastbound trains generally proceed from Bowdoin as soon as they have boarded passengers at the eastbound platform. Most recovery thus must take place at Wonderland.

During visits to Orient Heights Station, train starters and tower T operators complained that a small proportion of train operators tend to run significantly slower than average. The inadequate recovery time undoubtedly makes these operators stand out. Rightly or wrongly, these operators seem to be blamed for many of the delays on the Blue Line.

3.1.2 Real-Time Control Practice

Presently, the Blue line is controlled from Orient Heights station. The train starter, who is responsible for supervising train crews and monitoring schedule adherence is stationed here. Tower T, which controls interlockings on the line is also located at Orient Heights. Tower T and the Train Starter's office both contain model boards. The model boards each have a schematic diagram showing all revenue trackage on the Blue Line route, and indicator lights showing track circuit occupancy. Thus, the approximate location of each train on the line is available, though no train identity information is displayed. The visual location information is not completely analogous to headway data, since the actual headway between a given pair of trains is a function of speed as well as distance, and average speeds vary over different sections of the route. Nevertheless, an experienced supervisor should be able to identify large headways. For train identification, the train starter and tower operator both keep train sheets which have scheduled departure times for each train from the end terminals and Orient Heights photocopied onto them, and blanks for the entry of the actual times. The train starter's sheets also contain space for entering the badge numbers, swing-on, and swing-off times for train operators. Finally, both sheets contain space for comments explaining delays and indicating real-time interventions made, including short-turning, and removing trains from service due to failures. Between them, the train starter and the tower T operator make real-time control decisions such as short-turning. Some of these functions will eventually be transferred to the new Operations Control Center (OCC). Currently, the principal duties of the dispatcher at the OCC are limited to keeping a log of major incidents on the line, and coordinating the response to serious disruptions. One OCC dispatcher is able to handle both the Orange and Blue Lines. A number of field supervisors (inspectors) are assigned to the Blue Line as well. One monitors departures from Wonderland.

Early in the course of this research, several visits were made to Orient Heights during which operations were observed and a towerperson and several train starters were interviewed. In addition, two weeks worth of the train sheets filled out by the train starter were studied and short-turns made were examined. Unfortunately, only a small number of short-turns were recorded in this period, and only three of these were in the a.m. peak. Therefore, most of the information on actual short-turning practice is based on the discussions with the supervisors.

On the Blue line, short-turns are normally made at Orient Heights for outbound trains. While short-turns are made to recover from delays, they are also used to allow the slow train operators to "catch up" so that they do not delay following trains. Train starters indicate that they feel this is necessary due to the inadequate running time allowed. Train starters explained that they often arbitrarily short-turned these operators' trains because they would tend to "fall behind" or be less likely to recover sufficient time at Wonderland, delaying following trains as well. (Indeed, one starter said that as a rule two short-turns should be made during the course of the a.m. peak to maintain the schedule. It was not clear whether this is a normal practice, however.) Of the few short-turns for which there were records on the train sheets, at least a few appeared to have been made purely because the train involved was expected to run slow. In one or two cases, the short-turned train did not appear to have an excessive headway when it arrived at Orient Heights eastbound. These short-turns will be analyzed in detail in the next chapter. The turns were apparently implemented in anticipation of trouble later (the notation "extremely slow motorman" was entered on the train sheet with one example). Short-turns were observed both during the a.m. peak and mid-day base periods. However, short-turning would be far less effective during the p.m. peak period, since large numbers of passengers would be inconvenienced in the outbound direction with few inbound riders to benefit. The train starters are very much aware of this and no short-turns were observed in this period.

When a train which is to be short-turned arrives at Orient Heights, an announcement is made that the train will be leaving service and that passengers must alight. Once passengers have alighted, the train usually proceeds to a stub-end siding where the train crew can "change-ends" without delaying following trains. Once the train which will now immediately precede the short-turning train has departed Orient Heights inbound, tower T can signal the short-turning train to move back down to the westbound platform to board passengers and proceed with its trip.

Short-turning on the Blue Line usually involves overtaking one preceding train. However, short-turns involving the overtaking of two trains, and of no trains have also been observed. In any case, the position in the sequence that will be assumed by the short-turned train is generally determined beforehand by the train starter as part of the decision process. The decision is made based on the operating schedule. Beginning at 9:26 a.m., trains gradually leave service at both Orient Heights and Wonderland until the total number of trains in service has dropped from 14 to 6. In order to maintain the 8 minute off-peak headway, consecutive trains are not scheduled to end their runs on consecutive trips. Instead, alternating trains leave service generally eastbound at Orient Heights. The problem with most short-turns involving overtaking in the a.m. peak is that they will result in two successive trains with crews scheduled to pull back at the end of the peak period. This, in turn would create another excess headway. This problem can sometimes be rectified by swapping crews between trains at Orient Heights. However, this may require an extra train crew, which is often unavailable. In some cases, a second short-turn is made simply to restore the sequence of trains leaving service. However, all of these scheduling problems can be avoided by re-inserting the short-turned train into the same location in the sequence, as is often done. Thus, short-turns of this type are considered in this study.

3.1.3 Passenger Demand Characteristics

The average passenger flow over the peak load section (between Maverick and Aquarium) over the period from 7:00 to 10:00 a.m. is approximately 4500 passengers per hour. Given this volume, a train leaving Wonderland with a preceding headway of 6 minutes or more is likely to be overcrowded by the time it reaches Maverick. During the period 7:30 - 8:45 a.m., the inbound flow approaches 6300 passengers per hour (as compared to the scheduled capacity of 7540). However, in order to ensure that all short-turns made during the a.m. peak period could be compared, average passenger flow values were used. Details of the passenger demand data will be presented in section 3.2.5.

A substantial proportion of the a.m. peak inbound passenger flow boards in the segment skipped by the short-turning train. Approximately 44% of total inbound boardings in the a.m. peak are at platforms between Wonderland and Suffolk Downs (inclusive), the station immediately preceding Orient Heights westbound (the eastbound boardings in this segment are negligible in comparison). Thus, the number of skipped segment boarders (i.e. the passengers who must wait for the train following the short-turned train) are likely to be very substantial in proportion to the passengers benefited by the short-turn. This is a significant difference from short-turning on the Green Line at Park Street, where the number of outbound passengers Boarding at Government Center (the skipped segment) is a relatively small proportion of the entire outbound stream.

3.2 Simulation Development

3.2.1 Westbound Headways

Modeling the headways of trains departing Wonderland westbound was one of the most difficult challenges of this project, and is one of the principal sources of random variation in the model results. As will be explained, trains undergo a number of interdependent processes at this terminal, and there was not sufficient data available to understand all of them perfectly.

Eastbound trains arrive at the eastbound platform and, as soon as any passengers on board have alighted, proceed to the tail tracks where the trains reverse direction. Once the operator has taken his or her position at the western end of the train, each train runs back to the westbound platform to board passengers and await departure. There appeared to be considerable variability in both the time spent moving from the eastbound to the westbound platform and in the dwell time at the westbound platform. In general, one would expect that trains arriving eastbound at the terminal with headways below some threshold would be able to depart on their next westbound trip with the scheduled headway. Trains arriving eastbound with less than the scheduled headway could take more time turning around and wait longer at the westbound platform before departing. Trains arriving with greater than the scheduled but less than the threshold headway would have to move more quickly, but would have enough recovery time to leave with the scheduled headway. Those with eastbound headways greater than the threshold, however, will have difficulty turning and loading quickly enough to leave with the scheduled headway. The westbound headways of such trains will depend primarily on how quickly they can move from the eastbound to the westbound platform. Dwell times for these trains at the westbound platform will depend entirely on the number of boarding passengers, and these trains will depart as soon as they have loaded. Train operators are also expected to observe scheduled departure times. Unfortunately, this may tend to conflict with headway regulation. Since there is no layover scheduled at Bowdoin, the terminal at the opposite end of the line, the stop at Wonderland is the only opportunity for train operators to use the bathroom, etc. This may extend the time spent at Wonderland.

Ideally, trains should be dispatched from Wonderland as closely as possible to the scheduled headway. Unlike the terminals of some of the other MBTA heavy rail lines, there is no starting signal (at Alewife on the Red Line, for example, there is a buzzer which automatically sounds at intervals equal to the scheduled headway to signal trains to depart). Moreover, field supervisors on the Blue Line say they are reluctant to pressure train crews with tight headway regulation given that the crews are already under pressure from the limited running time allowed. Field observations suggest that the actual process primarily reflects train operators trying to observe the schedule, with intervention from the field supervisor stationed at Wonderland only in extreme cases. The train starter at Orient Heights may occasionally make some additional adjustment to headways by holding. Two different sets of data were studied in order to gain a better understanding of these processes.

Observations of a.m. peak train departures from Wonderland on two mornings were analyzed. Unfortunately, no data was available to correlate the recorded departures with the schedule. Thus, the analysis was based entirely on headways. Table 3.2 presents overall statistics on the preceding headways of trains departing the eastbound and westbound platforms at the Wonderland terminal during the a.m. peak period on two separate days. This data shows considerable random variation in westbound headways departing from Wonderland. As one would expect, the average headway is essentially the same in each direction and both are very close to the scheduled headway of 3 1/2 minutes. However, the standard deviation of the westbound headways is only 13 % smaller than that for the eastbound headways. This indicates than relatively little headway adjustment is taking place at this terminal. The statistics in the last column of this table are for the amount of time spent by each train moving from the eastbound platform to the tail tracks and back to the westbound platform, plus dwell time at the westbound platform (since nearly all trains seemed to spend a very small amount of time at the eastbound platform, this was not included in this figure). This time should reflect recovery; trains can shorten their headways by spending less time at this terminal.

Table 3.2: a.m. Peak Headways at Wonderland

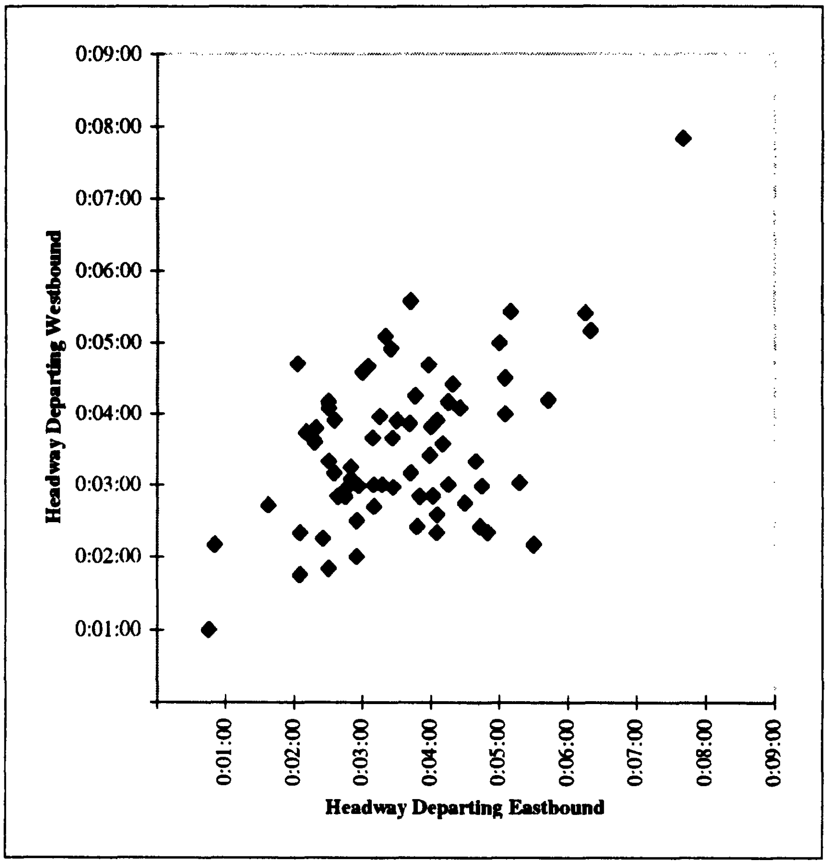
	Eastbound Dept. Hdwy.	Westbound Dept. Hdwy.	Overall Time*
Average	0:03:34	0:03:31	0:05:48
Std. Dev.	0:01:16	0:01:06	0:02:09
Minimum	0:00:45	0:01:00	0:02:15
Maximum	0:07:40	0:07:50	0:10:32

* Total time elapsed between departure from Wonderland Eastbound and Wonderland Westbound.

Figure 3.6 plots the westbound departure headway of each of these trains as a function of its headway on departure from the eastbound platform.

Note the shape of this distribution. Where the eastbound headway is greater than about 5 1/2 minutes, it appears that trains are less likely to be able to depart with the scheduled headway. Most departed Westbound with preceding headways greater than 4 minutes. However, this distribution also shows trains that left the eastbound platform with headways smaller than about 2 minutes also departing westbound with short headways. This is counter-intuitive, since these trains should easily be able to depart with the scheduled headway.

Figure 3.6: Headways Departing E.B. and W.B. Platforms at Wonderland



In order to investigate this behavior further, the observations were grouped by eastbound headway into three classes:

Group I:	E.B. Headway < 2 minutes
Group II:	2 minutes ≤ E.B Headway < 5 1/2 minutes
Group III:	5 1/2 minutes ≤ E.B. Headway

The average and standard deviation of the headways in each direction were calculated for each group. These statistics were also calculated for the overall time spent at the terminal by trains in each group. Dwell time at the eastbound platform appeared to be independent and so was not included. These statistics are presented in Table 3.3.

Table 3.3: a.m. Peak Headways at Wonderland

Eastbound Dept. Headway Range:	0:00:00 to 0:02:00			0:02:00 to 0:05:30			Greater than 0:05:30		
	Eastbound Dept. Hdwy.	Westbound Dept. Hdwy.	Overall Time*	Eastbound Dept. Hdwy.	Westbound Dept. Hdwy.	Overall Time*	Eastbound Dept. Hdwy.	Westbound Dept. Hdwy.	Overall Time*
Average:	0:01:04	0:01:58	0:03:16	0:03:28	0:03:29	0:05:57	0:06:18	0:04:57	0:05:24
Std. Dev.:	0:00:29	0:00:53	0:01:05	0:00:54	0:00:53	0:02:07	0:00:51	0:02:03	0:02:16
Minimum:	0:00:45	0:01:00	0:02:15	0:02:03	0:01:45	0:02:35	0:05:30	0:02:10	0:03:15
Maximum:	0:01:37	0:02:43	0:04:25	0:05:18	0:05:35	0:10:32	0:07:40	0:07:50	0:08:50
Total Observations:	3			63			5		

* Total time elapsed between departure from Wonderland Eastbound and Wonderland Westbound.

One would expect trains in Group III to spend less time at the terminal than trains in Group II because they would be using their recovery time to shorten their headway. By the same token, trains in Group I should spend more time at this terminal. Group III trains did shorten their average headways. Not surprisingly, the overall time spent by these trains at Wonderland was considerably shorter than the average for Group II. On the other hand, Group I trains lengthened their preceding headways somewhat, but nevertheless spent much less time than average at Wonderland before starting their westbound trips. Evidently, the trains that preceded these trains also moved quite quickly at Wonderland. For example, one Group I train had a 45 second eastbound headway and a 1 minute westbound headway. The train immediately preceding this train had a 2 ½ minute eastbound headway but departed westbound with a preceding headway of only 1 minute, 40 seconds. Thus, this preceding train spent even less time overall at Wonderland. This behavior is rather strange, but is exhibited by 3 data points out of a set of 71. The most probable explanation is that the trains were running behind schedule and the train operators were rushing to get back on schedule. Unfortunately, this behavior tended to worsen headway variability.

The automatically recorded Maverick passing time data was used to further investigate headway behavior. The data available was from different months, both earlier and later, than the observations at Wonderland. Dates were selected on which the train sheets showed no record of short-turns having been made. An effort was made to match up the headways in each direction of each train. However, since no train identification was included with this data it was not possible to do this with certainty. Table 3.4 and Table 3.5 present this comparison for two different a.m. peak periods. The first two columns are the eastbound passing times and headways, respectively. The third and fourth columns are the westbound passing times and headways for the same trains.

In Table 3.4 (12/14/93) the eastbound headways have approximately the same standard deviation as the eastbound departure headways observed in the Wonderland data set (Table 3.2). This seems reasonable; traffic is light in this direction in the a.m. peak period and thus dwell times should all be quite short and will probably also vary very little. Thus, there should be less headway variability in this direction. The standard deviation of the westbound headways in this data set is actually slightly smaller than that in Table 3.2. This is particularly interesting because at Maverick one would expect greater headway variation than at Wonderland due to dwell time effects (which in the a.m. peak should be much stronger in the westbound direction). This data also showed less variability for westbound headways than for the eastbound headways, as one expect given the opportunity to recover at Wonderland. Headways departing Wonderland westbound may have been very well regulated on this particular morning. Another possibility is that the headways of these trains were being controlled by holding them westbound at Orient Heights. Trains 1 and 15 had rather long eastbound headways and continued to have long headways in the westbound direction (assuming the times are correctly matched).

Table 3.4: E.B. and W.B. Headways for 12/14/93

	Maverick Eastbound Recorded	Headway		Maverick Westbound Recorded	Headway
0	7:24:41			7:58:52	
1	7:33:32	*0:08:51*		8:05:43	*0:06:51*
2	7:35:20	*0:01:48*		8:08:56	*0:03:13*
3	7:37:38	*0:02:18*		8:12:18	*0:03:22*
4	7:39:37	*0:01:59*		8:14:53	*0:02:35*
5	7:43:14	*0:03:37*		8:17:45	*0:02:52*
6	7:46:29	*0:03:15*		8:20:18	*0:02:33*
7	7:51:19	*0:04:50*		8:23:12	*0:02:54*
8	7:53:45	*0:02:26*		8:25:52	*0:02:40*
9	7:56:31	*0:02:46*		8:28:44	*0:02:52*
10	7:59:31	*0:03:00*		8:31:30	*0:02:46*
11	8:04:09	*0:04:38*		8:36:42	*0:05:12*
12	8:07:01	*0:02:52*		8:39:46	*0:03:04*
13	8:09:44	*0:02:43*		8:43:13	*0:03:27*
14	8:14:19	*0:04:35*		8:46:45	*0:03:32*
15	8:22:03	*0:07:44*		8:53:32	*0:06:47*
16	8:24:13	*0:02:10*		8:56:16	*0:02:44*
17	8:28:08	*0:03:55*		8:58:56	*0:02:40*
18	8:30:37	*0:02:29*		9:01:23	*0:02:27*
19	8:33:13	*0:02:36*		9:04:23	*0:03:00*
20	8:35:38	*0:02:25*		9:07:06	*0:02:43*
21	8:38:32	*0:02:54*		9:09:53	*0:02:47*
22	8:40:45	*0:02:13*		9:13:02	*0:03:09*
23	8:43:34	*0:02:49*		9:17:17	*0:04:15*
24	8:47:09	*0:03:35*		9:20:01	*0:02:44*
25	8:52:19	*0:05:10*		9:24:35	*0:04:34*
26	8:55:49	*0:03:30*		9:29:02	*0:04:27*
27	8:58:56	*0:03:07*		9:32:34	*0:03:32*
	Ave. 2 - 27	0:03:17			0:03:20
	Std. Dev.	0:01:17			0:00:59

Table 3.5 (6/13/94) shows somewhat more variation than the Wonderland observations, particularly in the eastbound direction. Much of this variation can probably be attributed to several very long headways followed by very short headways. However, the standard deviation of the westbound headways is still considerably smaller than that for the eastbound direction. The westbound standard deviation is only slightly larger than that observed at Wonderland. Again, one would expect greater variation at Maverick because

of its distance from the terminal and, in this case, the large variability of the eastbound headways in this time period. On the other hand, this data set does appear to show several fairly long eastbound headways being recovered from. For example, a headway of 9 minutes, 43 seconds (see number 15) is closed up with no particularly long headways in the westbound direction for several following and preceding trains.

Table 3.5: E.B. and W.B. Headways for 6/13/94

	Maverick		Maverick	
	Eastbound		Westbound	
	Recorded	Headway	Recorded	Headway
0	7:18:23		7:57:51	
1	7:26:05	*0:07:42*	8:01:06	*0:03:15*
2	7:31:09	*0:05:04*	8:09:09	*0:08:03*
3	7:34:42	*0:03:33*	8:13:39	*0:04:30*
4	7:37:13	*0:02:31*	8:17:01	*0:03:22*
5	7:42:30	*0:05:17*	8:19:44	*0:02:43*
6	7:45:01	*0:02:31*	8:22:44	*0:03:00*
7	7:52:25	*0:07:24*	8:25:34	*0:02:50*
8	7:54:23	*0:01:58*	8:28:37	*0:03:03*
9	7:59:03	*0:04:40*	8:32:21	*0:03:44*
10	8:01:10	*0:02:07*	8:35:50	*0:03:29*
11	8:03:50	*0:02:40*	8:39:21	*0:03:31*
12	8:07:34	*0:03:44*	8:43:04	*0:03:43*
13	8:09:30	*0:01:56*	8:46:10	*0:03:06*
14	8:12:50	*0:03:20*	8:49:13	*0:03:03*
15	8:22:33	*0:09:43*	8:52:17	*0:03:04*
16	8:27:27	*0:04:54*	8:56:46	*0:04:29*
17	8:30:53	*0:03:26*	9:00:25	*0:03:39*
18	8:34:06	*0:03:13*	9:03:00	*0:02:35*
19	8:36:40	*0:02:34*	9:05:43	*0:02:43*
20	8:38:53	*0:02:13*	9:09:52	*0:04:09*
21	8:43:51	*0:04:58*	9:15:05	*0:05:13*
22	8:46:01	*0:02:10*	9:17:52	*0:02:47*
	Ave. 2 - 22	0:03:48		0:03:39
	Std. Dev.	0:01:58		0:01:13

Overall, the results of this analysis are somewhat confusing. It is not clear how much headway trains can normally recover at Wonderland. The data collected at Wonderland showed trains with long headways failing to recover the scheduled headway of 3 ½ minutes. The Maverick data from 12/14/96 (Table 3.4) also seemed to suggest this. The other set of data from Maverick (6/13/94, Table 3.5) indicated much better headway recovery. All of this again suggests that the trains are tending to run late and that the train operators (and perhaps the supervisors as well) are focusing their efforts on getting back on schedule. The trains are therefore using up the recovery time that might otherwise be used to regulate their headways by leaving Wonderland as quickly as possible. The better performance on 6/13/94 may simply reflect a morning on which everything managed to run close to schedule.

Since neither sufficient time nor data were available to gain a full understanding of the westbound headway process, a compromise was reached between simulating the behavior observed at Wonderland, and that observed at Maverick. The initial arrangement for generating westbound headways is described below. As will be discussed in Chapter 4, this method had some significant flaws which later had to be corrected.

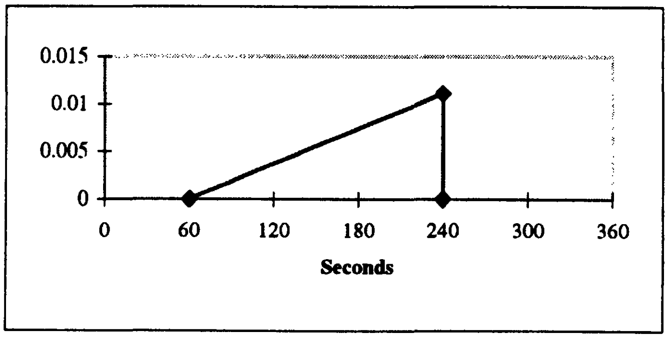
The first train in the sequence, which was assumed to have a constant headway throughout its trip through the model, was also given a fixed minimum dwell time at the westbound platform at Wonderland. After this train has boarded passengers, it is held until it has had a minimum dwell time of 7 1/2 minutes. This relatively long dwell allows the following trains to "catch up" to the first train so that they can, if required, be dispatched from Wonderland with shorter headways than they arrived with eastbound. In other words, 7 1/2 minutes of recovery time has been made available to the system. It would later be found that giving this train such a long dwell time was unrealistic and introduced a significant distortion to the simulation. The interstation time from platform N/2 (Wonderland eastbound) to (N/2) + 1 (Wonderland westbound) was treated as a constant, just like all of the other interstation times in the model. This time represents the time needed for the train to move from the eastbound platform up to the tail tracks, change ends at the tail tracks, wait to move back down to the westbound platform, and move to the westbound platform. Although it is not clear from the data available, the time actually occupied by this procedure is almost undoubtedly dependent on how soon a train is scheduled to depart. Thus, while there is clearly considerable variation in this running time, it was treated as constant with all of the headway adjustment taking place during the dwell at the west platform. This greatly simplified the modeling process by limiting the number of variables to one - the length of the dwell at the westbound platform.

All trains following the first one in each sequence were also held following boarding and were dispatched westbound on randomly generated headways. These headways were randomly generated according to the following scheme: Trains are classified into three groups according to their eastbound headways:

Group I: E.B. headways ≤ 2 minutes.
Group II: 2 minutes < E.B. headways ≤ 8 minutes.
Group III: 8 minutes < E.B. headways.

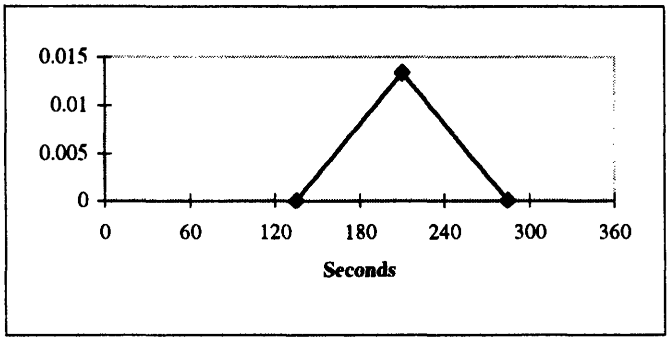
It was originally intended that Group III would cover trains with eastbound headways greater than 5.5 minutes. However, in view of the long headways that the Maverick data suggested could sometimes be recovered from, the boundary between groups II and III was moved up. Westbound departure headways for Groups I and II were randomly generated from triangular distributions. The distribution for Group I is a right triangle running from 60 seconds to 240 seconds, with the peak on the right-hand side. This gives a μ of approximately 187 seconds, a minimum of 60 sec., and a maximum of 240 sec.. Figure 3.7 illustrates this probability density function (PDF).

Figure 3.7: PDF for Target Headways for Group I Trains



The triangular distribution used for Group II headways, on the other hand, is an isosceles triangle. This approximated a symmetrical distribution with a μ of 210 seconds, a minimum of 135 sec., and a maximum of 285 sec. This PDF is shown in Figure 3.8.

Figure 3.8: PDF for Target Headways for Group II Trains



The advantages of these triangular distributions are that values far out in the tails, (including possible negative numbers) are avoided, and also that the asymmetrical distribution suspected of Group I can be approximated.

Group III includes all trains which may be unable to recover the scheduled preceding headway. In this case, the headway *savings* (in other words, the difference between the eastbound and westbound departure headways) is randomly generated from a normal distribution with a mean of 4 1/2 minutes and a σ of 45 seconds. This headway savings is subtracted from the train's eastbound headway to calculate the new westbound headway. Thus, a train with an eastbound headway of 8 1/2 minutes should have an expected westbound headway of 4 minutes. Since the first train in the sequence has been held at the Wonderland westbound platform for a minimum period of time, the following train should arrive there with a much shorter headway than it had when it departed the eastbound platform (to ensure this, a minimum headway of only 15 sec. is permitted at this platform). These headways will usually be short enough that each train in the sequence can be held to whatever westbound headway has been generated for it. Depending on the sequence of eastbound headways, and the westbound headways generated for these trains, the total amount of recovery time available will grow or shrink over the period of time that it takes for the trains to pass through Wonderland. In addition, if two (or more) consecutive trains arrive at Wonderland with excess headways, all of the recovery time can in effect be "used up"; some trains will arrive at the westbound platform with a headway equal to or greater than the one generated for it. These trains will then have to depart immediately after boarding passengers. This is a somewhat crude representation of what actually appears to be happening at Wonderland.

This arrangement was developed largely through trial and error. In the end, in order to verify the modeling of the Westbound headways, a special version of the model was set up to run an entire A.M. peak period worth of trains without any short-turn. The actual eastbound Maverick passing times were the input for this model. The westbound headways generated by the model at Maverick westbound were compared to the actual headways recorded at this location. Again, however, it is not certain whether the westbound times are perfectly matched to the eastbound times. Table 3.6 and Table 3.7 show the results of the simulation of the same two mornings that were analyzed in Table 3.4 and Table 3.5.

Table 3.6: Comparison of Modeled and Recorded Westbound Headways for 12/14/93

	Maverick		Wonderland		Wonderland		Maverick		Maverick	
	Eastbound		Eastbound		Westbound		Westbound		Westbound	
	Recorded	Headway	Model	Headway	Model	Headway	Model	Headway	Recorded	Headway
0	**7:24:41**								**7:58:52**	
1	**7:33:32**	***0:08:51***	7:47:38	*0:08:51*	7:54:22	*0:08:51*	8:09:56	*0:08:51*	**8:05:43**	***0:06:51***
2	**7:35:20**	***0:01:48***	7:49:10	*0:01:32*	7:56:57	*0:02:35*	8:11:41	*0:01:45*	**8:08:56**	***0:03:13***
3	**7:37:38**	***0:02:18***	7:51:27	*0:02:17*	8:01:12	*0:04:15*	8:14:37	*0:02:56*	**8:12:18**	***0:03:22***
4	**7:39:37**	***0:01:59***	7:53:26	*0:01:59*	8:05:00	*0:03:48*	8:18:23	*0:03:46*	**8:14:53**	***0:02:35***
5	**7:43:14**	***0:03:37***	7:57:08	*0:03:42*	8:09:40	*0:04:40*	8:23:12	*0:04:49*	**8:17:45**	***0:02:52***
6	**7:46:29**	***0:03:15***	8:00:19	*0:03:11*	8:13:21	*0:03:41*	8:26:46	*0:03:34*	**8:20:18**	***0:02:33***
7	**7:51:19**	***0:04:50***	8:05:15	*0:04:56*	8:17:40	*0:04:19*	8:31:05	*0:04:19*	**8:23:12**	***0:02:54***
8	**7:53:45**	***0:02:26***	8:07:36	*0:02:21*	8:21:57	*0:04:17*	8:35:25	*0:04:20*	**8:25:52**	***0:02:40***
9	**7:56:31**	***0:02:46***	8:10:21	*0:02:45*	8:26:11	*0:04:14*	8:39:35	*0:04:10*	**8:28:44**	***0:02:52***
10	**7:59:31**	***0:03:00***	8:13:23	*0:03:02*	8:29:07	*0:02:56*	8:42:27	*0:02:52*	**8:31:30**	***0:02:46***
11	**8:04:09**	***0:04:38***	8:18:05	*0:04:42*	8:32:24	*0:03:17*	8:45:45	*0:03:18*	**8:36:42**	***0:05:12***
12	**8:07:01**	***0:02:52***	8:20:52	*0:02:47*	8:35:31	*0:03:07*	8:48:47	*0:03:02*	**8:39:46**	***0:03:04***
13	**8:09:44**	***0:02:43***	8:23:37	*0:02:45*	8:38:59	*0:03:28*	8:52:21	*0:03:34*	**8:43:13**	***0:03:27***
14	**8:14:19**	***0:04:35***	8:28:15	*0:04:38*	8:43:04	*0:04:05*	8:56:30	*0:04:09*	**8:46:45**	***0:03:32***
15	**8:22:03**	***0:07:44***	8:36:05	*0:07:50*	8:49:15	*0:06:11*	9:02:54	*0:06:24*	**8:53:32**	***0:06:47***
16	**8:24:13**	***0:02:10***	8:38:02	*0:01:57*	8:52:58	*0:03:43*	9:06:18	*0:03:24*	**8:56:16**	***0:02:44***
17	**8:28:08**	***0:03:55***	8:42:04	*0:04:02*	8:56:57	*0:03:59*	9:10:25	*0:04:07*	**8:58:56**	***0:02:40***
18	**8:30:37**	***0:02:29***	8:44:29	*0:02:25*	8:59:45	*0:02:48*	9:13:02	*0:02:37*	**9:01:23**	***0:02:27***
19	**8:33:13**	***0:02:36***	8:47:04	*0:02:35*	9:03:31	*0:03:46*	9:16:55	*0:03:53*	**9:04:23**	***0:03:00***
20	**8:35:38**	***0:02:25***	8:49:27	*0:02:23*	9:07:05	*0:03:34*	9:20:26	*0:03:31*	**9:07:06**	***0:02:43***
21	**8:38:32**	***0:02:54***	8:52:23	*0:02:56*	9:11:33	*0:04:28*	9:24:59	*0:04:33*	**9:09:53**	***0:02:47***
22	**8:40:45**	***0:02:13***	8:54:35	*0:02:12*	9:16:02	*0:04:29*	9:29:31	*0:04:32*	**9:13:02**	***0:03:09***
23	**8:43:34**	***0:02:49***	8:57:25	*0:02:50*	9:19:11	*0:03:09*	9:32:28	*0:02:57*	**9:17:17**	***0:04:15***
24	**8:47:09**	***0:03:35***	9:01:01	*0:03:36*	9:23:06	*0:03:55*	9:36:30	*0:04:02*	**9:20:01**	***0:02:44***
25	**8:52:19**	***0:05:10***	9:06:14	*0:05:13*	9:26:23	*0:03:17*	9:39:42	*0:03:12*	**9:24:35**	***0:04:34***
26	**8:55:49**	***0:03:30***	9:09:42	*0:03:28*	9:29:33	*0:03:10*	9:42:53	*0:03:11*	**9:29:02**	***0:04:27***
27	**8:58:56**	***0:03:07***	9:12:46	*0:03:04*	9:32:39	*0:03:06*	9:45:58	*0:03:05*	**9:32:34**	***0:03:32***
	Ave. 2 - 27	**0:03:17**		0:03:16		0:03:47		0:03:42		**0:03:20**
	Std. Dev.	**0:01:17**		0:01:20		0:00:45		0:00:54		**0:00:59**

Arbitrarily assigned train numbers are given in column 1. Columns 2 and 3 are the actual eastbound passing times and headways at Maverick. Columns 4 and 5 are the simulated departure times and headways from Wonderland eastbound. Columns 6 and 7 are the westbound Wonderland departure times generated by the model. Columns 8 and 9 display the simulated departure times and headways from Maverick westbound. These should be compared directly with columns 10 and 11, which are the *actual* recorded passing times and headways at Maverick westbound. Note that train 1 has a constant headway throughout in the simulation.

Table 3.7: Comparison of Modeled and Recorded Westbound Headways for 6/13/94

	Maverick		Wonderland		Wonderland		Maverick		Maverick	
	Eastbound		Eastbound		Westbound		Westbound		Westbound	
	Recorded	Headway	Model	Headway	Model	Headway	Model	Headway	Recorded	Headway
0	**7:18:23**				*7:39:04*		*7:52:49*		**7:57:51**	
1	**7:26:05**	***0:07:42***	7:40:02	*0:07:42*	7:46:46	*0:07:42*	8:00:31	*0:07:42*	**8:01:06**	***0:03:15***
2	**7:31:09**	***0:05:04***	7:45:06	*0:05:04*	7:49:53	*0:03:07*	8:03:33	*0:03:02*	**8:09:09**	***0:08:03***
3	**7:34:42**	***0:03:33***	7:48:37	*0:03:31*	7:54:12	*0:04:19*	8:07:42	*0:04:09*	**8:13:39**	***0:04:30***
4	**7:37:13**	***0:02:31***	7:51:05	*0:02:28*	7:57:10	*0:02:58*	8:10:29	*0:02:47*	**8:17:01**	***0:03:22***
5	**7:42:30**	***0:05:17***	7:56:26	*0:05:21*	8:00:14	*0:03:04*	8:13:29	*0:03:00*	**8:19:44**	***0:02:43***
6	**7:45:01**	***0:02:31***	7:58:52	*0:02:26*	8:04:02	*0:03:48*	8:17:26	*0:03:57*	**8:22:44**	***0:03:00***
7	**7:52:25**	***0:07:24***	8:06:28	*0:07:36*	8:10:26	*0:06:24*	8:24:08	*0:06:42*	**8:25:34**	***0:02:50***
8	**7:54:23**	***0:01:58***	8:08:13	*0:01:45*	8:13:24	*0:02:58*	8:26:39	*0:02:31*	**8:28:37**	***0:03:03***
9	**7:59:03**	***0:04:40***	8:12:58	*0:04:45*	8:17:38	*0:04:14*	8:31:06	*0:04:27*	**8:32:21**	***0:03:44***
10	**8:01:10**	***0:02:07***	8:14:59	*0:02:01*	8:22:11	*0:04:33*	8:35:44	*0:04:38*	**8:35:50**	***0:03:29***
11	**8:03:50**	***0:02:40***	8:17:39	*0:02:40*	8:26:29	*0:04:18*	8:39:54	*0:04:10*	**8:39:21**	***0:03:31***
12	**8:07:34**	***0:03:44***	8:21:27	*0:03:48*	8:30:00	*0:03:31*	8:43:22	*0:03:28*	**8:43:04**	***0:03:43***
13	**8:09:30**	***0:01:56***	8:23:19	*0:01:52*	8:32:10	*0:02:10*	8:45:19	*0:01:57*	**8:46:10**	***0:03:06***
14	**8:12:50**	***0:03:20***	8:26:42	*0:03:23*	8:34:48	*0:02:38*	8:48:05	*0:02:46*	**8:49:13**	***0:03:03***
15	**8:22:33**	***0:09:43***	8:36:39	*0:09:57*	8:42:00	*0:07:12*	8:56:15	*0:08:10*	**8:52:17**	***0:03:04***
16	**8:27:27**	***0:04:54***	8:41:24	*0:04:45*	8:45:25	*0:03:25*	8:58:55	*0:02:40*	**8:56:46**	***0:04:29***
17	**8:30:53**	***0:03:26***	8:44:46	*0:03:22*	8:48:35	*0:03:10*	9:01:54	*0:02:59*	**9:00:25**	***0:03:39***
18	**8:34:06**	***0:03:13***	8:47:58	*0:03:12*	8:52:01	*0:03:26*	9:05:21	*0:03:27*	**9:03:00**	***0:02:35***
19	**8:36:40**	***0:02:34***	8:50:30	*0:02:32*	8:55:26	*0:03:25*	9:08:46	*0:03:25*	**9:05:43**	***0:02:43***
20	**8:38:53**	***0:02:13***	8:52:43	*0:02:13*	8:58:15	*0:02:49*	9:11:29	*0:02:43*	**9:09:52**	***0:04:09***
21	**8:43:51**	***0:04:58***	8:57:47	*0:05:04*	9:01:39	*0:03:24*	9:15:01	*0:03:32*	**9:15:05**	***0:05:13***
22	**8:46:01**	***0:02:10***	8:59:50	*0:02:03*	9:04:56	*0:03:17*	9:18:10	*0:03:09*	**9:17:52**	***0:02:47***
	Ave. 2 - 22	**0:03:48**		0:03:48		0:03:43		0:03:42		**0:03:39**
	Std. Dev.	**0:01:58**		0:02:03		0:01:11		0:01:26		**0:01:13**

Table 3.6 uses the data from 12/14/93. The model produced an average westbound headway of 3 minutes, 42 seconds at Maverick, which is slightly longer than the scheduled headway. This compares with the actual westbound headway of 3 minutes, 20 sec, which is somewhat shorter than scheduled. However, given that only 27 consecutive trains are modeled and that the standard deviations of both the modeled and actual headways are nearly 1 minute, this does not indicate any clear bias. The standard deviation of the

generated westbound headways at Wonderland is only 45 seconds, compared to eastbound standard deviation of 1 minute, twenty seconds. At Maverick, the standard deviation had grown slightly larger, as would be expected, and was even closer to the actual recorded value (54 vs. 59 sec.). The data from 6/13/94 (Table 3.7) gave similar results, with a very close match for both the average and standard deviation for westbound headways at Maverick. Individual long headways were partially, but not completely, recovered from. For example, number 15 on 6/13/94 had a 9 minute, 57 second eastbound headway at Wonderland, left Wonderland westbound with a 7 minute, 12 second headway, and had an 8 minute, 10 second headway at Maverick. In this case, it appeared that the train did recover its scheduled headway, though such is clearly not always the case on the Blue Line.

Given the limited amount of data available, this arrangement seemed to be a "best shot" at simulating the westbound headways, although is was later modified in an effort to make it more realistic as discussed in Chapter 4. Even with these changes, however, some serious questions remained about whether the data collected at Wonderland was truly representative and how this affected the realism of this part of the simulation. Given the importance of the westbound headways to the outcome of this model, more research in this area would be helpful.

3.2.2 Short-Turn Headways and Short-Turning Time

A slight modification of the above procedure was used to model westbound headways in the case of a short-turn. For short-turns that involve overtaking, it is generally intended that the train which will end up following the short-turned train be allowed to "drop back" into the following train's schedule. Where no overtaking is involved, the following train should simply try to depart Wonderland at its scheduled time. Thus, this following train's "target" headway should be twice the scheduled headway. However, if the excess headway is long enough, even this may not be possible. Two additional headway groups were introduced for 'following' trains:

Group IV: E.B. headways ≤ 11.5 minutes.

Group V: 11.5 minutes < E.B. headways.

For Group IV, the sum of two headways generated to the Group II distribution was used for the westbound headway, while Group V was treated in exactly the same way as group III, with headway recovery being randomly generated.

The time required for short-turning trains to make the short-turn move from the eastbound to the westbound platform at Orient Heights was randomly generated. This was the only interstation time in the simulation to be randomly generated. The distribution for this time was based on data collected during a temporary diversion, during which the Blue Line was closed from Orient Heights to Wonderland and all Blue Line trains were essentially short-turned at Orient Heights. Figure 3.9 shows a histogram of this data. The conditions under which these short-turns were done was perhaps less urgent than those for typical short-turns. However, it would have been impossibly time-consuming to observe a significant sample of actual short-turn movements. Extremely long times, in which train operators seemed to be taking a break while turning, were discarded from the sample. A triangular distribution was then fitted to this histogram, by choosing x-coordinates for the minimum, peak, and maximum of the triangle that minimized the sum of the squared error of each bin of the histogram (the height of the triangle, which is also the y-coordinate of the peak, is entirely dependent on the other three values, since the area of the triangle must equal 1). These three values are 169, 188 and 253 seconds respectively. The resulting PDF is shown in Figure 3.10.

Any delay to the train which ended up following the short-turning train was recorded (the following train would have to wait for the short-turning train since the new position of that train is specified). In nearly all of the short-turns simulated, however, even cases in which two trains were overtaken, the short-turn was done quickly enough not to delay the following train.

Figure 3.9: Probability Distribution of Turning Times at Orient Heights

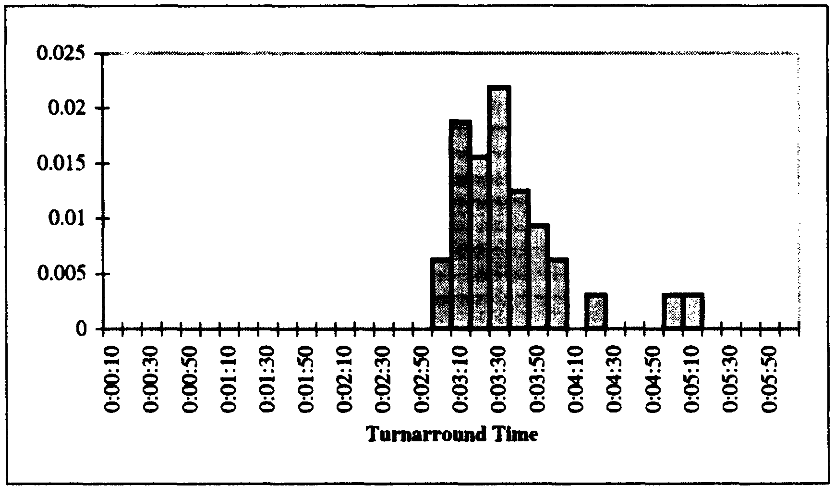
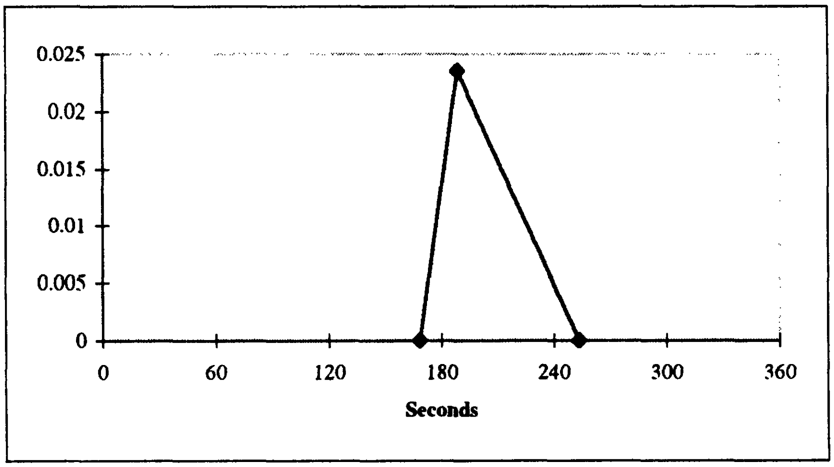


Figure 3.10: PDF Fitted to Short-turning Times



In the simulation, a target headway for the short-turned train was calculated as one-half of the headway which the train that would now follow it had when it departed Suffolk Downs, the stop preceding Orient Heights (recall that in this simulation, the stops of all trains at Suffolk Downs will already have been simulated before any stops at Orient Heights have occurred). If the short-turning train has boarded passengers at Orient Heights westbound in time to depart on this headway, it is held until it has this target preceding headway. In reality, the running time from Suffolk Downs to Orient Heights is short enough (a little over two minutes) that the following train would not necessarily have reached Suffolk Downs by the time that the short-turned train was ready to depart. Thus, in actual practice the following train's headway at an earlier location (such as departing Wonderland westbound) would have to be used. However, this would still provide a perfectly reasonable target headway.

3.2.3 Interstation Time Data

The data used to calculate average interstation times were collected by MBTA staff as part of two separate data collection efforts and are shown in Table 3.8.

The data in group A was collected by MBTA traffic checkers, while the three sets in group B were collected by a student intern accompanied by a supervisor. The figures in each numbered column are the number of seconds required by a particular train to reach each platform from the previous one. The columns on the extreme right-hand side are the overall averages and standard deviations respectively for all of the data. The bottom row shows the sum of all available times in each set, divided by the sum of the overall averages of these times. In this way, any systematic variation in running speed might be highlighted. Unfortunately, many of these data sets in Group A were incomplete. A number of data points were also deleted from this group because they were much larger than the other values for that segment. Many of these outliers may have resulted from interference from preceding trains (due to stop signals). It was assumed that the remaining data points were not influenced by interference from other trains and that their values did not vary by time of day. The available number of interstation time sample sets was too small to plot distributions. In any case, interstation times are undoubtedly at least somewhat correlated with the train operator, causing a systematic relationship for a given train across interstation segments. Therefore, no effort was made to generate these variables randomly. Instead, average values were calculated and used as constants. The overall averages, which are in the second column from the right, became the set of interstation times used for the simulation.

Table 3.8: Interstation Time Data

	Group A										Group B				Overall Statistics	
Data Set:	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**Ave.**	**10**	**11**	**12**	**Ave.**	**Ave.**	**Std. Dev.**
To:																
Bowdoin						83	95	100	97	**94**					**94**	**7.5**
Government Ctr.	25				27	41	39	49		**36**	44	46	43	**44**	**39**	**10.1**
State	50		51	59	66	53	53			**55**	67	61	60	**63**	**58**	**6.1**
Aquarium	55	58	60	64	40	62	66			**58**	62	72	73	**69**	**61**	**8.7**
Maverick	127	136	128	142	156	138	153			**140**		150	149	**150**	**142**	**11.3**
Airport	97	115	109	111	107	103	117			**108**	125	121	124	**123**	**113**	**6.9**
Wood Island	75	76	76	84	102	89	88			**84**	88	89	109	**95**	**88**	**9.8**
Orient Heights	165		178	152	122	183				**160**	158	153	156	**156**	**158**	**24.4**
Suffolk Downs		73		72	94					**80**	82	74	67	**74**	**77**	**12.4**
Beachmont	70	60		76	63					**67**	83	85	83	**84**	**74**	**7.2**
Revere Beach	85	87		96	79					**87**	89	89	93	**90**	**88**	**7.0**
Wonderland	85	98		100	69					**88**	92	97	96	**95**	**91**	**14.3**
Revere Beach	50		49	64	63					**57**	60	61	68	**63**	**59**	**8.1**
Beachmont	80	89	90	90						**87**	102	110	108	**107**	**96**	**4.9**
Suffolk Downs	63	70	66	71	74					**69**	62	77	74	**71**	**70**	**4.3**
Orient Heights	66	70	69	70	90					**73**	82	81	84	**82**	**77**	**9.6**
Wood Island	130	140	134		152		157			**143**	149	145	146	**147**	**144**	**11.6**
Airport	88	95	93	103		93	100			**95**	107	105	112	**108**	**100**	**5.4**
Maverick	85	104	98	120	124	95	100			**104**	116	113	126	**118**	**108**	**13.8**
Aquarium	110	105	105	121		114	115			**112**	128	128	140	**132**	**118**	**6.3**
State	55	57	52	61	49	55	58			**55**	61	62	70	**64**	**58**	**3.9**
Government Ctr.	45	61	58	55		48	54			**54**	62	61	61	**61**	**56**	**6.0**
Bowdoin	95				56	58	53	57		**64**	61	64	54	**60**	**62**	**17.5**
Sum:										**1875**				**2057**	**1937**	
Normalized Sum*:	0.91	0.96	0.94	1.01	0.98	0.97	1.01			**0.97**	1.05	1.06	1.08	**1.06**		

* Sum of all times in each set, divided by the sum of the overall averages of the times in that set.

Another disappointment with this data was that it was not possible to identify the behavior of 'slow' train operators. An attempt was made to record interstation times for a (believed-to-be) slow operator, but there simply was not sufficient time to find an operator that was significantly slower than the others. However, another 'best guess' was made of how much slower such trains might be. The data in subset B was evidently affected by the presence of the supervisor who accompanied the data collector. These interstation times were, on average, significantly longer than those in group A. In addition, the sum of the averages of these times was 3 minutes longer than the sum of the averages for group A, and 2 minutes longer than the sum of the overall averages. The averages from subset B was therefore used to represent the behavior of trains with 'slow' operators.

3.2.4 Passenger Demand Data

As indicated in Chapter 2, passenger arrival rate (pax) data in passengers per second and alighting proportion of passengers (pap) data were prepared for each platform as parameters for randomly generating boardings and alightings. A file of pax and pap values for each platform was prepared for the period 6:00 a.m. to 9:45 a.m.. These were generated from passenger count data collected by the Central Transportation Planning Staff (CTPS) in 1989 and 1993[22]. The 1993 counts were used to produce passenger arrival rate data, since it seemed more likely to reflect current ridership levels. The passenger count reports consist of total passenger arrival counts for each platform on the line for each quarter-hour period of a weekday, generally starting at 7:00 a.m.. The program allowed different values for each quarter-hour period. However, a constant set of average values were assigned to all intervals for each platform. This ensured that short-turns made at different times within the a.m. peak period could be directly compared. Table 3.1 shows the average line volume leaving each platform and the average passenger arrival rate at each platform in the a.m. peak in passengers per hour (though the input to the model was in passengers per second). Figure 3.11 shows the line volume for the line in the a.m. peak period. The station name labels on the horizontal axis refer to the tick mark to the immediate left of the name.

The data was prepared using the following procedure: for each platform, the total arrivals for the period 7:00 to 9:45 a.m. were added up and then divided by the number of seconds in this 2 hour, 45 minute period. The 7:00 to 9:45 a.m. period consists of the "peak" of the a.m. peak from about 7:00 to 8:45 (which has a fairly constant high boarding rate at all platforms) as well as the trailing shoulder period from 8:45 (9:00 at downtown stations) to

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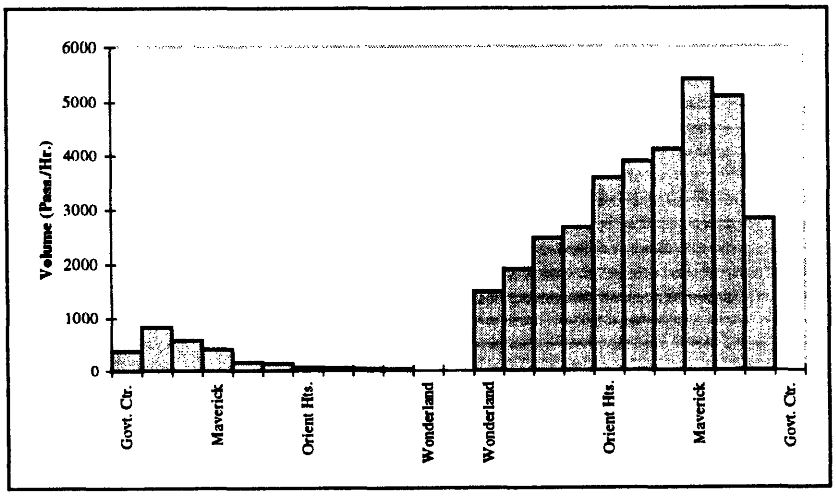
[22] Thomas J. Humphrey, "1989 Passenger Counts: MBTA Rapid Transit and Commuter Rail," Central Transportation Planning Staff, 1991.

9:45. There is presumably a complimentary shoulder leading up to 7:00 a.m., but no data had been collected for this period. Since no data was available for the period before 7:00, the 7:00 to 9:45 averages were applied to the entire 6:00 to 9:45 a.m. period, though the data in the 8:45 to 9:45 period was not weighted more heavily.

Table 3.9: Average Passenger Demand for Blue Line in A.M. Peak Period

Eastbound				Westbound			
Platform Number	Station	Line Vol. Departing (pass./hr.)	Passenger Arrival Rate (pass./hr.)	Platform Number	Station	Line Vol. Departing (pass./hr.)	Passenger Arrival Rate (pass./hr.)
1	Bowdoin	N/A	44	13	Wonderland	1490	1226
2	Government Center	378	379	14	Revere Beach	1919	380
3	State	833	437	15	Beachmont	2480	463
4	Aquarium	597	34	16	Suffolk Downs	2673	155
5	Maverick	413	13	17	Orient Heights	3581	755
6	Airport	166	10	18	Wood Island	3880	277
7	Wood Island	142	6	19	Airport	4109	243
8	Orient Heights	73	3	20	Maverick	5414	1157
9	Suffolk Downs	69	1	21	Aquarium	5104	49
10	Beachmont	51	2	22	State	2841	236
11	Revere	37	3	23	Government Center	N/A	6
12	Wonderland	-	-	24	Bowdoin	-	-

Figure 3.11: Blue Line A.M. Peak Volume Profile



Passenger alighting proportions were prepared using the line volume figures for each platform. Line volume data is, in practice, estimated by recording the loads of each train over each segment of the line. Train loadings are determined by adding boardings and subtracting alightings from the load of each individual train at each platform. The train loadings over each interstation segment can then be grouped to determine the total passenger volume over each segment for each 15-minute period of the day. The 1993 Blue Line Passenger Count Report did not include line volume calculations because the data was collected over several days and it was found to be infeasible to correlate trains. However, such figures had been generated with the 1989 Blue Line Passenger Count. Since pap is a dimensionless scalar, it seemed reasonable to assume that these proportions would not have changed significantly over the intervening 5 year period. The passenger alighting proportion values were calculated by dividing the total number of alightings at each platform by the line volume into that platform. The total volumes and alightings for the two-hour period 7:00 to 9:00 were used for these calculations and were applied to the entire 6:00 to 10:00 a.m. period. Using line volumes requires the assumption that passengers are equally likely to alight at a given stop, independent of where they boarded the train. In other words, the possibility that a disproportionate number passengers boarding at Aquarium alight at Airport is not allowed for. However, such an assumption is particularly safe to make with the Blue Line because the overall flow across the peak load point-between Downtown Boston on one side and East Boston and Revere on the other dominates everything else.

3.2.5 Boarding and Alighting Rates

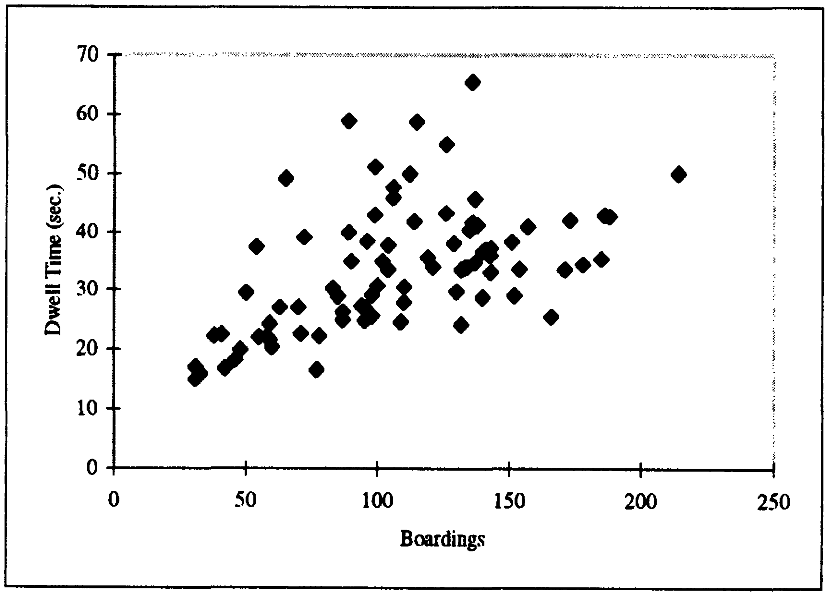
The boarding rate for Blue Line trains was estimated from data collected at the outbound platform of State St. Station during the evening peak period. This data was collected in the following manner: passenger arrivals on the platform were tallied between each pair of train departures; as each train closed its doors and departed the platform, a new count was started. At the same instant, any passengers remaining on the platform who had been either unable to board that train, or had chosen not to, were also counted. These leftover passengers were subtracted from the number counted between departures to obtain the actual number of boarders. As each train arrived at the platform, the load already on the train was estimated as closely as possible. The total period of time that the train doors remained open was measured using a stopwatch.

One would expect the boarding rate to decline as the train load increases because of congestion around the train doorways as the train gets more crowded. When the train is so overcrowded that boarding passengers are left behind, additional "excess dwell" time is usually required simply to close the doors. The sample of observations covered a wide range of loading conditions, including several instances of severe overcrowding. An effort was therefore made to correlate the initial train load with the boarding rate. However, the correlation was not statistically significant. Thus, a constant boarding rate was used for normal train boarding. The non-linearity caused by the excess dwell due to severe overcrowding was represented by a separate, randomly generated time period. It was also not possible to correlate the number of alightings in this data set with the dwell times. During the p.m. peak period, which is when this data was collected, boardings far outweigh alightings at the eastbound platform at State.

A linear regression of "door open" time as a function of boarders was then used to estimate the boarding rate and a constant term. A total of 97 data points were available. However, since the intention was to estimate the boarding rate independently of overcrowding conditions, seven data points in which more than 20 boarding passengers were left behind on the platform were deleted from the set. Figure 3.12 plots this data.

A coefficient for boardings of 0.134 seconds per boarding, with an intercept of 18 seconds, was obtained. The R^2 statistic for the regression was 0.286, the t statistic for the boardings coefficient was 5.936, and the t statistic for the constant term was 7.302. Note that since time is the dependent variable in this regression, the boarding *rate* is the inverse of the coefficient or 7.4 passengers per second. This rate seems intuitively reasonable, given that a Blue Line train has 8 doors per side but that passenger flow will not be uniformly distributed across all of them, and that passengers appear to pass through these doors at a rate of about 1.5 per second. A function based on these results also appears to generate realistic dwell times, based on field observations. The 18 second constant term represents the time required for the train guard to check that all passengers have boarded and to then close the doors. One possible bias in this data may stem from the fact that a field supervisor was stationed at State for much of the observation period, and would often hold the train for passengers running for the train. This would tend to lower the boarding rate estimate, since the supervisor was essentially extending the dwell time for just a few passengers to "arrive" at the platform and board the train through just one or two doors.

Figure 3.12: Dwell Time as a Function of Total Boarders



The "excess dwell" time invoked during conditions of overcrowding was randomly generated. This variable was uniformly distributed between 10 and 40 seconds. Since only limited data was available, this was based mostly on casual observations on various transit systems.

There was not sufficient time to collect similar data on alightings. However, it seemed to be a reasonable assumption that the alighting rate was similar to the boarding rate. Therefore, the same value was used in this project.

3.3 Analytical Procedure

3.3.1 Sequence Selection Procedure

As explained in section 2.4, one of the principal inputs for each short-turn simulated was an initial sequence of trains represented by the times they passed Maverick eastbound. Each sequence of "NUM_TRAINS" successive trains were screened by each train's headway to determine whether initial conditions for a potentially helpful short-turn were satisfied. The initial phase of the analysis considered three types of short-turns based on the number of trains overtaken: zero, one, and two. These probably represent the majority of short-turns done on the Blue Line, though short-turns combined with other strategies including dropping trips, adding a spare train, and expressing are or have been used at various times in the past.

The screening process was intended to limit the number of sequences tested to those for which short-turning seemed reasonably likely to be helpful. Sequences were selected to try short-turns based on the preceding headway of the second train (henceforth, h_1 will be used to signify the preceding headway of the first train in the sequence, h_2 for that of the second train, and so on) and on the average of the following headways in the sequence. Short-turning was only tested on sequences in which h_2 >= 0:08:00, and the average of the following NUM_TRAINS - 2 headways was < 0:06:00. The lower bound on h_2 was selected following a few trial runs with the simulation. Referring back to Table 3.1 in section 3.1.1, about 6% of headways at Maverick outbound in the a.m. peak are 8 minutes are more. In the next chapter it will be shown this should not screen out a significant number of potentially helpful short-turns. The screen on the following headways was used because in the a.m. peak overcrowding and denied boardings will "blow up" when the average headway in a sequence is greater than 0:06:00, and the model would fail to account for all passenger waiting time given the discrete number of trains simulated in each case.

The number of trains in the sequences simulated (NUM_TRAINS) was chosen based on having 2 trains following the train being short-turned (the short-turning "candidate"). Since the train following the candidate ends up with a greater headway once the candidate is extracted from the sequence at the short-turn point, this train has a greater likelihood of becoming overcrowded and leaving passengers behind. By including one additional train in the sequence, any passengers left behind by the train following the candidate can board this last train. To summarize the procedure:

Overtake 0 trains:	4 trains. Train 2 is re-inserted into the same position in the sequence.
Overtake 1 train:	5 trains. Train 3 is re-inserted into the second position in the sequence.
Overtake 2 trains:	6 trains. Train 4 is re-inserted into the second position in the sequence

It may seem surprising that short-turns in which no trains are overtaken are being considered here. For one thing, if the train being short-turned is the one with the excessive headway, this train is likely to have a much larger load than the train following it. Hence there will be more dumpees. In addition, an even larger gap will be created in the skipped segment than would be likely if the following train (which is likely to have a short headway) is removed. On the other hand, as indicated in section 3.1.1, there are situations in which a short-turn with no overtaking is the most desirable option. Therefore, such short-turns were included in this study. In general, however, if a very long headway is encountered, one should expect the following train (and perhaps several following trains) to have a shorter than scheduled headway due to dwell time effects. Thus, one should expect to have a better result in terms of passenger waiting time savings if the following train is short-turned. In the case in which the third train overtakes the second, the third train is likely to have a short headway and is therefore few passengers to dump. If h_2 is large enough, the fourth train should also have a short headway. Therefore removing train 3 from service should not result in an extremely large headway for train 4 (train 4 will end up with the sum of h_3, h_4, and the extra time required for train 3 to dump its passengers).

3.3.2 Simulating 'Slow' Trains

While the initial set of simulations assumed that all trains in each sequence had the same set of interstation running times, the data was also run with a simulation in which one train in the sequence moved more slowly than the others. As indicated in sections 3.1.1 and 3.1.2, supervisors on the Blue Line often select a specific train for short-turning because they feel its operator tends to run more slowly than average or are unlikely to recover time by running fast. The 'slow' behavior was assigned only the train with the excess headway (train 2) in each sequence. This is consistent with the idea that slow operators either cause excess headways or fail to recover from them. Thus, short-turning the slow train will allow it to recover its schedule. Short-turning the following train (train 3) into the position ahead of the slow train will allow the slow train to fall back into the schedule of train 3.

It is thought that the slow operators have longer running times because they are more cautious than most in their observation of speed restrictions. No conclusive data on operator performance is available. However, subset 'B' the interstation time data discussed in section 3.2.3 (see Table 3.8) differed from subset 'A' in that it was relatively consistent but considerably slower than the average for subset 'A'. This was evidently because subset B was collected with a supervisor on board the train. This may have caused the train operator to observe speed restrictions more carefully. Therefore, this sub-set of data was used to represent how the slow operators might perform.

Rather than providing a separate set of interstation times for slow trains, a scaling factor was used to lengthen all of the interstation times of the slow train by the same proportion. Again referring to Table 3.8, note the bottom row. The sum of the averages of the interstation times in subset 'B' was compared to the sum of the overall averages (again referring to Table 3.8, note the bottom row). The sum of the averages for subset 'B' is 106% greater than the sum of the overall averages. Therefore, each interstation time added to the time variable of the slow train was multiplied by 1.06. As will be seen in the next chapter, this relatively minor change had significant results.

Chapter 4

Results of the Blue Line Analysis

This chapter will first explain how the simulation model was used and how the output was analyzed. Results from the base model and with a 'slow' train 2 will be presented and analyzed. Next, the base model will be critiqued and some modifications tested. Additional short-turn results are produced using this modified model. Then, the validity of the model will be checked by estimating the outcome of several short-turns using a simplified spreadsheet model. The results from the base model, the 'slow train' model, and the modified model are used to prepare manual guidelines for short-turning on the Blue Line in the a.m. peak. Two alternative short-turn performance measures are considered. Finally, several short-turns actually recorded on the Blue Line are analyzed using the simulation model.

4.1 Using the Model

As outlined in Chapter 3, the same set of input data was used to test several different types of short-turns. Three months worth of Maverick passing time data was available. Weekends and all holidays observed in Massachusetts were deleted from this data so that only regular weekday a.m. peak periods were tested. Headway sequences were screened by the criteria explained in section 3.3.1. Each sequence also had to lie entirely within the time period during which 3 ½ minute headways were scheduled. The following short-turns were tested:

Overtake No Trains; train 2 is short-turned.
Overtake 1 Train; train 3 is short-turned.
Overtake 2 Trains; train 4 is short-turned.

For each sequence accepted, 50 trials of the model were run. For each set of 50 trials, averages and standard deviations were calculated for each output variable. Thus, for each sequence a distribution of results was generated for each output. Since several inputs to the model were randomly generated, notably passenger boardings and alightings and the westbound headway sequence, the outputs had considerable variability.

4.1.1 Model Outputs

The total passenger waiting time savings or "delta PWT" is the most important indicator for comparing the relative performance of short-turns. While the model had several other outputs, these were used only to check the validity of using delta PWT as the primary objective variable. The number of denied boardings saved by the short-turn was the most useful of these. While the overall capacity of the Blue Line is sufficient to meet peak demands, excess headways cause overcrowding. Passengers boarding near the peak load point are often unable to board the first train to arrive. A significant number of denied boardings is therefore a good indicator that overcrowding would occur in this scenario. Secondary indicators will be discussed further in section 4.6.

4.1.2 The Threshold Value

Short-turning should result in shorter waits and less crowding downstream from the short-turn point, but longer waits for passengers in the skipped segment. In addition, there are the skipped segment alighters, or "dumpees", who must wait for the following train, but experience the additional frustration of being unexpectedly forced to alight short of their destination. No effort was made to assign a cost to this inconvenience, but it almost certainly is significant in proportion to the perceived 'cost' of the dumpees' additional waiting time alone. Because of this ambiguity, and also because there is considerable uncertainty about whether a particular short-turn will actually save passenger waiting time, a threshold level was adopted. Deckoff, in his study of short-turning on the MBTA Green

Line, adopted a minimum expected benefit of 250 passenger-minutes saved for a short-turn to be considered beneficial. This is equivalent to one minute saved for each passenger on a fully loaded two-car green line train of 250 passengers. Since the Blue Line trains have nearly twice the passenger capacity of a two-car Green Line train, a threshold value of 500 passenger minutes (or 30,000 passenger seconds) saved was selected for this project. This is not to say that short turns in which delta PWT > –30,000 passenger seconds are to be avoided at all costs, however. The objective of getting the system back on schedule is important, as is reducing overcrowding and denied boardings. Therefore, short-turn outcomes were classified into three groups according to the following scheme:

'Beneficial': delta PWT ≤ –30,000 (pass.-sec.)
'Neutral': 0 ≤ delta PWT < –30,000
'Poor': delta PWT > 0

A 'Poor' or 'Neutral' outcome does not necessarily imply that no benefit would come from a particular short-turn. For example, there may be operating issues such as schedule adherence or the need to re-sequence trains and/or crews that are not captured in this model. In general, a 'neutral' impact on passenger waiting time simply indicates that there was no clear increase in total passenger waiting time and that therefore a short-turn made for some reason other than to fill a long headway may be an acceptable strategy.

4.2 Analyzing the Model Output

Table 4.1 presents the average and standard deviation of the delta PWT results for each headway sequence tested for short-turning. These are short-turns in which one train was overtaken and all trains had constant interstation times. These results have been ordered by the delta PWT outcome, with the most negative delta PWT outcome (i.e. the most 'beneficial') at the top.

For each different type of short-turn, about one full day was required to process the entire set of weekday a.m. peak data (about 65 days in total). Out of this period approximately

65 sequences met the selection criteria set for each of the three types of short-turn, although there were a number of sequences which only met the criteria for one or two types. Thus, there was an average of about one sequence per weekday a.m. peak that met the selection criteria.

4.2.1 Validating the Number of Trials Run

50 trials were run for each sequence because this number appeared to be large enough to give fairly reliable results without requiring excessively large calculation times. Referring back to Table 4.1, note that while the average delta PWT values range from −239,188 to 103,507, the standard deviations increased only slightly with the absolute value of the average. Indeed, all were within the same order of magnitude.

The validity of the sample size of 50 depends largely on the threshold value. The smaller the magnitude of the threshold value, the more trials would have been needed to assure reasonable confidence in the results. Hypothesis testing was used to determine whether 50 was a sufficient number, given the variation in outcomes across trials. Sequences whose average delta PWT result was only just below the threshold value were tested against the null hypothesis that the true mean would be greater than zero. In other words, short-turns whose outcomes were only just 'beneficial' were tested to ensure that the possibility that the true mean outcome was 'poor' could be ruled out. Z-testing showed that, with very high confidence, the null hypothesis that the true mean delta PWT was *greater than zero* (i.e. a 'poor; outcome) could be rejected for practically all examples with 'beneficial' outcomes. This supports the adequacy of the sample size of 50 for this threshold value.

Table 4.1: Simulation Results for Overtaking One Train, Initial Model

	Headway Sequence					Delta PWT	
Ranking	h_1	h_2	h_3	h_4	h_5	Average	Std. Dev.
1	0:07:24	0:13:04	0:01:39	0:03:01	0:02:30	-239188	65172
2	0:11:22	0:09:37	0:02:31	0:05:04	0:01:37	-154190	84690
3	0:08:27	0:09:54	0:01:49	0:01:58	0:02:17	-110272	55954
4	0:02:22	0:12:30	0:01:38	0:03:29	0:05:14	-92738	49625
5	0:08:09	0:09:38	0:02:37	0:03:43	0:05:31	-86104	56497
6	0:06:52	0:11:22	0:09:37	0:02:31	0:05:04	-76150	61060
7	0:08:13	0:10:41	0:03:30	0:05:18	0:07:44	-73523	39256
8	0:01:56	0:11:03	0:01:47	0:02:11	0:02:58	-69221	34204
9	0:03:26	0:11:14	0:02:11	0:02:48	0:02:55	-67751	33055
10	0:02:15	0:10:46	0:04:26	0:02:07	0:02:12	-63477	34681
11	0:03:38	0:11:13	0:02:15	0:02:00	0:01:57	-62618	37644
12	0:05:21	0:10:17	0:02:16	0:02:31	0:02:49	-61531	37301
13	0:08:55	0:09:07	0:01:42	0:02:11	0:02:28	-55830	47803
14	0:04:12	0:10:26	0:03:52	0:02:09	0:03:31	-50692	34012
15	0:03:08	0:10:46	0:01:37	0:02:53	0:04:15	-50412	33595
16	0:03:16	0:10:36	0:02:02	0:03:31	0:02:34	-46730	38646
17	0:06:56	0:09:12	0:02:16	0:02:35	0:02:31	-44630	47619
18	0:02:58	0:09:56	0:02:50	0:02:38	0:02:06	-36718	26846
19	0:03:41	0:10:03	0:02:34	0:02:53	0:03:06	-35383	21011
20	0:12:31	0:08:31	0:05:07	0:01:56	0:02:30	-33102	86161
21	0:09:13	0:08:27	0:02:14	0:02:05	0:02:11	-32677	54287
22	0:02:57	0:10:19	0:01:59	0:02:16	0:03:36	-31860	36413
23	0:02:48	0:09:44	0:02:53	0:02:05	0:02:40	-30781	29623
24	0:05:13	0:09:32	0:02:33	0:02:51	0:02:44	-27981	33649
25	0:10:00	0:08:42	0:01:49	0:07:32	0:02:29	-27398	54664
26	0:04:18	0:09:49	0:02:35	0:01:54	0:05:39	-26059	30027
27	0:04:14	0:09:48	0:02:44	0:01:51	0:02:23	-25672	24470
28	0:07:48	0:09:03	0:02:14	0:06:55	0:03:41	-25425	26090
29	0:03:16	0:09:33	0:03:01	0:02:11	0:02:39	-24430	30219
30	0:02:51	0:10:16	0:01:43	0:05:05	0:02:47	-22650	22854
31	0:03:00	0:09:24	0:02:15	0:02:38	0:02:21	-18906	28343
32	0:02:20	0:09:10	0:03:12	0:02:43	0:02:58	-14017	22545
33	0:02:48	0:08:59	0:02:15	0:04:17	0:02:10	-11672	19380
34	0:05:02	0:08:51	0:01:48	0:02:18	0:01:59	-11262	30035
35	0:01:40	0:08:54	0:02:50	0:03:07	0:01:40	-10513	25573
36	0:01:57	0:08:32	0:02:16	0:04:51	0:03:01	-10097	20501
37	0:02:31	0:08:58	0:01:39	0:03:33	0:02:03	-9584	20978
38	0:04:03	0:08:33	0:04:02	0:02:36	0:02:32	-9354	21767
39	0:04:05	0:08:59	0:03:12	0:03:04	0:02:42	-9318	28599
40	0:06:09	0:08:31	0:02:20	0:03:16	0:03:07	-9021	31912
41	0:02:33	0:08:45	0:02:14	0:02:49	0:02:43	-6014	22419
42	0:03:55	0:08:52	0:03:35	0:01:47	0:03:03	-5468	19908
43	0:05:17	0:08:09	0:09:38	0:02:37	0:03:43	-4254	48911
44	0:03:09	0:08:05	0:02:54	0:02:29	0:01:52	-2306	23126
45	0:04:11	0:08:40	0:02:24	0:03:20	0:01:48	-2040	26882
46	0:04:14	0:08:45	0:01:37	0:04:29	0:02:36	-521	25757
47	0:02:38	0:08:53	0:01:39	0:01:39	0:04:12	751	27971
48	0:03:31	0:08:46	0:06:38	0:03:01	0:02:46	3620	15372
49	0:02:31	0:08:12	0:02:46	0:02:00	0:03:08	4879	23562
50	0:05:30	0:08:06	0:01:55	0:02:58	0:01:57	7191	28714
51	0:03:09	0:08:03	0:03:34	0:02:14	0:02:09	8433	17776
52	0:04:40	0:08:02	0:01:45	0:03:04	0:03:35	8575	22220
53	0:02:53	0:08:13	0:01:57	0:05:28	0:04:14	8788	13281
54	0:04:13	0:09:09	0:04:06	0:04:46	0:04:56	10534	10242
55	0:06:47	0:08:02	0:03:01	0:01:41	0:04:19	10720	33319
56	0:01:54	0:08:02	0:02:07	0:02:16	0:03:54	11190	25099
57	0:03:25	0:08:05	0:01:45	0:04:02	0:02:29	12163	21737
58	0:05:35	0:08:59	0:02:58	0:02:40	0:08:55	14136	24821
59	0:04:35	0:10:22	0:05:39	0:01:59	0:06:45	18259	22650
60	0:02:42	0:08:15	0:01:54	0:08:02	0:02:07	21558	25501
61	0:03:38	0:10:57	0:03:26	0:01:40	0:08:54	34793	43873
62	0:02:44	0:08:55	0:03:58	0:07:44	0:01:43	57116	33480
63	0:05:45	0:08:06	0:05:21	0:10:17	0:02:16	94320	64169
64	0:02:40	0:08:55	0:05:29	0:09:42	0:02:00	94731	55522
65	0:02:05	0:12:31	0:08:31	0:05:07	0:01:56	94781	48694
66	0:03:41	0:13:57	0:05:36	0:07:31	0:04:30	103507	34409

4.2.2 Variability and the Validity of Threshold Value

As indicated in section 4.1.2, a threshold value for passenger waiting time savings was used partially to allow for the uncertainty of the outcome of a short-turn. Ideally, the threshold should be large enough so that the probability of a specific outcome having a negative passenger waiting time savings is reasonably small (the threshold was also used to cover the "inconvenience" cost incurred by the dumpees, though in this project no specific cost was assigned to being dumped). As can be seen in Table 4.1, most of the sequences whose outcomes were around the threshold value also had standard deviations of roughly 30,000 sec. However, a few examples showed considerably more variation. The cases in which the standard deviation was larger generally involved more serious incidents with two excessive headways in the sequence. This increased the amount of variation possible in the westbound headway sequence and therefore the variability in passenger waiting time.

The validity of the threshold was statistically tested using one or two examples from each of the three types of short-turns simulated. From each group, the 'beneficial' short-turn for which the average delta PWT was closest to the threshold was chosen for this analysis. From two groups, the 'beneficial' outcome that had the largest standard deviation relative to the average was tested as well; for the 'Overtaking No Trains' data, these turned out to be one and the same. The threshold was tested in two ways: first, frequency distributions of the delta PWT outputs of the 50 trials were prepared. The actual proportion of the 50 trials for which the delta PWT was 'poor' was then determined. For the other test, an assumption was made that delta PWT was normally distributed. Thus, the *expected* proportion of trails with 'poor' outcomes was calculated using the z-score. The results are presented in Table 4.2. Again, note that the last two columns simply show two different ways of checking the same thing.

Table 4.2: Statistics from "Worst Case" Distributions of Results for 'Beneficial' Short-Turns

				% Trials with 'Poor' Outcomes	
	Rank	**Average Delta PWT**	**Std. Dev.**	**Actual**	**Expected**
Overtake No Trains:	#11	-37141	50831	23%	24%
Overtake 1 Trains:	#23	-30781	29623	14%	15%
	#20	-33102	86161	34%	35%
Overtake 2 Trains:	#26	-31483	29257	18%	14%
	#21	-36041	83467	36%	33%

Both versions of this test indicated similar results for each example. For the 'overtaking no trains' case, for example, only 23% to 24% of the 50 trials came out in the 'poor' range; The remainder were either 'neutral' or 'beneficial'. Since the standard deviations increase only slightly as the averages decrease, confidence in a beneficial PWT outcome also increases. Overall, these tests indicate that in all but a few cases the threshold value should provide for reasonably high (say, 80% or better) probability of a beneficial outcome.

4.2.3 General Observations

Figure 4.1, Figure 4.2, and Figure 4.3 show the average delta PWT results as a function of h_2 for each sequence tested, for each of the three types of short-turn. h_2 is the 'gap' headway to be "filled in" by the short-turned train. It is quite clear from these plots that as h_2 increases, the expected PWT savings also increases.

By extrapolating each distribution of points to the left of h_2 = 8 minutes, it is evident that there should be few if any beneficial short-turns when h_2 is less than 8 minutes. This demonstrates that h_2 >= 8 minutes is a reasonable cut-off for sequence screening.

Figure 4.1: Average Delta PWT Results as a Function of H_2, Overtake No Trains

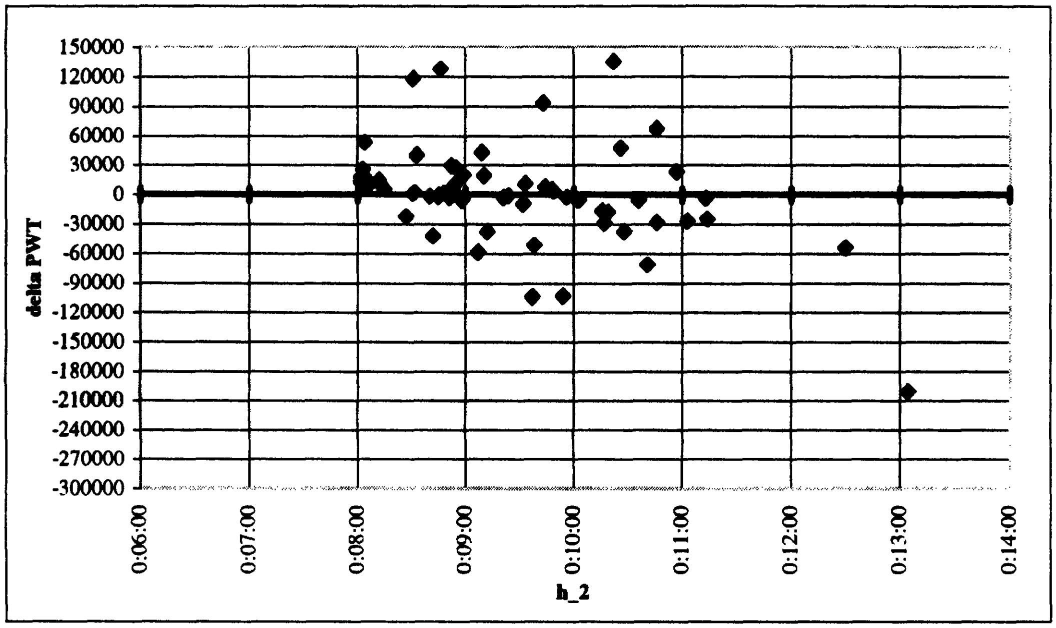


Figure 4.2: Average Delta PWT Results as a Function of H_2, Overtake 1 Train

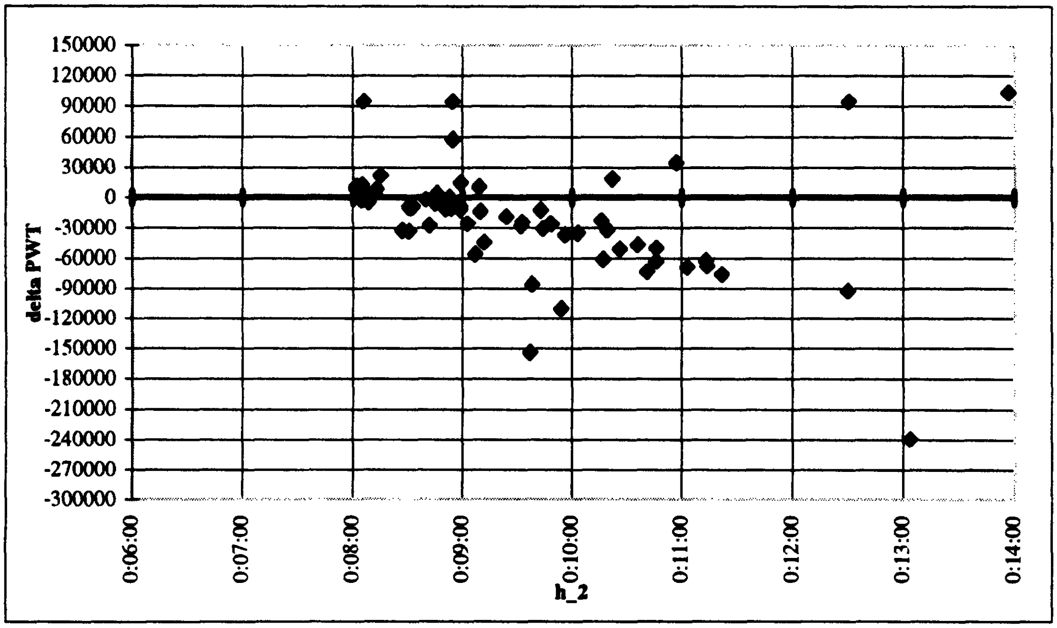
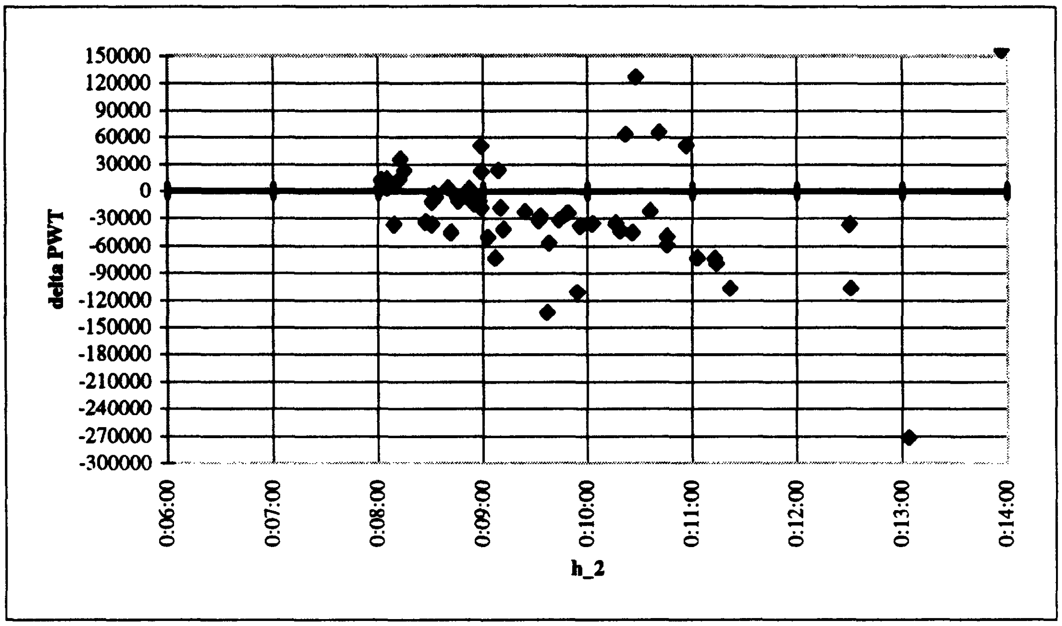


Figure 4.3: Average Delta PWT Results as a Function of H_2, Overtake 2 Trains



The larger h_2 is initially, the larger it is likely to be on departure westbound from Wonderland given no short-turn. h_2 will then remain long over the entire westbound leg of the trip. Most of the passenger demand in the a.m. peak is in this direction, so the impact of this long headway is very large. While the number of passengers affected by short-turning increases proportionally with h_2, the PWT impact increases with the square of h_2. Thus, it had been expected that h_2 would be the most important headway in determining whether a short-turn would be 'beneficial'.

It is also clear from this data that overtaking no trains (short-turning train 2) saved less passenger waiting time than overtaking one or two trains. Because train 2 is the one with the long headway, there will be a large number of passengers waiting to board this train. If this train is short-turned, all of these passengers are forced to wait for the following train. For overtaking 1 or 2 train, the train being short-turned normally has a much shorter headway because it is stuck behind a train with a long headway. This results in fewer skipped segment boarders. On the other hand, there seems to be no clear difference between the overtake 1 and overtake 2 cases. This is probably because when h_2 is longer than 8 minutes, both h_3 and h_4 are both likely to be fairly short.

4.2.4 Sorting the Results

Once sets of modeling results had been generated for all three types of short-turn, these results were further analyzed. The first step of this process was to sort the sequences and their modeling results within each type of short-turn by the initial headways.

Since h_2 appeared to be the most important factor, the results were first sorted by h_2 in descending order and then grouped into the following categories:

1) 0:11:00 ≤ h_2
2) 0:10:00 ≤ h_2 < 0:11:00
3) 0:09:00 ≤ h_2 < 0:10:00
4) 0:08:00 ≤ h_2 < 0:09:00

In each of these four groups sequences in which h_1, the headway preceding the headway to be filled by short-turning, was relatively long appeared to result in short-turns with more beneficial outcomes. Each group was therefore sorted in descending order by h_1. This second sorting strengthened the tendency of the sequences with the most beneficial delta PWT outcomes to move to the top of each of the four groups. Each group was then further subdivided into sequences in which h_1 was greater than or less than some threshold. This threshold was usually chosen at h_1 ≥ 0:06:00 because, with the passenger demand figures used for this analysis, a six-minute headway is where a train will begin to become overcrowded in the inbound direction. This is a particularly important factor with the original version of the model because the initial h_1 is assumed to remain constant throughout (although, as will be discussed later, this is not realistic). When h_1 is long enough to cause train 1 to become overcrowded, passengers will be left behind to wait for the following train. These passengers stand to benefit directly from the short-turn, since they should all be downstream from the skipped segment. As h_2 became smaller, h_1 had to be considerably longer than 6 minutes before it had a clear impact to delta PWT.

Each of these eight categories was then sorted a third time. For overtaking no trains, the sequences were sorted by ascending h_3, while for overtaking one or two trains the sequences were sorted in ascending order by the sum of the short-turn candidate train's headway and its following headway. In other words, the sequences were sorted by the size of the gap created by removing the candidate train from its original position in the sequence. The decision to do this sort following the sort by h_1 was reached by trial-and-error; h_1 seemed to be a stronger determinant of the success of a short-turn than did the 'created' headway. This third sorting again tended to move the most 'beneficial' short-turns to the top of each category and the poorest ones toward the bottom. Cut-off points in each of these eight groups between 'beneficial' and 'neutral' and 'neutral' and 'poor' could be identified. Each category also contained outliers which were highlighted for further analysis.

The results of this sorting process are shown in Table 4.3, Table 4.4, and Table 4.5.

Table 4.3: Sorted Results for Overtaking No Trains

			Beneficial	Neutral	Poor	Sub-Group Ave. delta PWT	Group Ave. delta PWT
h_2 >=11 min.	h_1 >= 6 min.		2	0	0		-284369
h_2 >=12 min.	h_1 < 6 min.		1	0	0	-54260	-26978
11 <= h_2 < 12 min.	h_1 < 6 min.		0	3	0	-17884	
10 <= h_2 < 11 min.	h_1 >= 6 min.		2	0	0		-54162
10 <= h_2 < 11 min.	h_1 < 6 min.	h_3 < 3 min.	0	6	0	-16715	17360
10 <= h_2 < 11 min.	h_1 < 6 min.	h_3 >= 3 min.	0	0	4	68472	
9 <= h_2 < 10 min.	h_1 >= 6 min.		5	0	0		-70762
9 <= h_2 < 10 min.	h_1 < 6 min.	h_3 < 3 min.	0	4	2	-757	15601
9 <= h_2 < 10 min.	h_1 < 6 min.	h_3 >= 3 min.	0	0	5	35231	
8 <= h_2 < 9 min.	h_1 >= 9 min.	h_3 < 2 min	1	0	0	-42040	18025
8 <= h_2 < 9 min.	h_1 >= 9 min.	3 >= h_3 > 2 min.	0	1	0	-21949	
8 <= h_2 < 9 min.	h_1 >= 9 min.	h_3 >= 3 min.	0	0	1	118065	
8 <= h_2 < 9 min.	h_1 < 9 min.		0	23	5		16319

Table 4.4: Sorted Results for Overtaking 1 Train

			Beneficial	Neutral	Poor	Sub-Group Ave. delta PWT	Group Ave. delta PWT
h_2 >=11 min.	h_1 >= 6 min.		2	0	0		-157669
h_2 >=11 min.	h_1 < 6 min.	h_3 + h_4 < 9 min.	4	0	0	-73028	
h_2 >=11 min.	h_1 < 6 min.	h_3 + h_4 >= 9 min.	0	0	2	99144	-15673
10 <= h_2 < 11 min.	h_1 >= 6 min.		1	0	0		-73523
10 <= h_2 < 11 min.	h_1 < 6 min.	h_3 + h_4 < 7 min.	7	0	1	-38161	
10 <= h_2 < 11 min.	h_1 < 6 min.	h_3 + h_4 >= 7 min.	0	1	1	-2195	-30968
9 <= h_2 < 10 min.	h_1 >= 6 min.	h_3 + h_4 < 9 min.	5	0	0	-90205	
9 <= h_2 < 10 min.	h_1 >= 6 min.	h_3 + h_4 >= 9 min.	0	1	0	-25425	-79409
9 <= h_2 < 10 min.	h_1 < 6 min.	h_3 + h_4 < 8:30 min.	2	7	0	-24091	
9 <= h_2 < 10 min.	h_1 < 6 min.	h_3 + h_4 >= 8:30 min.	0	0	1	10534	-20629
8 <= h_2 < 9 min.	h_1 >= 9 min.	h_3 + h_4 < 9 min.	2	0	0	-32890	
8 <= h_2 < 9 min.	h_1 >= 9 min.	h_3 + h_4 >= 9 min.	0	1	0	-27398	-31059
8 <= h_2 < 9 min.	h_1 < 9 min.		0	15	15		8380

Table 4.5: Sorted Results for Overtaking 2 Trains

			Beneficial	Neutral	Poor	Sub-Group Ave. delta PWT	Group Ave. delta PWT
h_2 >=11 min.	h_1 >= 6 min.		2	0	0		-189111
h_2 >=11 min.	h_1 < 6 min.	h_4 + h_5 < 9 min.	5	0	0	-73476	
h_2 >=11 min.	h_1 < 6 min.	h_4 + h_5 >= 9 min.	0	0	1	156692	-35115
10 <= h_2 < 11 min.	h_1 >= 6 min.	h_4 + h_5 >= 9 min.	0	0	2		96059
10 <= h_2 < 11 min.	h_1 < 6 min.	h_4 + h_5 < 8 min.	6	1	0	-41098	
10 <= h_2 < 11 min.	h_1 < 6 min.	h_4 + h_5 >= 8 min.	0	0	2	56656	-19374
9 <= h_2 < 10 min.	h_1 >= 6 min.		6	0	0		-77411
9 <= h_2 < 10 min.	h_1 < 6 min.	h_4 + h_5 < 8:30 min.	3	5	0	-26986	
9 <= h_2 < 10 min.	h_1 < 6 min.	h_4 + h_5 >= 8:30 min.	0	0	2	125820	3575
8 <= h_2 < 9 min.	h_1 >= 9 min.		3	0	0		-38223
8 <= h_2 < 9 min.	h_1 < 9 min.		0	12	15		2460

Columns 4, 5, and 6 are the number of ‘beneficial’, ‘neutral’, and ‘poor’ outcomes respectively in each group. Because the sorting by h_3 or the ‘created gap’ was based on where the boundaries between ‘beneficial’ and ‘neutral’ or ‘neutral’ and ‘poor’ appeared, the ranges of these sub-groups tended to vary quite a bit from one set of results to another. Thus, separate, overall averages are presented for the groups as sorted just by h_2 and h_1 to provide a standard set of comparable criteria.

4.2.5 Interpreting the Sorting Results

As pointed out in the previous section, h_2 is the most important factor in determining how 'beneficial' a short-turn will be. As h_2 gets shorter the other headway conditions become more restrictive. It is also clear from the data that when h_1 is greater than about 6 minutes, the expected savings in PWT is enhanced.

Section 4.2.4 also observed that as the gap created by removing the train for short-turning increases, the expected PWT savings diminishes. This 'created gap' is the sum of the preceding and following headways of the train that is short-turned. The preceding headway essentially determines the number of negatively impacted passengers, while the following headway indicates how much these passengers are impacted by additional waiting time. Passengers who would have boarded the short-turned train had it not been short-turned must wait the entire headway of the following train. In most instances during the a.m. peak periods, a train with a headway of at least 8 minutes should be followed by at least two trains with shorter-than-scheduled headways. Nevertheless, creating a long headway will increase passenger waiting time. If the created headway is too long (which was rare) overcrowding of this following train can result.

4.3 Slow Trains

The base model developed for this project made the simplifying assumption that all of the trains in each sequence had the same running times over each interstation segment. In reality, there is considerable variation in these running times and many excess headways are blamed on trains which consistently travel between stations more slowly than average. To investigate the implications of this, the model was run with train 2 moving more slowly relative to the other trains. The same sets of initial headway sequences were used. The slower movement was simulated by lengthening each interstation segment by a constant proportion as discussed in section 3.3.2. Since it was not clear how realistic this version of the simulation was, to save time trials were run only for the overtake no trains and overtake 1 train cases.

Figure 4.4 and Figure 4.5 show the average delta PWT outcomes for overtaking 0 and 1 trains respectively when train 2 is 'slow'. Comparison of these plots with Figure 4.1 and Figure 4.2 illustrate that most short-turns saved more PWT with train 2 'slow' than under the original conditions (nevertheless, extrapolating these distributions to the left where h_2 = 8 minutes still suggests that few potentially beneficial short-turns were screened out by the sequence selection procedure).

Figure 4.4: Average Delta PWT Results as a Function of H_2, Overtake No Trains, Train 2 is 'Slow'

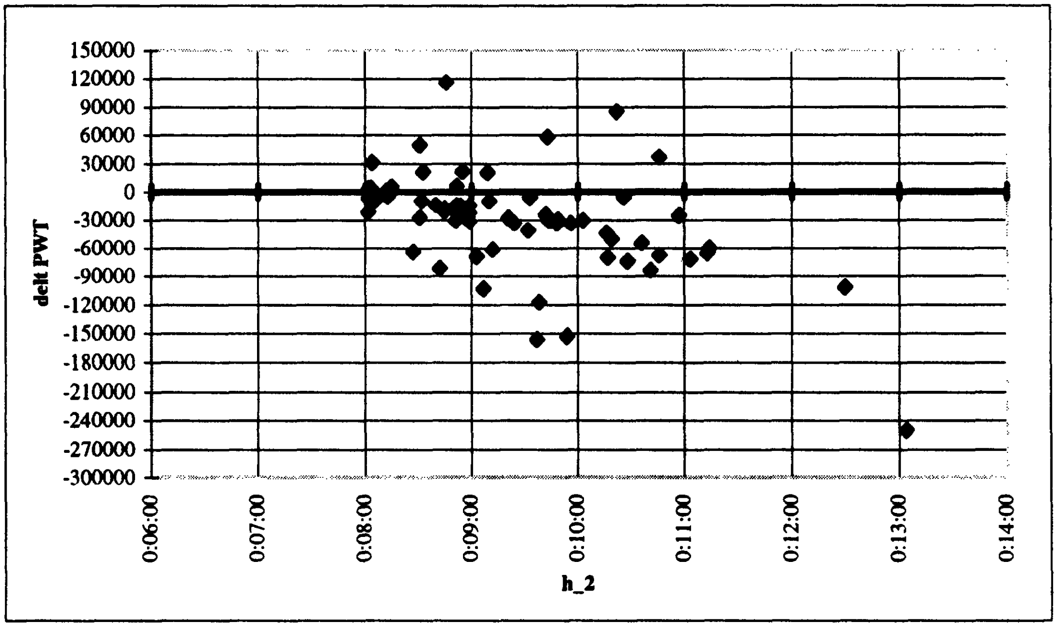
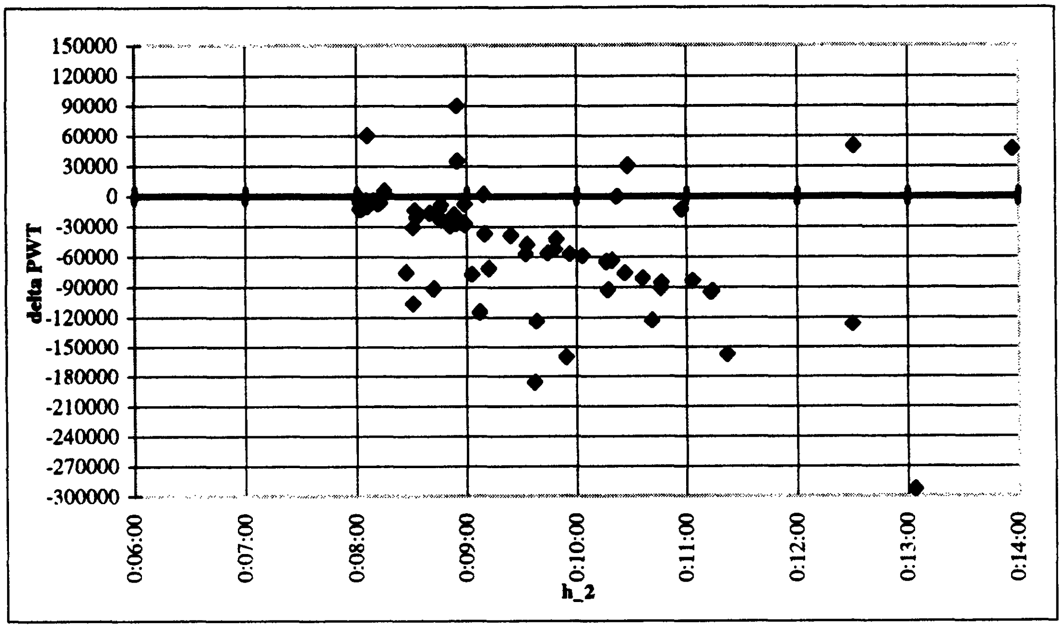


Figure 4.5: Average Delta PWT Results as a Function of H_2, Overtake 1 Train, Train 2 is 'Slow'



The two sets of results were sorted in the same way as the 3 initial sets of data. The sorting results are shown in Table 4.6 and Table 4.7.

Table 4.6: Sorted Results for Overtaking No Trains, Train 2 is 'Slow'

			Beneficial	Neutral	Poor	Sub-Group Ave. delta PWT	Group Ave. delta PWT
h_2 >=11 min.	h_1 >= 6 min.		2	0	0		-333251
h_2 >=11 min.	h_1 < 6 min.		4	0	0		-74952
10 <= h_2 < 11 min.	h_1 >= 6 min.		2	0	0		-78718
10 <= h_2 < 11 min.	h_1 < 6 min.	h_3 < 2:30 min.	6	0	0	-52767	
10 <= h_2 < 11 min.	h_1 < 6 min.	2:30 <= h_3 < 4 min.	0	2	0	-15274	
10 <= h_2 < 11 min.	h_1 < 6 min.	4 <= h_3	0	0	2	60886	-22538
9 <= h_2 < 10 min.	h_1 >= 6 min.		6	0	0		-110051
9 <= h_2 < 10 min.	h_1 < 6 min.	h_3 < 4 min.	5	5	0	-26738	
9 <= h_2 < 10 min.	h_1 < 6 min.	4 <= h_3	0	0	1	20613	-22433
8 <= h_2 < 9 min.	h_1 >= 9 min.	h_3 < 2:30 min	2	0	0	-73065	
8 <= h_2 < 9 min.	h_1 >= 9 min.	2:30 <= h_3	0	0	1	49789	-32114
8 <= h_2 < 9 min.	h_1 < 9 min.	h_3 < 3 min	2	17	4	-13149	
8 <= h_2 < 9 min.	h_1 < 9 min.	3 <= h_3	0	0	6	33391	-3520

Table 4.7: Sorted Results for Overtaking 1 Train, Train 2 is 'Slow'

			Beneficial	Neutral	Poor	Sub-Group Ave. delta PWT	Group Ave. delta PWT
h_2 >=11 min.	h_1 >= 6 min.		2	0	0		-225249
h_2 >=11 min.	h_1 < 6 min.	h_3 + h_4 < 9 min.	4	0	0	-99645	
h_2 >=11 min.	h_1 < 6 min.	h_3 + h_4 >= 9 min.	0	0	2	48555	-50245
10 <= h_2 < 11 min.	h_1 >= 6 min.		1	0	1		-46076
10 <= h_2 < 11 min.	h_1 < 6 min.		8	2	0		-62434
9 <= h_2 < 10 min.	h_1 >= 6 min.		6	0	0		-122175
9 <= h_2 < 10 min.	h_1 < 6 min.	h_3 + h_4 < 8:30 min.	8	0	0	-48358	
9 <= h_2 < 10 min.	h_1 < 6 min.	h_3 + h_4 >= 8:30 min.	0	0	1	1813	-42784
8 <= h_2 < 9 min.	h_1 >= 9 min.		3	0	0		-90966
8 <= h_2 < 9 min.	h_1 < 9 min.	h_3 + h_4 < 9:30 min.	24	1	0	-15268	
8 <= h_2 < 9 min.	h_1 < 9 min.	h_3 + h_4 >= 9:30 min.	0	1	4	37397	-6491

With the 'train 2 slow' assumption, a significantly larger proportion of sequences resulted in either 'neutral' and 'beneficial' outcomes. This was expected, since a slow moving train would stand to recover more time by short-turning than would an average train. If a train's headway is already long, its headway will grow longer even more rapidly if its interstation times are longer than those of the preceding train. Moreover, this slow train will become overcrowded and experience excess dwell times earlier in its trip.

Clearly, the model is quite sensitive to the assumption that train 2 has a long headway because it is slow. However, having just train 2 moving more slowly may not be much more realistic than having all trains move at the same speeds. The ideal model would allow for systematic variation in the interstation times of each train in the sequence. The impact of considering the relative speeds of all of the trains in the sequence may be somewhere between the two cases explored here; having other slow-moving trains in the sequence would tend to dilute the impact of just the 'late' train being slow. The factor used to lengthen the interstation times of the slow train may also be something of a worst case. The 'normal' and 'slow train' cases modeled might therefore represent upper and lower bounds on the potential outcomes of short-turns.

4.4 Critiquing the Initial Model

Having produced several sets of simulation results, it is important to review potential errors and biases in the model. Perhaps the most serious is the way which the train headways departing Wonderland in the westbound direction were generated. As explained in Chapter 3, under the right conditions, trains can recover from excess headways at Wonderland. Trains can also always be held there to lengthen their preceding headways if necessary. The headway sequences should remain relatively constant in the Eastbound direction from Bowdoin to Wonderland, especially in the a.m. peak, when passenger demand in this direction is very light. At Wonderland, however, the headway sequence can change substantially. The Westbound headway sequence, moreover, has a dominant impact on the outcome of the model, since most of the passenger load in the period being studied here is in this direction. As will be shown below, the passenger waiting time calculations are very sensitive to minor changes in the westbound headways, especially the excessive headways involved with short-turning.

The process from which the westbound headways result is also the least well understood part of the model. It was therefore very difficult to simulate in a realistic manner. On the Blue Line, train headways departing Wonderland are dependent on several factors. The most significant are probably a train's preceding headway and its scheduled departure time. Unless it is held by a supervisor, a train that is running behind schedule will probably depart Wonderland as quickly as possible, even if this will result in a shorter than scheduled headway for that train. Unfortunately, the train headway sequence data included no train identification data. Therefore, trains could not be accurately correlated with the schedule. Dropped trips and changes to the order of trains (due to short-turns or late pull-outs from the yard) would have lead to a high probability of errors if an attempt had been made to simply match train headway data with the schedule.

In addition to the above problem, one of the assumptions made in this model worsened the errors resulting from this process: The first train in the sequence was given a constant headway throughout its round trip. This is not realistic, especially for cases in which h_1 is excessively long. One would expect train 1 to recover time at Wonderland just like any other train. In addition, since most of the impact to passenger waiting time takes place in the inbound direction, the effect of this constant headway is particularly strong. If train 1 recovers time at Wonderland (by having a short dwell time there) then the following train will not be able to recover as much, it any, time. Thus, the entire sequence is impacted by this assumption.

A related flaw in the model application is the very long minimum dwell time for train 1 at Wonderland westbound. As explained in section 3.2.1, train 1 was given a minimum dwell time of 7 1/2 minutes (in addition to keeping a constant headway). Giving this train such a long dwell time appeared to be necessary to provide enough recovery time for all of the trains in the sequence to recover time in a realistic manner. In reality, only a portion of the "recovery time" is available at the westbound Wonderland platform, since some is included in the time used to 'turn' the train at the tail tracks. However, with two variables, this would have been much more difficult to model. Giving train 1 such a long dwell at Wonderland seemed to be a simple way to introduce sufficient recovery time into the system.

The problem with this long dwell time is that it causes train 1 to pick up an unrealistically large passenger load. Wonderland has one of the highest passenger arrival rates on the line in the a.m. peak. Thus, during the 7 1/2 minute dwell time approximately 120 extra passengers (above and beyond the number already waiting at that platform) are able to board train 1. When train 1 already has a long preceding headway, overcrowding will thus be even more likely and severe than it would be otherwise. These overflow passengers will impact the following trains. Moreover, overflow passengers weigh more heavily in the passenger waiting time calculations, since they all must wait the entire headway of the following train. This leads to significant distortions of the model in many cases.

4.4.1 Modifying the Westbound Headway Regime

In order to evaluate the significance of these assumptions to the model results, two modifications were made to the arrangement by which the westbound headway sequences were generated: First of all, the preceding headway of train 1 *was* allowed to change at Wonderland. Excess headway could be recovered in the same manner as the following trains. To allow this, train 1 no longer has a minimum dwell time at Wonderland. In stead, the dwell time was calculated based on an assumption that the "zeroth" train (the train preceding train 1, not included in the simulation) had the fixed dwell. In addition, this fixed dwell was reduced from 7 1/2 minutes to 6 minutes. Thus, if train 1 arrives at Wonderland with a preceding headway of 3 1/2 minutes, and the new randomly generated headway assigned to it is also 3 1/2 minutes, then train 1 will dwell for exactly 6 minutes. If train 1 arrives with a headway of 8 minutes, 15 seconds, and its new headway will be 0:04:45, its overall dwell time should be 0:02:30 (the train recovers 0:03:30 of headway; 6 min. minus 0:03:30 is 0:02:30). On the other hand, if train 1 is getting a longer headway than it arrived with, the dwell will be longer than 6 min. (however, this should only happen when the headway is close to or less than 3 1/2 minutes, so there still should be no overcrowding of train 0 in this case).

In cases where train 1 recovers time at Wonderland, the following train (the headway of which was greater than or equal to 8 minutes in all of the sequences simulated for this project) may not be able to recover as much time as it could have in the original model. Its dwell time at Wonderland can only be so much shorter that train 1's. The gap created by removing the short-turning candidate train will also become more difficult to recover from. Therefore, it was anticipated that the simulation results for the sequences in which h_1 was very long would be more significantly impacted by the changes to the westbound headway generation than the sequences in which h_1 was closer to average.

4.4.2 Sensitivity Analysis

The modified simulation model was run for just the overtake 0 and overtake 1 train cases, only with train 2 running at the same speeds as the other trains. Delta PWT results as a function of h_2 for each of these cases are presented in Figure 4.6 and Figure 4.7. Comparison of these plots with Figure 4.1 and Figure 4.2 illustrate that most short-turns saved more PWT with train 2 'slow' than under the original conditions (nevertheless, extrapolating these distributions to the left where h_2 = 8 minutes still suggests that few potentially beneficial short-turns were screened out by the sequence selection procedure). Table 4.8 presents a comparison of these results sorted only by h_2 and h_1. Tables 4.9 and 4.10 present the fully sorted results from the modified model.

Figure 4.6: Delta PWT as a Function of H_2, Overtaking No Trains, Modified Westbound Headway Modeling

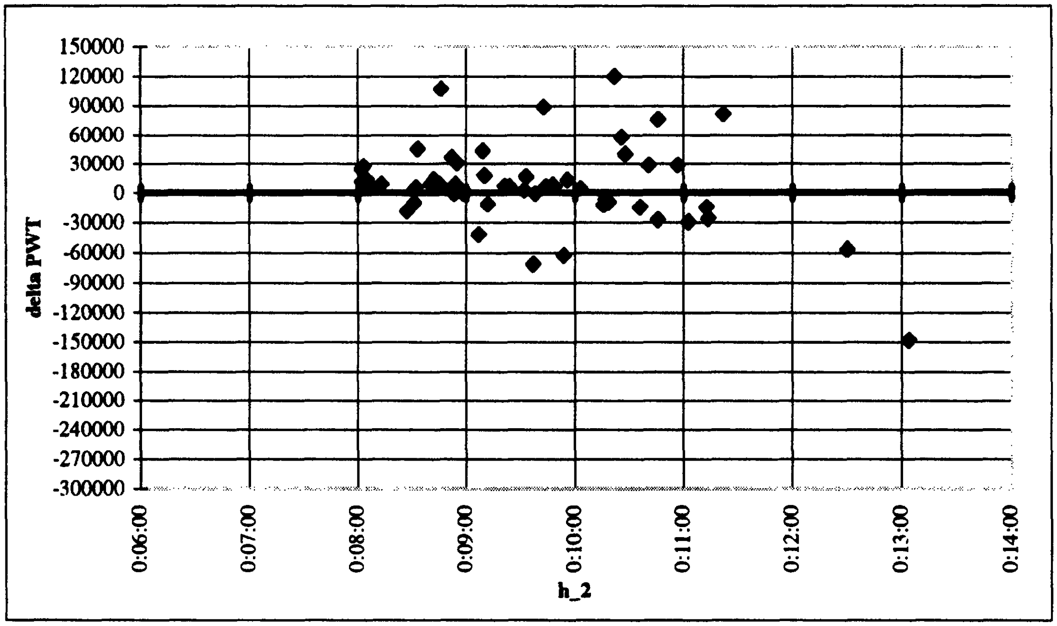


Figure 4.7: Delta PWT as a Function of H_2, Overtake 1 Train, Modifed WB Headway Generation

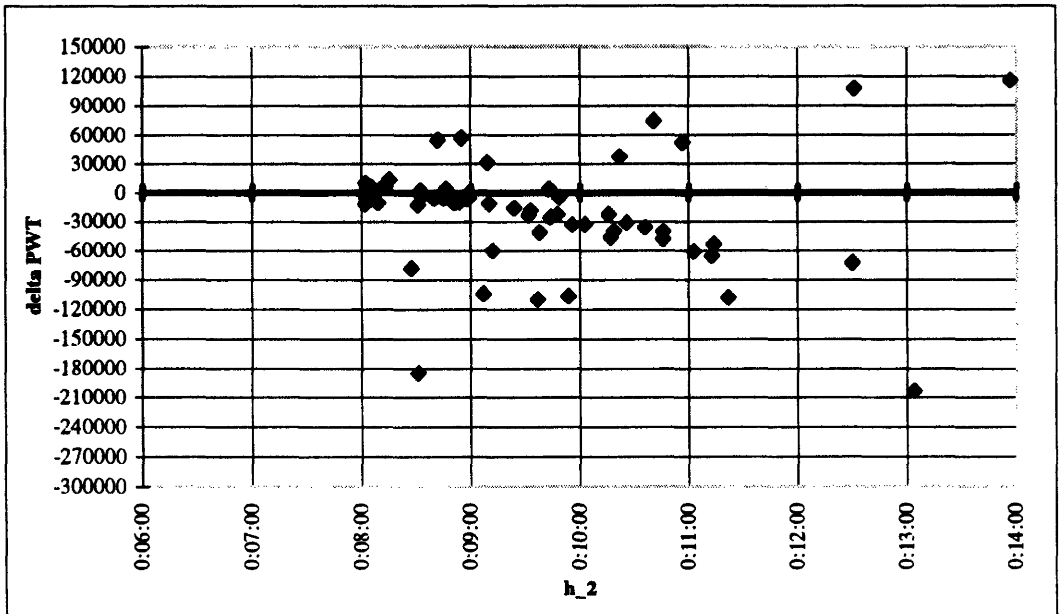


Table 4.8: Comparison of Results Sorted by H_2 and H_1

Overtake No Trains, All Trains Same:		Original Model:				Modified Model:				
		Beneficial	Neutral	Poor	Average	Beneficial	Neutral	Poor	Average	% Change
h_2 >=11 min.	h_1 >= 6 min.	2	0	0	-284369	2	0	0	-271303	5%
h_2 >=11 min.	h_1 < 6 min.	1	3	0	-26978	1	3	0	-31481	-17%
10 <= h_2 < 11 min.	h_1 >= 6 min.	2	0	0	-54162	0	0	2	34660	164%
10 <= h_2 < 11 min.	h_1 < 6 min.	0	6	4	17360	0	5	5	21894	-26%
9 <= h_2 < 10 min.	h_1 >= 6 min.	5	0	0	-70762	3	2	0	-37439	47%
9 <= h_2 < 10 min.	h_1 < 6 min.	0	4	7	15601	0	0	11	20072	-29%
8 <= h_2 < 9 min.	h_1 >= 9 min.	1	1	1	18025	0	2	1	-4586	125%
8 <= h_2 < 9 min.	h_1 < 9 min.	0	5	18	15737	0	2	21	16732	-6%

Overtake 1 Train, All Trains Same:		Original Model:				Modified Model:				
		Beneficial	Neutral	Poor	Average	Beneficial	Neutral	Poor	Average	% Change
h_2 >=11 min.	h_1 >= 6 min.	2	0	0	-157669	2	0	0	-155659	1%
h_2 >=11 min.	h_1 < 6 min.	4	0	2	-15673	4	0	2	-4790	69%
10 <= h_2 < 11 min.	h_1 >= 6 min.	1	0	0	-73523	0	0	1	74436	201%
10 <= h_2 < 11 min.	h_1 < 6 min.	7	1	2	-30968	7	1	2	-20491	34%
9 <= h_2 < 10 min.	h_1 >= 6 min.	5	0	0	-90205	5	0	0	-84377	6%
9 <= h_2 < 10 min.	h_1 < 6 min.	2	7	1	-20629	1	7	2	-11823	43%
8 <= h_2 < 9 min.	h_1 >= 9 min.	2	1	0	-31059	2	0	1	-69185	-123%
8 <= h_2 < 9 min.	h_1 < 9 min.	0	14	13	5477	0	13	14	9498	-73%

Table 4.9: Sorted Results from Overtaking No Trains, Modified Westbound Headway Generation

			Beneficial	Neutral	Poor	Sub-Group Ave. delta PWT	Group Ave. delta PWT
h_2 >=11 min.	h_1 >= 6 min.	h_3 < 9 min.	2	0	0	-271303	
h_2 >=11 min.	h_1 >= 6 min.	h_3 >= 9 min.	0	0	1	81383	-153741
h_2 >=12 min.	h_1 < 6 min.		1	0	0	-56581	
11 <= h_2 < 12 min.	h_1 < 6 min.		0	3	0	-23115	-31481
10 <= h_2 < 11 min.	h_1 >= 6 min.		0	0	2		34660
10 <= h_2 < 11 min.	h_1 < 6 min.	h_3 < 2:30 min.	0	5	0	-13612	
10 <= h_2 < 11 min.	h_1 < 6 min.	h_3 >= 2:30 min.	0	0	5	57401	21894
9 <= h_2 < 10 min.	h_1 >= 6 min.		3	2	0		-37439
9 <= h_2 < 10 min.	h_1 < 6 min.		0	0	11		20072
8 <= h_2 < 9 min.	h_1 >= 9 min.		0	2	1		-4586
8 <= h_2 < 9 min.	h_1 < 9 min.		0	2	21		16732

Table 4.10: Sorted Results from Overtaking 1 Train, Modified Westbound Headway Generation

			Beneficial	Neutral	Poor	Sub-Group Ave. delta PWT	Group Ave. delta PWT
h_2 >=11 min.	h_1 >= 6 min.		2	0	0		-155659
h_2 >=11 min.	h_1 < 6 min.	h_3 + h_4 < 9 min.	4	0	0	-62827	
h_2 >=11 min.	h_1 < 6 min.	h_3 + h_4 >= 9 min.	0	0	2	111285	-4790
10 <= h_2 < 11 min.	h_1 >= 6 min.		0	0	1		74436
10 <= h_2 < 11 min.	h_1 < 6 min.		7	1	2		-20491
9 <= h_2 < 10 min.	h_1 >= 6 min.		5	0	0		-84377
9 <= h_2 < 10 min.	h_1 < 6 min.	h_3 + h_4 < 9 min.	1	7	0	-19306	
9 <= h_2 < 10 min.	h_1 < 6 min.	h_3 + h_4 >= 9 min.	0	0	2	18107	-11823
8 <= h_2 < 9 min.	h_1 >= 9 min.	h_3 + h_4 < 9 min.	2	0	0	-131300	
8 <= h_2 < 9 min.	h_1 >= 9 min.	h_3 + h_4 >= 9 min.	0	0	1	55044	-69185
8 <= h_2 < 9 min.	h_1 < 9 min.		0	13	15		9174

In the ‘Overtake No Trains’ case in particular, a number of sequences for which the results had been ‘beneficial’ were now ‘neutral’ or even ‘poor’. Some ‘neutral’ outcomes also changed to ‘poor’. In addition, the average of the average delta PWT results for each group were also less negative (less ‘beneficial’) in most cases. The outcomes for some sequences changed dramatically, from being very ‘beneficial’ to being very ‘poor’. Further analysis was performed on several of these to 1) to verify that the model was correct and, 2) to ascertain what was causing the changes observed in the outcomes. Since train 1 can now recover its headway at Wonderland, it had been predicted that the results for sequences in which h_1 is greater than 6 minutes would be more heavily impacted than the results for the other sequences. This is by no means clear in this data, however. The best explanation for the lack of any clear effect it that when train 1 recovers a long headway, the following train is not able to recover as much time, leading to a net 'wash'.

4.4.3 Detailed Analysis and Validation

There were a number of specific sequences for which the short-turning outcome changed very significantly with the modified model. A few of these were selected for further analysis. It was possible to use a fairly simple spreadsheet model to approximate the passenger waiting time impacts of a particular short-turn given the trajectories of the trains over the line. The two versions of the simulation model were used to run additional, individual trials for each sequence. Each simulation was used to generate individual sets of results for a given initial headway sequence. The departure times of each train from the westbound Wonderland and Maverick platforms were recorded as additional output from the simulation. These times were used to prepare approximate trajectories for each train. Two short-turn trials, one using the model with the modified westbound headway arrangement, the other using the original model, could in this way be directly compared. The spreadsheet model was then used to compare the two versions and try to ascertain why the results differed. The spreadsheet also helped verify that the simulation program was working correctly.

Output for the trial selected from the modified model for the first sequence tested is shown below in Table 4.11. This was a short-turn in which no train was overtaken, and h_1 was very long. The average outcome of this short-turn had been –71,200 passenger-sec, (quite 'beneficial') using the original model. With the modified model, however, the outcome became 'poor', with the short-turn resulting in PWT increasing by 29,300 pass-sec. The outcome of the particular trial selected was somewhat worse than this, with a delta PWT of 61,025 passenger-sec.

Table 4.11: Trajectories for Sequence One from Modified Model

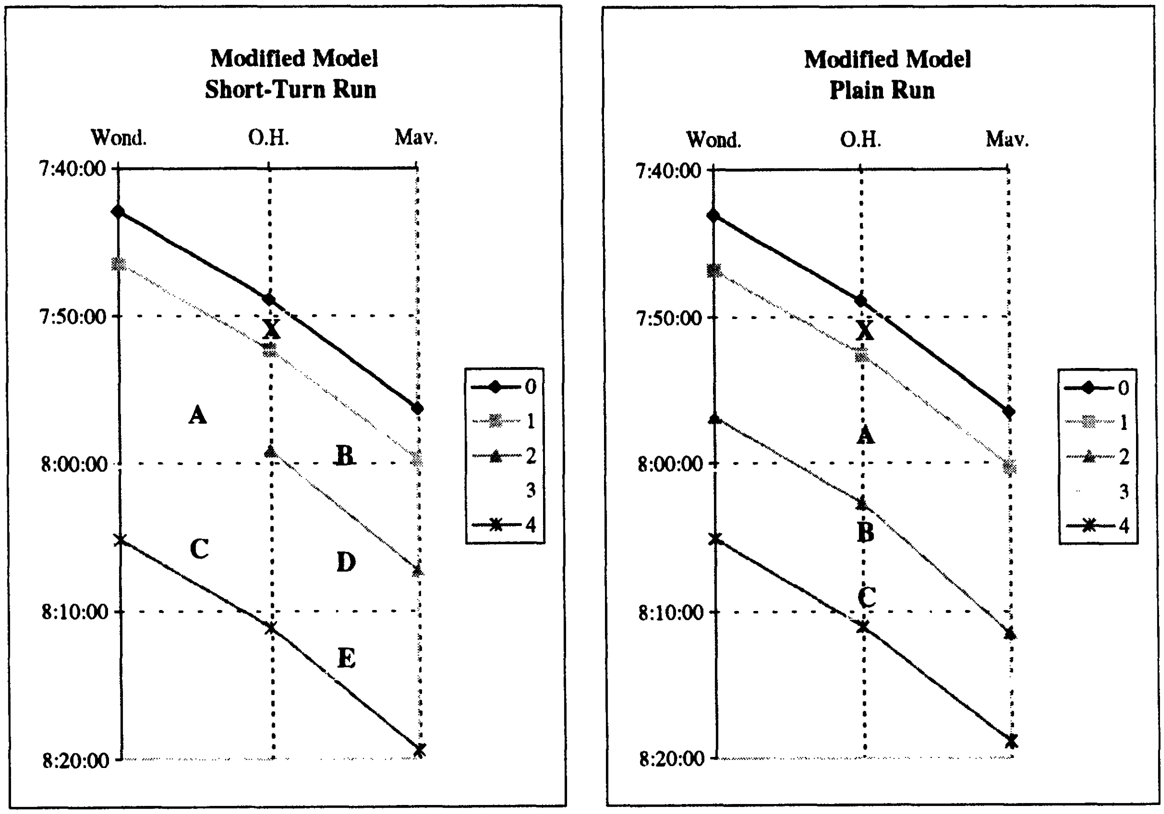
	Short-turn Run:						**Non-short-turn Run:**					
Train	Maverick E.B.	*Headway*	Wonderl'd W.B.	*Headway*	Maverick W.B.	*Headway*	Maverick E.B.	*Headway*	Wonderl'd W.B.	*Headway*	Maverick W.B.	*Headway*
0	7:21:01						7:21:01					
1	7:29:14	*0:08:13*	7:46:25	*0:03:25*	7:59:47	*0:03:25*	7:29:14	*0:08:13*	7:46:45	*0:03:44*	8:00:10	*0:03:44*
2	7:39:55	*0:10:41*			8:07:12	*0:07:25*	7:39:55	*0:10:41*	7:56:49	*0:10:04*	8:11:32	*0:11:22*
3	7:43:25	*0:03:30*	8:00:15	*0:13:50*	8:15:08	*0:07:56*	7:43:25	*0:03:30*	8:00:29	*0:03:40*	8:14:42	*0:03:10*
4	7:48:43	*0:05:18*	8:05:10	*0:04:55*	8:19:25	*0:04:17*	7:48:43	*0:05:18*	8:05:09	*0:04:40*	8:18:54	*0:04:12*
Dumpees:			12									
Add'l Wait:			195									
Denied Boardings:			524				Denied Boardings:			402		
Leftover Passengers:			244				Leftover Passengers:			18		
Delta PWT:			61025									

The initial eastbound sequence is shown in the left-most column for each of the two runs. The remaining columns show each train's westbound departure times and headways from Wonderland and Maverick. The lower boxes contain the results for each of the two runs of the simulation.

Several characteristics of the Blue Line made approximate PWT calculations quite simple. First of all, since a relatively small proportion of Westbound boarders alight upstream from the peak load point (which is between Maverick and Aquarium), it was assumed that *all* boarding took place upstream from there, and that no passengers alight until after Maverick. Under this assumption, it was very simple to apply the train capacity constraint, as will be shown below. An additional simplification was to ignore the waiting time of eastbound boarders and of westbound passengers boarding downstream from Maverick. The passenger arrival rate data shows that 87% of the westbound passengers board at Wonderland through Maverick during the time period being studied for this research. Passengers boarding in the eastbound direction downstream from the peak load point are an even smaller group in proportion to those boarding westbound between Wonderland and Maverick. Moreover, the only change that the short-turn makes in the eastbound direction is that it removes one train from the sequence, extending the wait just for the passengers who would have boarded the short-turning train. The extra PWT for the 'dumped' passengers *was* included, however, since the information to calculate it was readily available as output from the model.

The first step was to estimate the average headway of each train over their trajectories. The trajectories from the modified model for the first sequence examined are shown in Figure 4.8.

Figure 4.8: Trajectory Diagrams for Sequence One, Modified Westbound Headway Generation



The headways in each run were divided into 'areas'. These areas were labeled A, B, C, etc., with X used for the first train's headway (which drops out of the calculation for the case of the original model). For the short-turn run, each trajectory was divided into two areas. One set of areas was for platforms upstream from the short-turn point (i.e. Orient

Heights). Trains were generally assumed to retain the headway they had leaving Wonderland over this segment. The other areas were for the short-turn point and platforms downstream. A train's headway for this segment was taken as the average of its headways at Wonderland and at Maverick. For the non-short-turn case, each train's headway comprised just one area. Headways for each train in the non-short-turn (or 'plain') run were all calculated as the average of their headways at Wonderland and Maverick. The top half of Table 4.12 is the spreadsheet used to analyze this short-turn. The headway estimates (in seconds) for the short-turn run are in the second column. Those for the plain run are in the seventh column.

The expected number of passengers accumulating in each 'area' was then calculated. Aggregate passenger arrival rates (pax) were determined for each segment (see the upper right-hand box on the spreadsheet). The aggregate passenger arrival rates were simply the sums of the passenger arrival rates for all the platforms in each segment. The total new passengers arriving in each headway were calculated using the expression:

$$\text{New Pass.}_{\text{area}} = \text{Headway}_{\text{area}} * \text{Aggregate Pax}_{\text{segment}}$$

Overflow passengers were also calculated for each headway in each segment. Passengers who arrived in the preceding train's headway beyond that train's capacity of 470 became 'overflow' passengers waiting for the next train, as follows:

$$\text{Overflow}_{\text{area}} = \max(0, ((\text{New Pass.}_{\text{area}} + \text{New Pass.}_{\text{preceding area}} + \text{Overflow}_{\text{preceding area}}) - 470))$$

For example, in the 'plain run' of the above example, 832 passengers arrive in area A (train 2's preceding headway). The 362 passengers who are unable to board train 2 spill over into area B. They are joined there by 265 new arrivals. Of this total, 157 flow over into area C. These calculations are slightly more complex for the short-turn case because the boarders from a train's 'upstream' segment must be added to its downstream load.

Table 4.12: Spreadsheet Analysis of Sequence One

New Model:								
Area	Headway	New Pass. Overflow*	Tot. PWT		Area	Headway	New Pass. Overflow*	Tot. PWT
X:	205	285	29218		X:	224	311	34885
A:	830	513	212794		A:	643	832	267405
B:	430	291	62474		B:	205	265	27180
							362	74157
C:	295	182	26881					
		43	12613		C:	266	344	45763
							157	41740
D:	446	301	67059					
E:	276	187	25738					
		344	94890					
Dump.:	195	12	2340					
Leftover:		285					31	
		Total PWT:	534007				Total PWT:	491131
							delta PWT:	42876
Tot. Denied Boardings.:		672					550	
Original Model:								
Area	Headway	New Pass. Overflow*	Tot. PWT		Area	Headway	New Pass. Overflow*	Tot. PWT
W:	420	143			W:	420	143	
X:	493	638			X:	493	638	
A:	553	342	94461		A:	363	469	84989
							311	112653
B:	261	176	22929					
		311	80955		B:	187	241	22496
							310	57754
C:	251	155	19460					
		0	0		C:	167	215	17930
							81	13473
D:	261	176	23017					
		17	4385					
E:	231	156	17952					
		65	14938					
Dump.:	194	14	2716					
Leftover:		0					0	
		Total PWT	280812				Total PWT	309296
							delta:	-28483
Tot. Denied Boardings.:		392					701	
		* Second line for each area is for overflow passengers from previous headway						

Aggregate Passenger Arrival Rates (pass/sec.)	
Wond. only:	0.341
Wond. - Suff. D.:	0.618
Wond. - Mav.:	1.294
Wond. - Bow.:	1.391
O.H. - Mav.:	0.676
Aqu.-Bow.:	0.097

The next step was to calculate the passenger waiting time (PWT) for each group of passengers. PWT for the new arrivals in each segment is the headway times the total number of new passengers, times 1/2 (since the average arrival only waits 1/2 the headway). The additional PWT for 'overflow' passengers is simply the number of passengers times the headway, since all must wait the full headway.

Finally, the PWT accumulated in each area for each run was summed to obtain the 'Total' PWT for each run. The difference was taken to estimate the delta PWT. The total number of overflow passengers for each run was also calculated, since the total denied boardings was an important secondary performance measure.

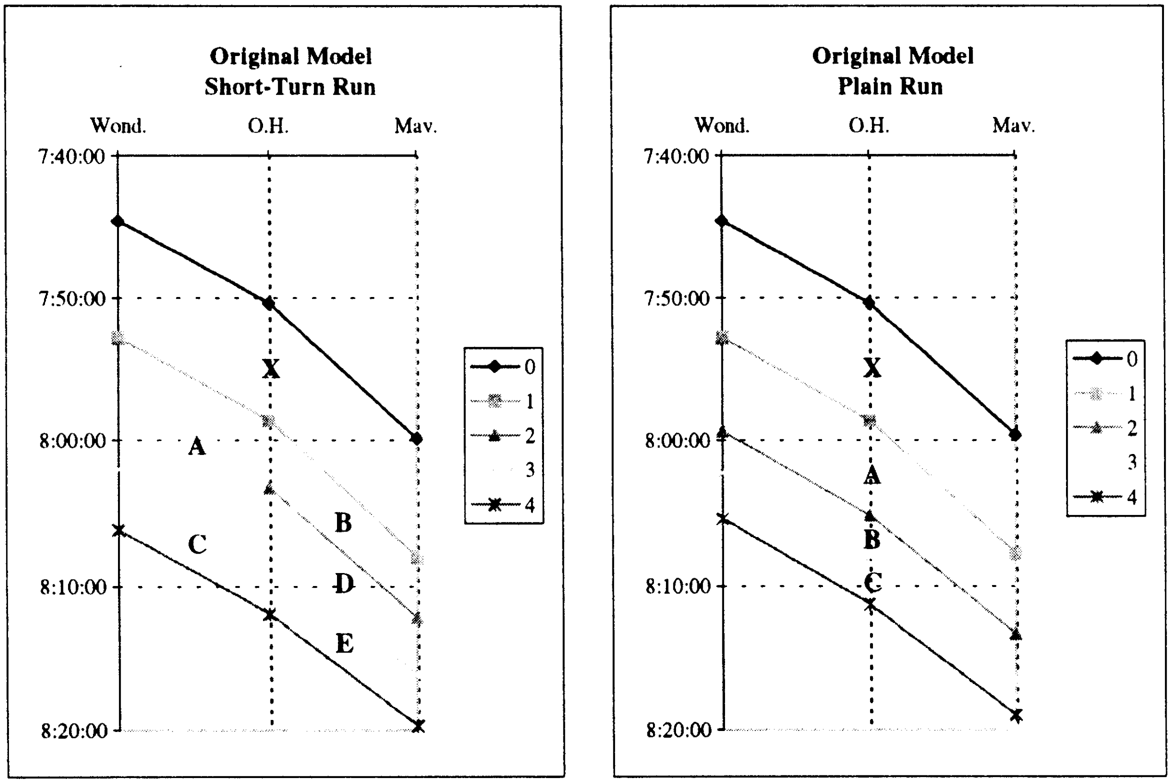
The same process was used to analyze a simulation trial from the original model. Trajectories and results are presented in Table 4.13 and Figure 4.9.

Table 4.13: Trajectories for Sequence One from Original Model

	Short-turn Run:						**Non-short-turn Run:**					
Train	Maverick E.B.	*Headway*	Wonderl'd W.B.	*Headway*	Maverick W.B.	*Headway*	Maverick E.B.	*Headway*	Wonderl'd W.B.	*Headway*	Maverick W.B.	*Headway*
0	7:21:01						7:21:01					
1	7:29:14	*0:08:13*	7:52:44	*0:08:13*	8:08:03	*0:08:13*	7:29:14	*0:08:13*	7:52:44	*0:08:13*	8:07:44	*0:08:13*
2	7:39:55	*0:10:41*			8:12:08	*0:04:05*	7:39:55	*0:10:41*	7:59:15	*0:06:31*	8:13:18	*0:05:34*
3	7:43:25	*0:03:30*	8:01:57	*0:09:13*	8:16:14	*0:04:06*	7:43:25	*0:03:30*	8:02:11	*0:02:56*	8:16:35	*0:03:17*
4	7:48:43	*0:05:18*	8:06:08	*0:04:11*	8:19:44	*0:03:30*	7:48:43	*0:05:18*	8:05:23	*0:03:12*	8:18:56	*0:02:21*
Dumpees:			14									
Add'l Wait:			194									
Denied Boardings:			451				Denied Boardings:		776			
Leftover Passengers:			5				Leftover Passengers:		12			
Delta PWT:			-61628									

The average delta PWT for the 50 trials had been –71,200 passenger-sec. The outcome of this particular trial was close to this at –61,628 passenger-sec. In this case, train 1 has the same trajectory on both the short-turn and non-short-turn runs. Therefore, no PWT was calculated for area 'X' in either run. However, the number of new passengers was determined, since with the long h_1, (8 min, 13 sec.), there would be overflow passengers from train 1. An additional area 'W' was also included here to account for the considerable number of passengers who were able to board train 1 at Wonderland during its unrealistically long dwell time there. The analysis of these trajectories is presented on the bottom half of Table 4.12.

Figure 4.9: Trajectory Diagrams for Sequence One from Original Model



The spreadsheet analysis of the modified simulation trajectories produced an output that was fairly similar to the results of the simulation itself. The spreadsheet model predicted an increase in passenger waiting time of 43,000 passenger-sec. versus an increase of 61,000 passenger-sec. for the simulation Both also showed the number of denied boardings increasing by the same amount - 120 passengers. The agreement between the original simulation and the spreadsheet was not as good: the simulation gave a result of

-61,600 pass.-sec., while the spreadsheet indicated an impact of -28,500 pass.-sec. - not even under the -30,000 pass.-sec threshold.

Some additional analysis was done to try to account for this discrepancy. Since the headways used for the spreadsheet were rather crude estimates, some adjustments were made to analyze the impact of subtle changes in the average headways on the model results. It was observed that in the non-short-turn run of the original model train 2 should retain a relatively constant headway for most of its westbound trip. h_2 should only begin to get shorter at the point where train 1 starts to be overcrowded and experience excess dwell time. This suggests that a more accurate average headway for area A would be closer to train 2's headway at Wonderland (where it was approximately one minute longer). As an experiment, the headway for area A was increased by 20 seconds. This minor adjustment lowered the delta PWT from -28,500 to -45,000 pass-sec., which is much closer to the simulation output of -61,600. Thus, the result decreased by 16,600 passenger-sec. for a 20 sec. (6%) increase in h_2.

This was a very speculative adjustment. All of the headways used in the spreadsheet are estimates. Therefore, this adjustment alone can not fully explain the discrepancy. However, the large impact of this small increase in one of the headway estimates indicates how sensitive the model can be. It is particularly sensitive to variation in h_2 when h_1 is also long. This is because the number of passengers affected will be large and will likely include overflow passengers from train 1. Overflow passengers effectively count twice as heavily as new arrivals toward waiting time. This is an important observation because it explains why the variations observed in the PWT results for the simulation were so large.

The two pairs of trajectories were studied to try to explain why the modified simulation model predicted a less 'beneficial' outcome than the original simulation. The most obvious difference between the two sets of trajectories involved the gap created by removing the short-turning candidate (train 2 in this instance) from the sequence. Under the modified westbound headway regime, the train following the short-turning candidate (train 3) was not able to recover as much time. Thus, this gap remained larger and more passenger waiting time was accumulated in the short-turn run. This, in turn, caused a much less 'beneficial' outcome.

The second sequence selected for analysis involved overtaking one train. However, h_1 was close to the average headway in this example. In this instance, the change observed with the modified simulation was not as dramatic as with the sequence just discussed. It was nevertheless significant: the average outcome remained 'beneficial' but with only 62% as much passenger waiting time saved. The same process was used as for the first sequence. The simulation output is presented in Table 4.14 and Table 4.15, while the trajectories are shown in Figure 4.10 and Figure 4.11. The spreadsheet analysis is presented in Table 4.16.

The spreadsheet result for the original model was -64,200 passenger-sec., versus -65,100 passenger-sec. for the simulation. However, the spreadsheet produced a significantly different result from the modified simulation. The spreadsheet indicated -56,700 passenger-sec. versus -31,200 for the simulation output (the average for 50 trials had been -31,500). Again, a minor but justifiable adjustment was made to the spreadsheet model. In the non-short-turn run area A, which is included in train 2's headway, involves the largest number of passengers. This headway also increases the most during the course of the trip, since train 2 is the only one that becomes overcrowded. However, the overcrowding was not severe and probably did not occur until Maverick was reached. Therefore, this headway probably only increased slightly before Maverick. This suggested that using the average of train 2's headway departing Wonderland and its headway departing Maverick over-estimated the average headway for area A. Using the headway departing Maverick (6 min., 38 sec.) as the average headway for area A pushed the delta PWT for this trial up to –40,200. Thus, it seems reasonable to conclude that at least some of the disagreement between the simulation and the spreadsheet can be attributed to error in the average headway for area 'A'. There could easily be significant error in the other headway estimates as well.

Table 4.14: Trajectories for Sequence Two from Modified Model

	Short-turn Run:						Non-short-turn Run:					
Train	Maverick E.B.	*Headway*	Wonderl'd W.B.	*Headway*	Maverick W.B.	*Headway*	Maverick E.B.	*Headway*	Wonderl'd W.B.	*Headway*	Maverick W.B.	*Headway*
0	8:05:48						8:05:48					
1	8:10:00	*0:04:12*	8:30:26	*0:02:45*	8:43:40	*0:02:45*	8:10:00	*0:04:12*	8:31:30	*0:03:49*	8:44:52	*0:03:49*
2	8:20:26	*0:10:26*	8:37:06	*0:06:40*	8:50:35	*0:03:26*	8:20:26	*0:10:26*	8:38:08	*0:06:38*	8:52:11	*0:07:19*
3	8:24:18	*0:03:52*			8:47:09	*0:03:29*	8:24:18	*0:03:52*	8:42:00	*0:03:52*	8:55:28	*0:03:17*
4	8:26:27	*0:02:09*	8:42:49	*0:05:43*	8:56:23	*0:05:48*	8:26:27	*0:02:09*	8:45:41	*0:03:41*	8:59:03	*0:03:35*
5	8:29:58	*0:03:31*	8:46:17	*0:03:28*	8:59:38	*0:03:15*	8:29:58	*0:03:31*	8:49:15	*0:03:34*	9:02:37	*0:03:34*
Dumpees:			4									
Add'l Wait:			125									
Denied Boardings:			2				Denied Boardings:			61		
Leftover Passengers:			7				Leftover Passengers:			9		
Delta PWT:			-31210									

Figure 4.10: Trajectory Diagrams for Sequence Two from Modified Model

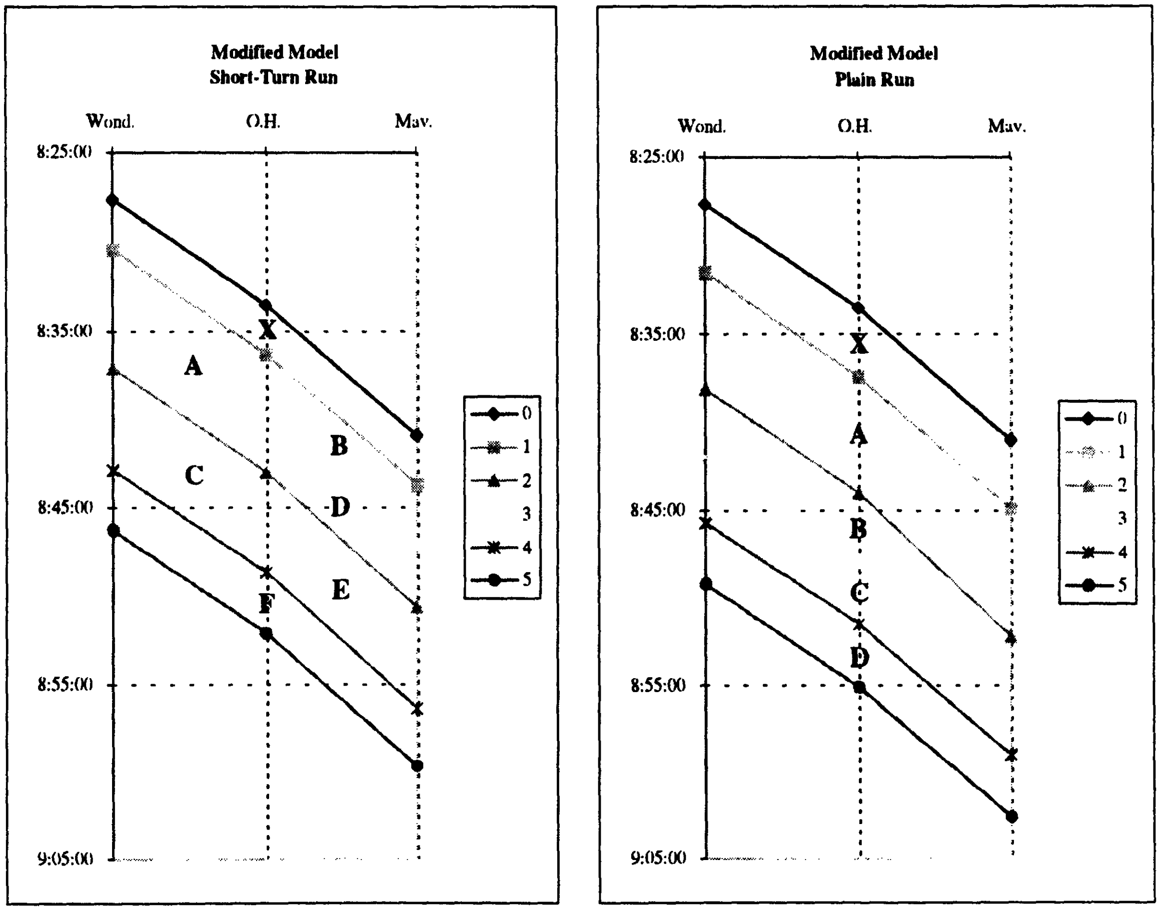


Table 4.15: Trajectories for Sequence Two from Original Model

	Short-turn Run:						Non-short-turn Run:					
Train	Maverick E.B.	*Headway*	Wonderl'd W.B.	*Headway*	Maverick W.B.	*Headway*	Maverick E.B.	*Headway*	Wonderl'd W.B.	*Headway*	Maverick W.B.	*Headway*
0	8:05:48						8:05:48					
1	8:10:00	*0:04:12*	8:33:23	*0:04:12*	8:46:48	*0:04:12*	8:10:00	*0:04:12*	8:33:23	*0:04:12*	8:46:48	*0:04:12*
2	8:20:26	*0:10:26*	8:40:23	*0:07:00*	8:53:52	*0:03:35*	8:20:26	*0:10:26*	8:39:25	*0:06:02*	8:53:04	*0:06:16*
3	8:24:18	*0:03:52*			8:50:17	*0:03:29*	8:24:18	*0:03:52*	8:43:15	*0:03:50*	8:56:35	*0:03:31*
4	8:26:27	*0:02:09*	8:43:32	*0:03:09*	8:56:46	*0:02:54*	8:26:27	*0:02:09*	8:46:45	*0:03:30*	9:00:03	*0:03:28*
5	8:29:58	*0:03:31*	8:46:17	*0:02:45*	8:59:29	*0:02:43*	8:29:58	*0:03:31*	8:51:07	*0:04:22*	9:04:38	*0:04:35*
Dumpees:			1									
Add'l Wait:			129									
Denied Boardings:			2				Denied Boardings:			1		
Leftover Passengers:			6				Leftover Passengers:			6		
Delta PWT:			-65092									

Figure 4.11: Trajectory Diagrams for Sequence Two from Original Model

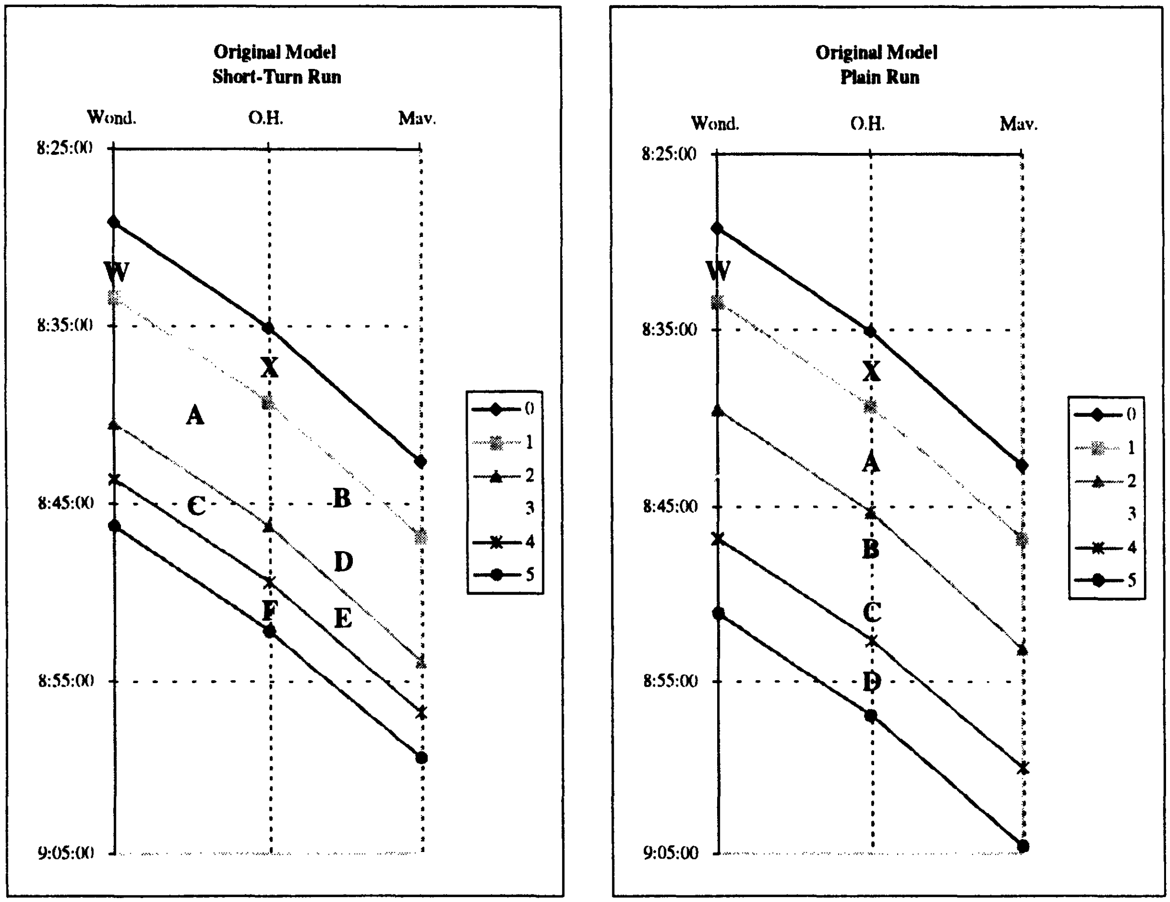


Table 4.16: Spreadsheet Analysis of Sequence Two

New Model:										**Aggregate Passenger**	
										Arrival Rates (pass/sec.)	
Area	Headway	New Pass.	Tot. PWT		Area	Headway	New Pass.	Tot. PWT			
		Overflow*					Overflow*			Wond. only:	0.341
X:	165	229	18928		X:	229	318	36460		Wond. - Suff. D.:	0.618
A:	400	247	49422		A:	419	541	113276		Wond. - Mav.:	1.294
B:	205	138	14130		B:	215	277	29758		Wond. - Bow.:	1.391
							71	15303			
C:	343	212	36340							O.H. - Mav.:	0.676
		0	0		C:	223	288	32163			
							0	0		Aqu.-Bow.:	0.097
D:	203	137	13924								
					D:	214	277	29619			
E:	346	233	40333				0	0			
		0	0								
F:	202	261	26260								
		0	0								
Dump.:	125	4	500								
Leftover:		0					0				
		Total PWT:	199838				Total PWT:	256580			
							delta PWT:	-56742			
Tot. Denied Boardings.:		0					71				
Original Model:											
Area	Headway	New Pass.	Tot. PWT		Area	Headway	New Pass.	Tot. PWT			
		Overflow*					Overflow*				
W:	420	143			W:	420	143				
X:	252	326			X:	252	326				
A:	420	259	54488		A:	369	477	88065			
							0	0			
B:	210	142	14830								
		0	0		B:	221	285	31446			
							7	1613			
C:	189	117	11034								
		0	0		C:	179	232	20723			
							0	0			
D:	213	144	15257								
		0	0								
					D:	269	347	46627			
E:	182	123	11130				0	0			
		0	0								
F:	164	212	17395								
		0	0								
Dump.:	129	1	129								
Leftover:		0					0				
		Total PWT:	124264				Total PWT:	188473			
							delta PWT:	-64210			
Tot. Denied Boardings.:		0					7				
		* Second line for each area is for overflow passengers from previous headway									

As with the previous sequence, making the short-turn resulted in a much larger 'created gap' with the modified model. Train 4 ended up with approximately a 5 minute, 43 sec. headway whereas in the non-short-turn run h_2 (the gap which the short-turn is intended to fill) was only about 7 minutes on this particular trial. With the original model, h_4 was only about 3 minutes on the westbound trip.

These spreadsheet analyses do not agree closely enough with the simulation to rule out any possible error or distortion in the simulation. However, given the clear sensitivity of the system to headway variations, the fact that the spreadsheet results seemed to generally mirror those of the simulation does provide reassurance that there are no serious errors. The observation that subtle headway variations can produce a large change in the delta PWT result is also very helpful as it explains the large standard deviations of the PWT results. Passenger waiting time savings evidently tend to decline under the modified westbound headway arrangement because gaps created by removing the short-turn candidate from the sequence can not as easily be filled in by the following trains. This is because the amount of recovery time has been reduced by eliminating the minimum dwell of 7 1/2 minutes for train 1. Allowing train 1 to recover further reduces recovery time in many instances.

Clearly, how the westbound headways are generated has a very substantial impact on the simulation results. Unfortunately, while the revised westbound headway arrangement is probably much more realistic that the initial regime, there may still be some significant flaws in it. Correcting these would take a significant amount of additional research.

4.5 Deriving Manual Rules

Manual guidelines for making short-turns were prepared from the modeling results. Such rules could be used by supervisors such as the train starters stationed at Orient Heights and hopefully would lead to more effective short-turning pactice. The guidelines are based entirely on the passenger waiting time savings and were therefore developed directly from the sorting results. Deckoff used his modeling results to derive similar rules for the Green Line. However, he had a slightly more complex set of objectives. First of all, he considered the relative time savings of short-turning different trains in the same sequence and wrote the rules to chose the short-turning candidate based on which would save more passenger waiting time. The position that the candidate would assume in the sequence after short-turning was not explicitly chosen by the user of these rules. Because of the lack of space to hold trains at Park Street, the short-tuning Green Line trains in Deckoff's model assumed a new position determined entirely on the positions of preceding trains. On the Blue Line, on the other hand, the large amount of time that can be saved by short-turning gives the controller much more latitude in deciding where to re-insert the short-turned train. Moreover, the choice of which train to short-turn is based more on crew scheduling considerations than on passenger waiting time impact. Since these operating issues seem to dominate the short-turning decision process, no effort was made to provide rules to determine the relative merit of alternative short-turns that could be classified as 'beneficial'.

The simulation results from the model where train 2 was 'slow' generally indicated less restrictive conditions for short-turning than the basic model. The modified model, on the other hand, suggested more restrictive conditions, for the most part. The results from the three different models represent bounds on a range of possible outcomes given a set of initial conditions.

4.5.1 Procedure

Seven different sets of data were now available as a basis for guidelines. These were split into categories 'A' and 'B' as follows:

A) 1) Overtake No Trains, All Trains Same (Original Model)
   2) Overtake No Trains, Train 2 is 'Slow' (Original Model)
   3) Overtake No Trains, All Trains Same, Modified WB Headway Sequence

B) 1) Overtake 1 Train, All Trains Same (Original Model)
   2) Overtake 1 Train, Train 2 is 'Slow' (Original Model)
   3) Overtake 1 Train, All Trains Same, Modified WB Headway Sequence
   4) Overtake 2 Trains, All Trains Same (Original Model)

The sets of results in category 'A' above were used to derive rules for short-turns without overtaking. Category 'B' was used for guidelines for both overtaking 1 and 2 trains. Overtaking 2 trains was grouped with overtaking 1 train because the conditions appeared to be very similar. The principal difference is that in the overtaking 2 trains case the 'created gap' is the sum of h_4 and h_5 in stead of the sum of h_3 and h_4. The data from the original, 'slow train' and modified models had all been sorted and grouped in the same manner. Thus, the results from each model could be directly compared. The 'average of the average' delta PWT results for each group were used as a guide in determining whether each group could be classified 'beneficial', 'neutral', or 'poor'. This made the process of deriving the manual rules somewhat simpler. In a few cases, however, this classification was also based partially on how the majority of short-turns in that group or subgroup came out. For example, in Table 4.22, (overtake 1 train, modified model) the group for which $10 \leq h\_2 < 11$ and $h\_1 < 6$, has an average outcome that is 'neutral'. However, 7 of the 10 sequences in this group resulted in 'beneficial' outcomes. Therefore, this group was treated as 'beneficial' for the purposes of preparing the guidelines.

The outcomes from the original and modified models were compared and the guidelines based on whichever model showed the more restrictive conditions for a given headway sequence group. The 'overtaking 2 trains' data was combined with the 'overtaking 1 train' data in this manner as well. Since no runs of the modified model were made with the ‘slow train’ conditions, the slow train data was treated cautiously. The following guideline was used: If the average outcome for a particular group with the ‘slow train’ condition was ‘beneficial’, and the result for the same group using the modified model (and the ‘all trains same’ condition) was at worst ‘neutral’, then that ‘slow train’ group was accepted as ‘beneficial’ for conditions in which train 2 is known to be a slow mover. Otherwise, that group was not considered ‘beneficial’.

4.5.2 The Guidelines

The guidelines developed are presented below. Additional copies of each table of sorted results are provided for reference .

Table 4.17: Sorted Results for Overtaking No Trains, Original Model

			Beneficial	Neutral	Poor	Sub-Group Ave. delta PWT	Group Ave. delta PWT
h_2 >=11 min.	h_1 >= 6 min.		2	0	0		-284369
h_2 >=12 min.	h_1 < 6 min.		1	0	0	-54260	
11 <= h_2 < 12 min.	h_1 < 6 min.		0	3	0	-17884	-26978
10 <= h_2 < 11 min.	h_1 >= 6 min.		2	0	0		-54162
10 <= h_2 < 11 min.	h_1 < 6 min.	h_3 < 3 min.	0	6	0	-16715	
10 <= h_2 < 11 min.	h_1 < 6 min.	h_3 >= 3 min.	0	0	4	68472	17360
9 <= h_2 < 10 min.	h_1 >= 6 min.		5	0	0		-70762
9 <= h_2 < 10 min.	h_1 < 6 min.	h_3 < 3 min.	0	4	2	-757	
9 <= h_2 < 10 min.	h_1 < 6 min.	h_3 >= 3 min.	0	0	5	35231	15601
8 <= h_2 < 9 min.	h_1 >= 9 min.	h_3 < 2 min	1	0	0	-42040	
8 <= h_2 < 9 min.	h_1 >= 9 min.	3 >= h_3 > 2 min.	0	1	0	-21949	
8 <= h_2 < 9 min.	h_1 >= 9 min.	h_3 >= 3 min.	0	0	1	118065	18025
8 <= h_2 < 9 min.	h_1 < 9 min.		0	23	5		16319

Table 4.18: Sorted Results for Overtaking No Trains, Train 2 is 'Slow'

			Beneficial	Neutral	Poor	Sub-Group Ave. delta PWT	Group Ave. delta PWT
h_2 >=11 min.	h_1 >= 6 min.		2	0	0		-333251
h_2 >=11 min.	h_1 < 6 min.		4	0	0		-74952
10 <= h_2 < 11 min.	h_1 >= 6 min.		2	0	0		-78718
10 <= h_2 < 11 min.	h_1 < 6 min.	h_3 < 2:30 min.	6	0	0	-52767	
10 <= h_2 < 11 min.	h_1 < 6 min.	2:30 <= h_3 < 4 min.	0	2	0	-15274	
10 <= h_2 < 11 min.	h_1 < 6 min.	4 <= h_3	0	0	2	60886	-22538
9 <= h_2 < 10 min.	h_1 >= 6 min.		6	0	0		-110051
9 <= h_2 < 10 min.	h_1 < 6 min.	h_3 < 4 min.	5	5	0	-26738	
9 <= h_2 < 10 min.	h_1 < 6 min.	4 <= h_3	0	0	1	20613	-22433
8 <= h_2 < 9 min.	h_1 >= 9 min.	h_3 < 2:30 min	2	0	0	-73065	
8 <= h_2 < 9 min.	h_1 >= 9 min.	2:30 <= h_3	0	0	1	49789	-32114
8 <= h_2 < 9 min.	h_1 < 9 min.	h_3 < 3 min	2	17	4	-13149	
8 <= h_2 < 9 min.	h_1 < 9 min.	3 <= h_3	0	0	6	33391	-3520

Table 4.19: Sorted Results from Overtaking No Trains, Modified Westbound Headway Generation

			Beneficial	Neutral	Poor	Sub-Group Ave. delta PWT	Group Ave. delta PWT
h_2 >=11 min.	h_1 >= 6 min.	h_3 < 9 min.	2	0	0	-271303	
h_2 >=11 min.	h_1 >= 6 min.	h_3 >= 9 min.	0	0	1	81383	-153741
h_2 >=12 min.	h_1 < 6 min.		1	0	0	-56581	
11 <= h_2 < 12 min.	h_1 < 6 min.		0	3	0	-23115	-31481
10 <= h_2 < 11 min.	h_1 >= 6 min.		0	0	2		34660
10 <= h_2 < 11 min.	h_1 < 6 min.	h_3 < 2:30 min.	0	5	0	-13612	
10 <= h_2 < 11 min.	h_1 < 6 min.	h_3 >= 2:30 min.	0	0	5	57401	21894
9 <= h_2 < 10 min.	h_1 >= 6 min.		3	2	0		-37439
9 <= h_2 < 10 min.	h_1 < 6 min.		0	0	11		20072
8 <= h_2 < 9 min.	h_1 >= 9 min.		0	2	1		-4586
8 <= h_2 < 9 min.	h_1 < 9 min.		0	2	21		16732

Overtake No Trains:

h_2 ≥ 12 min.
h_2 ≥ 11 min. and Train 2 is 'Slow'
h_2 ≥ 10 min. and h_1 ≥ 6 min.
h_2 ≥ 10 min. and h_3 < 2 ½ min. and Train 2 is 'Slow'
h_2 ≥ 9 min. and h_1 ≥ 6 min. and h_3 < 2 ½ min.
h_2 ≥ 8 min. and h_1 ≥ 9 min. and h_3 < 2 ½ min. and Train 2 is 'Slow'

Table 4.20: Sorted Results for Overtaking 1 Train, Original Model

			Beneficial	Neutral	Poor	Sub-Group Ave. delta PWT	Group Ave. delta PWT
h_2 >=11 min.	h_1 >= 6 min.		2	0	0		-157669
h_2 >=11 min.	h_1 < 6 min.	h_3 + h_4 < 9 min.	4	0	0	-73028	
h_2 >=11 min.	h_1 < 6 min.	h_3 + h_4 >= 9 min.	0	0	2	99144	-15673
10 <= h_2 < 11 min.	h_1 >= 6 min.		1	0	0		-73523
10 <= h_2 < 11 min.	h_1 < 6 min.	h_3 + h_4 < 7 min.	7	0	1	-38161	
10 <= h_2 < 11 min.	h_1 < 6 min.	h_3 + h_4 >= 7 min.	0	1	1	-2195	-30968
9 <= h_2 < 10 min.	h_1 >= 6 min.	h_3 + h_4 < 9 min.	5	0	0	-90205	
9 <= h_2 < 10 min.	h_1 >= 6 min.	h_3 + h_4 >= 9 min.	0	1	0	-25425	-79409
9 <= h_2 < 10 min.	h_1 < 6 min.	h_3 + h_4 < 8:30 min.	2	7	0	-24091	
9 <= h_2 < 10 min.	h_1 < 6 min.	h_3 + h_4 >= 8:30 min.	0	0	1	10534	-20629
8 <= h_2 < 9 min.	h_1 >= 9 min.	h_3 + h_4 < 9 min.	2	0	0	-32890	
8 <= h_2 < 9 min.	h_1 >= 9 min.	h_3 + h_4 >= 9 min.	0	1	0	-27398	-31059
8 <= h_2 < 9 min.	h_1 < 9 min.		0	15	15		8380

Table 4.21: Sorted Results for Overtaking 1 Train, Train 2 is 'Slow'

			Beneficial	Neutral	Poor	Sub-Group Ave. delta PWT	Group Ave. delta PWT
h_2 >=11 min.	h_1 >= 6 min.		2	0	0		-225249
h_2 >=11 min.	h_1 < 6 min.	h_3 + h_4 < 9 min.	4	0	0	-99645	
h_2 >=11 min.	h_1 < 6 min.	h_3 + h_4 >= 9 min.	0	0	2	48555	-50245
10 <= h_2 < 11 min.	h_1 >= 6 min.		1	0	1		-46076
10 <= h_2 < 11 min.	h_1 < 6 min.		8	2	0		-62434
9 <= h_2 < 10 min.	h_1 >= 6 min.		6	0	0		-122175
9 <= h_2 < 10 min.	h_1 < 6 min.	h_3 + h_4 < 8:30 min.	8	0	0	-48358	
9 <= h_2 < 10 min.	h_1 < 6 min.	h_3 + h_4 >= 8:30 min.	0	0	1	1813	-42784
8 <= h_2 < 9 min.	h_1 >= 9 min.		3	0	0		-90966
8 <= h_2 < 9 min.	h_1 < 9 min.	h_3 + h_4 < 9:30 min.	1	24	0	-15268	
8 <= h_2 < 9 min.	h_1 < 9 min.	h_3 + h_4 >= 9:30 min.	0	1	4	37397	-6491

Table 4.22: Sorted Results from Overtaking 1 Train, Modified Westbound Headway Generation

			Beneficial	Neutral	Poor	Sub-Group Ave. delta PWT	Group Ave. delta PWT
h_2 >=11 min.	h_1 >= 6 min.		2	0	0		-155659
h_2 >=11 min.	h_1 < 6 min.	h_3 + h_4 < 9 min.	4	0	0	-62827	
h_2 >=11 min.	h_1 < 6 min.	h_3 + h_4 >= 9 min.	0	0	2	111285	-4790
10 <= h_2 < 11 min.	h_1 >= 6 min.		0	0	1		74436
10 <= h_2 < 11 min.	h_1 < 6 min.		7	1	2		-20491
9 <= h_2 < 10 min.	h_1 >= 6 min.		5	0	0		-84377
9 <= h_2 < 10 min.	h_1 < 6 min.	h_3 + h_4 < 9 min.	1	7	0	-19306	
9 <= h_2 < 10 min.	h_1 < 6 min.	h_3 + h_4 >= 9 min.	0	0	2	18107	-11823
8 <= h_2 < 9 min.	h_1 >= 9 min.	h_3 + h_4 < 9 min.	2	0	0	-131300	
8 <= h_2 < 9 min.	h_1 >= 9 min.	h_3 + h_4 >= 9 min.	0	0	1	55044	-69185
8 <= h_2 < 9 min.	h_1 < 9 min.		0	13	15		9174

Table 4.23: Sorted Results for Overtaking 2 Trains, Original Model

			Beneficial	Neutral	Poor	Sub-Group Ave. delta PWT	Group Ave. delta PWT
h_2 >=11 min.	h_1 >= 6 min.		2	0	0		-189111
h_2 >=11 min.	h_1 < 6 min.	h_4 + h_5 < 9 min.	5	0	0	-73476	
h_2 >=11 min.	h_1 < 6 min.	h_4 + h_5 >= 9 min.	0	0	1	156692	-35115
10 <= h_2 < 11 min.	h_1 >= 6 min.	h_4 + h_5 >= 9 min.	0	0	2		96059
10 <= h_2 < 11 min.	h_1 < 6 min.	h_4 + h_5 < 8 min.	6	1	0	-41098	
10 <= h_2 < 11 min.	h_1 < 6 min.	h_4 + h_5 >= 8 min.	0	0	2	56656	-19374
9 <= h_2 < 10 min.	h_1 >= 6 min.		6	0	0		-77411
9 <= h_2 < 10 min.	h_1 < 6 min.	h_4 + h_5 < 8:30 min.	3	5	0	-26986	
9 <= h_2 < 10 min.	h_1 < 6 min.	h_4 + h_5 >= 8:30 min.	0	0	2	125820	3575
8 <= h_2 < 9 min.	h_1 >= 9 min.		3	0	0		-38223
8 <= h_2 < 9 min.	h_1 < 9 min.		0	12	15		2460

Overtake 1 Train:

h_2 ≥ 11 min. and h_3 + h_4 < 9 min.
h_2 ≥ 10 min. and h_1 ≥ 6 min.
h_2 ≥ 10 min. and h_3 + h_4 < 6 ½ min.
h_2 ≥ 9 min. and h_1 ≥ 6 min. and h_3 + h_4 < 9 min.
h_2 ≥ 9 min. and h_3 + h_4 < 7 min. and Train 2 is 'Slow'
h_2 ≥ 8 min. and h_1 ≥ 9 min. and h_3 + h_4 < 9 min.

Overtake 2 Trains:

h_2 ≥ 11 min. and h_4 + h_5 < 9 min.
h_2 ≥ 10 min. and h_1 ≥ 6 min.
h_2 ≥ 10 min. and h_4 + h_5 < 6 ½ min.
h_2 ≥ 9 min. and h_1 ≥ 6 min. and h_3 + h_4 < 9 min.
h_2 ≥ 9 min. and h_4 + h_5 < 7 min. and Train 2 is 'Slow'
h_2 ≥ 8 min. and h_1 ≥ 9 min. and h_4 + h_5 < 9 min.

Under normal circumstances, the restrictions on following headways should not come into play. Since the scheduled headway is 3 ½ minutes, if train 2 has a 10 minute headway trains 3, 4, and possibly even 5 are very likely to have short headways. Thus, given no knowledge about train 2's performance, short-turns with no overtaking should be 'beneficial' when h_2 is at least 12 minutes, and short-turns overtaking one or two trains should be 'beneficial' when h_2 is at least 10 minutes. From comparison of the tables and plots of results for no overtaking and overtaking short-turns, it is clear that under a given initial set of conditions short-turns with overtaking should almost always be more 'beneficial' than short-turns without. Therefore, short-turns with overtaking are recommended over those without whenever scheduling constraints permit.

The sequences in which h_1 is greater than 6 minutes were mostly from early in the a.m. peak period and thus probably represented late pull-outs. Since 6 minutes is an unusually long headway and did have an impact on the outcome of a short-turn, these were treated separately. Intuitively, however, the long h_1 sequences are special cases, since normally a train with a headway greater than 6 minutes should have a much reduced probability of being followed by a train with a long headway.

Referring back to the discussion of the eastbound headway distribution in Section 3.1.1, only about 4% of eastbound headways at Maverick are greater than or equal to 10 minutes. Given that there are about 27 trips scheduled on the Blue Line during the a.m. peak, about 1 such headway should appear per weekday morning. Thus, one might expect an average of one short-turn per a.m. peak period, not counting short-turns done only to re-sequence trains. Less than 0.5% of headways are greater than or equal to 12 minutes, so it is not surprising that so few of the 'no overtaking' short-turns were 'beneficial'. On the other hand 'slow train' conditions enhance the results of short-turns without overtaking to the point that they most likely *would* be beneficial where h_2 ≥ 10 minutes. Thus, 0.5% may somewhat underestimate the frequency of opportunities for beneficial short-turns. Overall, however, short-turning should be a relatively rare procedure on the Blue Line, given that the conditions under which it is an effective policy are very limited. Maintaining uniform headways does appear to be a problem on this line, but it seems unlikely that short-turning should be the principal strategy for headway regulation.

4.6 Alternative Performance Measures

Although minimizing passenger waiting time was the principal objective used in this research, there are additional motives for short-turning. For example, short-turning gets trains back on schedule so that crews can complete their runs without incurring overtime.

Since short-turning restores more uniform headways, overcrowding and therefore denied boardings can also be reduced. Denied boardings can therefore be a useful proxy for passenger comfort. The model output included the total number of denied boardings for both the short-turn and non-short-turn runs. The number of denied boardings saved by short-turning was examined for short-turns overtaking 1 train. The results from both the original and modified models were considered. Figure 4.12 and Figure 4.13 present the change in the number of denied boardings for each sequence as a function of the delta PWT.

Not surprisingly, the average number of denied boardings avoided was closely correlated with the PWT savings. The clusters of 'delta denied boardings' results along the zero axes probably represent sequences for which overcrowding was not a significant factor in either the short-turn or non-short-turn run.

Figure 4.12: Delta Denied Boardings as a Function of Delta PWT for each Initial Sequence, Overtaking One Train, Original Model

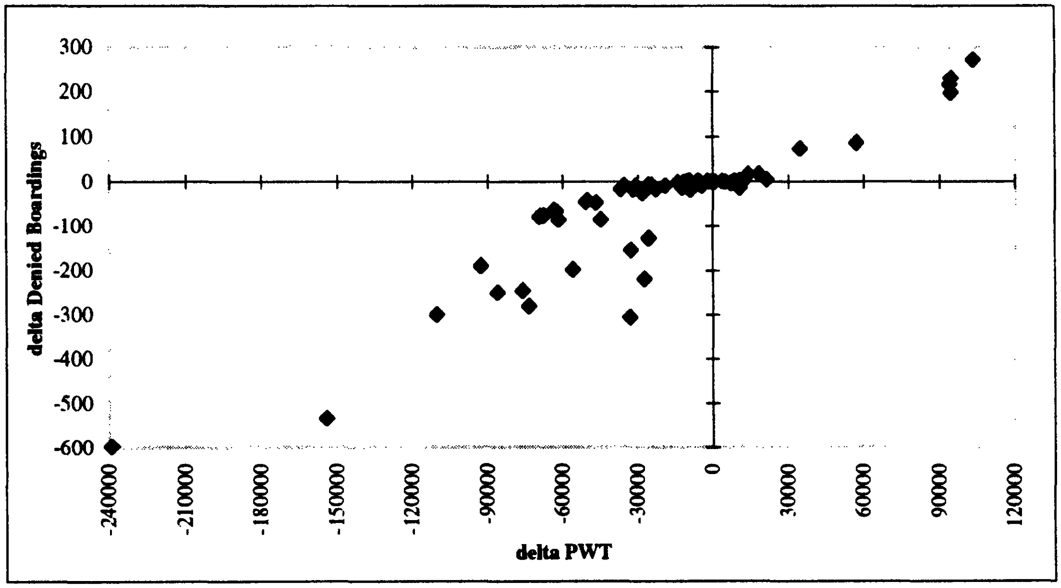
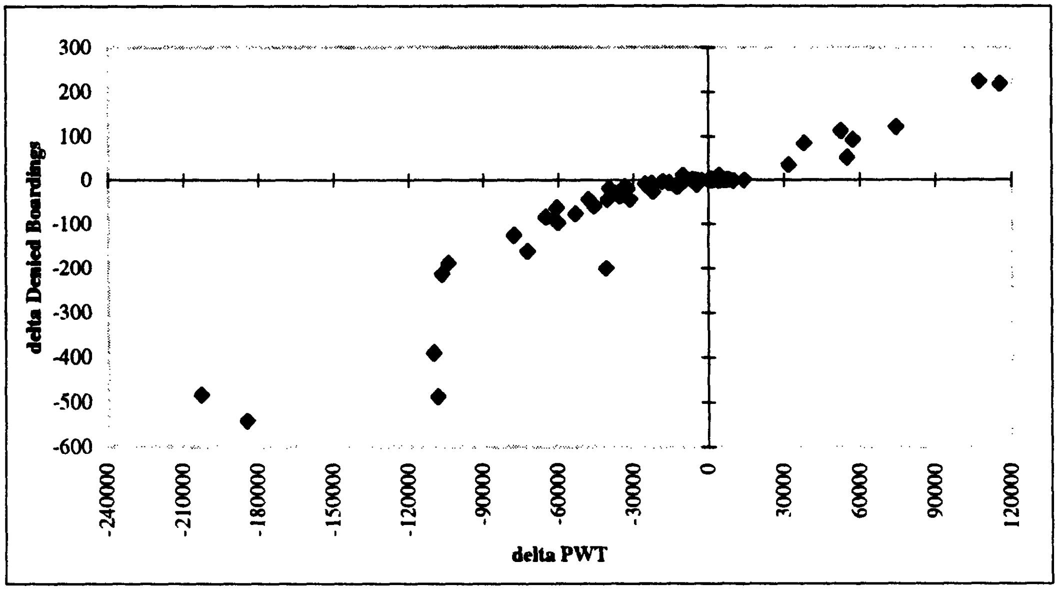


Figure 4.13: Delta Denied Boardings as a Function of Delta PWT for each Initial Sequence, Overtaking One Train, Modified Model



The plot from the original model shows a number of 'beneficial' and even two 'neutral' outcomes for which an average of more than 100 denied boardings were avoided. While most of these points follow a clear pattern, there are a number of outliers in the -90,000 < delta PWT < -30,000 range. Nearly all of these resulted from sequences in which h_1 ≥ 6 minutes. When h_1 ≥ 6 in the original model, train 1 will become overcrowded by the time it reaches the peak load point and will leave passengers behind. These passengers, in turn, are likely to contribute to overcrowding of train 2 unless another train is short-turned into train 2's long headway. Thus, when h_1 is greater than 6 minutes more denied boardings may be avoided relative to the expected passenger waiting time savings.

It is interesting to note that two of these sequences have 'neutral' delta PWT results but a very large savings in denied boardings. These short-turns would therefore probably have been very helpful even though their passenger waiting time savings was not below the threshold. Since being unable to board a train due to overcrowding is very frustrating to passengers, this is a very important consideration.

The plot from the modified model has a much tighter distribution in the -90,000 < delta PWT < -30,000 range. In the modified model, train 1 is able to recover a long headway. Thus, when train 1 has a very long initial headway, overcrowding is less likely to occur than in the original model. This is probably much closer to reality, even if it is not certain whether the modified model is much more realistic overall.

These observations suggest a couple of things about delta denied boardings. First of all, it is a poor indicator of short-turn results when capacity is not an important issue. This would be the case when the scheduled level of service is well in excess of passenger demand. This would also be true when the excess headways in the sequence are not long enough to cause significant overcrowding. For the most part, however, delta denied boardings is closely correlated with delta PWT and in some cases may indicate strong benefits from short-turning, even when the delta PWT is not in the 'beneficial' range. More importantly, the correlation of delta denied boardings supports the validity of delta PWT as the principal performance indicator for short-turning.

The number of skipped segment alighters, the passengers 'dumped' by a short-turn, is also an important secondary impact. The largest expected number of dumpees occur in the case where there is no overtaking. This is because the train with the long headway (train 2) is the one being short-turned. It's expected passenger load will therefore be relatively large. However, on the Blue Line the eastbound passenger flow in the a.m. peak is so light that the largest expected number of dumpees observed is 19 (for a train with a 17 minute preceding headway). The average for all of the sequences in this set is only about 10 dumpees, even for the 'poorest' short-turns. Other than this, probably not much can be concluded from the dumpees indicator on the Blue Line because it simply does not show a significant correlation with anything other than the headway of the short-turn candidate train.

4.7 Actual Short-Turns

Short-turning is a relatively rare practice on the Blue Line. As a result of this, unfortunately, only three records could be found of actual short-turns in the a.m. peak period. Moreover, only one of these short-turns met the selection criteria for input sequences. The other two involved sequences in which none of the headways even approached the 8-minute minimum for the gap to be filled by the short-turn.

The sequence which did meet the selection criteria is presented in Table 4.24.

Table 4.24: Initial Sequence for Documented Short-Turn with 'Beneficial' Outcome

Date	**Time**	**No Overtaking**	
12/17/93	**7:03:24**		
h_1	**h_2**	**h_3**	**h_4**
0:03:16	0:14:05	0:02:35	0:02:29

The short-turned train had a 14 minute preceding headway and was short-turned into the same position in the sequence. Since no trains were overtaken and some time would probably have been recovered at Wonderland anyway, the model predicted that only about 5 minutes were saved by the short-turned train (this was determined by having the model output the departure times of the short-turning candidate train from Maverick westbound in both the short-turn and non-short-turn cases). Table 4.25 shows simulation results from both the original model and the 'slow train' model. Since h_2 is very long and h_2 and h_3 was fairly short this short-turn was very 'beneficial', even though there was no overtaking. Note also the large number of denied boardings saved.

Table 4.25: Results for 'Beneficial' Short-turn, Without and With Train 2 'Slow'

12/17/93	No Overtaking, Train 2 is NOT 'Slow'		
7:03:24	Delta PWT	Delta Denied Boardings	Dumpees
Average	-73,244	-185	15
Std. Dev.	83,072	169	3

12/17/93	No Overtaking, Train 2 is 'Slow'		
7:03:24	Delta PWT	Delta Denied Boardings	Dumpees
Average	-116,506	-285	15
Std. Dev.	59,436	138	3

The other two short-turns observed were probably not to fill long headways. A more likely reason was that the train starter assumed that these trains were so slow that they would fall behind later if they were not short-turned. One involved overtaking 1 train and so may also have been done to exchange the positions of two trains due to some earlier scheduling problem. In any case, simulation of both of these short-turns, even with train 2 'slow', indicated 'poor' outcomes (see Table 4.26 - Table 4.29).

Observations of Blue Line operations, and discussions with train starters and tower T operators gave reasonable assurance that short-turns to fill excess headways are nevertheless a typical practice. Still, these two examples suggest that a significant number of short-turns are made which increase passenger waiting time, though they may be considered necessary due to other operating reasons. Perhaps the more important conclusion to be drawn from the discussions with the train-starters, if not necessarily from the empirical evidence, is that the amount of recovery time available is insufficient. This encourages supervisors to take actions (such as short-turning) to reduce the potential for more serious delays later on but that increase passenger waiting time.

Table 4.26

Date 12/13/93	Time 7:46:08	No Overtaking	
h_1 0:03:00	**h_2** 0:04:36	**h_3** 0:02:29	**h_4** 0:03:45

Table 4.27

12/13/93	No Overtaking, Train 2 is 'Slow'		
7:46:08	Delta PWT	Delta Denied Boardings	Dumpees
Average	12,289	1	5
Std. Dev.	18,422	5	2

Table 4.28

Date 12/17/93	Time 7:57:37	Overtake 1 Train		
h_1 0:02:43	**h_2** 0:05:32	**h_3** 0:03:19	**h_4** 0:02:31	**h_5** 0:03:13

Table 4.29

12/17/93	Overtake 1, Train 2 is 'Slow'		
7:57:37	Delta PWT	Delta Denied Boardings	Dumpees
Average	6,135	1	3
Std. Dev.	18,914	5	2

Out of the 10 days for which complete train sheet data was available, there were 5 additional sequences which were accepted by the model's screening criteria. However, there was no record of any actual short-turn attempts in these cases. Of these, only two short-turns could have resulted in a savings in passenger waiting time, and these would only have been for cases in which train 2 was slow moving. Unfortunately, the behavior of these trains could not be ascertained from the data available, and in any case the gaps were all rectified without any apparent intervention. This is clearly not a large enough sample from which to draw definitive conclusions. It is therefore not really possible to determine whether opportunities for beneficial short-turns are routinely being missed. Recall that an average of only one sequence per weekday a.m. peak period met the screening criteria. Moreover, less than 1/3 of these sequences resulted in 'beneficial' short-turns. Thus, these observations are hardly surprising.

Chapter 5

Generalizing the Short-Turning Effectiveness Results

The purpose of this chapter is to reach a general set of conclusions about the conditions under which short-turning should be a beneficial strategy. First, it will review the a priori conditions under which short-turning should be beneficial. Next, it will review research conducted by Deckoff on short-turning on the MBTA Green Line. The conclusions of the Blue Line study will also be summarized. Finally, a general set of rules will be derived.

5.1 Conditions for Short-Turning

There are a number of conditions which intuitively should govern whether short-turning will be helpful at a particular point, on a particular line, and at a particular time. These include the location of the short-turn point, the amount of time that can be recovered without short-turning, passenger demand patterns, and the initial headway sequence. However, all of these characteristics are closely interrelated. Therefore, it will be helpful to review the process of short-turning.

Figure 5.1 and Figure 5.2 are schematic diagrams showing the negatively and positively impacted passengers in a hypothetical short-turn. To simplify things, it has been assumed that no recovery is possible at the skipped terminal and that therefore, aside from the short-turn, vehicles will retain their initial headway sequence throughout. The initial headway sequences are arbitrary but, as will be discussed below, realistic. The vertical lines represent times at which each vehicle in the sequence passes some arbitrary point - first in the skipped segment and then in the segment downstream from where the short-turned train reenters service. Headways are thus represented by the horizontal distance between these lines. The bold horizontal arrows indicate the headways over which the impacted passengers accumulate, while the adjacent plain arrow directly to the right of each bold arrow shows the change in waiting time for that group of passengers.

The short-turned train is advanced in the sequence by the 'time savings'. This train assumes the midpoint of the headway it is inserted into. Both pairs of diagrams illustrate that short-turning results in both positively and negatively impacted passengers. A significant proportion of all of the impacted passengers will experience ***longer*** waits under a short-turn. On the segment of the route skipped by the short-turn most, if not all, boarding passengers will be forced to wait longer. This is particularly likely to be true where, as was assumed in Figure 5.1 and Figure 5.2, headways remain constant through the skipped terminal. Passengers traveling *to* the skipped segment - the dumpees - also experience additional waiting time (ignoring, of course, the considerable added inconvenience of having to alight unexpectedly and re-board). All of the positively impacted passengers in these figures are in the 'benefited' segment, from 'S' downstream. However, this segment has negatively impacted passengers as well. These are the passengers who would have boarded the short-turned vehicle had it been in its original position. The relative size of each group of passengers will of course depend on the relative passenger demand to and from each segment. The magnitude of the time savings or penalty imposed on each group will be determined by the initial headway sequence, the time saved by the short-turning train, and other factors that affect the final headway sequence. Where recovery *is* possible at the skipped terminal, the relative number of benefited and 'dis-benefited' passengers is not quite as clear. This is because all of the vehicles in the sequence can change their relative headways. Nevertheless, this simplified model illustrates the different groups of impacted passengers.

With this simplified short-turning process in mind, the different categories of conditions can be examined more or less individually. In order to allow systematic screening of instances where short-turning is likely to be helpful, the sections below will deal first with permanent line characteristics, then with demand characteristics which vary but follow a regular pattern over time, and finally with real-time events.

Figure 5.1: Overtake No Trains (Train 2 is Short-Turned)

Skipped Segment:

```
Train:       0           1                        3       4
S-T:         |           |                        |       |
             |           |                        |       |
Neg. Imp.:   |           |<--------------->|----->|       |
             |           |                 |      |       |
Pos. Imp.:   |           |                 |      |       |
             |           |                 |      |       |
No S-T:      |           |                 |      |       |
             0           1                 2      3       4
```

Downstream Segment:

```
Train:       0           1            2           3       4
S-T:         |           |            |           |       |
             |           |            |           |       |
Neg. Imp.:   |           |            |<-->|----->|       |
             |           |            |    |      |       |
Pos. Imp.:   |           |<---------->|<---|      |       |
             |           |                 |      |       |
No S-T:      |           |                 |      |       |
             0           1                 2      3       4
```

Figure 5.2: Overtake 1 Train (Train 3 is Short-Turned)

Skipped Segment:

```
Train:       0           1                   2              4        5
S-T:         |           |                   |              |        |
             |           |                   |              |        |
Neg. Imp.:   |           |                   |<---->|------>|        |
             |           |                   |      |       |        |
Pos. Imp.:   |           |                   |      |       |        |
             |           |                   |      |       |        |
No S-T:      |           |                   |      |       |        |
             0           1                   2      3       4        5
```

Downstream Segment:

```
Train:       0           1         3         2              4        5
S-T:         |           |         |         |              |        |
             |           |         |         |              |        |
Neg. Imp.:   |           |         |         |<---->|------>|        |
             |           |         |         |      |       |        |
Pos. Imp.:   |           |<------->|<--------|      |       |        |
             |           |                   |      |       |        |
No S-T:      |           |                   |      |       |        |
             0           1                   2      3       4        5
```

5.1.1 Time Savings and the Location of the Short-Turn Point

On bus routes, short-turns can potentially be implemented at any point at which a bus could drive around a block to turn around. With rail systems, on the other hand, short-turns will only be possible where crossovers or turning loops are available. Short-turning requirements should therefore be an important consideration when new systems are being designed or existing track layouts are revised.

The location of the short-turn point affects two key factors in short-turning effectiveness. The first is the amount of time saved by short-turning. The second is the relationship of the skipped and benefited segments to the passenger demand profile. Obviously, the short-turn must save enough time to allow vehicles either to recover at least some of their scheduled headway or to allow them to overtake the preceding vehicle and assume something approaching the scheduled position of the preceding vehicle. On the other hand, if the short-turn point is too distant from the skipped terminal, other problems arise. For one thing, the short-turning train is not being well utilized if it must wait for a long time to re-enter service. In cases where there is no space at the short-turning point for the short-turning vehicle to wait, the time savings is particularly critical. This is because the short-turned vehicle will have to go right back into service in the return direction with no way to optimize the resultant sequence. The obvious solution might be selecting a vehicle later in the sequence for short-turning. However, as will be further explained in section 5.1.5, the headways further back in the sequence are likely to be much less favorable to short-turning.

The second set of factors in locating the short-turn point involve passenger impacts directly. The greater the distance of the short-turn point from the skipped terminal, the longer the skipped segment and thus the lower the proportion of benefited to dis-benefited passengers will be. The shorter the skipped segment, the smaller the number of negatively impacted passengers. Therefore, the skipped segment should be as short as possible while providing sufficient recovery time. The passenger demand profile of the line in each time period will also be key in determining the suitability of a particular short-turn point. This will be covered with passenger demand characteristics in section 5.1.3.

5.1.2 Recovery Time

The most important factor working against short-turning is the amount of recovery time available at the skipped terminal. When a vehicle can close up a long headway by spending less time than average at a terminal no passengers need be skipped. The added inconvenience to 'dumped' passengers is also avoided. The drawback of recovery time is that it reduces vehicle utilization. Therefore, the total allowed time (running time plus recovery time) should be just sufficient for all but, say, 5% of trips to begin with the scheduled headway. Station skipping strategies should then be reserved only for the remaining 5% for which recovery time can restore service to a reasonable level. On the other hand, if *no* recovery is possible, then station skipping strategies are the only alternative to doing nothing.

5.1.3 Passenger Demand

While beneficial short-turns might be possible at a particular short-turn point under certain passenger demand conditions, these conditions change throughout the day. Thus, some locations may only be useful during certain time periods.

Figure 5.1 and Figure 5.2 do not give a full picture of the net passenger waiting time impact of a short-turn. The relative numbers of benefited and inconvenienced passengers will depend also on the relative passenger demand to and from the benefited and skipped segments. If demand to and from the skipped segment is relatively light, the net amount of inconvenience caused here will be relatively unimportant to the outcome of the short-turn. On the other hand, if passenger demand to and from the skipped segment heavily outweighs demand from the skipped segment, then short-turning is unlikely to be a useful strategy.

These observations suggest several things about the location of the short-turn point relative to the demand profile at a given time of day. For one thing, the short-turn should be implemented in the non-peak or lighter density direction. The benefited segment, which is downstream from the short-turn, should then lie in the peak direction where boardings should be heavier. Short-turning in the peak direction would dump more passengers and benefit relatively fewer. The short-turn point should also be as far upstream from the peak load point as possible. This will maximize the number of boarding passengers in the benefited segment and also maintain capacity over the peak load segment. A more general conclusion is that the skipped segment should ideally be located at the suburban end of a radial route, since demand to and from this end will always be lighter that demand to and from the opposite end.

5.1.4 Capacity

A related consideration is how close to capacity the transit line is running. When a line is running just below capacity, overcrowding and denied boardings will rapidly increase total passenger waiting time. Moreover, following vehicles with short headways will likely be under-utilized. Short-turning one of these closely-spaced following vehicles allows existing capacity to be better distributed without simply shifting the overcrowding to a later train. In situations where demand is in excess of scheduled capacity, on the other hand, this advantage will vanish. In this case there will always be queues of passengers at stations approaching the peak load point and the net reduction in overcrowding will be a minor consideration.

5.1.5 Initial Headway Sequences

Once locations and time periods where short-turning may be effective have been found, the real-time conditions must be addressed. Headway sequences are the principal real time conditions. Others, which will not be covered here, include train length, destination, and expected running speed.

The size of the headway or "gap" to be filled by short-turning (always the headway of the second train in the sequence or "h_2" in the convention of this project) is one of the most important factors here. In general, as this headway increases, so does the number of passengers waiting for the vehicle. At the same time, the total passenger waiting time accrued increases as the square of the headway. As the headway becomes excessive, the likelihood of overcrowding, and further delay also increases. Clearly then, as this headway increases, the potential benefit from short-turning also grows. Referring again back to Figure 5.1 and Figure 5.2, it should be clear that as h_2 increases, the number of positively impacted passengers as well as the waiting time saved by each, should also increase.

Equally significant is the vehicle selected for short-turning and its preceding and following headways. A vehicle with a long preceding headway will in all likelihood have a large number of passengers on board relative to a vehicle with a short preceding headway. There will therefore be a large number of prospective dumpees. Short-turning a vehicle with a long preceding headway will also inconvenience a relatively large number of skipped segment boarders, as can be seen by comparing Figure 5.1 to Figure 5.2. Boarders in the skipped segment will have had the entire long headway to accumulate. The headway of the vehicle *following* the one that is being short-turned determines the additional wait experienced by the skipped segment boarders and alighters.

On transit lines with high-frequency service (say, scheduled headways of 10 minutes or less) headways will have a strong dependence on their preceding headways. In particular, if a vehicle has a preceding headway that is substantially greater than the scheduled headway, the first and possibly additional following vehicles will most likely have shorter than scheduled headways. This has very important implications for short-turning. First, if the vehicle following the one with the excess headway has a short headway, relatively few passengers will be on board. Nor will many be waiting for it downstream. Thus, short-turning this vehicle will minimize both dumpees and skipped segment boarders. This is why in section 5.1.4 "bunched" following vehicles were referred to as excess capacity that could be re-allocated. Moreover, if the second following vehicle also has a short headway, these negatively impacted passengers will not have to wait long for another vehicle. In Figure 5.2, for example, the number of negatively impacted passengers is determined by h_3. The additional waiting time for each of these passengers is equal to h_4 (assuming there is sufficient capacity on train 4 for all of the extra passengers). Essentially the same thing is happening in Figure 5.1, with h_2 and h_3. Trains further back in the sequence should have headways closer to the scheduled headway. Thus, they would be less suitable for short-turning.

5.2 Short-Turning on the MBTA Green Line

Deckoff examined short-turning on the MBTA Green Line. In contrast to the Blue Line, the Green has a branching structure of 4 routes. Two of these routes, the B and the D have their inner terminal right in Boston's Central Business District (CBD) at Government Center. The C and E routes run somewhat further - to North Station and Lechmere respectively. Remarkably, a large number of B and D route trains are short-turned at the inner end of the line at Park Street. These short-turns skip just one station: the Government Center Terminal. The short-turns are actually implemented one station upstream at Bolyston (S-1 in the notation used for this project). The decision to short-turn is generally made by a field supervisor (chief inspector) stationed at the end of the northbound Boylston platform. At this location, the loop track used to short-turn trains diverges from the northward main track. After discharging passengers at Park St., short-turned trains return directly to service in the Westbound direction.

5.2.1 Modeling the Green Line

One of the main reasons that short-turning is done at Park Street (and also one of the reasons that it is often helpful) is that no significant recovery time is available at the Government Center terminal. Trains turn on a simple loop track and reenter the Westbound main track. Since both B and D lines use this track there is no space for trains to lay over or queue before beginning their return trip. For this reason, Deckoff assumed that B and D trains left to run their normal course would retain their northbound headways in the westbound direction (Deckoff's model also assumed constant dwell times for all trains). C and E trains, on the other hand, do have some recovery time at their northern terminals. Therefore, the westbound headways of C and E trains given as inputs to Deckoff's model were randomly generated. Short-turning B and D trains are also unable to hold significantly at Government Center. This again is due to a restricted track layout at Park St. The time savings was randomly generated with a mean of 4.6 minutes (in contrast, the short-turns on the Blue line can save 15 minutes or more of running time). Because these trains can not be held, the number of trains to be overtaken was not a specified input to Deckoff's model. Rather, the short-turned train was advanced through the sequence of preceding trains by the amount of time saved. Train capacity constraints were included in the model, with the additional complication that both one and two car trains would appear. Lengths of westbound C and E trains also varied. The lengths of C and E trains were also randomly generated.

The branching structure of the Green Line made for much more complex passenger load and waiting time calculations than for the Blue Line. Different groups of passengers are able to board different trains to continue their trips. Boarders skipped at Government Center by short-turned B trains are a good example: those traveling to points between Park St. and Copley can board any following train; those traveling to Hynes or Kenmore can board any train except an E; those traveling to points along the B branch beyond Kenmore must wait for the next B train.

Deckoff used his model to consider short-turning *every* B and D train over a period of one week. Each day was divided into am peak, mid-day, p.m. peak, and evening periods. The deterministic inputs to the model were passenger demand data and northbound headways. The northbound headway data came from train sheets recorded by the Inspector at Boylston. The model was used to determine the conditions in terms of preceding and following headway under which short-turning would be beneficial in terms of passenger waiting time saved. No effort was made to screen the initial headway sequences. Average outcomes were sorted by the first and second preceding headways of the short-turn candidate. However, in order to simplify the analysis, these were the headways only with respect to other trains running on the same route (i.e. for short-turning B trains the first and second preceding B trains were used). The headways of trains on the other 3 routes were essentially treated as random variables. The outcomes were then analyzed based partially on the expected following headways. Following headways were not treated directly as decision criteria because the field supervisor who makes the short-turning decisions normally does not know what the following headways are unless the following train can be seen directly behind. However, in the analysis careful consideration was given to expected following headways (as influenced by train "bunching" effects, etc.).

5.2.2 Conclusions from Green Line Research

Deckoff used his short-turn simulation results to derive manual guidelines. However, these guidelines were designed partially to select the optimal train out of a given sequence for short-turning. This goes beyond what was done with the Blue Line guidelines. In order to compare Deckoff's results directly with the Blue Line research, his results were reviewed and converted into the notation used in this project. The conditions for which beneficial outcomes resulted for B trains in the a.m. peak period are shown in Table 5.1. Deckoff considered short-turning on both the B and D lines separately in four different time periods. However, this comparison will focus on short-turning on the 'B' line in the a.m. peak. This is because this is the only period for with complete demand data is available.

From the simulation results, a basic set of guidelines were prepared in terms of the number of trains overtaken. This required determining how many trains would be overtaken under different conditions. In the convention of the Blue Line research, Train 2's headway (h_2) was always the headway into which the short-turned train would be inserted. The guidelines developed are shown in Table 5.2.

Table 5.1: Green Line Simulation Results: Conditions for 'Beneficial' Short-Turns, Green Line 'B' Branch, A.M. Peak Period

H1P[1] <= 1 min. and H2P[2] <= 1 min.
H1P <= 3 min. and H2P >= 8 min.
H1P >= 10 min. and any H2P

Footnotes:

1: H1P = first preceding headway

2: H2P = second preceding headway

Table 5.2: Manual Short-Turning Guidelines: Green Line 'B' Branch, A.M. Peak Period:

	Short-Turn Train	Conditions:
Overtake O:	2	h_2 >= 10 min.
Overtake 1:	3	h_2 >= 8 min. and h_3 <= 3 min.
Overtake 2:	4	any h_2 and h_3 <= 1 min. and h_4 <= 1 min.

To produce Table 5.2 Deckoff's guidelines were processed in the following manner: Where h_2 is equal to or greater than 10 minutes, the expected time savings of 4.6 minutes will simply advance the short-turned train closer to its preceding train and farther from its following train. When h_3 ≤ 3 minutes and h_2 ≤ 8 minutes, the randomly generated time savings will with very high probability place train 3 ahead of train 2 if train 3 is the one being short-turned. If h_3 and h_4 are both ≤ 1 minute, it is most likely because h_2 was very long. In this case the expected time savings should put train 4 ahead of train 2 if train 4 is short-turned. In this case, no explicit minimum 'gap' headway was determined. It seems likely, however, that there would need to be an excess headway in order for short-turning to be a beneficial strategy.

5.2.2.1 Recovery Time and Time Savings

Since no recovery is possible at Government Center, real-time interventions such as expressing or short-turning (or dispatching a run-as-directed train when one is available) are the only way to recover from an excess headway. Therefore, even though the amount of time saved by short-turning is a very modest 5 minutes, it is a powerful strategy. Five minutes is approximately the mean headway on the 'B' line in the a.m. peak. This turns out to be nearly optimal. Very short headways are possible on the Green Line (less than 1 minute) and should be expected following a headway of 10 minutes or more. Thus, short-turning a train without overtaking (as allowed by the rules in Table 5.2) should advance it to roughly one scheduled headway in front of its following train. A short-turning train that overtakes 1 train should end up between 2 and 5 minutes ahead of what had been its preceding train (again following the guidelines). These outcomes are not necessarily as beneficial as would be placing the short-turned train at the midpoint of a very long headway (say greater than 10 minutes). Overall, however, where no holding is possible at the short-turn point, a time savings roughly equal to the scheduled or mean headway might be ideal.

5.2.2.2 Green Line Demand Profile

In light of section 5.1's conclusions, it seems highly counterintuitive that beneficial short-turns are possible at the inner end of Green Line, right between the line's peak load segments (between Boylston and Park St. each way). However, because only one station is skipped the number of passengers negatively impacted does not necessarily dominate the net change in PWT. This sub-section will again look specifically at demand on the B route in the a.m. peak.

The total volume on this route in the a.m. peak is of roughly the same scale in each direction: 4150 boardings per hour northbound and 4900 boardings per hour westbound (the somewhat higher outbound flow in this period reflects the role of the Green Line as a distributor of commuters to Back Bay locations). In the northbound direction, 34% of B train passengers are destined for Government Center. Westbound, only 27% board at Government Center. Therefore, 73% of westbound passengers are potential beneficiaries of a short-turn. This is considerably more than on the Blue Line, where only about 55% of westbound passengers are potential beneficiaries.

While about 34% of eastbound B train passengers are potential dumpees, they would be unlikely to experience much additional waiting time because all of them could board any other Green Line train to reach Government Center, and these trains are likely to be following closely.

5.2.2.3 Headway Sequences

Deckoff's primary short-turning performance measure was delta PWT. However, the ratio of benefited to dis-benefited passengers was analyzed as a secondary performance measure. In the process, Deckoff reached a number of general observations about short-turning. First of all, he pointed out that the benefited to dis-benefited ratio generally decreases as the short-turning train's first preceding headway increases. This is because the number of skipped segment alighters and boarders increases in direct proportion to the preceding headway. He also observed, however, that as a train's preceding headway grows longer , its following headway is likelier to be shorter. Thus, the dumpees and skipped segment boarders should have a relatively short wait for the next train if a train is short-turned under these conditions. Therefore, when the short-turning 'B' train's preceding headway is greater than 10 minutes, so that no trains will be overtaken, a large number of passengers will be inconvenienced. However, those who would have boarded the short-turned train but who now must wait for the next 'B' train are unlikely to experience much *additional* waiting. In addition, when the short-turned train's original headway was long, there will be a large number of benefited passengers downstream from the short-turn. Moreover, in the case of this model, each of these passengers will be saved the full amount of time saved by short-turning. This explains why short-turns with no overtaking are a successful strategy on the Green Line.

An additional observation by Deckoff related to trains with short preceding headways. Short preceding headways are most likely to be associated with long second preceding headways. Therefore, short-turning a train with a very short headway should advance it into a long headway. Because this train's initial headway was short, only a small number of dumpees and skipped segment boarders should result. At the same time, a substantial number should benefit, since the train is being inserted into a long headway. Therefore, the ratio of positively impacted passengers should be relatively large and the net result of the short-turn is likely to be beneficial even if the average amount of time saved by each benefited passenger is relatively small.

The short-turning guidelines can now be re-examined in view of these observations. When the candidate train's headway is ≥ 10 minutes there should be no overtaking. Under this condition, the first following headway should be quite short, minimizing the additional waiting time imposed on passengers traveling to and from Government Center. In addition, the short-turned train will end up with at least a 5 minute headway and so there should be a large number of beneficiaries. When h_3 ≤ 3 min. and h_2 ≥ 8 min., the guidelines recommend short-turns that will most likely overtake one train. Because h_3 is relatively short, the number of skipped segment boarders and alighters should be fairly small. Short-turns overtaking two trains are permissible where h_3 and h_4 are both ≤ 1 minute. Because h_4 is so short, there should few dumpees and skipped segment boarders. Two successive headways this short almost certainly would result from a very long h_2, so there will be a large number of benefited passengers.

5.3 Conclusions from Blue Line Research

It is somewhat harder to make general observations about short-turning from the Blue Line modeling results. This is primarily because the availability of recovery time at the skipped terminal (Wonderland) allows headway sequences to change considerably between the eastbound and westbound trips. Changes in headways at this terminal were a major component of the Blue Line model. Figure 5.3 and Figure 5.4 below illustrate some hypothetical examples of this process.

Figure 5.3: Overtake No Trains (Train 2 is Short-Turned)

```
Initial Eastbound Sequence:

Train:      0         1                             2    3    4
S-T:        |         |                             |    |    |

Skipped Westbound Segment:

Train:      0         1                   3                  4
S-T:        |         |                   |                  |
            |         |                   |                  |
Neg. Imp.:  |         |<----------->|---->|<----------->|--->|
            |         |             |     |             |    |
Pos. Imp.:  |         |             |<--->|<------------|    |
            |         |             |                   |    |
No S-T:     |         |             |                   |    |
            0         1             2                   3    4

Downstream Westbound Segment:

Train:      0         1         2         3                  4
S-T:        |         |         |         |                  |
            |         |         |         |                  |
Neg. Imp.:  |         |         |<->|---->|<----------->|--->|
            |         |         |   |     |             |    |
Pos. Imp.:  |         |<------->|<--|<--->|<------------|    |
            |         |             |                   |    |
No S-T:     |         |             |                   |    |
            0         1             2                   3    4
```

Figure 5.4: Overtake 1 Train (Train 3 is Short-Turned)

Initial Eastbound Sequence:

```
Train:       0         1                             2    3    4    5
S-T:         |         |                             |    |    |    |
```

Skipped Westbound Segment:

```
Train:       0         1                   2                   4    5
S-T:         |         |                   |                   |    |
             |         |                   |                   |    |
Neg. Imp.:   |         |<------------>|--->|              |<-->|--->|
             |         |              |    |              |    |    |
Pos. Imp.:   |         |              |<-->|<-------------|    |    |
             |         |              |                   |    |    |
No S-T:      |         |              |                   |    |    |
             0         1              2                   3    4    5
```

Downstream Westbound Segment:

```
Train:       0         1         3         2                   4    5
S-T:         |         |         |         |                   |    |
             |         |         |         |                   |    |
Neg. Imp.:   |         |         |<-->|--->|              |<-->|--->|
             |         |         |    |    |              |    |    |
Pos. Imp.:   |         |<------->|<---|<-->|<-------------|    |    |
             |         |              |                   |    |    |
No S-T:      |         |              |                   |    |    |
             0         1              2                   3    4    5
```

These diagrams are not a completely accurate representation of the simulation used for this project. For one thing, the final westbound headway generation arrangement used would have held back trains 4 and 5 and dispatched them with expected headways of 3 1/2 minutes. However, the passenger impacts are somewhat more clear with the depiction used here. This is also a somewhat more accurate, if simplified, representation of the actual behavior of Blue Line trains given that they will be trying to run to schedule.

When train 2 is short-turned with no overtaking (Figure 5.3), the first following train (train 3) should generally be able recover some time at the skipped terminal (Wonderland). Since short-turns were only tested where h_2 ≥ 8 minutes, h_3 leaving S (Orient Heights) would be 9 1/2 minutes or more. In this scenario, train 3 would try to depart Wonderland with a preceding headway of 7 minutes, since it would be trying to depart as close a possible to its scheduled time. It would thus recover between 3 minutes and the maximum amount of recovery time available (at which point the train would leave Wonderland as soon as it had loaded passengers). However, had train 2 not been short-turned, it would have recovered even more time than train 3, since it would be trying to regain as much of its 3 1/2 minute headway as possible. This might well use up all the available recovery time, making it impossible for train 3 to recover any time at all (which is what is happening in Figure 5.3). Some passengers thus have a shorter wait for train 3 because it appears earlier. However, many more passengers who would have boarded it must wait for train 4 instead. As a result, h_4 is also a factor in the outcome of the short turn.

In instances in which one or two trains are being overtaken (Figure 5.4), recovery time also influences the net outcome of short-turning. In these cases, it is assumed that the first preceding train, the one with the long headway (train 2) will "drop back" into the following train's schedule. This train should therefore depart Wonderland with a 7 minute preceding headway. It is often the case, however, that this train could have recovered considerably more than a 7 minute preceding headway at Wonderland. Thus, an even larger number of passengers boarding between Wonderland and Suffolk Downs experience increased waiting time because train 2 runs later than it would have had there been no short-turn. On the other hand, since train 2 recovers less time in the short-turn case, the first following train should be able to recover *more* time. In Figure 5.4, train 4 actually appears at the same time at which train 3 would have appeared had it not been short-turned (although this was only done to ensure that the diagram was as clear as possible). In this particular instance, there is no impact on passengers who would have boarded train 3, while passengers who would have boarded train 4 in its original position must wait now wait for train 5.

The most important difference between these figures and the earlier pair is that there are both positively and negatively impacted passengers in the skipped segment as well as in the downstream 'benefited' segment. The ability of trains to shorten their headways, subject to the availability of recovery time, makes for much more complex passenger impacts.

5.3.1 Time Savings

The running time saved by short-turning Blue Line trains (about 15 minutes) is quite generous compared to the Green Line B trains turning at Park St. Moreover, trains can be held at the short-turn point and dispatched in the desired position. Even when this means that trains must sit out of service for as much as 10 minutes, short-turning is beneficial. Thus, having *too much* time savings is evidently not a problem in this case. Since the Blue Line has only one route, holding a short-turning train will not block other trains as would be the case at Park St. on the Blue Line.

5.3.2 Recovery Time

Viewed in terms of the gap headway to be filled (h_2), the guidelines derived for short-turning on the Blue Line are somewhat more restrictive than those for the Green Line. For overtaking no trains, the Blue Line guidelines generally require an h_2 of at least 12 minutes unless other special conditions are met. The Green Line rules permit such short-turns when h_2 is only 10 minutes. Similarly, short-turns overtaking one or two trains normally require h_2 to be at least 10 minutes on the Blue Line, but only 8 minutes on the Green. This seems particularly significant considering that the scheduled headway for the Blue Line is shorter than that for the Green Line (3 1/2 minutes versus 5 minutes).

In terms of the following headways, on the other hand, the Blue Line conditions do not seem very restrictive at all, at least when 1 or 2 trains are being overtaken. In these cases, following headways almost as long as the scheduled headway are not a problem (though such headways may nevertheless be unlikely given bunching effects).

Both of these observations can probably be accounted for by the ability to recover time at the Blue Line's skipped terminal. Recovery time enables gaps in service to be at least partially filled without intervention. Consequentially, h_2 must be longer before a short-turn would be beneficial. Recovery will not negatively impact as many passengers as short-turning does because no trains skip stations. Recovery also explains the more relaxed following headway requirements. If train 3 will overtake train 2 and h_2 is only 10 minutes or so, train 2 will only have to recover about 3 minutes. There should then still be some recovery time left over to ensure that train 4 will be able to depart Wonderland with a reasonably short headway. This will minimize the additional waiting time for passengers who would have boarded train 3 had it not been short-turned. If h_2 is much longer than 10 minutes, it will use up the recovery time, but it will not matter so much that h_4 is longer because there will be more positively impacted passengers. In the case where there is no overtaking, on the other hand, train 3 would end up with a very long headway at S even if it were close behind train 2. h_2 would already be at least 12 minutes. However, if train 3 also has a long headway, the skipped segment alighters will have a long additional wait.

5.3.3 Blue Line Demand Profile

In the a.m. peak on the Blue Line, approximately 56% of passenger demand in the westbound direction is in the downstream segment, from Orient Heights (S') westward. This proportion is high enough that the waiting time savings from a short-turn will, under the right conditions, benefit enough people to result in a net waiting time savings for the system. At the same time, travel to and from skipped stations in the *eastbound* direction is particularly light in the a.m. peak. This helps to minimize the total number of passengers experiencing increased waiting time.

In the *p.m.* peak, in contrast, roughly the opposite is true and short-turning is not likely to be an effective strategy. In the p.m. peak, the eastbound passenger flow is much heavier than the westbound. Assuming that the eastbound flow in the p.m. peak roughly mirrors the westbound flow in the a.m. peak, then approximately 44% of westbound traffic will be destined for the skipped segment. On the other hand, westbound demand will be comparatively light. Therefore, while the average waiting time saved by the positively impacted passengers might be large, the number of such passengers will be quite small relative to the number of dis-benefited eastbound passengers. Thus, the gross time savings will be more than offset by gross time penalty, and the net outcome will be a poor short-turn.

5.3.4 Capacity Constraints

The Blue Line runs quite close to capacity in the a.m. peak period. Thus, long headways can quickly result in overcrowding. Trains following closely behind a train with an excess headway will likely have lighter than average passenger loadings. Short-turns that ranked 'beneficial' in terms of passenger waiting time savings tended also to reduce overcrowding and denied boardings. Thus, by reducing headway variation, short-tuning can improve passenger comfort and optimize utilization of available capacity. The skipped segment is also far enough upstream form the peak load point that lost capacity is not an issue; the short-turned train still covers the busiest section of the line.

5.3.5 Headway Sequences

In general, the intuition about how initial headway sequences will impact short-turn results seemed to bear itself out. The longer the 'gap' headway (h_2) was, the more likely the short-turn was to be beneficial. Likewise, the shorter the following headways were, and in turn the shorter the 'created gap' was, the more likely the short-turn was to be beneficial. The created gap, which is the sum of the short-turn candidate's initial first preceding and first following headways, turns out to be an excellent proxy indicator of the negative impact of the short-turn (though as discussed in section 5.3.2, recovery may dilute this). Ideally, the first preceding headway of the short-turning train is proportional to the number of skipped boarders and alighters, while the first following headway approximates the additional waiting time for each of these skipped passengers. The product of these two terms, times the passenger arrival rate would give total negative PWT impact (ignoring capacity constraints, headway variation, etc.).

5.4 General Conclusions

These general conclusions about short-turning are necessarily limited by the characteristics of the MBTA Blue and Green Lines. Nevertheless, it appears that a number of important observations have been made about the conditions under which short-turning is likely to be an effective strategy.

The short-turn point must be positioned to save enough time to create a significantly more uniform headway sequence. If no holding of the short-turning vehicle is possible at the short-turn point, then the exact amount of time saved will be one of the main determinants of the new sequence resulting. This will probably place considerable limits on the kinds of short-turns that will be effective under a given set of conditions. An inability to hold may even limit the conditions under which short-turning will be a beneficial strategy (although this is not completely clear from the Green Line simulation results because short-turning only saves a relatively small amount of time). In any case, where no holding is possible, the optimal time savings will be roughly equal to the mean headway, since this will place the short-turned train about one mean headway in front of the following vehicle. On the other hand, if holding *is* possible, there will be somewhat more latitude as to where in the sequence the short-turned vehicle can return to service. The magnitude of the time savings is primarily a function of the length of the skipped segment. However, the number of negatively impacted passengers is also largely dependent on the length of the skipped segment. This puts another upper bound on the time savings.

The availability of recovery time at the terminal skipped by the short-turn should generally detract from the usefulness of short-turning. This is because vehicles will be able to regain their scheduled headways without skipping stations and therefore without inconveniencing any passengers. The more recovery time is available, the larger the service disruption must be before short-turning will be a potentially beneficial strategy. Schedules for a given time period should include enough recovery time for a high percentage of vehicles to start their next trip on schedule (or with the scheduled headway) based on the probability distribution of trip times in that period. However, there is clearly some point beyond which it is not efficient to provide recovery time. It is at this point that station skipping strategies such as short-turning may be appropriate provided the other necessary conditions are met.

On the other hand, the availability of recovery time may allow beneficial short-turns with following headways that are not particularly short. This is because the gap made by removing the short-turning vehicle may be partially closed up by recovery. This is nevertheless most likely to be true in cases where the initial excess headway (to be filled by the short-turned vehicle) is short enough that the vehicle that will end up following the short-turned vehicle does not use up all of the available recovery time. This following vehicle would not use all of the recovery time because it would be departing the terminal with twice the scheduled preceding headway to leave space for the short-turned vehicle.

The numbers of positively and negatively impacted passengers, and also the change in waiting time experienced by each group of passengers, will be determined partially by the initial headway sequence, the time savings, and recovery time. However, the relative sizes of these different groups, and therefore also the net amount of PWT accumulated by each group are also dependent on the demand to and from the different segments of the line. If the demand from the segment of the line downstream from the short-turn is too weak, the total PWT saved will not exceed the total PWT cost to the negatively impacted passengers plus the threshold. Likewise, if the demand to the skipped segment is too strong, the total cost in PWT will exceed savings minus the threshold. The impact of the demand profile will of course vary with the location of the short-turn point, and with the time of day.

Capacity is also an important consideration in short-turning. The closer to capacity a transit line is running, the more likely a large gap is service is to cause overcrowding and denied boardings. When overcrowding starts to occur, PWT begins to increase more rapidly. Such conditions will enhance the opportunity for short-turning to have a beneficial outcome. By reducing or avoiding overcrowding, even more PWT can be saved. Reducing overcrowding also improves passenger comfort.

Provided that the physical characteristics of the line and the demand profile in the time period are favorable, headway sequences may then be screened for short-turning. Clearly, there must be an excessive headway to be "filled" by short-turning a vehicle. Excessive headways cause long wait times and are likely to lead to overcrowding and denied boardings. The denied boarders, moreover, must wait for the following vehicle. In addition, overcrowded vehicles will experience excess dwell times which will aggravate the excess headway by further delaying the vehicle. The results from the Blue Line simulation indicates that the longer this headway is, the more likely short-turning is to be a helpful strategy.

Also important is that either the following headway, the preceding headway, or both, of the short-turning vehicle should be as short as possible. A short preceding headway will reduce the number of negatively impacted passengers. A short following headway will hold down the additional waiting time for these negatively impacted passengers. Again, the Blue Line simulation results indicate that the longer either of these headways are, the less likely a short-turn is to be 'beneficial' (given that all other necessary conditions are met). Fortunately, on a high-frequency transit line a vehicle with a long headway should have at least one, if not several, short following headways. Thus, the optimal headway sequence conditions are the most likely pattern.

Chapter 6

Proposed Applications

This chapter will describe the existing operations control system of the Massachusetts Bay Transportation Authority (MBTA) as well as the new system being implemented. The discussion will focus on how to incorporate the results of this research project in the form of a decision support system to assist with real-time control

6.1 The Operations Control System

The MBTA's rail transit system currently has a highly decentralized supervision structure. This is largely due to the dated technology on which the supervision system is based. However, a new Operations Control System (OCS) is under development which could allow greater centralization of most supervisory functions for the three heavy rail transit (HRT) lines. Centralization could potentially greatly increase the effectiveness of supervision and control of these lines, which in turn could improve the reliability and efficiency of service. A decision support system could be developed as part of the OCS to facilitate effective supervision and real-time control.

6.1.1 The Existing MBTA Operations Control Center

The MBTA Operations Control Center (OCC) supervises the operations of the system's three HRT and one light rail transit (LRT) lines. However, supervision and control of these lines is divided between the OCC and field supervisors, with the scope of the OCC's control varying across lines.

The OCC plays a very active role in the in the supervision of the Red Line, controlling train routing and monitoring on-time performance. In this capacity, the OCC can also perform real-time control interventions such as expressing and short-turning. During peak periods, it also dispatches run-as-directed (RAD) trains to alleviate disruptions in service. A model board provides track circuit occupancy information. The Red Line dispatcher is assisted by master control operators (MCO's), three during peak periods and two at other times. The MCO's perform routine functions such as routing and keeping train sheets, which are used to monitor on-time performance and also to track train identities, since these are not indicated by the model board. Field supervisors (inspectors) are stationed at a number of key points along this line to provide passenger information, to assist train operators with equipment problems, to relay information about platform and train loading conditions to the dispatcher, and to implement real-time control actions. While there are also two train starters stationed on this line, they are not normally involved with train operations.

The OCC does not play as extensive a role in the operation of the Orange Line, with just a single dispatcher able to oversee the route. There are several reasons for this. Most significantly, the line does not branch and control of the crossovers at the terminals is normally automated. Therefore, routing intervention is normally limited to trains entering or leaving service at Wellington Yard. Wellington is also the only location where short-turns are occasionally implemented. These operations are carried out by towerperson stationed at Wellington Tower. The OCC dispatcher's primary function is therefore to coordinate responses to incidents such as equipment failures and medical emergencies, and to monitor service reliability. This involves relaying information to and from inspectors, the towerperson and the train starter.

The dispatcher who monitors the Orange Line is also responsible for the Blue Line, although no train location information for the Blue Line is currently available at the OCC. Therefore, the role of the OCC is limited to recording events and relaying information to field supervisors. Routing at (but not dispatching from) the Wonderland terminal is automated. All other routing functions, which are normally limited to pull-ins, pull-outs, and the occasional short-turn, are controlled by the Orient Heights towerperson.

Monitoring of on-time performance and the decision to short-turn or make any other real-time intervention are the responsibility of the train starter stationed at Orient Heights.

In the case of the Green Line, service is monitored and regulated primarily by inspectors stationed at a number of locations. These field supervisors have full responsibility for real-time intervention such as expressing, deadheading, and short-turning. Routing is controlled by an automatic vehicle identification (AVI) system or by train operators themselves using wayside controls. Although the Green Line OCC dispatcher does play a fairly active role in coordinating actions between the field supervisors, the principal OCC responsibility is again to record incidents and coordinate the response to emergencies.

6.1.2 Problems of the Existing OCC

Highly centralized supervision should be the most effective and efficient arrangement. Because an OCC can have a view of the entire system and can utilize a broad range of information, it can potentially result in much better control decisions. Unfortunately, for several reasons, the current MBTA OCC is not equipped to play a more active role. With the exception of the Red and possibly the Orange Lines, the OCC supervisors do not have sufficient information on train locations and headways. The Blue Line dispatchers in particular are effectively "blind". Even for the Red Line, the OCC relies on field supervisors to relay information on train and platform loads, and to disseminate information to passengers.

There are a number of serious weaknesses in the current supervisory system. First of all, it is difficult for field supervisors to deal effectively with service disruptions, particularly on the Green Line, because they have only a limited view of operations. For example, field supervisors generally do not know the locations, headways, or loads of trains approaching them. The fast pace of transit operations allows only limited coordination between field supervisors. Train starters and towerpersons may have access to more information, but have only limited spheres of responsibility. Moreover, inspectors will often be called away from their posts to assist with equipment problems, etc. Train starters are accountable for on-time departures, but are not necessarily responsible for the performance of the entire line. Towerpersons are only responsible for routing trains as prescribed by the schedule or directed by dispatchers or train starters. An additional problem is that field supervisors record on-time performance and headway information manually, but have a disincentive to do this accurately when this data may reflect badly on their work.

6.1.3 The New MBTA Operations Control System

The MBTA is currently nearing completion of a new OCS as well as of a number of significant enhancements to field equipment. This new system, combined with other improvements, could potentially allow greater centralization of control. The decision to develop the new OCS was motivated by a number of issues. First of all, it was felt that a more efficient control system would improve safety and security by reducing response times to incidents. Dispatchers would have more information available for planning responses and coordinating with police and rescue agencies. There was also a desire to reduce labor requirements be automating routine functions such as keeping train sheets. Finally, it was felt that service reliability could be improved by more effective supervision.

The basis of the new OCC will be a microcomputer assisted dispatching system. Microcomputers with multiple CRT monitors will replace the model boards and electromechanical routing controls. The dispatching software will automate the collection of train sheet data. Full Automatic Vehicle Identification (AVI) will be provided (since the three HRT lines have continuous track circuits, this can be done with little or no additional field-side hardware - once the software has the train identity information, it can track the trains along the line using track-circuit and switch-point indication data). Installation of this equipment will not require significant changes to signaling equipment in the field. The dispatching software should be able to provide additional information to the dispatchers. This would include train schedules including pull-in and pull-out times, and a facility to alert dispatchers to late departures or excess headways.

Another set of improvements under way is the provision of closed-circuit television (CCTV) monitoring of many station platforms. While this is primarily to improve security, it will also allow OCC dispatchers to estimate manually platform loads and possibly even train loads. This will be faster and easier than relying on information relayed by field supervisors. Improvements are also being made to the automated routing and dispatching equipment at terminals. These systems sound a buzzer and display a visual signal at the departure time of each train. The new equipment is microcomputer-driven and can either be controlled manually or work from a schedule downloaded to it. The previous generation of terminal equipment was controlled by a simple timer. Dispatchers will be able to adjust this equipment manually to deal with disruptions. For example, if a scheduled trip has been dropped, the disruption can be minimized by lengthening the departure headways of several preceding and following trains by a small amount.

The new OCS, when fully implemented, should be able to assume most routing functions, except for yard movements, on the Blue and Orange Lines. While the OCS's role in Red Line operations will remain roughly the same, two dispatchers will operate the line instead of 2 or 3 MCO's and a dispatcher,. It is not yet clear whether the Orange and Blue Lines will each be allocated a separate dispatcher, or if one will still be expected to oversee both lines. This will undoubtedly be determined by how much routing control is transferred from the towers.

Unfortunately, the new facility will not assume additional control of the Green Line, largely because train location information for the Green Line is not collected at the track-circuit level of detail. In addition, there are only a few interlockings on the Green Line and these are controlled automatically by the AVI system. Thus, there is little signal system indication data being sent back to the OCS. While the AVI data is relayed back to the OCC, it does not indicate train locations to a high level of detail. In addition, it is not now presented in a manner that is helpful for real-time control. Therefore, there will be no significant changes in this line's supervision arrangements as a results of the current initiative.

6.1.4 Opportunities Presented by the New OCC

While the new OCS represents a significant advance over the current system, the amount of additional control it will be able to assume is still limited. There will still be a need for a large number of field supervisors to assist train operators with equipment problems, to help implement real-time control actions, and to monitor stations. There is some risk that continued reliance on a large number of field supervisors will discourage greater centralization. Nevertheless, improvements in service reliability and safety alone should justify moving responsibly for control to the OCC.

One potential barrier to increased centralization is the large workload the dispatchers will face. There will still be a substantial amount of routine work to perform, even though some routine functions will be automated. For example, for the foreseeable future there will continue to be a considerable number of scheduled and non-scheduled routing tasks. Scheduled routing includes pull-outs and pull-backs and ensuring Ashmont and Braintree Red Line trains alternate with one another. Non-scheduled routing would cover short-turns and shop-orders (disabled trains returning to yards for repair). Most of these routing functions are presently handled by towerpersons and MCO's. Another routine function is relaying train information to Field Supervisors, particularly on the Red Line. This information includes train numbers, destinations, lengths, headways, and estimated arrival times. This function apparently takes up a considerable portion of the dispatcher's time.

In the current OCS, most of these routine functions are handled by MCO's and towerpersons. One potential problem with the new OCS is that these routine functions may tend to conflict with the dispatcher's traditional "management by exception" role in operations. This seems particularly likely since a serious service disruption at one point on a line will tend to lead to other disruptions elsewhere later on. These routine functions must not suffer when dispatchers are fully occupied by incident management. Therefore, as many as possible of these routine functions should be automated or shifted to field supervisors. For example, field supervisors' information needs could be completely filled by providing them with terminals similar to those used by the dispatchers, perhaps with display capability only.

A related problem will be processing the large volumes of information that will be coming into the OCC. It is likely that dispatchers will quickly learn to filter information themselves. However, automated equipment could be provided to make better use of large amounts of data that will be available. This relates to another potential problem, which is that there will still be some important pieces of information which will not be easily accessible to the dispatchers. For one thing, little passenger demand information will be available. While it should often be possible to estimate platform loadings visually using the CCTV system, there will not be any direct way to monitor train loads. It is therefore likely that dispatchers will still be reliant on field supervisors to monitor train loadings at key stations.

While the OCC specifications include a facility for projecting train trajectories, the proposed model for this uses average train dwell times. This is unlikely to be sufficiently accurate, especially since such a system would potentially be most useful during disruptions. Trains with excess headways will likely be overcrowded and will tend to experience long dwell times. Dwell time would probably account for most of the variation in running time under such circumstances. Therefore, as proposed this system is unlikely to be of any practical use as an aid to dispatchers.

The automatic "ring-off" or dispatching system should be extended to all terminals as well as to short-turn points such as Orient Heights. Headways departing terminals could even be automatically re-calculated *in advance* of a delayed train (subject to the dispatchers approval). Thus, long gaps could be closed from both ends. This would also be helpful when trips must be dropped.

Dispatchers will also need ready access to general information for incident management, including information for troubleshooting equipment, on who to contact for assistance with particular types of problems, and procedures for dealing with different types of emergencies. Several other types of data would also be very useful as well, including availability of spare trains and crews, which would save time in recovering from in-service equipment failures. Data on swing-off times for train crews would be helpful in making real-time interventions; this is an important consideration in selecting trains for short-turning. While it would be simple to provide OCC dispatchers with scheduled crew assignments, actual assignments vary from day to day due to absences. However, train starters could be provided with workstations to update operator assignments in real time. An automated system could also simplify work for the train starters.

If the OCC is to take a more active role, it is also essential that staffing levels be sufficient. The desire to reduce labor costs at the facility are understandable. However, if the OCC can take on a greater role in supervision, the potential savings from reduced field staffing levels could be greater. While there will still be a need for inspectors to deal with incidents, it seems unlikely that the current level of field supervision maintained by the MBTA Subway Operations would still be required. Some field supervisors could be re-deployed to provide passenger assistance and monitor stations. This would be particularly valuable if the number of collectors are reduced with the modernization of the fare collection system.

6.1.5 Proposed Decision Support System

There will still be a number of significant limitations in the capabilities of the new OCC. Dispatchers will still have a heavy workload and it will be very challenging to process the large amounts of information that will be available to make optimal control decisions. Moreover, some valuable items of information will not be directly available to the dispatchers and will be too difficult to calculate manually. However, many of these problems could be eased by developing a decision support system. Dispatchers will be too busy to monitor every train, but an automated system could alert dispatchers to trains with headways longer than some threshold, or that depart timepoints more than a specified amount past their scheduled departure time. Moreover, by employing a simulation such as the one developed for this project, a number of additional facilities could be developed. For one thing, a simulation could forecast train trajectories and predict overcrowding conditions before they arise. A simulation could also provide the basis for a system that could evaluate control actions in real time. The new OCS as currently specified will flag trains with excess headways or late departures. This section will therefore examine possible enhancements to this system.

The most basic utility would be continuous estimation of platform and train loads. Approximate headways of each train departing from each platform should be available from the track circuit and AVI data. If a reasonably accurate database of passenger demand data were available, approximate platform and train loads could be calculated. Historical records might be supplemented in real-time by estimates made by Dispatchers using the CCTV observations. This would help accommodate exceptional events such as July 4th celebrations.

The next level of sophistication would use the simulation to forecast events. Given the actual locations of each train on a transit line at a particular instant, the future time-distance trajectories of these trains on the line could be predicted. Other inputs would include the schedule and passenger demand data. This facility could have several related uses. First of all, trains that are likely to fall so far behind schedule that they will fail to make their next scheduled departure could be flagged. By the same token, trains whose headways will become longer than some threshold, or which will become overcrowded at some point, could be brought to the dispatcher's attention. These features should operate automatically. This will relieve the dispatcher from having to monitor system performance and alert him or her to impending or potential trouble.

A fully developed support system would have the capability to evaluate or recommend (or both) real-time control actions such as short-turning, deadheading, or expressing. The evaluation facility would require models similar to the one used for this research - simulations incorporating passenger waiting time models. Such a system could be implemented in several ways: with a forecasting utility in place, dispatchers would be alerted to conditions that might require intervention. They could then use the software to test whether a particular action would be beneficial. For example, if the equipment indicated an excessive headway on the eastbound Blue Line, the dispatcher might select a particular train for possible short-turning. The dispatcher would then ask the system to evaluate the outcome of short-turning that train. An alternative arrangement would be to have the system test the short-turning of *every* eastbound train approaching Orient Heights that met certain initial screening conditions and recommend the most beneficial of these to the dispatcher. However, the feasibility of this would be limited by computing power or time. Indeed, the biggest problem with simulation is that when there is wide variability of outcomes a large number of trials must be run to assure sufficient confidence in the average outcome. With short-turning, this is further exacerbated when a number of different trains can be short-turned to fill a particular gap.

If the simulation model can not be made fast enough to be useful in real time, there are several alternatives. One would be to use simplified simulation models. Simplification would reduce computation time but would reduce the accuracy of the model. Thus, a simplified model might require more conservative threshold values. By the same token, if more conservative thresholds were accepted, fewer trials of the simulation might be sufficient.

An alternative approach might be a system based on guidelines derived off-line. A computer could work with very complex sets of decision rules with inputs such as demand conditions for different times of day, differing initial train loads and lengths, and multiple preceding and following headways. A slower, but much more realistic model would then be used during the design of the system to generate an extensive set of decision rules.

(This is somewhat different from an "expert system", which would attempt to replicate the manual decision making process.) The dispatching system would still be provided with the simulation for real-time trajectory and loading projections. However speed should be less critical here, since a single prediction based on "most likely" conditions would be sufficient.

All of the above functions would require one or more of the following improvements to the simulation model developed thus far:

1) Accurate and up-to-date passenger demand data, with reference to variations for different days of the week, different seasons, and weather. The passenger demand data would either need to be maintained by regular traffic surveys, or provided by more advanced fare collection equipment (possibly in real-time).

2) A more accurate dwell time model.

3) Incorporation of variations in train travel times. This would be particularly useful if historical records of train operator performance could be maintained automatically. In this way, a data base of relative average running times for each train operator would be available.

4) Accurate models of turnaround behavior at terminals with reference to the schedule and preceding headways.

For practical purposes, it seems unlikely that a decision support system should accommodate more than a limited repertoire of real-time interventions for each line. There are a number of reasons for this. If a guideline-based system is employed, there will be a practical limit to the number of different sets of guidelines that could be generated. The most important reason, however, is simply to avoid confusion. Since train operators and supervisors are likely to be under stress during service disruptions, and real-time interventions should hopefully be exceptional events, every effort should be made to make their treatment routine. In any case, it seems likely that a fairly small set of strategies would be sufficient for any given line. Passenger demand patterns and track layouts will generally dictate what strategies are likely to be effective. For example, it is unlikely that any given transit line would have more than two potential short-turn points.

Chapter 7

Conclusions and Future Research Directions

This chapter will summarize the principal findings of this research. In addition, some directions for additional research will be recommended.

7.1 Conclusions

7.1.1 Simulating High-Frequency Transit Systems

Modeling terminals, including terminals of rail lines, is difficult. Headways departing terminals exhibit considerable random variation, but are nevertheless highly dependent on scheduled departure times, preceding headways, and the availability of recovery time. Thus, in order to model terminals realistically, reference to each vehicle's headway and scheduled departure time (including any real-time revisions to the schedule) is needed.

Passenger waiting time calculations are very sensitive to changes in the headway sequences, particularly changes in the long 'gap' headway being corrected by the real-time intervention. This is because passenger waiting time increases as the square of the headway. Modeling terminals was particularly problematic for this reason. The longer headways underwent the largest change at the skipped terminal and hence any error in how the terminal was modeled has a significant influence on the overall accuracy of the simulation.

Interstation running times are clearly subject to random variation. It also seems likely that some of this variation is systematic to individual operators or vehicles. Such systematic variation has significant implications for real-time control actions, since it influences the amount of time that will be saved by station skipping strategies. Short-turning skips interstation segments, so more total running time will be saved by short-turning a 'slow' train. In addition, the headway of a 'slow' train with an excess headway will become longer more rapidly than it would by dwell time effects alone. This further enhances the benefit from short-turning. Indeed, the model was quite sensitive to 'slow' trains being short turned, even though the 'slow' trains' interstation times were less than 10% longer than those of the other trains in the sequence.

A realistic dwell time model is an important element of any simulation of a high-frequency transit line. A general dwell time model should ideally be a function of boardings and alightings by the vehicle or by the door. This is because boarding passengers will generally not distribute themselves uniformly along platforms. In addition, the distribution of passengers on board trains will also vary.

7.1.2 Short-Turning Practice

7.1.2.1 Conditions for Beneficial Short-turns

The running time saved by short-turning must be sufficient to allow a significant improvement in the uniformity of headways. This is particularly important for short-turns involving overtaking, since the short-turning vehicle must advance in the sequence by its own headway, plus the headways of any intervening train, plus a significant portion of the 'gap'. On the other hand, the longer the skipped segment, the more skipped segment boarders and alighters there will be, detracting from the net benefit of the short-turn. When no recovery time is available at the short-turn point or the skipped terminal, the short-turning vehicle will advance in the sequence by an amount equal to the short-turn time savings. Under these circumstances, the optimal time savings may be roughly equivalent to the scheduled headway.

The more recovery time is available at the skipped terminal, the easier it will be for excess headways to correct themselves without skipping stations and inconveniencing passengers. Thus, the larger the 'gap' headway must be before short-turning will be an effective strategy. However, in cases in which the 'gap' is not exceedingly large, and one of the following headways is somewhat excessive, there may be sufficient recovery time available to close up the gap left by the vehicle being short-turned, thus enhancing the PWT savings from short-turning.

The passenger demand from the segment downstream from the short-turn must at least be similar to the demand to and from the skipped segment. Since most of the positively impacted passengers will be in the downstream segment, there must be enough benefited passengers to outweigh the net dis-benefit to the negatively impacted passengers.

When passenger volume over a transit line is close to the scheduled capacity, excess headways will lead to overcrowding and passengers left behind. Under these conditions, real-time interventions that restore uniform headways are especially helpful. 'Spillover' boarders must wait the entire headway for the following train and so effectively accumulate twice as much PWT as newly arriving passengers. Moreover, overcrowding exacerbates dwell time effects. Finally, overcrowding and denied boardings inconvenience passengers above and beyond the additional waiting time and harms the image of the transit system.

Not surprisingly, the longer the 'gap' headway to be filled by the short-turn, the more beneficial the short-turn is likely to be. The headway preceding the 'gap' may also be significant if it is excessive. First of all, if the preceding vehicle has a long headway, it will likely use up much of the recovery time available by leaving the skipped terminal as quickly as possible. This will reduce the amount of recovery possible for the vehicle with the gap headway, potentially making short-turning a more attractive option. If the preceding vehicle's headway is very long, that vehicle may become overcrowded and leave passengers behind. If these passengers are downstream from the short-turn, they would be additional beneficiaries of a short-turn.

Short following headways will enhance the outcome of a short-turn by reducing the additional waiting time for skipped segment boarders and alighters, and downstream passengers who would have boarded the train that was short-turned had it not been. However, a train with an excessive headway will in all likelihood be followed by trains with short headways.

7.1.2.2 Current Short-turning Practice on the MBTA Blue Line

Short-turning is a relatively rare procedure on the Blue Line. Even so, it appears that when it is used, it is not necessarily beneficial to passenger waiting time. Some trains are apparently short-turned because the train starter assumes that they will either fail to recover time if they are running behind schedule, or will fall behind schedule later in the a.m. peak period because the motorperson tends to run slowly. Part of the problem may be that the Blue Line train starter has conflicting priorities. While the starter is responsible for regulating headways, he or she is also expected to ensure that train crews complete their runs on time so as to avoid excessive overtime costs. The starter may also be under pressure from train crews who want to start their breaks on time. The train starter supervises motorpersons and guards and calls them for overtime work to fill absences. Thus, the starter must maintain a good rapport with these employees. Unfortunately, passenger service quality probably suffers from some of these short-turns.

It is evident both from the data collected and from discussions with Blue Line personnel that the current Blue Line schedules do not provide enough recovery time. Even a modest increase in the scheduled round trip running time might be very helpful, especially for train operators who may fall behind schedule over several successive trips.

In any case, the conditions under which short-turning is a beneficial strategy on the Blue Line are considerably more restrictive than those on the Green Line at Park St. The initial 'gap' headway must be larger and the strategy is only likely to be useful at all in the a.m. peak period. As a result, short-turning is really only useful for relatively serious delay incidents. There are probably instances, even in the a.m. peak, in which trains can not recover the scheduled headway at the terminals *and* where short-turning would increase total passenger waiting time.

7.1.3 Real-time Control

The simulation model used in this research is probably much too slow to be useful in real time, particularly if several alternative short-turns or other interventions are to be evaluated. A support system based on detailed guidelines and using automatically collected input data might be much more feasible.

7.2 Future Simulation Research

There were two areas in this thesis in which additional research would have been very helpful had sufficient time been available. The first of these is the behavior of headways for trains departing Wonderland in the westbound direction. The manner in which these headways were generated detracted from the realism of the simulation used in this research. The second weakness stemmed from the model's assumption that all trains would take the same time to travel between stations except when the signal system effect comes into play (by way of the minimum headway constraint). In reality, there is probably considerable variation in train running times or average speeds.

7.2.1 Terminal Departure and Schedules

The behavior of trains at terminals appears to be surprisingly complex. The primary determinants of when a train will depart a terminal include when the train arrived at that terminal, how many trains are queued ahead of it, when the train is scheduled to depart, and whether any effort is being made to regulate headways by dispatching the trains. In the Blue Line simulation, this process was not modeled in detail because insufficient data was available. The biggest omission, however, was probably correlation with the schedule. In general, Blue Line train operators will try to keep to their schedules as much as possible. It seems likely, however, that this may tend to work against regulation of headways. It was observed that some trains that arrived at Wonderland eastbound with very short preceding headways also departed on their next westbound trip with very short headways. These trains were generally closely following trains with headways that were considerably longer than the scheduled headway. Thus, it seems likely that these trains were trying to keep as close as possible to their scheduled departure times. Unfortunately, these observations were not correlated with the schedule when they were made, so it is difficult to be certain about these observations.

The behavior of train departures with respect to their scheduled departure times must be studied. The actual departures will lie in some distribution about the scheduled departure time, most likely with the mean somewhere to the right of the scheduled time and the right tail much longer than the left tail. This shape would reflect the fact that early departures can be controlled while late departures often can not. However, if the data were segmented by how long prior to the departure time the vehicle arrived at that terminal, a range of shapes could be obtained. For arrivals up to some threshold, the departure time distribution would probably be much more symmetrical and have a mean much closer to the schedule. There would probably still be some bias toward the right due to delays occurring at the terminal. Once the arrival time passes some threshold, it starts to become difficult for vehicles to begin their next trip on time and the distribution should quickly spread to the right. At some point, it will become impossible to start the next trip on time.

In this region, the departure time will be correlated only with the arrival time. All of this is ignoring any intervention to regulate departure headways. Dispatching introduces a further layer of complexity. Vehicle operators are expected to give instructions from supervisors absolute precedence over the schedule. However, supervisors may also be working within the constraints of the schedule. They may not wish to hold a departure to the point that the vehicle can not start its following trip on time.

If a model has vehicle identification data available to it, then vehicles could be matched to their scheduled departure times. In the case of short-turning with overtaking, a model used in a decision support system must also know when a vehicle is going to "drop-back" into a following train's run. This could be a function of updating the AVI system as part of the short-turning procedure. What is needed here is a larger data collection effort that takes scheduled departure times into account. The entire turnaround process at terminals must also be analyzed in greater detail.

7.2.2 Variation in Interstation Times

Systematic variation in interstation times also needs additional research. There is at least anecdotal evidence that some train operators tend to have longer average running times than others. In fact, this may be a significant cause of excessive headways. It also seems likely that train operators will tend to operate more slowly if they think they either are ahead of schedule or have a short preceding headway, and attempt to run faster if they are late or have a long headway. An additional possibility is that more skilled or experienced operators are able to recover time by running faster while less experienced ones fail to do so. On rail lines with automatic train operation (ATO) that automatically controls train speeds, any such variation may be negligible. On lines with manual control, however, there is considerable scope for variation. Systematic variation may be concentrated on certain segments of a line. For example, on the Blue Line it was observed that some train operators were more nervous about making the changeover from third-rail to overhead current collection at Maverick (later Airport) Station. There is also the theory that the speed signals on this line slow some operators down more than others.

It will probably be very difficult to collect data on this until an AVI system is in place. One reason is that train operators will probably behave differently when they know they are being timed. AVI data could be used to time trains over groups of track circuits between stations. Observations of trains that are closely following preceding trains would be deleted to filter out the effects of signal checks. The study could be done in several ways. One would be to analyze average trip times as a function of each operator. Another would be to try to account for the variability of running times over several interstation segments. It may be that the faster operators are simply those who are able to recover time by running faster as needed.

A working support system provided with both AVI and real-time operator data could potentially keep records of the average running time behavior of each operator. It might then be possible to maintain a separate vector of average interstation times for each train operator on each line. A variation on this idea would be to rate each operator on their ability to recover time and provide a separate set of 'fast' times for them. In either case, this data would be used by the simulation model.

7.3 Deadheading on the Blue Line

While there are a number of improvements that could be made to the simulation model, review of the conclusions of Chapter 5 indicates that expressing or deadheading trains eastbound on the Blue Line may be more beneficial than short-turning in some cases.

On the Blue Line in the a.m. peak, most of the negatively impacted passengers are in the westbound leg of the skipped segment, between Wonderland and Suffolk Downs inclusive. Ridership in the eastbound direction is relatively light in this period, although there is significant traffic within the downtown area (between Government Center and

State) and between downtown and Airport. Expressing or deadheading eastbound trains would have the distinct advantage of not skipping any westbound stations.

One possibility would be to express trains from Maverick, Airport, or Orient Heights to Wonderland. Supervisors are stationed at Maverick and Orient Hts. and would be available to provide assistance. Their main task would be telling passengers bound for skipped stations to alight and board the next train. The advantage of expressing from Airport or Orient Heights is that line volume falls off sharply beyond Airport and so the number of skipped segment alighters would be minimized. An additional issue here is that many riders to Airport are air travelers who may have luggage and are under extra time pressure. Thus, the perceived cost to them of being 'dumped' would be very high. The drawback of expressing is that time savings would be minimal. First of all, the train would have an extra-long dwell at the beginning of the express segment. Expressing seems to be confusing to many passengers who may not know if their station will be skipped. In addition, most of the time savings will be from dwell time; trains would still have to slow to about 10 MPH while passing the skipped platforms. However, because demand on the outer end of the Blue Line is very light anyway, dwell times at each of the skipped platforms would have been only about 20 seconds. Thus, even if the express were implemented from Maverick, the time savings from avoided dwell time would only be on the order of 2 minutes. Tests runs would be necessary to determine the time savings more exactly.

It would probably be much more beneficial to simply deadhead trains with long headways all the way from Bowdoin to Wonderland (although this would be feasible only for trains delayed prior to their eastbound trip). After discharging passengers at Bowdoin westbound, trains would proceed non-stop all the way to the tail tracks at Wonderland. By skipping all 12 stations, including the busy ones, time savings would probably be more on the order of 5 minutes. Again, however, tests would need to be run so that the average 'deadhead' running time could be estimated. Since the deadheaded train had a long headway, the following train should be close behind, so additional waiting time for westbound passengers should be minimal. Because no passengers would board the deadheaded train, none would experience the added inconvenience of being dumped. Moreover, the delay to the expressed train at the beginning of the express segment is avoided with deadheading, further enhancing the time savings.

Assuming the time savings from deadheading were about 5 minutes, it would probably be most useful for trains with headways of between 8 and 12 minutes. In this range, a 5 minute time savings would just about restore the scheduled headway sequence. With a headway of more than 12 minutes or so, the time savings plus recovery time at Wonderland would still leave a westbound headway of more than 6 minutes, which would lead to overcrowding. This is the point at which short-turning starts to become effective, however. Deadheading would also be particularly useful where overtaking would be complicated be scheduling issues, and might even be more beneficial than short-turning with no overtaking in many instances.

As already indicated, since deadheading is not a normal practice on the Blue Line, determining the time savings would require a special effort. Since a deadheading train that did not have a long headway would probably catch up with regular service trains, special test runs would need to be made after the end of regular service hours. Ideally, several round trips should be timed in each direction without stopping. The times for the first trip might need to be discarded, since train operators may not have experience running non-stop past some stations and many platforms lie along track circuits governed by speed signals. Since trains normally have dwell time in these sections, the average speeds of trains that do stop, not counting the dwell time, can be considerably higher than the overall average speed enforced by the signals. Train operators thus might need to get used to regulating their speed in these sections to avoid being forced to stop.

Currently, deadheading is used on the Blue Line eastbound only at the height of the *p.m.* peak, on the downtown section. If a westbound train arrives at Government Center with a long headway, the Inspector stationed there will instruct its crew to deadhead from

Bowdoin to State. In some cases, the first train may even be deadheaded to Aquarium and the following train deadheaded to State. This deadheading is done primarily to avoid overcrowding that would further exacerbate delays, since demand from all of the downtown stations is extremely heavy in the p.m. peak. The waiting time for the skipped passengers is only slightly longer than it would have been otherwise, and crowding and excess dwell time are reduced. It is unlikely that more than 1 or 2 minutes of running time are saved. It is not clear why deadheading is not currently used in the a.m. peak. The most likely reason is that real-time control is primarily the train starter's responsibility and it is easier to implement real-time control actions from Orient Heights. However, the train starter can see the locations of all trains on the model board and should be able to observe excess headways as they develop. Indeed, the train starter should be in a position to make even better deadheading decisions than the inspector at Government Center because he or she will also be able to verify that the following trains are close behind. Perhaps deadheading needs to be established as a regular procedure for recovering from long headways.

Bibliography

Abkowitz, Mark and Engelstein, Israel, "Methods for Maintaining Transit Service Regularity," *Transportation Research Record 961,* (1984): 1-8.

Barnet, A., "On Controlling Randomness in Transit Operations," *Transportation Science,* Vol. 8, No. 2, (1974): 102-106.

Barnet, A., "Control Strategies for Transport Systems with Nonlinear Waiting Costs," *Transportation Science,* Vol. 12, No. 2, (1978): 102-116.

Boston Street Railway Association, Inc., *Boston Track Map,* Cambridge, MA, July 1986.

Chapman, R. A. and Michel, J. F., "Modeling the Tendency of Busses to Form Pairs," *Transportation Science,* Vol. 12, No. 2, (1978): 165-167.

Deckoff, Anthony A., "The Short Turn as a Real-time Transit Operating Strategy", M.S. thesis, Department of Civil and Environmental Engineering, MIT, 1990.

Duerr, Peter A. and Wilson, Nigel H.M., "Supervision in Transit Operations", MIT, research paper, 1990.

Eberlein, Xu Jun, "Real-Time Control Strategies in Transit Operations: Models and Analysis," Ph.D dissertation, Department of Civil and Environmental Engineering, MIT, 1995.

Fellows, Robert E., "Using and Enhancing Automatic Vehicle Identification to Improve Service Control on the MBTA Green Line" M.S. (Transportation) thesis, Department of Civil and Environmental Engineering, MIT, 1990.

Humphrey, Thomas J., "1989 Passenger Counts: MBTA Rapid Transit and Commuter Rail", Central Transportation Planning Staff, August, 1991.

Joliffe, J. K. and Huchinson, T. D., "A Behavioral Explanation of the Associations Between Bus and Passenger Arrivals at a Bus Stop", *Transportation Science,* Vol. 9, No. 3, (1975): 248-281.

Koffman, D., "A Simulation Study of Alternative Real-Time Bus Headway Control Strategies," *Transportation Research Record 663,* (1978): 41-46.

Lam, Chi Fun Jimmy, "The Application of Information Technologies to Public Transportation", M.S. (Transportation) thesis, Department of Civil and Environmental Engineering, MIT, 1994.

Levinson, Herbert S., "Supervision Strategies for Improved Reliability of Bus Routes" *Synthesis of Transit Practice 15,* Transportation Research Board, Washington, D.C., 1990.

Li, Yihua, "Real-Time Scheduling on a Transit Bus Route," Ph. D. dissertation draft, Ecole des Hautes Etudes Commerciales, Affiliee a l'Universite de Montreal, Canada, 1994.

Lin, Tyh-Ming, "Dwell Time Relationships for Urban Rail Transit Systems", M.S. (Transportation) thesis, Department of Civil and Environmental Engineering, MIT, June, 1990.

Macchi, Richard, "Expressing Vehicles on the MBTA Green Line", M.S. thesis, Department of Civil and Environmental Engineering, MIT, 1989.

Mayworm, P., Lago, A. M., McEnroe, J. M., *Passenger Impacts of Changes in Transit Fares and Services,* Executive Summary, U.S. DOT, UMTA, RR 135-1, September 1980, 7-18.

Newell, G. F. and Potts, R. B., "Maintaining a Bus Schedule," *Proc. Austrailian Road Research Board Conf.* 2 (1) (1964): 388-393.

Potts, R.B. and Tamlin, E. A. "Pairing of Busses," *Australian Road Research* 2 (1) (1964): 3-9.

Soeldner, David W., "A Comparison of Control Options on the MBTA Green Line", M.S. thesis, Department of Civil and Environmental Engineering, MIT, 1993.

Turnquist, Mark A., and Blume, Steven W., "Evaluating Potential Effectiveness of Headway Control Strategies for Transit Systems," *Transportation Research Record 746,* (1980): 25-29.

Vuchic, Vukan R., Eisele, Donald O., et. al. "NYCTA Control Center Modernization: Phase I" Report for the New York City Transit Authority, University of Pennsylvania and Parsons, Brinkerhoff, Quade and Douglas, Inc., Philadelphia, PA, 1990.

Vuchic, Vukan R., "Propagation of Schedule Disturbances in Line-Haul Passenger Transportation," *UITP Revue* 18, (1969): 281-284.

Wilson, Nigel H.M. et al., "Improving Service on the MBTA Green Line Through Better Operations Control", *Transportation Research Record 1361* (1991).

Wilson, Nigel H.M. et al., "Service Quality Monitoring for High Frequency Transit Lines", *Transportation Research Record 1349,* (1992): 3-11.

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