THE SHORT-TURN AS A REAL TIME TRANSIT OPERATING STRATEGY

by

Anthony Adlai Deckoff

B.A., Physics and Philosophy
Yale University, 1988

Submitted to the Department of Civil Engineering in Partial Fulfillment of the Requirements for the Degree of

Master of Science in Transportation

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Anthony Adlai Deckoff

Submitted to the Department of Civil Engineering on May 18, 1990, in partial fulfillment of the requirements for the degree of Master of Science in Transportation

Abstract

This thesis attempts to measure and predict the impacts on transit passengers of short-turning trains on a real time basis. Such a strategy, consisting of turning a transit vehicle around to run in the opposite direction before it has reached its scheduled terminus, is intended to decrease the average passenger's wait time by improving reliability in the reverse direction. This tactic is frequently used on the light rail Green Line of the Massachusetts Bay Transit Authority (MBTA).

The study presented here models the passenger impacts of short-turning a northbound B or D line train at Park Street, one station before its scheduled terminus. Prediction of the impacts requires knowledge of a large array of inputs related to trains preceding and following the train under consideration. When the MBTA completes installation of an automatic vehicle identification (AVI) system, most of these inputs will then be known, and the system controller will be able to make short-turn decisions based on accurate predictions of their passenger impacts. This study predicts that under these conditions, approximately the same number of short-turns made under current practices can be made, but with a twenty-seven per cent higher success rate, the percentage of short-turns made that yield positive net passenger impacts.

Until then, the thesis demonstrates, the success rate can be improved by a similar margin by making short-turn decisions according to a more restrictive set of manual guidelines than is currently in place. Implementation of such guidelines, derived from careful analysis of the model presented here, would result in a decrease by one quarter of the number of short-turns currently made, accompanied by a thirty-nine per cent increase in the total passenger wait time saved.

Thesis Supervisor: Nigel H. M. Wilson, Ph.D.
Title: Professor of Civil Engineering
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I dedicate this thesis to my grandmother, Sonya Deckoff, whose enthusiasm for things scholastic I have never fully understood. My parents, brother, sister and she always seemed to have more faith in the value of this project than did any of my fellow students here at M.I.T., who actually knew what it was about. While on the subject of family, I cannot fail to thank my cousins Juliet and Stanley Wolf, who have provided me with room and board for more of the spring term than any of us probably care to remember.

The institutions that have provided the funding for this research also deserve thanks for enabling its completion: the MBTA, whose Boylston inspectors also provided much of the data used here, the UPS Foundation, and again, my parents, whose aid remained forthcoming even after they discovered that I was being paid to be a student.

Lastly, I would like to thank my friends and teachers at M.I.T., particularly Nigel Wilson, who fits both of these descriptions, and who told me when I first arrived in Cambridge that he thought there might be a place for me in the Green Line project. On the whole, and in spite of my occasionally greater interest in the schedule at the Brattle Theatre or the cheese steaks at Buzzy's Roast Beef, he was right, and I appreciate the opportunity I have had to write this thesis.
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Chapter 1

Introduction

The research described in this thesis aims at rationalizing the decision process leading to the short-turning of specific trains in an urban rail transit system. I present in particular a detailed treatment of the Green Line light rail division of the Massachusetts Bay Transportation Authority (MBTA), yet my approach, custom tailored though it be, could be applied to any similar system, including heavy rail rapid transit, in which short-turning is an acceptable strategy.

To short-turn a train is to discontinue its run before its arrival at its scheduled terminus and then to turn it around to begin service in the opposite direction. The dispatcher (controller) of a system would ordinarily apply such a strategy in order to allow a train to catch up with its schedule by cutting off the end of its route near one of its termini or in order to fill an unusually long gap in service in the opposite direction. Needless to say, by doing so, one improves service for some passengers, by decreasing their wait time, and worsens it for others, by forcing them to wait for the next train.

1.1 Transit System Performance

Any transit riders' advocacy group will tell you what
the desired characteristics of transit system performance are. The service ought to be inexpensive, fast, frequent, reliable and friendly, and the system should be easily accessible, clean, comprehensive and easily understood. For the most part, transit operating agencies ultimately desire these same characteristics, but are constrained by their budgets in the pursuit of these objectives. This thesis is concerned primarily with the reliability aspects of an ideal transit service since short-turning is largely aimed at the improvement of this facet of service.

Reliability, which we define narrowly in terms of the variation of the headways between trains, clearly has a major impact on the level of service supplied to the system's riders; much work has been done to analyze its effects (Abkowitz et al. 1978; Welding 1957). Specifically, it directly influences the passenger waiting time, which is a function of both reliability and frequency. If one line runs trains at a higher frequency than another line, both with the same level of reliability, then the average passenger on the higher frequency line will have less time to wait for a train than the average passenger on the other line, because the average time between two trains is shorter on his line. Similarly if one line has greater reliability than another, but both run trains at the same frequency, then a passenger on the higher reliability line will, on average, wait less time than a passenger on the other line because the first passenger is less likely to
arrive at the station during a very long headway gap between trains.

This relationship is described by the formula

\[ E(w) = \frac{1}{2}h \left( 1 + \frac{\sigma^2}{h^2} \right), \]  

(Eq. 1.1)

where \( E(w) \) is the average passenger wait time, \( h \) is the average headway, and \( \sigma^2 \) is the variance in headway; for a derivation and discussion of this equation, refer again to Abkowitz et al. (1978, 137) or to Kulash (1971). Thus passenger wait time increases with the variance of the headway as well as with the average headway. So the transit system's operators, after establishing the system's frequency levels, must attempt to maintain a high level of reliability.

Operating agencies can attempt to achieve higher frequencies and reliability either by means of service planning or by means of real time operating strategies. Service planning improvements are built into the long-term, planned routing and scheduling of trains. Within the constraints of the budget, train availability, and system layout, the service planner wants to achieve as frequent a service as can possibly be operated reliably. When, in the course of operation, trains deviate further and further from the official schedule, the line's manager can make real-time adjustments to the operating plan intended to improve the reliability observed by the passenger. These unscheduled adjustments are known as real time operating strategies.
Short-turning is one such strategy, but not the only one. A train can be sent expressed, for example, to allow it to catch up to its schedule; this strategy shares some similarities with short-turning in its impacts on passengers. Expressing has the advantage over short-turning of requiring no special turn-around loop or crossover track and can thus be carried out, at least in theory, at any point on the system. Unless, however, a special express track is available for it, a fair amount of clear track must be available in front of the expressed train before significant time savings can be realized; short-turning allows a train actually to bypass those in front of it. The converse of expressing, "holding" a train may also even out headways under some circumstances. Holding consists simply of keeping a train waiting at a station platform while the preceding train is given some time to put some distance between them. Holding faces the same passing limitations as expressing, but has the advantage of not forcing any passengers to alight from a train; the train still serves all of its scheduled stations. Further discussion of these strategies can be found in Abkowitz et al. (1978).

Sometimes, when the analysis described in this thesis recommends the implementation of a short-turn, expressing or holding may turn out actually to have a greater positive impact on operations. We consider herein only the net value of a given short-turn decision in isolation, not as
compared with other strategies. Nothing, however, would prevent the ultimate comparison of our short-turn results with those from similar analyses of other strategies to arrive at truly optimal operating decision guidelines.

1.2 System Description

Part of the Green Line was the first subway built in the United States. It is built in the form of a downtown trunk line with four branches diverging to the west. A route map is shown in figure 1.1, and more detailed track layout diagrams appear in figures 1.2 and 1.3. Each of the four branches is served by a separate train line, or operating route, the B line serving the Commonwealth Avenue branch originating at Boston College, the C line serving the Beacon Street branch originating at Cleveland Circle, the D line serving the Riverside branch, and the E line serving the Arborway branch, currently originating at Heath Street. The branch lines are almost entirely built at grade, usually running in the medians of urban arterials. All four lines converge in the central subway portion of the system.

At the downtown end of the system, the B and D lines terminate at Government Center, the C line at North Station and the E line out at Lechmere, the last stop on the system. Trains traveling towards Lechmere are referred to as northbound, or sometimes "inbound", while those
figure 1.1: MBTA System Map
Green Line trackage currently in passenger service

figure 1.2: Green Line Layout Map
courtesy of Boston Street R'way Assoc.
figure 1.3: Downtown Subway Layout Map
traveling away from Lechmere are referred to as westbound, or "outbound", though these latter terms are less well defined.

As is to be expected, the heaviest passenger loads occur in the downtown segment of the system, and the greatest passenger turnover occurs at Park Street, where a transfer is provided to the MBTA's rail rapid transit Red Line. Further north along the line transfers also connect with the Blue and Orange lines. It is at Park Street that the short-turns in which we are chiefly interested are carried out.

Because the system includes a loop track at Park Street (see figure 1.3), trains can easily be short-turned there with a minimum of disruption and wasted time. Many people board and alight at Park Street, and it is only one station short of the B and D lines' terminus at Government Center. Thus, short-turning at Park Street can be carried out quickly and efficiently and is strategically situated to make such an action likely to benefit a large number of people and distress a small number of people. Park Street is an ideal station on which to carry out an analysis of the benefits of short-turning because it allows for the possibility of beneficial short-turns, a characteristic not found at all points on the system.
1.3 The Short-Turning Procedure

As practice exists on the Green Line today, a good deal of short-turning is carried out at the Park Street station in the morning and evening rush hours. In one five day period of weekdays in March of 1989, no fewer than two hundred and seventy B and D trains were short-turned. These are among 1656 B and D trains observed at Boylston Street, indicating that about sixteen per cent of the trains on these lines are short-turned at Park Street. Park Street is the busiest station on the line, with from seventy-six to ninety percent of northbound passengers on incoming trains alighting here and with from 1.9 to 2.2 times as many westbound boarders as are to be found at Government Center; these decisions clearly have the most impact on the system's performance of any of the short-turn procedures possible on the system.

Yet the current decision process does not clearly result in consistently beneficial short-turn decisions. The decisions, which are made by the inspector at Boylston Street, one station before Park Street on the northbound side, are based on incomplete information, on necessarily incomplete interpretation of the available information, and on the personal style of the inspector manning the post.

Currently, B and D trains selected for short-turning while traveling northbound to Government Center are directed by the inspector at Boylston Street, one station
before Park Street, to end their run at Park Street. Just beyond the Boylston station the train is diverted onto another track which does not allow for travel past Park Street (see figure 1.3). At Park Street all passengers must alight, and the train goes around a loop to pull up empty at the westbound Park Street platform. From that point on the westbound train run continues as usual.

1.3.1 Current Information Base

The Boylston inspector currently bases his decisions almost exclusively on what he sees at Boylston. He can look at a string of headways and decide that, given those headways before it, the train presently in the station is a likely candidate for short-turning. He also has some information from the telephone; other inspectors at different points along the line may let him know about possible long following headways in the common event of a delay, often due to minor mechanical problems. But for the most part, his record of preceding headways is his best resource. He also has a pretty good idea of how much time the average train has historically saved by being short-turned by looking at the westbound trains across the track; e.g. he can see that the average D train going to its scheduled terminus takes about ten minutes before it comes back through Boylston in the other direction and takes about six minutes if it is short-turned at Park.
Street. These are the limits of the information available to him.

1.3.2 Future Information Base

At some time in the fairly near future the MBTA hopes to have completed installation of an automatic vehicle identification (AVI) system on the Green Line of the "T", as the system is colloquially known. This will consist of detection boxes located along the track at thirty-three points on the system, according to current plans. They will relay route, train number, train length, and time information to a central controller. With this new real time information, controllers will be in a much better position to make sound short-turn decisions. They will know not only the headways preceding the short-turn candidate, but also the following headways, and with great accuracy. They will also know the sequence of westbound trains into which we are inserting the train upon short-turning it, a statistic on which the Boylston inspector currently has no hard information.

Under both operating contexts, with and without AVI, a thorough mathematical analysis of the available information is necessary to make rational short-turn decisions, as will be demonstrated in this thesis. Even with the incomplete set of information presently available to the Boylston inspector, too much relevant data is available to be
properly interpreted by intuition. Thus, I have derived a mathematical model of benefits achieved by short-turning at Park Street and have used it to analyze this difficult problem.

1.4 Modelling Approach

As will become clear from the development of the model that follows, these figures made available by the AVI system are of great use in predicting success of a short-turn. Thus we will use the model in two ways. In the simpler, AVI-based context, most of the inputs required by the model will be known exactly and we will be able to get a fairly straightforward yes (short-turn) or no (do not short-turn) answer. In the current manual scheme, without enough information for a definite calculation, the model will require a probabilistic treatment of many of the inputs, and thus an answer will only be valid at a given level of confidence. Such a result would still be the best one possible under the circumstances.

The model's complexity would require that to use it directly requires automatic computation. This poses no problem when the data is collected by the AVI system and may be analysed immediately. But direct use of the model under the current manual system would require that data collected by the inspector be punched into a hand-held unit for processing by computer. Presently all information is
simply written by hand in a large table. Thus, in order to satisfy current conditions, we must attempt to distil a few simple guidelines from the results of the model, so that they may be applied quickly and easily by the inspector in the field with no time for cumbersome calculations.

The model will be described in detail in chapter two.

1.5 Prior Related Research

Previous research on transit operations control has leaned heavily towards purely mathematical analysis of the problems involved. Most of the papers cited here are attempts to derive closed form solutions to analytical treatments of real time strategies for simplified transit systems. Often, their authors acknowledge that the results are interesting primarily as a means to a deeper academic understanding of the problems at hand rather than as directly applicable answers to those problems. Others suggest that the analytic solutions may indicate whether actual practices on transit systems are at least in the right range of solutions.

This thesis will instead carry out a highly specific analysis of a particular system, keeping under consideration as many of the day to day exigencies of the system's operation as is possible. But the previous research mentioned here has clearly been helpful as a means to understanding the problem better and to pointing out the
primary factors necessary to any treatment of real time decision strategies.

Osuna and Newell (1972) presented an early analytical treatment of holding strategies on a simple bus service. Barnett (1974), Turnquist and Blume (1980), and Abkowitz, Eiger and Engelstein (1986) all presented further analytical formulations for optimal holding strategies on idealized transit lines. All of these studies use minimization of the average or, equivalently, total passenger wait time as the objective for an optimal decision rule.

The more empirical treatment of holding rules carried out by Abkowitz and Engelstein (1984) more closely resembles the approach taken here towards short-turning.

Barnett (1978) continued his treatment of holding rules using non-linear passenger wait cost functions. This thesis could not undertake such a complex approach to an already complicated problem, but attempted to consider inequities of additional wait time distribution by examining some alternative objective measures; these are first discussed in the next chapter.

All of these studies pertain to holding, a simpler control strategy than short-turning or expressing due to its avoidance of passenger dumping. Among the very few works to be found treating short-turning in detail, that of Furth (1987) does a good deal towards clarifying the passenger impacts of short-turning, but deals expressly
with scheduled short-turning as a routing strategy rather than with the real time corrective short-turning treated here.

More directly related to the work presented here are the thesis on expressing guidelines (Macchi 1989) and the preliminary report on short-turning presented by Chen and Wilson (1988), both parts of the MBTA Green Line study of which this thesis also is a product.

1.6 Thesis Organization

The second chapter will develop the short-turn model used for the analysis of the problem as developed in the following chapters. This presentation will give the particulars of the model as well as attempting to explain the general principles on which it was built.

Chapter three will analyse available data on Green Line headways and train lengths in order to develop probability distributions for the results of short-turning given the known input conditions. Much of the chapter will be devoted to analysis of the probabilistic inputs developed for the unknown values required by the model in the current, manual operations situation. These values primarily consist of headways following the short-turn candidate train. The rest of the chapter will determine how to collect variables necessary to the short-turn decision making process under AVI control.
Chapter four will catalogue the results of the model with the probabilistic inputs developed in chapter three. I will give some examples of favorable and unfavorable situations for short-turning with the model's treatments of them. At the end of this chapter will appear the summarized guidelines for beneficial short-turning intended for use by the Boylston inspector under current conditions.

The fifth chapter will provide a critique of the procedures and results described in its predecessors, and the sixth and final chapter will summarize the thesis and present some suggestions concerning use of the chapter four guidelines.
Chapter 2
Model Development

This chapter will describe the assumptions and structure behind the model used in this research. It begins by describing the informal procedure used by the T currently. It then goes on to enumerate and justify the more severe assumptions behind my own model before going into a full explanation of the model structure itself.

2.1 Current Practice

The inspectors at Boylston have no detailed information on passenger arrival rates and departure rates at the different stations and thus cannot use passenger minutes as a criterion for their decisions. The best inspectors at Boylston appear to use evenness of westbound headways as the chief objective in deciding when to short-turn. If, for example, several B line trains have become bunched together over the course of their inbound trip and have a large headway gap preceding them, the Boylston inspector may short-turn one if them to reduce the size of the gap, thereby producing more even headways on the B line outbound.

On a simpler system, headway spacing might be a rather good proxy for passenger minutes saved, since, as was shown in chapter one, passenger wait time increases
with the variance in headways. If a great number of passengers is being skipped, however, they do not benefit from the even headways. And the Green Line is a complicated system to which to apply such a simple rule, because it merges several lines and runs them together in the central subway portion of the system of which Park Street and Boylston are a part.

A significant proportion of the riders never leave the central, multi-line section of the system and thus have no interest in the evenness of headways on any given line. Passenger counts show that in the morning peak period sixty-three per cent of all westbound riders are bound for destinations in the central subway; and even in the evening peak when many passengers are travelling to suburban residences, thirty-nine per cent of westbound passengers still have central subway destinations. They gain only from even headways on all four of the lines combined.

Thus, what may be a good short-turn for passengers travelling to the surface line served only by B trains may be detrimental to the large number of people who are not restricted to taking a B train. Such a decision is likely to have a negligible or even negative impact on total passenger minutes in spite of its improving one line's performance. The model developed here will, in fact, later show that about twenty-six per cent of the short-turns made under current strategies have a net negative impact on the riders. Thus, while many good short-turns are carried out,
the guidelines could still clearly be improved.

2.2 Model Objectives

The analysis presented here is based primarily on the minimization of passengers' waiting time. This measure is, of course, not the only conceivable way to determine the success of a short-turn. Some passengers may say that what they look for in transit service is the smallest possible number of transfers or vehicle changes; others may want the fastest possible vehicle, i.e. the smallest possible in-vehicle travel time.

The service may even be considered from perspectives other than the passengers'. The operating agency may desire to minimize costs or work force size, or to maximize on-time performance or number of passengers carried. The work force may want to avoid inconvenient or dangerous strategies or to allow operators to finish early or work late.

But most of the research previously carried out assumes that most passengers will measure the effect of a short-turn in the long run by the simple criterion of passenger minutes spent in the system. This measure is a useful one and will be used here because it is relatively easy to understand and measure, and passengers do, to a large degree, judge the merits of a trip by transit system on the expected time the trip will take them.
It is probably true, however, that, with no perspective on what function a short-turn serves, the average passenger is likely to be very annoyed if he is forced off a train before his destination and only mildly pleased if a train arrives earlier than at what he could not have known to be its expected arrival time. In light of such an understandable attitude, this study will also examine two supplementary measures meant to take into account the inherent annoyance value of a short-turn. The number of passengers dumped due to a short-turn will give us a rough measure of the total annoyance wrought by a short-turn. And the ratio of the number of benefitted passengers, defined as those for whom time has been saved, to the number of disbenefitted passengers, those who have lost time, will be useful as an indicator of the equitability of the distribution of impacts resulting from the short-turn.

The use of passenger minutes as the primary measure of success would seem to be unbiased. Yet if one does decide to undertake an operating strategy with some short-term annoyance value for some of the passengers, such as short-turning, one ought to make extremely sure that the decisions one makes are likely to be good ones. No transit system's ridership is so loyal that it can afford to carry out annoying operating strategies that also frequently turn out to have resulted in no residual service improvements. Thus our model deems a short-turn decision to be a good one if the calculations it carries out prove the short-turn
likely to result in positive passenger minute impacts greater than some threshold value.

This study admittedly fails to take into account some of the other impacts mentioned above, largely because it assumes that they have already been considered in other aspects of the Green Line's operation, nor does it seem likely that short-turning could have any significant effect on them. Of these, operating costs stand out primarily. There are times when the agency stands to save on costs by getting a train and its operator back out to the terminus by a certain time. But it is beyond the scope of this research to measure tradeoffs between cost and service quality, nor is the information to do so available. I have assumed that such factors are considered in the scheduling and service planning of the system and that no short-turn decision is likely to have any very significant impact on such considerations.

This study is a microscopic one, and its analysis is carried out entirely in the context of the existing scheduling, route network, budget, and ridership patterns on the Green Line. When any major changes in these background factors occur the model used here will have to be recalibrated, as would be necessary also for the application of this approach to any system other than the Green Line.
2.3 Passengers Affected by Short-Turning

In considering impacts of short-turning, one finds that, as with expressing, several distinct categories of passengers are affected. In describing them, I will, as far as is possible, keep my notation consistent with that of Richard Macchi's thesis on expressing strategies (1989); I have attempted to use his notation throughout this thesis.

The categories consist of
1) skipped segment alighters,
2) short-turn point boarders,
3) skipped segment boarders, and
4) reverse direction passengers.

The members of the first passenger impact category, that of skipped segment alighters, are colloquially described as "dumped passengers". These are the passengers aboard the train selected for short-turning who want to travel beyond the station at which the train is to be short-turned. They are negatively affected by the short-turn, since they must alight before their destination and wait for the next suitable train. In formulae, these passengers will be referred to as "pax_dump_line", where "line" is the line designation of the train on which they are riding.

Short-turn point boarders make up a second group. These are the people who would have boarded the short-
turned train at the short-turn station if the train had been directed to continue to its usual terminus. In the case of a B train being short-turned at Park Street, these are the people at Park Street who would have boarded the train to travel to Government Center. Though each of them loses exactly the same amount of time as do members of the first group, having to wait until the next suitable train pulls into the station, we distinguish between the two groups because they perceive the short-turn differently. This latter group, which has never been allowed onto the train to begin with, has no sense of having been abandoned by the train; they have established no "squatters' rights" to it. Thus they experience a milder frustration at not being allowed to board it. Technically, these can also be classified as "dumped" passengers, and I will refer to them using the notation "pax_dump_station", where "station" is the short-turn point.

Skipped segment boarders make up the third group of affected passengers. These are passengers waiting at stations the short-turned train would have stopped at but is now skipping. In our example above, passengers waiting at Government Center westbound would fall into this group if they could take a B train to their destination. These passengers are designated by "Pax_skip_segment", where "segment" is the section of the Green Line to which they are travelling. It is important to keep track of this "segment" distinction because passengers travelling to
different parts of the Green Line will have different restrictions on which trains they may take and will thus have different wait times until the next "suitable" train pulls in. I will elaborate on this distinction in the next section.

At last we come to a category of passengers which may be positively affected by the short-turn, and fortunately it is a large group. Passengers waiting to travel in the opposite direction from that in which the train to be short-turned is travelling, and who are not in the skipped section of the route, may experience improved waiting times. These passengers will be referred to as reverse direction passengers.

When the train is short-turned, it is inserted at a new point in the sequence of trains travelling in its new direction. Passengers arriving in the gap between the short-turned train and the previous train that would have suited their purposes will now wait a shorter time, because the short-turned train has arrived earlier than the next suitable train would have. On the other hand, there are also the passengers in this direction who would have boarded the train if it had not been short-turned and had appeared in its original place in the sequence of trains. They will now have to wait longer than previously, because they must wait for the next suitable train.

So of the reverse direction passengers, some will benefit, and some will not. In formulae, all of them will
be referred to as "pax_after_segment", where "segment" refers to the section of the route to which they are travelling, since again this will affect what constitutes a "suitable" train for that group. This issue will be discussed further on.

Given that most of these preceding groups are negatively affected by short-turns and that the group that benefits does so only under the right conditions, these categories emphasize the need for a careful set of short-turn decision rules. One can be certain that any short-turn will inconvenience some people. One is not, however, guaranteed that anyone at all will benefit from a bad short-turn. In making a complete analysis of the difficult decision process at hand we will next examine the basic formulae that determine the number of passengers in and the passenger minute impacts on each of the groups listed above.

2.4 Initial Assumptions

The passenger impact formulae that will be given below constitute a simple short-turn model of their own, one which will later be expanded into the full model actually used for analysis. These formulae are given chiefly to clarify the issues at hand by giving in simple form the structure of the expanded model that follows. But as a model in their own right, they make an array of assumptions
about the behavior of the Green Line and its passengers that must be stated at the beginning.

First, I should explain that both models were designed as deterministic treatments of the Green Line. All inputs must be given exactly, not as probabilistic distributions, and the passenger minute impacts are given as definite numbers by the model. To represent probabilistic behavior of some of the inputs, one must run the model repeatedly with a random number generator creating the probabilistic inputs. In this way the model derives probabilistic distributions for the results of a given short-turn decision; these results appear later in the thesis. For now discussion of the model will be confined to its deterministic use.

2.4.1 Passenger Arrivals and Departures

Passenger arrivals and departures are treated as deterministic even in the later probabilistic development of the model. They are derived from counts made at each station by the Central Transportation Planning Staff (CTPS) in the fall of 1985. Sample counts made since then suggest that only minor changes in Green Line ridership patterns have occurred since then. Should any major changes in these patterns occur, the model would need to be recalibrated.

The CTPS survey aggregates its data into four periods
of the day, across which all of the various inputs differ significantly. Though variation in arrival rates clearly also occurs within each period, all work in this thesis is done only at the period level. Discussion of the assumptions implied by this decision can be found in chapter five. Period 1 is the morning peak period, defined as running from 7 a.m. to 10 a.m. Period 2 is the midday base period, from 10 a.m. to 3 p.m. Period 3, the evening peak period, runs from 3 p.m. to 6 p.m. And Period 4, from 6 p.m. to 9 p.m., covers the evening off-peak hours.

The CTPS data is not as comprehensive as one might wish; the model needs not only to know how many people get on at each station but where they are going, since it must have them board the proper train. No data is available on Green Line passengers' origin-destination patterns, so I have used the theoretically derived origin-destination table that Richard Macchi developed from the CTPS data for his 1989 thesis, cited previously. This table assumes that once a passenger enters the system he behaves just like every other passenger in the system, no matter what his point of origin. Thus, if a certain number of people must get off a train at a given station to satisfy the CTPS figure for alightings at that station, the people who get off are drawn randomly from the people on board the train. To say this in another way, no matter where one boarded the train, one is as likely to get off the train at a given station as anyone else on the train.
Using such an approach one can develop a simple and fairly accurate origin-destination table by keeping track of how many boarders from a particular station remain on the train at any following station and then reducing their number by the fraction of the train load that is known to alight there. For example, if ten passengers board a westbound train at Park Street and one knows that at the next station, Boylston Street, ten per cent of the train's passenger load alights, then one can say that ten per cent of the passengers remaining from Park Street are among those alighting, as is true for each of the origin groups on the train. Thus one Park Street passenger alights at Boylston, and one now knows the figure for one entry in the origin-destination table. One proceeds this way along the route until one has disposed of all of the Park Street passengers, which, unless the train is empty at some point, will not be until the end of the line. Of course, all the calculations are carried out in passengers per unit time. The scheme works well except at occasional anomalies where two stations are very close together and no one is likely to get off at the second station after just having boarded. But these are the exception rather than the rule.

2.4.2 Short-Turn Headway Effects

Next come a set of assumptions involving the behavior of trains' headways in a short-turn situation. In the
particular case this thesis focuses on, that of short-turning B and D line trains at Park Street rather than sending them on through Government Center, I have assumed that a sequence of B and D trains left to run their natural course through Government Center will maintain as a westbound sequence of headways the same northbound set of headways that they went in with. If, however, one train of a sequence is short-turned at Park Street, it will be advanced in the sequence by the amount of its short-turn time savings. If four minutes (which is the actual mean value in this situation) are saved by short-turning the train, it advances by that amount in the sequence of headways, whether or not it passes any of the preceding trains by so doing.

A liberal cap has been placed on the number of preceding trains a short-turned train may pass, since the model cannot look at an infinite number of preceding headways. This cap was established from an observation of the maximum number of westbound trains recorded in a six minute period at Park Street through a day's worth of data; it is different for each line.

Westbound headways of C and E trains, however, are assumed to be independent from the northbound sequence of headways observed at Boylston. This difference results from the holding and dispatching of C and E trains at their northern termini, where the B and D trains have no holding track at Government Center and must continue their
westbound runs with no recovery time at the end of the northbound run.

2.4.3 Headway Propagation

In relation to the above assumptions, the model has been designed under the assumption that, unless a real time strategy such as holding or short-turning is carried out, headway sequences observed at Boylston hold constant over the entire trip, from one end of the line to the other. Thus, if two B trains leave Lake Street five minutes apart, they will remain five minutes apart for the rest of their round trip journey unless one of them is purposely diverted. Though this assumption is hardly realistic, it is perhaps a best estimate for the Boylston inspector, who has no other reliable information on the subject. We will discuss this further in the fifth chapter.

2.4.4 Suitability of Trains

Other assumptions concern what constitutes a "suitable" train for a given passenger to board. For the most part, these matters are clear; a passenger will board a train only if it is going to the station for which he is bound. For example, a westbound passenger at Park Street destined for a surface station on the D line will only get on a D train. If he is going to Auditorium, then he will
take a B, C or D, all of which stop there. But if a
"suitable" train does not stop at one's origin station, 
then one must take an unsuitable train to get to a station
where a suitable train may be found; in other words, a
transfer is required.

Here are the anomalies of interest and how they have
been treated. Westbound passengers boarding at Lechmere or
Science Park and bound for stations not served by the E
line will take an E train to Park Street, where all their
transfers are made. Westbound passengers boarding at North
Station and bound for any station not on the E branch
beyond Copley Square will board C trains only, because of
the station layout, which prevents passengers from choosing
whichever line's train comes in first. If such a passenger
is not bound for a station served by the C line, he will
transfer at Park Street; passengers bound for the E branch
will take E trains only. Westbound passengers boarding at
Haymarket and bound for the E branch will take E trains
only; passengers travelling anywhere else will board the
first train that arrives and transfer at Park Street if
this train does not serve their station.

Northbound passengers boarding on the B and D branches
and bound for stations beyond Government Center will
transfer at the end of the line (usually Government
Center). Northbound passengers boarding at Kenmore Square
or Auditorium and bound for stations beyond Government
Center will take any train and transfer at the end of the
line if the train selected does not serve their destination. Passengers travelling from one branch to another branch, and thus changing their direction of travel, do not need to be treated separately because the way the CTPS data was collected counts such a trip as two trips, one of them northbound and the other westbound.

2.4.5 The Capacity Question

One of the most important of the simple model's assumptions, in that I went to great trouble to avoid it in the expanded model, is that of ignoring train capacity as a constraint. The simple model allows whoever wants to board a train to do so whatever the current load or number of cars in the train. This assumption is unacceptable for a model of the Green Line, where capacity is a major concern of management and riders alike and cannot be ignored as a constraint, particularly during the rush hours. The assumption, however, does not hinder the use of our initial model as the simple sketch of the passenger impacts it is intended to be.

2.5 Passenger Impact Formulae

As is the case for most of the examples that will be presented, the impact formulae developed here will pertain to the case of a northbound B train short-turned at Park
Street. Before the notation used here can make any sense, one must refer to the schematic route map provided in figure 2.1, which gives the "segment" designations for different sections of the Green Line. The significance of these segments lies in route structure; each segment is served by a unique combination of the lines making up the Green Line's routing or requires special treatment of the passengers due to the nature of the short-turn. For example, segment Q is served by all four lines whereas segment R is served only by the B, C and D lines. Park Street, which makes up all of segment P, is singled out as the site of a unique and complex set of passenger transfers.

A sample matrix of the passenger flow rates between the different segments appears in table 2.1. The wait time impacts for each of the previously described, affected passenger groups, namely, skipped segment alighters, short-turn point boarders, skipped segment boarders, and reverse direction boarders, now follow.

2.5.1 Skipped Segment Alighters

For a short-turned B train, only passengers on board prior to Park Street and destined for Government Center fall under this category, since those travelling beyond Government Center would have had to transfer at Government Center, and are now merely forced to make that same
Figure 2.1: Segment Notation Map

Segment M:
- Park
- Station
- Key

Segment N:
- Station
- Park
- Key

Segment O:
- Park
- Station
- Key

Segment P:
- Park
- Station
- Key

Segment Q:
- Park
- Station
- Key

Segment R:
- Park
- Station
- Key

Segment E:
- Park
- Station
- Key

Segment D:
- Park
- Station
- Key

Subsegments:
- M1
- M2
- M3

Magnification of Segment M:
Table 2.1: Sample O-D Matrix at Segment Level

Morning Peak Period (period 1)
arrival rates in passengers per minute

<table>
<thead>
<tr>
<th>to</th>
<th>M</th>
<th>N</th>
<th>P</th>
<th>Q</th>
<th>R</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
</tr>
</thead>
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<td>M</td>
<td>4.67</td>
<td>6.37</td>
<td>2.14</td>
<td>0.07</td>
<td>0.09</td>
<td>0.15</td>
<td>0.12</td>
<td>0.15</td>
<td>0.14</td>
</tr>
<tr>
<td>N</td>
<td>12.75</td>
<td>---</td>
<td>16.26</td>
<td>1.61</td>
<td>2.02</td>
<td>3.44</td>
<td>2.76</td>
<td>3.47</td>
<td>3.22</td>
</tr>
<tr>
<td>P</td>
<td>3.11</td>
<td>6.77</td>
<td>---</td>
<td>5.43</td>
<td>6.82</td>
<td>11.60</td>
<td>9.32</td>
<td>11.72</td>
<td>10.85</td>
</tr>
<tr>
<td>Q</td>
<td>5.23</td>
<td>11.39</td>
<td>34.53</td>
<td>3.59</td>
<td>3.84</td>
<td>6.54</td>
<td>5.25</td>
<td>6.60</td>
<td>6.11</td>
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<td>6.88</td>
<td>2.04</td>
<td>1.04</td>
<td>3.06</td>
<td>2.46</td>
<td>3.09</td>
<td>---</td>
</tr>
<tr>
<td>B</td>
<td>0.72</td>
<td>1.57</td>
<td>4.76</td>
<td>1.41</td>
<td>1.41</td>
<td>12.50</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>C</td>
<td>0.21</td>
<td>0.46</td>
<td>1.41</td>
<td>0.42</td>
<td>0.42</td>
<td>---</td>
<td>4.40</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>D</td>
<td>0.55</td>
<td>1.19</td>
<td>3.61</td>
<td>1.07</td>
<td>1.07</td>
<td>---</td>
<td>---</td>
<td>10.73</td>
<td>---</td>
</tr>
<tr>
<td>E</td>
<td>1.65</td>
<td>3.59</td>
<td>10.88</td>
<td>3.23</td>
<td>---</td>
<td>---</td>
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<td>---</td>
<td>NA</td>
</tr>
</tbody>
</table>
transfer one station earlier. Thus, by "pax_dump_B" we
designate the arrival rate of passengers from segment B,
the B surface branch, to Government Center. These
passengers, who boarded our short-turn candidate train out
on the Boston College branch, are a subset of the full
number of dumped passengers. They will have collected at
arrival rate Pax_dump_B for "H_prev_B" minutes, where
H_prev_B was the headway between our short-turn candidate
and the preceding B train. Thus, with no load restric-
tions, there will be (Pax_dump_B*H_prev_B) such passengers
on board.

Similarly, from segment R, there will be
(Pax_dump_R*H_prev_BCD) passengers to be dumped, since
passengers from Kenmore and Auditorium bound for Government
Center will only have been collecting since the previous B,
C or D train, all of which go to Government Center. And
from segment Q, there will be (Pax_dump_Q*H_prev_any)
relevant passengers, since they will only have been
collecting since the most recent train of any sort went
through.

With the origin-destination matrix developed from the
CTPS data it is no great task to determine the Pax_dump
arrival rates necessary to compute these figures. The
number of passengers is thus

\[ Pax_dump = Pax_dump_B*H_prev_B + Pax_dump_R*H_prev_BCD \\
+ Pax_dump_Q*H_prev_any . \]  
(Eq. 2.1)

Once the train is short-turned at Park Street and all of
these passengers are dumped, they will be forced to wait until the next train of any sort pulls into Park Street northbound. This following headway is designated by "H_next_any". Thus, the total number of passenger minutes lost by this passenger group is given by

\[
Pax. \text{ minutes} = [(Pax\_dump\_B*H_{prev\_B}) + \\
(Pax\_dump\_R*H_{prev\_BCD}) + \\
(Pax\_dump\_Q*H_{prev\_any})]*H_{next\_any} \text{ .} \quad (Eq. 2.2)
\]

Now, for a given string of northbound headways, we have a simple formula for the passenger minute impact on passengers dumped at Park Street.

2.5.2 Short-Turn Point Boarders

Passengers travelling from the station at which the train is short-turned to the segment skipped by the train are affected in the same way as those dumped at the short-turn point. Thus we find their wait time impact to be

\[
Pax. \text{ minutes} = (Pax\_dump\_P*H_{prev\_any})*H_{next\_any} \text{ .} \quad (Eq. 2.3)
\]

in our B train example, very similarly to any one of the terms above.

2.5.3 Skipped Segment Boarders

People who would have boarded the short-turned train
in the segment it skipped form the next category; in our example, these are composed entirely of passengers waiting to board westbound trains at Government Center. No passenger travelling to any of the surface branches other than the B branch would have been interested in boarding our train to begin with, so we can ignore these groups, which are not affected.

The "Pax_skip_B" group, i.e. those travelling from Government Center to the Boston College branch, however, is certainly affected. They have collected at rate Pax_skip_B for H_prev_B minutes, since they are restricted to taking B trains. Those travelling from Government Center to the R segment, who can take B, C or D trains, will have been collecting at rate Pax_skip_R for H_prev_BCDout minutes and will be forced to wait for an extra H_next_BCDout minutes. The "BCDout" notation denotes that we are looking at westbound (i.e. "outbound") headways rather than northbound ones; the notation is only necessary when C or E trains are being considered, since B and D outbound headways have been assumed to remain the same as they were inbound.

And similarly, those travelling from Government Center to segments P and Q, which can be accessed from any line, will have been collecting at rate (Pax_skip_P+Pax_skip_Q) for H_prev_anyout minutes and will have to wait for an additional H_next_anyout minutes. Thus we can write the total negative wait time impact on skipped passengers as
\[
Pax. \text{ minutes} = (Pax\_skip\_B \times H_{\text{prev B}} \times H_{\text{next B}}) + \\
(Pax\_skip\_R \times H_{\text{prev BCDout}} \times H_{\text{next BCDout}}) + \\
([Pax\_skip\_P + Pax\_skip\_Q] \times H_{\text{prev anyout}} \times H_{\text{next anyout}}).
\]  \hspace{1cm} (Eq. 2.4)

2.5.4 Reverse Direction Passengers

The final category of passengers affected by the short-turn are its potential beneficiaries, those waiting to travel in the reverse direction of the short-turned train and not in the skipped segment. As noted above, some of these passengers will benefit, and others will lose from the short-turn decision. Clearly, everyone who boards the short-turned train gains, because they have experienced a shorter waiting time than they would have if the train had appeared at a later point in the sequence of headways; they would have had to wait for the next suitable train, which, one should note, may or may not have been the train being considered for short-turning. Passengers, however, who would have boarded the un-short-turned train but who have now missed it because it went through earlier than it would have, now have to wait for the next suitable train themselves; these form another negatively affected group.

The analytic formulae for the wait time gains and losses of this passenger category will not be included here due in part to their high level of complexity and to the fact that they were not actually used in the final expanded
model. They were replaced by a simpler method to be explained further on. The main point to be made here concerns the insertion of the short-turned train into the sequence of headways in the reverse direction. First, the model assumes knowledge of the westbound C and E headways at Government Center. Though the Boylston inspector actually has no real time knowledge of these figures, they will be available when the AVI system is completed. For the initial, manual results, these inputs have been placed among those that need to be generated randomly.

We have already made the assumption that the B and D westbound headways are the same as were their northbound headways. Now, if one knows how much time is saved by short-turning the train in question, i.e. how much earlier it appears at Park Street westbound than it would have had it not been short-turned, it is no great matter to place the train at its new proper place in the westbound headway sequence. The expected value for this time savings is about four minutes for B and D trains being short-turned at Park Street, but in the analysis section, this variable too will be randomized based on available data.

To place the train in its proper place, however, one must keep track of enough preceding headways from where it would have been in the westbound sequence so that one can be sure to know its preceding and following headways for each line even if it passes an unusually large number of intermediate trains. A simple analysis revealed that even
with an unusually large time savings of six minutes, a short-turned B or D train is not likely to pass more than three B trains, three C trains, four D trains or two E trains; "passing" a C or E train means that a train finds itself in front of the C or E train, when, if it had not been short-turned, it would have been behind the C or E train in the westbound sequence. These figures determine the number of preceding headways the model needs to keep track of. Thus, if a B train is short-turned at Park Street and it saves four minutes over its Government Center route, the model has kept track of at least four preceding B trains, so that if the train actually passes three of them, the model will still know what the train's new first preceding headway is to the fourth train. It will simply be

\[
H_{\text{prevB\_new}} = H_{\text{prev1\_B}} + H_{\text{prev2\_B}} + H_{\text{prev3\_B}} + H_{\text{prev4\_B-time\_sav}},
\] (Eq. 2.5)

where time\_sav is about four minutes, as mentioned previously.

Now that this section has established the basic principles required for each of the passenger minute calculations, the next will describe their full treatment in the expanded model.

2.6 Form of the Full Short-Turn Model

The full short-turn model makes the same set of
assumptions as do the simple formulae given in the previous section with one exception, that of load constraints. The full model assumes that each car of a Green Line train has a maximum capacity beyond which no one will board the train. Although the maximum capacity is slightly stochastic, due to passengers sometimes crowding the doors and sometimes moving to the center of the car, the model makes the reasonable approximation that capacity is deterministic. All of the analysis carried out with the model uses a maximum crush capacity of one hundred and fifty for a modern articulated Green Line car. Any value desired could be input, but past observation indicates this as a reasonable expected value. By keeping a record of the number of cars of each train, one knows the capacity of each train.

We will look at how this new degree of freedom affects the model by going through its design and structure in the order in which it carries out its calculations. The model described here was written specifically for the short-turning of B and D Green Line trains at Park Street on their northbound runs. It begins with the calculation of impacts on northbound passengers. Afterwards it begins its treatment of the westbound, short-turned runs, which are modelled very differently from the northbound.
2.6.1 The Northbound Trip Preceding Short-Turning

In the face of load constraints not everyone who wants to board a train may be able to do so. It is the task of the model to determine how many people on board the short-turned train at Park Street can be classed as dumped passengers and thus be counted towards the loss of passenger minutes. The number arrived at under the simple formulae will no longer hold true because some of the passengers counted there may have been unable to board the train due to crowding. Any delay they experience is not associated with the short-turning decision, and they must not be counted. The most direct way to determine how many dumped passengers are on board at Park Street is to keep a running tally of the train's load at every station along its route as well as a tally of how many of those people fall under what category; only if they are travelling to segment N, Government Center, will they really be dumped passengers. So, first of all, we must now look at the load at every station rather than just from one segment, as in the simple model.

Now we find that we cannot look at just one train either. We must look at the loads of preceding trains as well, in order to determine whether their load constraints caused spillover passengers to board our candidate train. Theoretically, with high enough passenger arrival rates, the Green Line could wholly fail to meet demand and many
cars could be filled to capacity, with extra passengers often being left behind at station platforms. Such a scenario would oblige us to look at an infinite number of preceding trains to determine the number of spillover passengers boarding the one train in which we are interested.

Since the Green Line is clearly not performing in such a manner, and to avoid the unnecessary task of looking at the loads of countless preceding trains in order to determine the number of "spillover" passengers, the model makes the justifiable assumption that the third train preceding the short-turn candidate train is never filled to capacity and that any spillover passengers would derive from the first two preceding trains of any sort. This assumption is accurate, since even if the third preceding train is filled to crush capacity, its overflow is likely to have been taken care of by the two trains following it, thus not requiring the assistance of our candidate train. In other words, the probability that three consecutive trains have loads at or close to capacity is approximately zero.

So now, rather than just H_prev1 for each line, as was required by the simple model, the new model also needs H_prev2 and H_prev3 for each line, as well as the number of cars for the first and second preceding trains of each line. It then finds the overflow from the previous train (usually zero at most stations) and adds it to the ordinary
boarders of the candidate train, who have arrived only during the previous headway. It does this at every station, always keeping track of passengers destined for Government Center as well as of the total load, so that it knows how many dumped passengers there are when it gets to Park Street.

Note that not all the passengers waiting to board at a given station will get on the candidate train. As in the simple formulae, only passengers for whom the train is a suitable one will board it. This practice results in some rather complicated formulae involved in the loading of passengers at each station, especially for the first two preceding trains, whose line designations are indeterminate after the lines have merged at Kenmore Square. For instance, at Copley Square inbound, if the train pulling in is a B or D, then everyone waiting at the platform who is bound for the Q, P and N segments only will attempt to board; if it is a C, then everyone bound for Q, P, N, M3 or M2 will attempt to board; if it is an E train, then everyone will attempt to board, because it serves all of the remaining northbound stations.

As well as forcing us to look at multiple preceding headways to determine load of the short-turn candidate, the capacity constraint requires an inspection of multiple following headways in order to determine the wait time imposed upon dumped passengers. The simple model multiplied the number of dumped passengers by the time until the
next following suitable train to get the number of passenger minutes lost. But if the first following suitable train is full, the dumped passengers will not be able to board it. Thus the model now also keeps track of the load of the first following train of each line and of the second following headway as well as the first; if dumped passengers are unable to board the first following suitable train, we assume that they are able to board the second, another reasonable approximation.

One other interesting feature of this section of the model is its combining of the headway sequences of two or more lines at the merge points of the Green Line. Each train is placed in order according to its headway relative to the train being considered for short-turning. Thus the model treats the short-turn train as being at time zero and sorts the trains and their respective corresponding statistics according to their positive (for preceding trains) or negative (for following trains) relative time positions.

In this way we follow our short-turn candidate from its initial station all the way to Park Street, where all passengers would have to alight. To calculate the passenger minutes lost by dumped passengers and short-turn point boarders, the model considers passengers who have lost time in terms of several categories. First we have dumped passengers, bound for Government Center, who succeed in boarding the first following train, which is necessarily
a suitable train, since any following train will presumably
take them to Government Center. If any dumped passengers
cannot board the first following train due to crowding,
they are assumed to be able to board the second following
train.

A third category is composed of Government Center
bound passengers who would have boarded the short-turned
train had it not been short-turned, and who succeed in
boarding the first following train; such passengers who are
forced by overcrowding to wait for the second following
train make up the fourth category. The fifth, sixth and
seventh categories are made up of passengers bound
respectively for segments N, M2M3 and M1 (see again fig.
2.1), who were unable to board the first following train,
but would have done so if the short-turn had not been
carried out. Each of these categories is then subjected to
an additional wait for the next following suitable train.
The calculations are made as follows, with explanations
where necessary.

Notation:

\[ \text{N}_1\text{-dumped} = \text{passengers on train one, the short-turned}\]
\[ \text{train, bound for segment N}, \]
\[ \text{N}_1\text{-skipped} = \text{passengers at Park Street bound for}\]
\[ \text{segment N, who would have boarded train one}, \]
\[ \text{N}_1\text{-skipped} = \text{passengers at Park Street bound for}\]
\[ \text{segment N, who would have boarded the first following}\]
\[ \text{train if train one had not been short-turned}, \]
M2M3-1_skipped = passengers at Park Street bound for segments M2 and M3, who would have boarded the first following train if train one had not been short-turned,

M1-1_skipped = passengers at Park Street bound for segment M1, who would have boarded the first following train,

%_boarded = the fraction of new boarders able to get on the first following train

= 1, if load_-1_0 > capac_-1, otherwise
= [capac_-1 - (load_-1_Boy1 - alighters)] / boarders

Passenger Delay Calculations:

1) N_1_dumped delayed by one train
   = N_1_dumped * %_boarded
   passenger minutes of delay
   = H_next1_any * N_1_dumped delayed by one train,

2) N_1_dumped delayed by two trains
   = N_1_dumped * (1 - %_boarded)
   passenger minutes of delay
   = (H_next1_any + H_next2_any) * N_1_dumped delayed by two trains,

3) N_1_skipped delayed by one train
   = N_1 new boarders * %_boarded
   passenger minutes of delay
   = H_next1_any * N_1_skipped delayed by one train,

4) N_1_skipped delayed by two trains
   = N_1 new boarders * (1 - %_boarded)

(continued)
passenger minutes of delay

\[ = (H_{\text{next1\_any}} + H_{\text{next2\_any}}) \times N_{\text{-1\_skipped delayed by two trains}}, \]

5) \[ N_{\text{-1\_skipped}} = (N_{\text{-1\_pax turned away}}) - (N_{\text{-1\_dumped delayed by two trains}} + N_{\text{-1\_skipped delayed by two trains}}) - (N_{\text{-1\_pax turned away without the short-turn}}), \]

passenger minutes of delay =

\[ H_{\text{next2\_any}} \times N_{\text{-1\_skipped}}, \]

6) \[ M2M3_{\text{-1\_skipped}} = (M2M3_{\text{-1\_pax turned away}}) - (M2M3_{\text{-1\_pax turned away without the short-turn}}), \]

passenger minutes of delay =

\[ H_{\text{next2\_CE}} \times M2M3_{\text{-1\_skipped}}, \]

7) \[ M1_{\text{-1\_skipped}} = (M1_{\text{-1\_pax turned away}}) - (M1_{\text{-1\_pax turned away without the short-turn}}), \]

passenger minutes of delay =

\[ H_{\text{next2\_E}} \times M1_{\text{-1\_skipped}}. \]  \[ \text{(Eqs. 2.6-2.20)} \]

The passenger minutes of delay from each of the seven categories are added together resulting in the total impact in passenger minutes of the proposed short-turn on northbound travellers. These northbound travellers comprise all of the affected passenger groups referred to previously as skipped segment alighters and short-turn point boarders. Having completed the tabulation of impacts related to the northbound journey, the model now begins a similar treatment of the westbound journey from Park Street after the short-turn.
2.6.2 The Westbound Trip

The chief difference between the model's treatment of the northbound and westbound trips lies not so much in the procedure for tabulating the train loads along the line as in the final summation of lost passenger minutes. Because the westbound passengers affected are not a well defined group in the load constrained treatment, and because not all of the affected passengers are neatly clustered at one station along the line, the calculation of passenger minutes becomes highly non-analytic. If, for example, a passenger waiting for a westbound E train to take him to the surface E branch from Boylston Street cannot board the first E train to arrive because it is full of passengers from Park Street bound for Copley Square, he will have been affected by a decision to make or not to make a given short-turn, since those passengers might have been carried by a different train. But in the load unconstrained case, a passenger bound for the E branch would not have been considered as relevant to a short-turn.

Rather than implementing a complex passenger minute counting procedure at every station along the line, I chose to go through the westbound run twice, once with the candidate train in its un-short-turned position in the sequence of headways and once in its short-turned position. From each of these runs the model calculates the total number of passenger minutes waited and takes the difference
between the two figures to get the total wait time effect on skipped segment boarders and passengers after the short-turn.

The other significant difference between the treatments of the two directions concerns the number of trains to be considered. Since we are not sure how many trains forward in the sequence our candidate will be shifted by short-turning it, we do not directly know the number of trains whose loads and headways we will need to keep track of. So for reasons mentioned in the "initial assumptions" section, it has been assumed that it can "pass" no more than three B trains, three C trains, four D trains and two E trains. Since even if the short-turn candidate passes three B trains the model will still need to know the three preceding headways and the number of cars of the first two preceding B trains, it will need to keep records of no fewer than six preceding B trains. Thus the model will have records of the three trains preceding the train of interest for both the short-turned and un-short-turned cases. And it needs, as in the northbound case, to keep track of two following trains as well, all for the same load factor reasons detailed in the previous section.

Similarly the model will need to keep records on six preceding C trains, seven preceding D trains, and five preceding E trains, as well as of the following two for each line. This is a large number of trains to keep track of, and not all of them will be relevant if the short-
turned train does not pass the maximum possible number of trains, a feat it will almost never perform. Therefore the model records as zero the loads of all trains further forward than the two trains preceding the short-turned train; this artifice simply reduces the profusion of numbers one needs to look at in the model without affecting the numerical results.

Recall also that since the C and E westbound headways are assumed to have no relation to the C and E northbound headways, the model's inputs require a full eight new train records for the C line and seven new records for the E line, whereas, since the previously recorded B and D headways still hold value, only three and four additional train records for the B and D lines respectively are required by the westbound run.

The model begins at Lechmere Square, the northern end of the Green Line and terminus for the E trains. The passenger loads for the E line are propagated down the line for two stations, where a merge with the C line is implemented. The two lines continue together for two stations, North Station and Haymarket, where boarding passengers are assigned to trains according to the somewhat complicated rules described in the "initial assumptions" section. They are merged with the B and D lines at Government Center.

At Government Center, the only station in the skipped segment of our short-turn, the model begins its dual
treatment of the westbound run. In the un-short-turned run, the candidate train appears at Government Center in its old place in the sequence where it remains out to the end of the line. In the short-turned run, the candidate train has no place in the sequence at Government Center, but then appears at Park Street in a position forward from its old one by the number of minutes input as the time savings achieved by short-turning. Again, it remains at this point in the sequence out to the end of the line.

Since the calculation of loads for each of these runs is carried out just as in the northbound case, the only new development now is the calculation of total wait time of the passengers boarding any of the trains in our sequence. At each station along the line, starting at Government Center, two figures are found for each train in our sequence that pulls into the station. The first of these is passenger wait time accumulated by passengers who have arrived only since their last suitable train departed. Thus, if the train pulling in is a C train, this group includes passengers bound for the C branch who have arrived since the last C train departed, passengers bound for the R segment (Kenmore and Auditorium) who have arrived since the last B, C or D train departed, and passengers bound for stations only within the central subway (Copley and stations previous) who have arrived since the last train of any sort departed. If the calculation is being carried out at stations beyond any of the segments in question, the
passenger arrival rates for passengers bound for that segment will, of course, be zero.

The other wait time figure associated with each train gives passenger minutes waited by passengers who arrived previous to the departure of their last suitable train, but who were unable to board due to the capacity constraints. These are the spillover passengers, i.e. passengers who were unable to board their proper train solely as a result of crowding on that train. This number simply gives the amount of time waited by whatever spillover passengers happen to be in the station since the last train of any line departed. The formulae for these two sorts of passenger minutes follow.

1) passenger minutes waited due to headway sequence
   \[ \frac{1}{2} \times \left( \frac{H_{\text{prev any}}^2}{2} \right) \times (Pax_{\text{after PQ}}) + \frac{1}{2} \times \left( \frac{H_{\text{prev BCD}}^2}{2} \right) \times (Pax_{\text{after R}}) + \frac{1}{2} \times \left( \frac{H_{\text{prev branch}}^2}{2} \right) \times (Pax_{\text{after branch}}), \]

2) passenger minutes waited due to crowding
   \[ H_{\text{prev any}} \times (\text{no. of spillover pax for last headway}). \]

(Eqs. 2.21-2.22)

"Pax_after_segment" gives the arrival rate at the station being examined of passengers bound for the segment or segments named.

The headway squared divided by two and multiplied by the arrival rate formulation used in the first equation derives simply from the fact that over the past headway, the number of passengers to have arrived will be the
arrival rate times the length of the headway, i.e.

\((H_{\text{prev}}) \times (\text{arrival rate})\),

and the average passenger among this group will have been waiting for half the headway when the next train pulls in. So we multiply the number of passengers by the average time they have waited to get the total passenger minutes waited, a procedure that gives us the form

\[\frac{(H_{\text{prev}})^2}{2} \times (\text{arrival rate})\].

Having calculated these two figures for the arrival of each train in our sequence at each station out to the end of the line, the model adds up all the pairs of figures to get a total passenger wait time. This is done for both the run with the short-turn and the run without the short-turn. The difference between these two figures plus the effects tabulated from the northbound run give us the total impact in passenger minutes of the proposed short-turn, in positive figures for time saved and negative figures for time lost.

2.7 Model Summary

The model has been organized in three sections. The first of these simulates the running of a sequence of trains from the western termini of the Green Line in to Government Center and calculates the number of passengers dumped at Park Street and how many passenger minutes are lost due to the candidate train's not continuing to
Government Center. The second and third sections carry out the westbound run of the candidate train, once without the implementation of the short-turn and once with it. For each run, a record is kept of all of the passenger minutes spent, and the total wait time savings on the westbound run are calculated by taking the difference between the two results. The net wait time savings are found by subtracting the time loss of the first section from the westbound result. Much of the complexity of this model derives from the need to keep track of passengers unable to board due to crowding.

The model has been built in the form of a Lotus 123 spreadsheet. It uses version 2.2 of that software. The model requires the inputting of about fifty values, all of which are either train headways or train lengths, i.e. the number of cars making up a train. The model was developed on an IBM PC-based 80386 machine. The program requires 640K of standard memory and at least 1000K of extended memory due to its size. Also because of its size, recalculation of the spreadsheet is quite slow, but suits our purposes adequately.

This completes the description of the model. As the reader will have noticed, it requires a great number of inputs, not all of which are available to the Boylston inspector. The next chapter will describe the procedure used to make a useful analysis of the short-turn problem from the perspective of both the current manual decision
process and the future AVI-based process. The results of that procedure will follow in the fourth chapter.
Chapter 3
Input Modelling

Of the seventy-four inputs required by the model developed in the previous chapter only thirty-five will have been directly observed by the Boylston inspector at the time he makes his short-turn decisions. And even the ones he observes may be treated as deterministic when a probabilistic formulation would be more realistic. This chapter will describe how each of these inputs is entered into the model for the predictive analysis at hand and how they might be entered should the model be used as a decision maker under AVI control.

3.1 Use of the Model

Under a manual decision procedure the Boylston inspector will actually be able to use only a small fraction of the model inputs of which he has direct knowledge. A computer assisted dispatcher using the AVI system can do much better, since only one variable will be unknown to him, and he will presumably be able to process all of the data available. In either case, to make any use of the model, the unknown variables must be analyzed so that probable values may be assigned to them. Once values have been entered for all of the inputs, the model can evaluate a potential short-turn. The following sections
will analyze the unknowns so that the model may be used to obtain results for the analysis made in chapter four and under AVI control.

3.1.1 Monte Carlo Modelling

If values are randomly generated for the unknown inputs according to the probability distributions developed for them, then it will be possible to develop a distribution for the outcome of a proposed short-turn, as measured in number of passengers affected and in passenger minutes. Such an outcome distribution is arrived at by generating multiple arrays of the unknown variables and inputting them with the single array of known variables to get multiple possible outcomes. These multiple possible outcomes form the probability distribution for the outcome of a short-turn decision given the array of known inputs we started with.

If, for example, the short-turn model has definite values for every input except short-turn time savings, then one can generate multiple values for this input using a probability distribution based on historic data. For each value entered for this input, a new passenger impact result is calculated by the model. The resulting set of passenger impact figures comprises a probability distribution for the impacts of a short-turn carried out under the given array of known inputs that one began with. One can use such a
distribution to determine the expected impacts of a short-turn carried out under these conditions and the probability of the impacts falling within the acceptable limits of a successful short-turn.

Such a procedure is known as "Monte Carlo" modelling, simply because of its use of probabilistic processes. Chapter four will use such a process to obtain the results it presents. For now, our task is to develop the probability distributions for the unknown inputs as they will be required for the Monte Carlo process and to discuss the probabilistic nature of variables treated by the model as deterministic.

3.2 Distributions of Unknown Variables

This section presents the distributions derived for model inputs the values of which are not collected by the Boylston inspector. In chapter four the model is going to process a week's worth of data collected by the Boylston inspector, but it is neither his duty, nor even possible, for him to collect all of the inputs required by the model. The others, therefore, will be entered as Monte Carlo variables so that the chapter four results will be based on probabilistic Monte Carlo distributions of what really occurred during the study week. Each of the following subsections presents the required distribution for a different input.
3.2.1 Short-Turn Time Savings

The study team collected data on short-turn time savings at the Park Street station on the afternoon of Friday, September 29, 1989. The data was collected with several issues in mind. The first of these was getting enough data; trains were timed for three hours, in which time twenty-seven short-turns were observed. It was also necessary to determine what was meant by time savings. The short-turn time savings was defined as the difference between the time for a B or D train to run from Park Street to Government Center and back, and the time for a short-turned train to get from Park Street northbound to Park Street westbound. Moreover, great care was taken to record the arrival times of all trains at the platforms, not just of B and D trains, so that the effect of high train frequencies on run times through Government Center could be judged.

This latter issue, of congestion of trains at Government Center, was cited by some familiar with central subway Green Line operations as one motivation for short-turning trains at Park Street. I attempted to relate the length of the first previous headway, both inbound and outbound, before a B or D train to the time it took to make the Park to Government to Park run. But as can be seen from figures 3.1 and 3.2, no clear correlation of these variables can be distinguished.
figure 3.1: Government Center Congestion, Inbound
GC time vs. H_previout

first preceding headway, any line

figure 3.2: Government Center Congestion, Outbound
Based on this data, in the form unrelated to preceding headways, as shown in figure 3.3, the circuit time through Government Center was modelled as a random variable normally distributed with a mean value of 7.6 minutes and a standard deviation of 0.9 minutes. In the actual data, ninety-five per cent of the data points fell within 2.7 minutes of the mean. An example of the computer generated random distribution used to represent this variable is shown in figure 3.4 for comparison. As a comparison between the two distributions, the second highest actual value for this variable is 10.5 minutes, whereas the second highest modelled value is only 9.4 minutes, indicating that the actual process has a bias towards high end outliers not evidenced in a Gaussian distribution, but the two distributions are certainly comparable.

The same procedure was used to model the Park Street northbound to Park Street westbound time of a short-turned train through the turnaround loop. This too was modelled as an independent Gaussian variable, this time with a mean of 3.0 minutes and standard deviation of 0.9 minutes. Ninety-five per cent of the actual data fell within 2.2 minutes of the mean. The distributions of this variable as measured and as modelled can be seen in figures 3.5 and 3.6. This time the second highest outliers are more closely matched at 5.2 minutes for the actual data and 5.0 for the generated data, indicating that turning a train around at Park Street is closer to being a pure Gaussian
figure 3.3: Government Center Turnaround Time, Actual

figure 3.4: Government Center Turnaround Time, Generated
figure 3.5: Park Street Turnaround Time, Actual

figure 3.6: Park Street Turnaround Time, Generated
Now, for each Monte Carlo trial of the model, all that needs to be done to generate a short-turn time savings input value is to generate these two figures and take their difference to get the input value. It could be generated directly from one distribution, since the sum of two Gaussian distributions is simply another Gaussian distribution, but the formulation used here is adopted for the sake of clarity.

3.2.2 E Line Westbound Headways

Trains on the E line are dispatched according to a schedule westbound out of Lechmere, the northernmost terminus of the Green Line. Thus their northbound headway sequence can be expected to bear little relationship to their westbound headways. So rather than attempting to derive westbound E headways from the northbound ones, this treatment simply generates probabilistically a new westbound headway sequence. Data on westbound E line sequences was combined from morning and evening peak services during which periods scheduled headways are the same. Separate distributions were derived for periods two and four. These headway distributions were derived from twenty-two observations made partly on Friday, September 29, 1989, in the afternoon peak, and partly on Tuesday, December 20, 1988, in the morning peak.
Once again, the distribution appears roughly Gaussian and was again modelled as such, this time with a mean value of 7.9 minutes and a standard deviation of 1.5 minutes. Ninety-five percent of the data points fall within 2.6 minutes of the mean value. The distribution of recorded observations appears in figure 3.7, and, for comparison, a sample randomly generated distribution appears in figure 3.8. The second highest actual value was 9.5 minutes, and the second highest generated value was 10.0 minutes; the two graphs are very similar, even more so visually than this statistic might indicate.

One might object that the succeeding headways should not be generated independently, as is done here, and that, due to bunching, successive headways should be generated as a whole sequence. The trains, however, have only recently been dispatched from their terminus, and bunching effects have had little time to propagate. The data gives little evidence of high correlation between long preceding headways and short following ones, so I have let the simple treatment described above stand as is.

Headway distributions for the E line westbound in the midday base service and evening offpeak service have been similarly treated. The E line westbound headways for period two were also found to have a mean value of 7.9 minutes and standard deviation of 1.5 minutes; for period four, a mean value of 8.0 minutes and standard deviation of 2.6 minutes.
Headway Distribution, E line West
Park St, 9/29 p.m.

figure 3.7: E Line Westbound Headways, Actual

Headway Distribution, E line West

generated values

figure 3.8: E Line Westbound Headways, Generated
3.2.3 E Line Westbound Train Lengths

Train lengths are a much simpler unknown to generate randomly, since train lengths are necessarily discrete numbers as measured in number of cars. Using the same database as in the previous section, a simple probability mass function was developed giving the probabilities of an outbound E train's length being one, two, or three cars. Though currently no three car E trains are run, due to power constraints, it was thought best to keep the treatment general, since three car trains are actually being run currently on the D line.

As it turned out, virtually all of the outbound E trains in the peak and base hours are two car trains and all of the E trains in the evening offpeak are one car trains, as indeed they are scheduled to be.

3.2.4 C Line Westbound Headways

The same treatment as was used for the E line can also be applied to the C line westbound headways. Again, the C trains have been recently dispatched from their terminus and little correlation is observed between successive headways. Though the observed data, consisting of twenty-nine observations collected at the same times as was the E line data, is somewhat less convincingly Gaussian, tending perhaps more to a uniform distribution, it is not
any more convincingly anything else. The somewhat uneven distribution from periods one and three seen in figure 3.9 could conceivably appear Gaussian given more data collection, and I have chosen to accept it as such pending further investigation.

A sample randomly generated distribution for the peak C line headways appears in figure 3.10, with a mean headway of 5.7 minutes and a standard deviation of 2.2 minutes. In the actual data, ninety-five per cent of the points are within 3.5 minutes of the mean, and the second highest outlier is at 8.9 minutes; the second highest value among the generated points is at 10.2 minutes, a significant, but not a conclusive difference.

The data for period two indicated a mean value of 5.5 minutes and a standard deviation of 2.4 minutes; for period four, a mean of 6.1 minutes and a standard deviation of 4.2 minutes.

3.2.5 C Line Westbound Train Lengths

Once again, the C line westbound analysis repeats the E line analysis, this time with respect to train lengths. A simple probability mass function assigns probabilities to a C train's length being one two or three cars, though again, no three car trains are currently run on the C line. Though, as with the E line, very few one car trains are found during peak hours on the C line, as is consistent
Headway Distribution, C line West

figure 3.9: C Line Westbound Headways, Actual

Headway Distribution, C Line West

generated values

figure 3.10: C Line Westbound Headways, Generated
with the schedule, only one car trains appear on the C line during the base period; and in the evening offpeak period, C line trains are two cars with thirty-nine per cent likelihood and one car with sixty-one per cent likelihood, though most of the former appear early in period four.

3.3 AVI Treatment of Unknown Variables

The previous subsection concludes the development of variables not available in the Boylston data that is used in the next chapter. All the other factors, which are available from the Boylston sheets, will be input as determinate values. The headway sequences observed at Boylston are not, however, determinate over the entire system. As mentioned previously, the assumption that headways do not change as a sequence of trains moves along the line is a weak, but, for now, necessary one. Neither are the passenger arrivals derived from the CTPS data really determinate. Though chapter four will treat these inputs as fixed, we have good reason to be suspicious of them. The use of AVI control, however, will allow us to capture the variability of at least some of these other factors with solid numbers.

Eventually the AVI system should be capable of making short-turn decisions automatically, by entering all of the available inputs into a model like the one presented in chapter two, entering mean values for the unavailable
inputs, and initiating a short-turn if the number of passenger minutes it saves exceeds some threshold value and the number of dumped and otherwise inconvenienced passengers is below some other threshold, thus ensuring a high likelihood of its being a good short-turn. Such a threshold value will depend upon the number and variance of the unknown input values and upon the degree of risk aversion assumed by MBTA managers.

When this time comes, information on the presently untreated variability of the headway sequence will become available. Thus, the headways of the trains of interest will be known at several points along the line, and more accurate calculations of the dependent passenger loads will become possible. This section will describe how some of the presently "unknown" variables will be collected for input to the model under AVI control. References to AVI detector box numbers and positions are taken from the map in figure 3.11, a preliminary scheme released by the T in the fall of 1989.

3.3.1 Northbound Headways on All Lines

The AVI system will allow two improvements to the model in respect to northbound headways. First, it will allow for more accurate calculation of the northbound passenger loads. Secondly, it will allow for knowledge of the following headway sequence before the following trains
western portion

northern portion

cut line

figure 3.11: AVI Detector Locations Map
arrive at Boylston.

The model currently uses the northbound headways primarily to determine the train loads at Park Street. It applies the headways observed at Boylston to the whole inbound trip of every train in the sequence. But in calculating the number of passengers waiting to board, for example, a B train at Blandford Street, use of the previous headways actually observed at Blandford Street would produce significantly more accurate values. Thus, in determining the load on any inbound train observed at Boylston Street, the model would apply the recorded headway sequences observed at the terminus, whence the train was dispatched, to the calculation of its passenger load at every station from the terminus to the next detector box. The calculation of load over the succeeding set of stations will be based on the new headway sequence.

For example, a B train pulls out of the Lake Street yard. The number of new passengers who have arrived at the first station, Boston College, since the last train pulled out, will be calculated by multiplying the passenger arrival rate by the preceding headway observed by the detector at Lake Street, number twenty-one in the figure. This same preceding headway would be used for this calculation at each station until Washington Street, after which the preceding headway recorded by box twenty would be used. Following this procedure for all trains in the sequence, by the time the short-turn candidate train
arrives at Boylston, the model will have good estimates of the passenger loads of all the trains in the sequence, both preceding and following. Or, even more elaborately, the model could linearize the differences between the two headway sequence records and calculate an accurate approximation of the headway sequence at every station.

Knowledge of the following headway sequence at the time of making the short-turn decision also allows for great improvement in the decision making ability of the model. It allows us to replace many of the indefinite model inputs with accurate numbers, but not without some careful treatment. Note that if a relevant following train has not yet merged with the line of the short-turn candidate, e.g. the first following E train has not yet merged at Copley at the time a B or D train has arrived at Boylston, its position in the following headway sequence will have to be estimated by taking the difference between the expected run time from the last detector it passed to the detector at its merge point (either Copley or Kenmore) and the time since it passed its last detector; this time, added to the time since the candidate train triggered the detector at that merge point, gives a good estimate for the how far behind the candidate train the following train of interest is. This figure, the time gap between the candidate train and any other train, is what the model uses to determine that train's position in the headway sequence.
3.3.2 Northbound Train Lengths on All Lines

All of the preceding northbound train lengths will be collected automatically at box number eight at Boylston Street, just as the inspector presently collects them manually. Since, for reasons described in chapter two only the first following train length is made use of by the model, the box at Copley, number ten, will probably be able to supply us with all of the following train lengths required. If there is no train between Boylston and Copley at the time of making the short-turn decision, the procedure for determining the following headway sequence, described above and intended to account for the relative positions of unmerged trains, will determine which train is most likely to be the next following train and what its length is.

3.3.3 C and E Line Westbound Headways

As is the case for the calculation of the passenger loads on inbound trains, the AVI data will also allow improved calculations of westbound C and E trains up to the points they have reached at the time of the candidate train's arrival at Boylston. This procedure differs not at all from that described above. Nothing can be done, however, to change the model's propagation of the headways after the decision is made, since AVI will not aid us in
predicting the future. The continued use of the relative headways as they stand at the time at which the decision is made is still probably the best estimate a model of this sort can make. Greater benefits in the realm of westbound headways are to be achieved by gaining knowledge of the westbound C and E train headway sequence.

A more extreme merging problem than that witnessed in the northbound case occurs in the determination of the westbound headway sequence; whereas before, the possibility of following trains not yet having merged with the main line existed, now there is a certainty that none of the following westbound C and E trains, nor perhaps many of the preceding trains, will have yet merged with the B or D candidate train’s route at the time of the candidate train’s arrival at Boylston. So a similar procedure is carried out to determine the likely westbound headway sequence.

The simplest method of determining the westbound headway sequence of C and E line trains begins by using the AVI data to compile a complete record of where all west-bound C and E trains are located at the time of the candidate train’s arrival at Boylston; this record would indicate how far ahead of (or behind) the candidate train each of the C and E trains is. The AVI system indicates how many minutes have elapsed since any given train last passed a detector. For each train west of Government Center one adds this value to the expected run time between
Government Center and the last detector passed by the train; this is the number of minutes beyond Government Center of the train. Add this to the expected run time of a B or D train between Boylston and the Government Center westbound platform to obtain the distance in minutes by which each of these C and E trains is ahead of the candidate train westbound.

For westbound C and E trains east of Government Center at the time the candidate train arrives at Boylston, the number of minutes elapsed since the last detector is subtracted from the expected run time between that detector and Government Center; the result is added to the Boylston to Government Center westbound run time to get the time distance to the candidate train. Positive figures indicate preceding trains, and negative figures, following trains. If not enough westbound C and E trains have yet left their northern termini to supply all of the required entries in the headway sequence, estimates of their scheduled departures should be used.

If this procedure for determination of the outbound headway sequence sounds complicated, one should not be distressed. It is merely a lot of arithmetic intended to convert the reference points of the AVI system into those required by the short-turn model, the primary reference point of which is the location of the train under consideration for short-turning.
3.3.4 C and E Line Westbound Train Lengths

Just as in the case of the northbound following trains, the same procedure that passes to the model the positions of westbound C and E trains will be able to give their lengths. Trains that have not yet left their northern termini should be assumed to be made up of the number of cars indicated by the schedule.

3.3.5 AVI Unknowns

The preceding section should not be interpreted to imply that AVI will provide all the information necessary to make guaranteed successful short-turns. It takes us a long way in that direction, but passenger arrivals, short-turn time savings, headway propagation after the decision point, and run times, all remain unknown under AVI control, and indeed some of them are inherently unknowable. Especially those that beyond the time of the decision can at best be represented by expected values. The next chapter attempts to account for some of the remaining randomness in its derivation of estimated AVI-based results.

This last section on AVI determination of input variables is in some ways a digression since it does not contribute directly to the development of the next chapter. Rather, it is meant to serve as the counterpart to the
section on modelling of inputs (3.2) to demonstrate how many of the factors that require simulation in use of the model will be collected directly in real life.

Chapter four will present first the base results of the Monte Carlo process applied to the model as developed in this chapter. In the previously described manner it will then analyze these results to derive the useful information relevant to both the AVI case and the current, manual operations case.
The Monte Carlo model described in the preceding chapter was applied to both the B and D lines for the four time periods defined in the CTPS passenger arrival data set. This chapter will treat the results for the B line in the morning peak demand period (aka period one) in detail. The results for other periods on the B line and for periods one and two on the D line were arrived at in the same manner and discussion of the analysis of these results will be abbreviated.

The first section describes the form of the results output by the model. The sorting of these results, described in the following section, allows for the derivation of rules of thumb for the short-turning of trains under the manual operations scenario. Concluding sections estimate the success rates of different short-turning strategies and summarize the recommended rules for the current situation.

4.1 The Modelled Results

As described in the previous chapter, input data was taken from the Boylston inspector's records for the week of March 13-17, 1989, from Monday through Friday. For any given B train all of the information on preceding and
following inbound trains was extracted from these records and input into the model. These records included data on headways and train lengths for all northbound trains. The information not available in the Boylston records, related to westbound C and E trains and schedule time savings, were generated randomly according to the distributions estimated in the preceding chapter.

For each set of known variables, i.e. for each B train observed during the week, thirty-five sets of unknown variables were generated, and the model outputs were recorded for each of these thirty-five trials. The model thus provides us with a probability distribution of the results of short-turning the train in question. I applied this procedure for all the B trains observed during the course of the trial week.

So the raw results consist of large generated samples from the distributions of the three figures given by the model: passenger minutes saved, number of passengers dumped, and ratio of benefitted to disbenefitted passengers. Each of these distributions is associated with a set of variables corresponding to a given train as observed by the inspector at Boylston. Input variables associated with a single train are shown in table 4.1, and a sample passenger impact result distribution for the same train is given in table 4.2.

Table 4.1 is simply meant to illustrate what values specific to a short-turn candidate train are taken from the
**Table 4.1: Model Inputs**

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<thead>
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<th>time at</th>
<th>07:36</th>
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<tr>
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**Input Information**

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<tr>
<td>H_prev3_</td>
<td>3.00</td>
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<td>no.cars</td>
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<tr>
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<td>7.00</td>
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Table 4.2: Model Outputs

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<th>Distribution of Monte Carlo results</th>
<th>passenger minute savings</th>
<th>ratio of benefited to disbenefitted</th>
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<tr>
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<tr>
<td>trial 2</td>
<td>377.5</td>
<td>0.42</td>
</tr>
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<td>trial 3</td>
<td>304.7</td>
<td>0.27</td>
</tr>
<tr>
<td>trial 4</td>
<td>222.3</td>
<td>0.43</td>
</tr>
<tr>
<td>trial 5</td>
<td>492.9</td>
<td>0.46</td>
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<tr>
<td>trial 6</td>
<td>624.2</td>
<td>0.47</td>
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<td>trial 7</td>
<td>238.9</td>
<td>0.63</td>
</tr>
<tr>
<td>trial 8</td>
<td>221.9</td>
<td>0.21</td>
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<tr>
<td>trial 9</td>
<td>58.3</td>
<td>0.47</td>
</tr>
<tr>
<td>trial 10</td>
<td>457.9</td>
<td>0.80</td>
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<tr>
<td>trial 11</td>
<td>303.2</td>
<td>0.11</td>
</tr>
<tr>
<td>trial 12</td>
<td>164.0</td>
<td>0.54</td>
</tr>
<tr>
<td>trial 13</td>
<td>148.4</td>
<td>0.32</td>
</tr>
<tr>
<td>trial 14</td>
<td>202.8</td>
<td>0.34</td>
</tr>
<tr>
<td>trial 15</td>
<td>330.6</td>
<td>0.36</td>
</tr>
<tr>
<td>trial 16</td>
<td>233.5</td>
<td>0.35</td>
</tr>
<tr>
<td>trial 17</td>
<td>170.1</td>
<td>0.30</td>
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<td>trial 18</td>
<td>15.1</td>
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<td>trial 19</td>
<td>158.3</td>
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<td>trial 20</td>
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<td>trial 21</td>
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<td>trial 22</td>
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<td>trial 23</td>
<td>90.4</td>
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<td>trial 24</td>
<td>96.2</td>
<td>0.46</td>
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<tr>
<td>trial 25</td>
<td>393.5</td>
<td>0.60</td>
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<td>trial 26</td>
<td>455.1</td>
<td>0.23</td>
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<td>trial 27</td>
<td>260.7</td>
<td>0.24</td>
</tr>
<tr>
<td>trial 28</td>
<td>181.4</td>
<td>0.16</td>
</tr>
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<td>trial 29</td>
<td>397.1</td>
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<tr>
<td>trial 30</td>
<td>-5.8</td>
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<tr>
<td>trial 31</td>
<td>365.2</td>
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<td>trial 32</td>
<td>465.6</td>
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<td>trial 33</td>
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<td>trial 34</td>
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<td>trial 35</td>
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<td>average</td>
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</tr>
<tr>
<td>std dev</td>
<td>148.7</td>
<td>0.16</td>
</tr>
</tbody>
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number of dumped passengers: 26
Boylston sheets for input to the model. Note that an $H_{\text{prevn}}$ entry gives the headway preceding the $n$th train and that the number of cars given below this entry is the length of the $n$th train, not of the $(n+1)$th train. Also, the $H_{\text{prevl}}$ entries for trains not on the line being considered for short-turning (in this case the B line) are distances ahead of the short-turn candidate, not of the next train of their own line. So the time between the first C train preceding our candidate and the first following C train is given by $(H_{\text{prevl}}_C + H_{\text{nextl}}_C)$, or in this case, eleven minutes. Therefore, the number of cars under the $H_{\text{prevl}}$ entry of lines other than the B line is left blank, since this entry would simply repeat the information given for the short-turn candidate in the B line entry.

Table 4.2 lists the passenger impacts generated by thirty-five Monte Carlo trials carried out for one candidate train, in this case the one described in table 4.1. The number of dumped passengers, given at the bottom, does not change from one trial to the next since none of the generated input values affect this result. Note, however, the broad range of results obtained for the other two measures. Passenger minute savings average 265 minutes, indicating that this is a good candidate for a short-turn; but a -5.8 minute result is possible given our lack of knowledge of the C and E westbound headways and of the short-turn time savings. The modelled impacts of C and
E westbound headways are derived primarily from their influence on the number of passengers with central subway destinations who board the short-turned train. The high standard deviation observed here, therefore, indicates the importance of central subway interline effects to short-turn decision making; AVI control should greatly improve the response to such central subway conditions. The high variance of the benefitted ratio has similar implications.

4.1.1 The Threshold Value

While we are considering this example, it behooves us to consider the 250 minute wait time threshold chosen as the value above which a short-turn is considered desirable in this analysis. This example, for which a mean wait time savings of 265 minutes is predicted, was modelled only once in thirty-five trials as resulting in a negative wait time impact. Considered in terms of passenger minutes only, this record implies a ninety-seven per cent success rate for a short-turn predicted to result in impacts just slightly over our threshold. If one assumes the modelled results are distributed according to a Gaussian function, a short-turn with mean modelled wait time impact equal to our threshold value and with the standard deviation observed in our example (149 minutes), will result in negative wait time impacts in only 4.6 per cent of its
modelled trials.

These two statistics indicate that our threshold is quite conservative, and not likely to result in guidelines conducive to making many poor short-turns. The following pages will attempt to derive a reasonable set of decision rules under the manual and AVI operating scenarios and to compare the performance of the current decision making procedure with the success rate of the decision rules derived from the 250 minute threshold.

4.2 Derivation of Manual Rules

Under the manual decision procedure for short-turning, as it is currently carried out by the Boylston inspector, the decision maker cannot reasonably be expected to take into account more than two or three of the relevant numbers available to him. This limitation holds true especially when, as is the case with the Boylston inspector, these decisions are not the only duty of the decision maker.

Following the lead of current practice, I have chosen to use the first two preceding headways of the same line as the most salient factors in making a manual short-turn decision. These are the two figures known by the inspector that contribute most directly to the net impact of short-turning the train. The first preceding headway on the line is the foremost factor in determining the number of passengers on the train, and this passenger load at
Boylston is directly related to the number of passengers that will be dumped at Park Street.

Both the first and second preceding headways are the two strongest determinants of the westbound headway sequence to be experienced by outbound passengers. If the train under consideration can be inserted close to midway between the two preceding trains on the line, or if it can be placed closer to midway between its first preceding and first following trains, then the westbound headway sequence may be made substantially more even for the line in question. These are the two most likely possibilities for a successful short-turn decision, so keeping track of further preceding headways will add a good deal of complexity but not a proportionate amount of reliability.

While the model indicates that interline effects in the central subway are important in making a short-turn decision - a result that will be demonstrated later - they are simply too complex to be of use in a manual decision making process. Of the numbers actually available to the inspector, the two preceding headways are among the most readily understood as well as being of primary importance.

To determine what combination of the two preceding headways on the line, denoted by H_prev1_branch and H_prev2_branch, allow for the most advantageous short-turns, I grouped the model's result distributions according to the H_prev_branch values associated with them. For each train in the data set, the average value
of passenger minutes saved was found from the distribution of results. These values were averaged together for all of the trains in one previous headway class to get an expected value for passenger minutes saved by the short-turning of trains in that class.

If a class of trains has an expected passenger minutes benefit greater than some threshold level, then all trains in that class are promising candidates for short-turning. A figure of 250 passenger minutes was initially adopted as the threshold value in order to account for the nuisance value of a short-turn and to ensure a better than fifty per cent success rate for the decisions. We will later gauge the accuracy of this threshold from the performance of the rules derived from it.

The first previous branch headway was broken down into seven classes as follows:

1) \( H_{\text{prev}} = 0 \) or 1 minute,
2) \( H_{\text{prev}} = 2 \) or 3 minutes,
3) \( H_{\text{prev}} = 4 \) or 5 minutes,
4) \( H_{\text{prev}} = 6 \) or 7 minutes,
5) \( H_{\text{prev}} = 8 \) or 9 minutes,
6) \( H_{\text{prev}} = 10 \) or 11 minutes,
7) \( H_{\text{prev}} \geq 12 \) minutes.

While the model can handle fractions of minutes, Boylston data is collected at only the integer-minute level. Thus, rules derived from the data are rounded to
the conservative end of their headway class bounds.

The second previous headways have also been broken down into two minute periods, but, for the sake of graphic display, with no twelve minute upper bound on the period categories. These breakdowns thus define the complete set of classes of the two preceding branch headways. The sorting of the results described above was carried out for the four periods of the day as defined by the CTPS survey.

4.2.1 B Line, Period 1

The averaging of passenger minute effects by class to get expected effects within a class resulted in the set of graphs shown in figures 4.1-4.7, which apply to B line trains in period 1, the morning peak period. Each graph is for a given first previous headway category and plots the passenger wait time effect as a function of the second previous headway. By examining these graphs, we may determine fairly accurately which classes offer expected benefits, as predicted by the model, above our threshold level.

In figure 4.1, for example, which examines B line trains within one minute in front of which there is another B line train, one can see the expected passenger minute wait given different second preceding headways. If the second preceding B train is also a very short headway of zero or one minute in front of the first preceding B train
figure 4.1: Wait Time, B Line Period 1, H1P = 0-1

figure 4.2: Wait Time, B Line Period 1, H1P = 2-3
Pax Min vs H2P, H1P = 4-5

Pax Min vs H2P, H1P = 6-7

figure 4.3: Wait Time, B Line Period 1, H1P = 4-5

figure 4.4: Wait Time, B Line Period 1, H1P = 6-7
Pax Min vs H2P, H1P = 8-9

Figure 4.5: Wait Time, B Line Period 1, H1P = 8-9

Pax Min vs H2P, H1P = 10-11

Figure 4.6: Wait Time, B Line Period 1, H1P = 10-11

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Pax Min vs H2P, H1P = 12+

figure 4.7: Wait Time, B Line Period 1, H1P = 12+
then a large amount of passenger wait time may be saved by short-turning the candidate train. But at second preceding headways of two and three minutes, i.e. with the second preceding train further ahead, the number of passenger minutes saved drops well below the threshold level and does not rise above it again until the second preceding headway increases to the eight and nine minute level. Beyond this point, expected time savings increase dramatically with the second preceding headway.

Note that the numbers labelling each point on the graph record the number of observations used in the analysis of the respective headway class. Points based on more observations can be expected to yield more reliable results. I have therefore discounted the occasional outliers calculated from insignificant amounts of data, such as the graphed point, based on a single data point, in figure 4.3 just barely above our threshold at four to five minutes of first preceding headway and eight to nine minutes of second preceding headway.

Ignoring such outliers and in light of the suggested threshold level of 250 passenger minutes saved, an analysis of the whole set of morning B line graphs demonstrates that the following classes of preceding headway combinations satisfy the requirements for short-turning:

- $H_{prev1} = 0,1$, and $H_{prev2} = 0,1$,
- $H_{prev1} = 0,1$, and $H_{prev2} > 8$,
- $H_{prev1} > 10$. 

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The rules derived from this analysis must also be consistent with the model's requirement that no two trains in a row in such a sequence be short-turned. Thus, since cases in which \( H_{\text{prev1}} \) is zero or one and \( H_{\text{prev2}} \geq 10 \) minutes yield as great or greater benefits than do cases in which \( H_{\text{prev1}} \geq 8 \) minutes, if three trains are separated by consecutive gaps of eleven and then one minute, we want to short-turn the train immediately after the one minute gap. But the inspector will only know that the third train is actually within one minute of its preceding train if he can see it behind the second train. Otherwise he may be missing an opportunity for a good short-turn by waiting for a third train. For the sake of the analysis, if the third train is within half a minute of the second train, we will assume it is within sight of the inspector at the moment of his decision regarding the second train. Our manual decision short-turn rules, therefore, for \( B \) trains in the morning peak take the following form:

Short-turn the train if

- \( H_{\text{prev1}} \leq 1 \text{ min. and } H_{\text{prev2}} \leq 1 \text{ min.} \)
- \( H_{\text{prev1}} \leq 1 \text{ min. and } 8 \text{ min.} \leq H_{\text{prev2}} < 10 \text{ min.} \)
- \( H_{\text{prev1}} \leq \frac{1}{2} \text{ min.} \) (i.e. the inspector can see the candidate train when train \( \text{prev1} \) is at the decision point) and \( H_{\text{prev2}} \geq 10 \text{ min.} \)
- \( H_{\text{prev1}} \geq 10 \text{ min. and } H_{\text{next2}} \geq \frac{1}{2} \text{ min.} \) (i.e. the inspector cannot yet see the following \( B \) train).
This set of rules maximizes the benefits of short-turn decisions given the information available to the Boylston inspector at the moment of making the decision. Furthermore it only allows two B line trains in a row to be short-turned if the second one is at least ten minutes behind the first one, a case the model deals with well enough not to invalidate the results given here.

4.2.2 The Impact of Train Length

Another key factor in short-turn success, train length, greatly influenced the structure of the model and was also considered in the establishment of the manual decision rules. Each of the B line morning classes graphed in figures 4.1-4.7 was further broken down into subcases in which the candidate train's length was specified. This resulted in two sets of graphs, one for one car trains and the other for two car trains.

In spite of the importance attributed by the model to train length in the AVI based scenario, the manual results indicated that the effects of train length were largely drowned out by other factors untreated by the Boylston inspector. The two sets of graphs differed in no great respect. The one and two car graphs for the zero to one minute first preceding headway cases have been included here as figures 4.8 and 4.9 to illustrate this point.

At no point do the two graphs differ by more than a
figure 4.8: Wait Time, One Car Trains

figure 4.9: Wait Time, Two Car Trains
hundred passenger minutes and usually by no more than fifty. Note that a smaller amount of data is available for each of the classes now due to the further subdivision, so no comparison is possible at the interesting zero to one minute second preceding headway point. Other cases were also broken down into one and two car graphs with similar results.

4.2.3 The Other B Line Periods

The same procedure that was used for the B line morning peak period was used for the three other periods. The graphs derived from the model for the other periods appear here as figures 4.10-4.30. The following sets of manual decision rules were extracted from them.

B Line, Period 2 (midday base):

Short-turn the train under the same conditions as those described for period one.

B Line, Period 3 (evening peak):

Short-turn the train if

\[ H_{prev1} < 1 \text{ min. and } H_{prev2} < 3 \text{ min.} \]

or if \[ H_{prev1} > 8 \text{ min.} \]

B Line, Period 4 (evening off-peak):

Short-turn the train if

\[ H_{prev1} < 3 \text{ min. and } H_{prev2} < 1 \text{ min.} \]

(continued)
Figure 4.10: Wait Time, B Line Period 2, H1P = 0-1

Figure 4.11: Wait Time, B Line Period 2, H1P = 2-3
Pax Min vs H2P, H1P = 4-5

![Graph](image)

Figure 4.12: Wait Time, B Line Period 2, H1P = 4-5

Pax Min vs H2P, H1P = 6-7

![Graph](image)

Figure 4.13: Wait Time, B Line Period 2, H1P = 6-7
figure 4.14: Wait Time, B Line Period 2, H1P = 8-9

figure 4.15: Wait Time, BLine Period 2, H1P = 10-11
figure 4.16: Wait Time, B Line Period 2, H1P = 12+
Pax Min vs H2P, H1P = 0-1

H2P in minutes

figure 4.17: Wait Time, B Line Period 3, H1P = 0-1

Pax Min vs H2P, H1P = 2-3

H2P in minutes

figure 4.18: Wait Time, B Line Period 3, H1P = 2-3
Pax Min vs H2P, H1P = 4-5

**Figure 4.19:** Wait Time, B Line Period 3, H1P = 4-5

Pax Min vs H2P, H1P = 6-7

**Figure 4.20:** Wait Time, B Line Period 3, H1P = 6-7
figure 4.21: Wait Time, B Line Period 3, H1P = 8-9

figure 4.22: Wait Time, B Line Period 3, H1P = 10-11
Fax Min vs H2P, H1P = 12+

Figure 4.23: Wait Time, B Line Period 3, H1P = 12+
figure 4.24: Wait Time, B Line Period 4, H1P = 0-1

figure 4.25: Wait Time, B Line Period 4, H1P = 2-3
Pax Min vs H2P, H1P = 4-5

figure 4.26: Wait Time, B Line Period 4, H1P = 4-5

Pax Min vs H2P, H1P = 6-7

figure 4.27: Wait Time, B Line Period 4, H1P = 6-7
figure 4.28: Wait Time, B Line Period 4, H1P = 8-9

figure 4.29: Wait Time, B Line Period 4, H1P = 10-11
document content
or if \( H_{\text{prev1}} \leq 3 \text{ min.} \) and \( 10 \text{ min.} \leq H_{\text{prev2}} < 12 \text{ min.} \)

or if \( H_{\text{prev1}} \leq \frac{1}{2} \text{ min.} \) (within sight) and \( H_{\text{prev2}} \geq 12 \text{ min.} \)

or if \( H_{\text{prev1}} \geq 12 \text{ min.} \) and \( H_{\text{next1}} > \frac{1}{2} \text{ min.} \) (not within sight)

These results agree with an intuitive expectation for the problem to a degree; the conditions for a short-turn become somewhat more relaxed in the evening peak when outbound passenger trips are at their highest level, thereby providing us with the largest number of potential beneficiaries. The most restrictive conditions for a short-turn are recommended in the evening off-peak period, when train frequencies and the number of potential beneficiaries are lowest.

Note that sometimes, though a given headway class on the graphs appears to be a suitable one for short-turning, the candidate train it describes will not be eligible for short-turning because the guidelines have specified that either the train before it or after it should be short-turned instead; the other train is given preference either because its short-turning would yield higher benefits, or because the inspector does not yet know of the presence of the possibly more advantageous following train. Also note that the "\( H_{\text{prev1}} = 2-3" \) of period four is, for lack of data, assumed to drop below the threshold for the intermediate \( H_{\text{prev2}} \) values, like its counterparts from other periods.
4.2.4 The D Line

The D line results were derived only for the morning and evening peak periods due to the amount of computing time required for the analysis. But the rules from these two periods, in comparison with those for the B line, indicate fairly clear extrapolated rules for the less critical off-peak periods; so I will recommend rules for all four periods.

The guidelines directly suggested by the graphs in figures 4.31-4.44 are given here.

D Line, Period 1 (morning peak):
Short-turn the train if
\[ H_{prev1} \geq 8 \text{ min.} \]

D Line, Period 3 (evening peak):
Short-turn the train if
\[ H_{prev1} \geq 8 \text{ min.} \]

Two characteristics clearly differentiate the D line short-turning guidelines from those of the B line. First, no short-turns are recommended for trains whose first preceding headway is very short. Second, trains with long preceding headways need not have as long a preceding headway before short-turning becomes worthwhile.

By way of explanation, the D line service and ridership differ in two critical ways from those of the B line. The service is more frequent, and the passenger arrival rates are slightly lower. In the morning peak
figure 4.31: Wait Time, D Line Period 1, H1P = 0-1

figure 4.32: Wait Time, D Line Period 1, H1P = 2-3
Pax Min vs H2P, HIP = 4-5

figure 4.33: Wait Time, D Line Period 1, H1P = 4-5

Pax Min vs H2P, HIP = 6-7

figure 4.34: Wait Time, D Line Period 1, H1P = 6-7
Pax Min vs H2P, H1P = 8-9

figure 4.35: Wait Time, D Line Period 1, H1P = 8-9

Pax Min vs H2P, H1P = 10-11

figure 4.36: Wait Time, D Line Period 1, H1P = 10-11
Pax Min vs H2P, H1P = 12+

Figure 4.37: Wait Time, D Line Period 1, H1P = 12+
Figure 4.38: Wait Time, D Line Period 3, H1P = 0-1

Figure 4.39: Wait Time, D Line Period 3, H1P = 2-3

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Pax Min vs H2P, H1P = 4-5

figure 4.40: Wait Time, D Line Period 3, H1P = 4-5

Pax Min vs H2P, H1P = 6-7

figure 4.41: Wait Time, D Line Period 3, H1P = 6-7
figure 4.42: Wait Time, D Line Period 3, H1P = 8-9

figure 4.43: Wait Time, D Line Period 3, H1P = 10-11
Figure 4.44: Wait Time, D Line Period 3, H1P = 12+
period, the week of data from Boylston indicates an average D line headway at Boylston of three minutes and forty-three seconds as opposed to an average B line headway of four minutes and thirty-one seconds. Higher frequency service cuts down on the possibility of a short-turn's success for a train with low preceding headway because, in passing the preceding train, the short-turned train is much less likely to find itself in a long gap between D trains. In other words, with D trains running closer together, the probability of two of them being within a minute of each other without having a long gap in front of the first one is fairly high.

If, on the other hand, we know the gap in front of a D train is a long one, then the gap behind it is likely to be a very short one, and passengers dumped or skipped by the short-turning of the train will not lose much time before the next suitable train arrives. Thus, for a D line train, the preceding gap need not be as long as for a B train before short-turning becomes useful.

On the basis of these premises I suggest that the guidelines for periods two and four for the D line be derived by discarding the short preceding headway cases from the corresponding B line guidelines and by lowering the length of the requisite long preceding headways by one headway class, i.e. two minutes. This procedure results in the following rules:
D Line, Period 2 (midday base):

Short-turn the train if

\[ H_{prevl} \geq 8 \text{ min.} \]

D Line, Period 4 (evening off-peak):

Short-turn the train if

\[ H_{prevl} \geq 10 \text{ min.} \]

This set of D line guidelines turns out to be considerably simpler than the B line rules.

4.2.5 Alternative Short-Turn Measures

As discussed in chapter two, the number of passenger minutes saved is not the only criterion by which to measure the success of a short-turn. Consequently, the model was designed also to record the number of passengers dumped and the ratio of benefitted to disbenefitted passengers for each short-turn under consideration. So just as with passenger minutes, I have graphed both the expected numbers of passengers dumped and the ratio of benefitted to disbenefitted passengers as a function of their preceding headway classes for the B line in period one. The passengers dumped graphs appear in figures 4.45-4.51, and the ratio graphs in figures 4.52-4.58.

Both sets of graphs clearly follow the same simple pattern. As first preceding headway increases, short-turning becomes less desirable. All of these graphs are fairly indifferent to second preceding headway variations.
figure 4.45: Pax Dumped, B Line Period 1, H1P = 0-1

figure 4.46: Pax Dumped, B Line Period 1, H1P = 2-3
figure 4.47: Pax Dumped, B Line Period 1, H1P = 4-5

figure 4.48: Pax Dumped, B Line Period 1, H1P = 6-7
Pax Dumped vs H2P, H1P = 8-9

![](chart1.png)

figure 4.49: Pax Dumped, B Line Period 1, H1P = 8-9

Pax Dumped vs H2P, H1P = 10-11

![](chart2.png)

figure 4.50: Pax Dumped, B Line Period 1, H1P = 10-11
figure 4.51: Pax Dumped, B Line Period 1, H1P = 12+
Ratio of Ben. to Dis. vs H2P, H1P = 0-1

figure 4.52: Benefitted Ratio, B Line Period 1, H1P = 0-1

Ratio of Ben. to Dis. vs H2P, H1P = 2-3

figure 4.53: Benefitted Ratio, B Line Period 1, H1P = 2-3
figure 4.54: Benefitted Ratio, B Line Period 1, H1P = 4-5

Ratio of Ben. to Dis. vs H2P, H1P = 4-5

H2P in minutes

figure 4.55: Benefitted Ratio, B Line Period 1, H1P = 6-7

Ratio of Ben. to Dis. vs H2P, H1P = 5-7

H2P in minutes
Ratio of Ben. to Dis. vs H2P, H1P = 8-9

Ratio of Ben. to Dis. vs H2P, H1P = 10-11

figure 4.56: Benefitted Ratio, B Line Period 1, H1P = 8-9

figure 4.57: Benefitted Ratio, B Line Period 1, H1P = 10-11
Ratio of Benefited to Disbenefited vs H2P, H1P = 12+

figure 4.58: Benefitted Ratio, B Line Period 1, H1P = 12+
But as the first preceding headway increases, the number of passengers dumped increases, and the ratio of beneficiaries decreases.

Both of these results suggest that short-turning should be carried out only for trains with short preceding headways and that we should reconsider the long preceding headway cases in our decision guidelines. What happens when a short-turn is carried out under one of these measures? When a train is short-turned after two very short preceding headways, it is usually inserted in the outbound headway sequence in a long gap preceding the two short gaps. It dumps only few passengers due to its small preceding headway, which gives no time for a large accumulation of passengers at the inbound stations. For the same reason, there are also very few outbound passengers who would have boarded it had it not been short-turned. So the number of passengers dumped is small and the ratio of benefitted passengers is large.

When a train is short-turned after a long gap, it almost certainly passes no trains of its own line in the process; it simply narrows the gap between it and its first preceding train. It dumps a large number of people, who had a long time in which to collect at inbound stations. But since the first following train is probably very close behind, they are not likely to be delayed very long. The same is true for the large number of outbound passengers who would have boarded the train had it not been
short-turned. They may have to wait only an extra minute or so for the next train, which will be considerably less crowded than the short-turned train would have been. The beneficiaries, who are also a large group, are each saved the full four or five minutes of the short-turn time savings. So the number of passengers dumped and otherwise delayed is large, but the length of their delay is likely to be small. The number of beneficiaries is also large, but so is the time savings realized by them.

So, where the guidelines allow it, the short-turning of the second train after a long gap in service, rather than the first train, makes sense. But, in the current manual scenario, it is not often known if the second train is close enough behind the first to allow for this practice, and the current guidelines thus cannot allow it very often. Visual contact with the following train by the inspector is the limiting constraint.

And the benefitted passengers ratio values only seem intuitively discouraging if the numbers frequently approach zero. A ratio of 0.6, for example, is not a bad result if it has been demonstrated that net passenger minutes are saved by the decision; such a figure implies that a fairly large number of people were inconvenienced by a fairly small amount of time in order to save a slightly smaller group of people a more significant amount of time. This is a bad result only when the small group is very small indeed, not often the case in these graphs.
So while these alternative success measures do not fully support the decision guidelines developed in the preceding sections, they fall far short of discrediting them. This thesis has made use of passenger minutes saved as the best single measure for the success of operating decisions on a transit system. The alternative measures presented here simply indicate that some of the short-turns suggested here have other costs than those focussed on in this thesis. If we were to shift the emphasis of this research, more severely limited short-turning, or even no short-turning at all, might seem to be reasonable strategies. Some further discussion of these alternative perspectives will be found in the conclusion of this thesis.

4.3 Success of the Guidelines

A study of the B line period one raw results yielded measures for the success of short-turn decisions made under each of the three scenarios of interest: current practice, manual control using the recommended guidelines, and AVI control using the model as a decision maker in the manner envisioned in chapter three. A successful short-turn decision was defined as one which resulted in positive net passenger wait time savings. For each of the three scenarios, the number of short-turns carried out during the period under study, the percentage of them that were
beneficial, and the total number of passenger minutes saved were derived.

The number of short-turns carried out under current practice was determined from the records kept by the Boylston inspector. The percentage of beneficial short-turns was estimated by calculating, for each of the short-turned trains, the fraction of the thirty-five modelled trials with positive passenger minute savings, and then adding up the fractions; i.e. for each train short-turned, there is a likelihood of its being a beneficial short-turn, and by adding up these percentages we get the expected number of beneficial decisions. Dividing this number by the number of short-turns made gives a percentage success rate. The total number of passenger minutes saved is arrived at by adding together the average number of minutes saved by each of the short-turned trains.

The number of short-turns that would have been carried out under the recommended guidelines was derived simply by applying the guidelines to the known headways for each of the trains in the study period. The resulting list of short-turned trains was then treated in the same way as the list of trains short-turned under current practice to get the other two values.

Under AVI control, the model will give an actual number of passenger minutes saved for each candidate train. So the rule for short-turning a train becomes simply that
the model indicate savings of over two hundred and fifty passenger minutes for the proposed short-turn. So to derive the number of short-turns made under AVI control, one finds the fractional number of times each train is predicted to yield over two hundred and fifty minutes by being short-turned, and then one adds up these fractions for all the trains in the study period. Thus, if out of the thirty-five trials in the modelled distribution, ten of them have indicated savings of over two hundred and fifty minutes, then the train is considered to have been short-turned an average of ten thirty-fifths, or two sevenths, times.

The expected number of passenger minutes saved under AVI control is then calculated by multiplying the fraction derived above for the train in question by the average number of minutes saved for that train; this gives an expected number of minutes saved under AVI control for each train. The list of expected minutes saved is then summed up to get the total number of minutes saved in the AVI scenario.

If one believes the model is perfectly accurate, it will never make a bad decision, and, not only will every short-turned train have a positive associated net wait time savings, it will result in savings of at least 250 minutes. Thus, the percentage of success is one hundred per cent, according to the model.

But if, as suggested in chapter two, we treat the
modelled distributions as proxies for the distributions of the actual passenger minute results around the determinate result given by the model, we can make a rough approximation of a more realistic success rate. This dummy success rate is derived by multiplying the percentage likelihood of a short-turn's resulting in passenger minute savings of more than 250 minutes, i.e. the likelihood of our selecting the train in question for short-turning under AVI control, by the percentage likelihood of its resulting in positive passenger minute savings. This gives an expectation for the number of successful short-turns made for each train under consideration. These are summed to get a total number of expected successful short-turns.

The figures for each of these scenarios appear in table 4.3. The trend revealed in the table indicates that tightening up the decision rules to those recommended here will decrease the number of short-turns made in the study period, from forty-four to thirty-two out of a total of 146 trains considered, but that the success percentage will increase substantially, from seventy-four per cent to ninety-four per cent, and that the total number of passenger minutes saved will increase from about 9400 to about 13,000 in spite of the smaller number of short-turns.

Instituting the AVI control system should allow the number of short-turns to be brought back up to its current level while maintaining the accuracy of the stricter set of manual rules. Note that the ninety-three per cent success
Table 4.3: Aggregate Results for Three Scenarios

<table>
<thead>
<tr>
<th>scenario</th>
<th>current</th>
<th>recommended</th>
<th>AVI-controlled</th>
</tr>
</thead>
<tbody>
<tr>
<td>number of ST's in period</td>
<td>44</td>
<td>32</td>
<td>42.9</td>
</tr>
<tr>
<td>success percentage</td>
<td>73.8%</td>
<td>93.6%</td>
<td>92.7%</td>
</tr>
<tr>
<td>pax minutes saved</td>
<td>9378</td>
<td>13022</td>
<td>17199</td>
</tr>
</tbody>
</table>

number of trains considered here, all from a.m. peak: 146
rate for AVI control is not directly comparable to the figures for the other two scenarios. For the reasons given above, the directly comparable figure is one hundred per cent, but a more realistic comparison would be made by revising the current and recommended success rates according to some probability distribution in the same manner that the AVI figures were revised; however, not enough data is presently available for this procedure.

4.4 Summary of the Guidelines

The recommended manual decision guidelines presented in section 4.2 are repeated here in summary form. Trains should be short-turned on each line under the following circumstances:

B Line

7a.m.-3p.m.

\[ H_{prev1} \leq 1 \text{ min. and } H_{prev2} \leq 1 \text{ min.} \]

OR \[ H_{prev1} \leq 1 \text{ min. and } 8 \text{ min.} < H_{prev2} < 10 \text{ min.} \]

OR the inspector can see the candidate train when \(\text{train prev1 is at the decision point} \)
and \[ H_{prev2} \geq 10 \text{ min.} \]

OR \[ H_{prev1} \geq 10 \text{ min. and the inspector cannot yet} \]
see train next1.

3p.m.-6p.m.

\[ H_{prev1} \leq 1 \text{ min. and } H_{prev2} \leq 3 \text{ min.} \]

OR \[ H_{prev1} \geq 8 \text{ min.} \]
6 p.m.-9 p.m.

\[ H_{prev1} \leq 3 \text{ min. and } H_{prev2} \leq 1 \text{ min.} \]

OR \[ H_{prev1} \leq 3 \text{ min. and } 10 \text{ min.} \leq H_{prev2} < 12 \text{ min.} \]

OR the inspector can see the candidate train when

\[ \text{train prev1 is at the decision point} \]

\[ \text{and } H_{prev2} \geq 12 \text{ min.} \]

OR \[ H_{prev1} \geq 12 \text{ min. and the inspector cannot yet} \]

\[ \text{see train nextl.} \]

D Line

7 a.m.-6 p.m.

\[ H_{prev1} \geq 8 \text{ min.} \]

6 p.m.-9 p.m.

\[ H_{prev1} \geq 10 \text{ min.} \]

I hope that these guidelines may prove useful for the short-term operation of the Green Line. They should be used, however, with the warnings of the next chapter in mind and should serve not as hard and fast rules, but only as guidelines.
Chapter 5
A Critical Assessment

This penultimate chapter will reconsider some of the weaknesses of the approach taken by this thesis which have been alluded to earlier. A complicated operations problem of the sort studied here does not easily submit to analytical treatment, and those who use the results of such a treatment should know its limitations. I do not intend to say that analytical treatment is useless, for the results of an intuitive approach to this problem, necessarily deduced from insufficient information on many of its aspects, are almost certain to be inferior. Rather, I mean only that the user of analytically derived results should know to what degree they are the best that can be achieved and in what ways they probably ought to be improved.

This chapter will look first at internal weaknesses of the approach used, weaknesses related not to the structure of the model but to the information it processes. It will then summarize the weakest of the assumptions on which the model was based.

5.1 Sensitivity to Changes in the Principal Inputs

This section consists primarily of three sensitivity analyses carried out on the model to determine to what
degree inaccuracies in the input data used by the model might affect the results produced. The three critical input values examined include run time savings effected by a short-turn, C and E line westbound headways, and passenger arrival rates. If the data used in this study differ significantly from actual figures, or if the figures change dramatically in the future, to what degree are the results produced by the model invalidated?

This question has been approached by running modelled trials on seven randomly selected trains from the morning peak period after shifting the input values of interest and then comparing the passenger wait time savings and other results with those derived previously. The average percentage change in the results is judged to represent the expected effect on the final results of a change in the inputs. If the inputs were to change in the manner suggested, the resulting short-turn guidelines would almost certainly change from those suggested in chapter four. Such a change, however, would not affect the analysis given here, which is independent of the decision guidelines.

Table 5.1 gives the impacts on the number of dumped passengers, on the ratio of the number of passengers benefitted to those disbenefitted, and on passenger wait time, of the stated changes to the inputs.
Table 5.1: Sensitivity Test Results

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Passengers Dumped</th>
<th>Benefitted / Disbenefitted Ratio</th>
<th>Avg Passenger Minutes Saved</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turnaround time decreased 50%</td>
<td>unch</td>
<td>+1.1%</td>
<td>+11.4%</td>
</tr>
<tr>
<td>Passenger arrivals increased 10%</td>
<td>+11.3%</td>
<td>unch</td>
<td></td>
</tr>
<tr>
<td>C &amp; E westbound headways decreased 20%</td>
<td>unch</td>
<td>+10.7%</td>
<td>+12.0%</td>
</tr>
</tbody>
</table>
5.1.1 Short-Turn Time Savings

The first input variable changed was the turnaround time for a short-turned train at Park Street. In other words, if the time a train short-turned at Park Street took between opening its doors at Park Street northbound and opening its doors at Park Street westbound were cut by fifty per cent, what impact would this have on the resulting output values? Cutting the average value of this figure by fifty per cent would clearly increase the average time savings achieved by a short-turned train.

As one might expect, the number of passengers dumped is unaffected by a change in time savings, because nothing that affects the passengers on board the train at Park Street northbound is influenced by the train's proposed short-turn time savings increase. The benefitted to disbenefitted ratio also changes very little, because the average numbers of people affected have not been changed much in this test; only the time they are saved is changed significantly. So, predictably enough, the real change occurs in the passenger minutes saved result, which increases by eleven per cent, a reasonable result since the test has eliminated a couple of minutes of dead time for the train of interest.
5.1.2 Passenger Arrival Rates

In this sensitivity test passenger arrival rates over the entire system have been increased by ten per cent. Unless such an increase puts severe pressure on the capacity constraints of the current service, one would expect such a test to increase the absolute numbers of everything by approximately ten per cent, but not to affect any of the proportions. And indeed, such is the result we see. The number of passengers dumped and the number of passenger minutes saved both increase about ten per cent along with the population of passengers affected. But the benefitted to disbenefitted ratio changed negligibly, since the proportions of the passenger classes of the base case have not changed significantly.

5.1.3 C and E Line Westbound Headways

The third sensitivity test decreased average headways on the C and E lines westbound, meaning an increase in westbound service. Once again, such a change had no impact on the number of passengers dumped, because no change in westbound service affects the northbound passengers in this model. The dominating effect of this change on the other two measures was to improve the benefits achieved. The benefitted to disbenefitted ratio increased by eleven per cent, and the wait time saved increased by twelve per cent.
These increases probably resulted from the lower extra wait times experienced by westbound central subway passengers. Such passengers, who could take any of several lines, now have more frequent service available to them, so that the short-turned train becomes less likely to have been the one they would have boarded anyway. Thus the number of disbenefitted passengers decreases and, the number of extra passenger minutes waited decreases, resulting in an increase in net passenger minutes saved.

5.1.4 Significance of Sensitivity Tests

The fairly modest changes in the results caused by the input changes of these sensitivity tests are in line with the intuitively expected behavior of the system. Nor do they indicate any weakness of the model that may lead to drastic changes in the results associated with relatively minor input changes.

They are not, on the other hand, such minor variations that the results presented in this thesis can be treated as inelastic. Large changes in the operation or ridership of the Green Line will clearly require recalibration of this model if appropriate decision guidelines are desired. It is to be hoped, however, that a comprehensive AVI operating system will enable frequent updating of many of the variables that are here input as fixed values, thereby obviating much of the need for continual recalibration of
such a model. Taking accurate calibration of the model for
granted, a system operator making use of the model's
results should lay more stress on an understanding of the
model's built-in limitations.

5.2 Critique of Assumptions

This thesis has made many assumptions concerning the
operations and ridership of the Green Line, most of which
were unavoidable and perfectly defensible. A careful
reading of chapter two should give one a good picture of
what these are. This section will discuss only a few of
the most important of these assumptions, ones which may
have a great impact on the results and whose certainty is
in doubt.

5.2.1 Passenger Arrival Rates

The passenger arrivals extracted from the CTPS data
are wholly deterministic in the model used here; fixed
arrival rates are used for passengers at each station.
Allowing for variability of these figures might result in
significant variation in the derived passenger loads of
each train and give different final output values. But
consider the difficulties of implementing a more accurate
model.

The data as tabulated by CTPS is broken down into
fifteen minute intervals, probably not a small enough period to allow for an accurate picture of the true variability of the arrival rates. To generate an accurate random distribution of arrival rates, a model of this nature would require arrival figures at about the one minute interval level, i.e. a period on the scale of the train headways. To achieve such detail would require a tremendous data collection effort, clearly beyond the means of this project. One could instead simply assume that the arrival of passengers is a Poisson process, but, even then, the generation of so many random numbers, one for every station in each direction, would probably overwhelm the computational capabilities of the system on which the model was developed.

Furthermore, such an elaborate stochastic procedure would probably increase the accuracy of our model very little. At most stations, the variance in passenger arrivals is probably not very great. The modelled result of making passenger arrivals probabilistic would largely be to spread the distributions of the final passenger minute results, i.e. to increase the standard deviations of the second previous headway graphs in chapter four.

To some extent, the AVI results given in chapter four have already accounted for such a possibility by applying the existing distributions, attributable to variables that would be known under AVI control, to the AVI case, in which only variance not considered by the model, and unknown to
the AVI system, will play a part. In this way the results use variance resulting from such things as C and E headway distributions as a proxy for variance that stems from such figures as passenger arrival rates, which will not be definitively known in the AVI scenario.

At only two stations might passenger arrival variance be so high as to result in unpredictable train capacity effects, Park Street and Government Center, where transfers with other lines result in heavy, periodic surges of arriving passengers. At these points, more careful modelling of minute to minute arrivals might be merited.

The other incompletely treated aspect of passenger arrivals is the continuous change in rates over the course of the day. The CTPS counts, which are organized into fifteen minute intervals, would allow significantly more detailed treatment of these changes than has been undertaken here. Modelling each of these periods separately would result in a custom designed rule for every part of the day, rather than the current rules derived for four broadly aggregated periods of the day. But such a profusion of rules is unsuitable for manual control as well as requiring a tremendous analytical effort.

Nonetheless, the continuous variation of expected passenger arrivals as a function of the time of day should be taken seriously and is worth consideration in the implementation of an automated decision process. Period four, especially, which combines the tail end of the p.m.
peak with the true off-peak period, deserves consideration for further disaggregation.

5.2.2 Congestion Effects at Government Center

Several parties at the MBTA indicated that one potential benefit of short-turning was a decrease in train congestion at Government Center. They felt that running too many B and D trains close together into their northern terminus sometimes results in time lost because trains physically block each other in the loop at this station, e.g. turning B and D trains might get in the way of westbound C and E trains and slow each other down by preventing following trains from pulling in at the platform.

However, no trends relating the time it took for a train to travel through Government Center to the crowding of trains into the station could be established. Such other effects as dwell times related to passenger numbers, train operator differences, and signalling presumably drowned out any congestion effect. At higher service frequencies, further treatment of this aspect of short-turning may be necessary, but at its current level, it forms just another element of the random noise affecting any decision on the system.
5.2.3 Headway Treatment

The model currently accepts the headways seen at Boylston as the headways that held true for the whole run of each train in from its terminus and as holding true, except insofar as operating decisions influence them, for the whole run of each train back out to the terminus. This is a gross assumption that will clearly very rarely hold true. If the system is operating properly, trains should leave their termini at the even intervals dictated by their schedules; a conspiracy of uneven passenger arrivals, varying train operator behavior, dwell time effects, and traffic lights will result in the rather uneven headways observed at Boylston.

By using the Boylston headways as representative of the whole route, the model clearly biases the passenger load figures, so that heavy loads are probably heavier than they will actually be and lighter loads lighter than they will actually be. A B train right behind another B train will have almost no passengers on board at Boylston according to the model. But this presumes that there has been no gap between the trains ever since they set out from the Lake Street terminal. Actually, before the following train caught up to the first train, it may have collected a significant number of passengers.

Only data observable at Boylston, however, is currently available to the Boylston inspector, and the
research in this thesis was based mostly on his observations. A careful study of headway propagation was not within the scope of this paper. So we must ask how the approach taken is likely to influence the results.

The model's assumption relative to the outbound run is probably not bad, because at the time the decision is made the decision maker can know little about how the headway sequence will propagate through the westbound run. The sequence used here is a reasonable expectation.

The inbound run, the influence of which is fortunately less critical to the results than that of the outbound run, might be more accurately modelled, however, by averaging the scheduled headways with the observed headways at Boylston in calculating the passenger loads. Because of the overestimation of heavy loads and underestimation of light ones, the results may be biassed too much in favor of short-turning the second of two closely spaced trains. To what degree it is biassed this way this thesis can not say. Carrying out such sensitivity tests lies in the realm of further research suggested in the next chapter.

When AVI control is established, however, much more will be known about the propagation of the inbound headway sequence. Thus, when a model like the one presented here is developed for short-turn decision making, it ought to employ a more sophisticated calculation of inbound passenger loads than the current model's. Since headway figures will be available at several points on a train's
inbound run, each set of headways can be used to furnish the passenger load changes since the last detector in the manner described in chapter three, section three. Such a process will largely eliminate any of the load biasing risked here.

5.3 Encapsulation of the Critique

To redress all of the assumptions of the modelling carried out in this thesis would require a combination of large new data collection efforts, implementation of AVI and other automated information and control systems, and design of expanded modelling treatments of the problem. Within the limited scope that the thesis set for itself, however, the research described here presents a tolerably complete picture of the short-turn problem. The next chapter will summarize what has been done in the preceding pages, suggest directions for further research, and present some of the author's conclusions from the work done.
Chapter 6
Conclusion

The three sections that compose this final chapter will summarize the work described in this thesis, suggest extensions of this work, and comment on the perspective from which this thesis was written.

6.1 Thesis Summary

The opening sections began with a discussion of headway variability's impacts on transit passengers' wait time and described the real time operating strategies that can be used to correct unnecessary variation in the headway distribution. Among the strategies that are frequently used on the MBTA's Green Line light rail system are holding, expressing and short-turning, the last of which is the focus of this thesis. The current decision process and its weaknesses were described in chapter two, as were the reasons for selecting total passenger minutes waited as the primary criterion for judging the value of any given short-turn's success. The further criteria, number of passengers dumped and the ratio of benefitted to disbenefitted passengers, were selected as supplementary to an understanding of the problem.

The bulk of chapter two was devoted to the development of a computer model that estimates the impacts of a short-
turn. By entering real Green Line data into the model, one makes it possible to identify situations in which short-turning is likely to be beneficial.

Chapter three develops values to be input to the model for variables not recorded in the data sheets kept by the inspector at the Boylston Street station, the primary record from which the model inputs are derived. This chapter also develops the procedure by which all variables may be input to the model when data collection on the Green Line is automated by use of an AVI system. When this is in place, the results presented here, based on likelihoods and translated into simple rules, can be replaced by an automated short-turn recommendation process that analyzes actual rather than probable conditions on the Green Line.

Analysis of computer generated simulations of short-turns appears in the next chapter; these simulations are based on the inputs developed in chapter three as well as on a week of headway data extracted from the Boylston sheets. Expected results are broken down according to the handful of inputs available to the Boylston inspector to indicate under what circumstances a short-turn has an expected beneficial impact on passengers's wait time. The other criteria for success are also analyzed in an attempt to understand the results better. The manual scenario recommendations derived from these analyses are summarized in section 4.4. Use of these recommendations is predicted to save passengers almost forty per cent more wait time.
than is currently saved by short-turns and to inconvenience many fewer passengers in the process. Parallel analysis of short-turning under AVI control indicated an eighty-three per cent increase from today's rate of passenger minutes saved.

A critique of the methods used to derive these results appears in the chapter just previous to this one. The criticisms offered are significant and offer many openings for improvement of the techniques used here, yet they do not invalidate the considerable improvements possible through use of these techniques.

6.2 Recommendations for Further Research

With respect to directly improving the reliability of the results obtained from the model used here, only the supplementing of the C and E westbound headway data might prove truly helpful. The data used to estimate the median and standard deviation values from which these figures were generated came from a rather small data set, though an accurate one as far as it went. But this is the only direct improvement I can suggest to the model as it stands.

More importantly, the model could be used to further an understanding of the impact on wait time savings of short-turning two trains in a row or of short-turning two trains within several trains of each other. The latter of these is not forbidden by the results given here, but the
model is not explicitly designed to handle such a case. A modification of the model would be required to carry out a careful analysis of this problem. I believe that the short-turning of trains several headways apart from each other will not significantly affect the results given here, but that the short-turning of sequential trains will usually negate the positive benefits of short-turning either of them separately. The interesting cases will be the in-between ones.

Of equal importance in terms of testing the reliability of the results presented here are the sensitivity tests that could be carried out by a simulation model of the Green Line. The study of which this thesis forms a part is currently developing a probabilistic computer simulation of the system that will explicitly consider such factors on headway sequences as dwell times, line merges, and operator performance. By running a number of cases based on the Boylston data in from the western termini, the accuracy of the passenger load figures used in this model could be judged. If they prove significantly inaccurate, the judicious use of the simulation model could suggest a correction factor to the numbers in the model used here.

Another important research effort will hopefully amalgamate the findings of this study on short-turning with other, compatible studies on expressing and holding of trains. These alternative operations strategies, described
in the first chapter, will be weighed against each other to determine the most suitable action. Which, this research will determine, is the most beneficial strategy, or combination of strategies, among those available? What will save the most wait time among all the possible actions that can be taken? This thesis forms the first companion volume to Richard Macchi's thesis on the expressing of Green Line trains in furtherance of the ultimate goal of developing comprehensive real time operating strategies.

6.3 Concluding Remarks

This thesis essentially assumes that short-turning is a potentially beneficial real time operating strategy. If, however, one treats one of the measures suggested in chapter two, number of passengers dumped, as the dominant impact consideration, short-turning will never seem to be a good strategy. Short-turning a train necessarily dumps passengers, sometimes in large numbers. Therefore, to maximize benefits measured in this way, one ought never to short-turn trains.

People, in general, remember service problems on a transit system in terms of the worst experience they have had on it. For many riders of the Green Line, being on a short-turned train while travelling to Government Center is the most inconvenient experience of the system that they have undergone. Rarely does the relatively unobtrusive
experience of a long wait engender such frustration. Short-turning costs more in passenger relations than almost any other operations strategy in frequent use on transit systems, and should generally be carried out as infrequently as possible.

When the situation allows it, a redesign of the scheduling or routing might preferably be carried out in such a way as to minimize the need for extraordinary real time operating strategies. If unscheduled route changes need to be carried out with such regularity, perhaps the scheduled routes need reconsideration. I have not made a careful study of routing requirements on the Green Line, and there are significant operational considerations to be dealt with, but it seems possible that a route change along the following lines could serve as an alternative to the great numbers of short-turns currently made.

The B line, not surprisingly, has the headway distribution with the highest standard deviation of the four lines on the Green Line. This fact is due to the B line's having the second longest route with the longest section of non-grade separated right of way. The D line, though grade separated, has by far the longest route of the four; it has the second highest headway standard deviation. Consider then that these two lines terminate at the only northern terminus from which trains cannot be dispatched according to a schedule.

Both the C and E lines can be redispachted from their
northern termini, thereby virtually eliminating the need to undertake real time strategies to even out their westbound headways. This is possible because North Station and Lechmere Square have space for trains to be held without interrupting other services. But the C and E lines are precisely the two lines that do not need this advantage. The E line especially, with the shortest route and smallest standard deviation of headways, would seem to have little need for such a luxury.

With regard to evening out westbound headways and thereby saving passengers considerable waiting time, therefore, it makes sense to terminate the B and D lines at North Station and Lechmere, in either order, and to turn the C and E lines around at Government Center.

Unfortunately, it is never simple to optimize all aspects of a transit system's operation simultaneously, and possible obstacles to such a scheme are not in short supply. The E line, for example, has no staging area other than Lechmere since the discontinuance of service to Arborway, and its trains need to be dispatched from somewhere. And it is possible that the current run times on each of the lines are especially compatible with an efficient work force allocation and schedule.

But should a redesign of the Green Line routing take place, service reliability considerations and the operating strategy responses to them ought to be carefully examined. This thesis is not intended to give the impression that
short-turning is a purely beneficial practice when carried out properly. When by less obtrusive means it can be avoided, then it ought to be avoided. Real time operating strategies are necessary evils intended to correct service failures not correctable by alternative means. If route and schedule planning can reduce the need for such strategies, an operating agency earns little credit by carrying out such strategies well.
References


