Improving Service on the MBTA Green Line Through Better Operations Control

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The Massachusetts Bay Transportation Authority (MBTA) Green Line is a four-branch light rail network that includes the nation's oldest subway section. It is operated with one- and two-car trains using articulated vehicles at trunk headways of less than 90 sec. Although a major investment has been made in track reconstruction, upgrading the power distribution system, and vehicle acquisition over the past decade, the high-frequency, high-ridership nature of the system makes it difficult to maintain good service quality given the myriad disruptions in service that routinely occur. Until now the critical operations control function has been performed principally in the field by supervisors located at key points in the system deciding whether and how to intervene in ongoing operations. Currently an automatic vehicle identification system is being implemented for the Green Line that will eventually provide the opportunity to restructure the operations control process.

The performance of any transport system is most strongly influenced by its infrastructure and vehicles, the operations plan, and operations control procedures. In the short run, because infrastructure and vehicle characteristics cannot be changed because of the associated long lead times and high capital costs, improvements in performance are most likely to come through changes in the operations plan and through better operations control. The operations plan, which includes routes, service frequencies, and vehicle and crew schedules, should reflect typical operating conditions in terms of both demand characteristics and vehicle operating characteristics. Although a well-designed operations plan is essential for good system performance for any public transport service, in general it is rare that the plan is executed exactly because of inevitable major and minor events that disrupt operations. Dealing with these deviations from the operations plan is the function of the operations control process.

Operations control is the general description of actions that are determined dynamically, in real time, to minimize the negative effects of disruptions in operations and to maintain high service quality despite these unexpected events. Although operations control is necessary in any public transport system, its importance will vary depending on the frequency and magnitude of deviations from the operations plan. The Massachusetts Bay Transportation Authority (MBTA) Green Line is a high-frequency, highly constrained branching light rail system in which operations control is critical in determining system performance.

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MBTA GREEN LINE

The MBTA, the dominant public transport operator in the Boston metropolitan area, provides service on four major interconnecting rail transit lines, the Red, Orange, Blue, and Green lines, and on an extensive bus and commuter rail network. Of these four lines the Green Line, the major light rail line, provides perhaps the critical element in the whole system. It runs south then west from the Lechmere terminus to the branch termini at Boston College, Cleveland Circle, Riverside, and the Arborway, interconnecting with all three rapid transit lines. Thus the Green Line serves a vital collection and distribution function for the transit system as a whole, as well as providing the rail commuter network for the inner western suburbs (see Figure 1).

The Green Line has four branches, referred to as B, C, D, and E, that converge into a common central subway in the downtown area of Boston. The D Line is the longest line (only about one-half of the D branch is visible in Figure 1), its stops are spaced the farthest apart, and it is the only line operating on a fully reserved right-of-way. The B, C, and D lines meet at Kenmore station, whereas the E Line joins the central subway at Copley. Operation in street traffic results in running time uncertainty on the B and C lines especially, and to a lesser degree on the E Line, while the length of the D line also contributes to running time variation.

Within the central subway, turnback tracks exist at Park Street, Government Center, and North Station, providing some flexibility in both route design and real-time control actions for the different branches. The current Green Line operating route structure is as follows:

- B line—Boston College to Government Center,
- C line—Cleveland Circle to North Station,
- D line—Riverside to Government Center, and
- E line—Heath Street to Lechmere (the section from Heath Street to Arborway is closed for reconstruction).

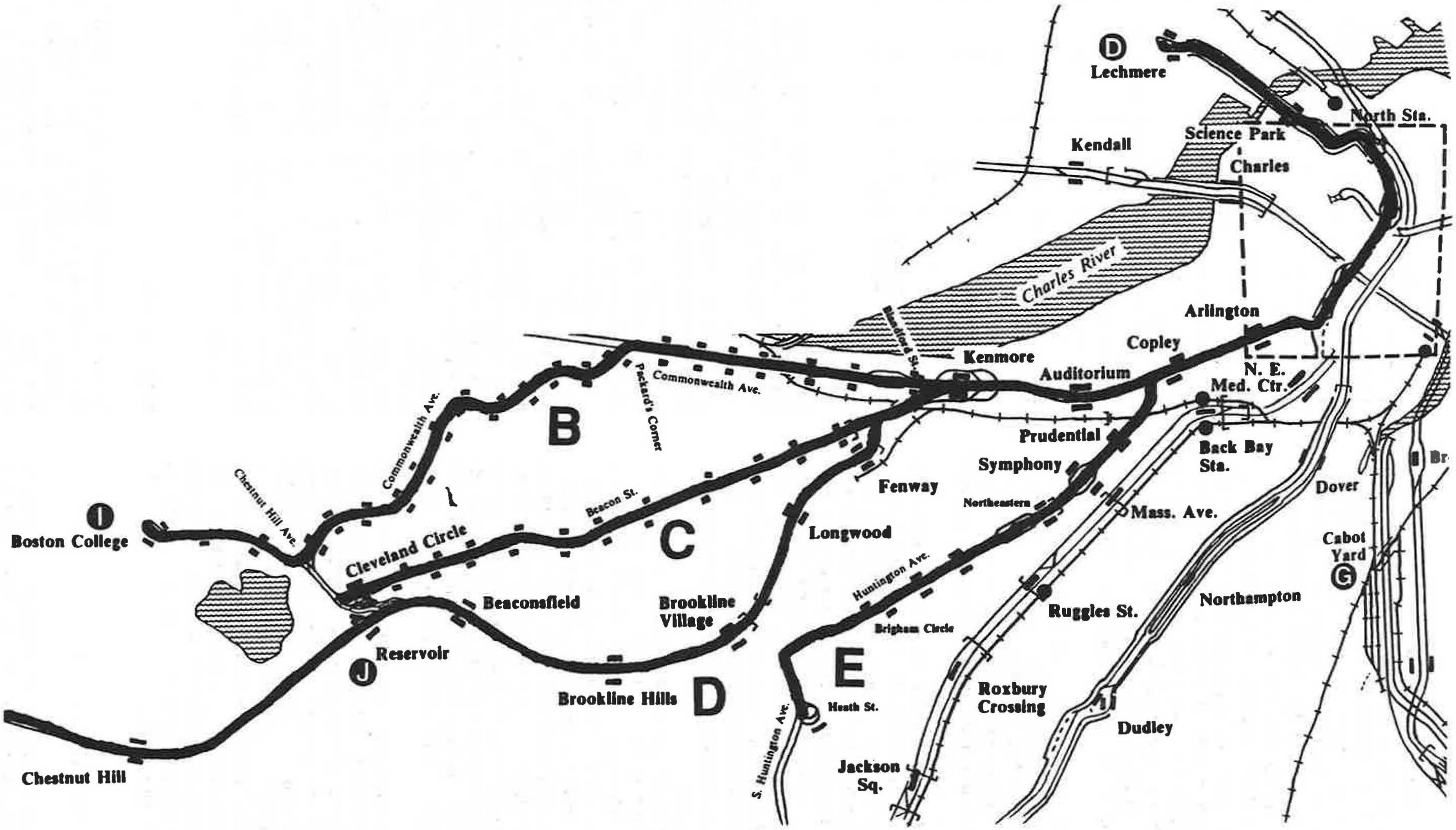

FIGURE 1 Green Line subway and branch lines (source: Boston Track Map, © 1986 Boston Street Railway Association, reprinted with permission).

North Station and Lechmere serve as termini for the C and E lines, respectively, and these lines have scheduled departure times at both ends. In contrast, B and D line trains in the central subway simply turn around at Government Center without any recovery time built in, because there is no place to store trains. Thus C and E line running time variation can be corrected at each end of the line, whereas inbound B and D variations, if left alone, propagate to the outbound direction because they are essentially dispatched from their western termini as loop systems. Park Street Station, the interchange point between the Red and Green lines and the highest volume station on the line, is particularly important because the Red Line frequently generates large surges in passenger volume, and much of the Green Line operations control is focused here.

The Green Line operates one- and two-car trains using articulated light rail vehicles (LRVs), at scheduled headways of 5 to 10 min on the four branches (see Table 1), which, when combined, produce central subway headways of 1 to 2 min for much of the day. These short headways are required to serve an estimated 189,000 daily riders.

The structure and ridership of the Green Line both create significant operations problems and afford (to some extent) the opportunity to intervene to correct these problems as (or even before) they occur. It is the combination of mixed street traffic, merging branch lines, passenger surges from connecting lines, low headways, and high ridership that presents a considerable challenge to Green Line management. The question is not whether to intervene to improve operations—the line requires constant monitoring and intervention—only where and how the intervention should occur to maximize benefits to the riders.

Before turning to the operations control function, it is appropriate to indicate to what extent actual operations correspond to the operations plan. Table 1 presents information on schedules and actual headways for a randomly selected day (January 20, 1988, the winter 1988 schedule) at the start of this study for each line by time of day at Boylston Street Station (northbound) in the central subway. Actual headways were derived from the log kept by the chief inspector stationed at Boylston. Mean headways may vary from scheduled headways because of trips not run (thus increasing headway) or two-car trains being run as two single-car trains (thus reducing headway).

Of particular interest is the standard deviation of the headway. Ideally the standard deviation would be at, or very close to, zero, indicating evenly spaced trains. As the table indicates, typical headway standard deviations are in the range of 4 to 6 min, or about 75 percent of the mean scheduled headways. This clearly suggests that passengers will see the service as being much less reliable than the schedule promises.

With such variation in headways, average passenger waiting times will be several minutes higher than the ideal case, and in a significant number of cases some operations control intervention may be appropriate.

TABLE 1 Headway Analysis for January 20, 1988

	Time Period		
Line	**7 - 10 a.m.**	**10 a.m. - 3 p.m.**	**3 - 6 p.m.**
B Line			
Scheduled Headway	5.0	5.0	6.0
Mean Headway (H)	5.3	5.2	6.1
Std. Deviation (H)	5.0	4.9	7.0
C Line			
Scheduled Headway	6.5	5.0	7.0
Mean Headway (H)	6.4	5.3	6.8
Std. Deviation (H)	4.0	3.7	5.5
D Line			
Scheduled Headway	5.0	5.0	6.0
Mean Headway (H)	5.8	5.1	6.8
Std. Deviation (H)	4.1	4.2	4.6
E Line			
Scheduled Headway	6.0	6.0	6.0
Mean Headway (H)	6.3	6.1	6.4
Std. Deviation (H)	4.0	2.7	5.0
Central Subway			
Mean Scheduled Headway	83 secs	78 secs	93 secs

OPERATIONS CONTROL OPTIONS

The general aim of operations control actions is to optimize system performance given the system state. Although system performance includes both the authority's and the passengers' perspectives, in the case of real-time decisions, effects on operating costs are likely to be relatively unimportant because the labor costs are fixed, except for possible incremental overtime payments as a result of delayed trips, and the incremental direct operating costs associated with different decisions should be small. From the passengers' perspective, however, there are likely to be effects on a range of service quality attributes, including passenger waiting time, riding time, and additional transfers required, and the issue of how to weight these in evaluating alternative actions is not trivial. In general, however, the aims of operations control intervention will be to minimize waiting and riding time for all passengers and to minimize the number of the passengers negatively affected (*1*).

Four types of control actions aimed at improving service quality can be made on the Green Line: holding a train, short-turning, expressing, and deadheading (*2*). Each of these actions is briefly discussed below with emphasis on the ideal scenario for making such a decision in the specific context of the Green Line. Because of the low Green Line headways, and the resulting assumption that passengers arrive at stations independent of the schedule, maintenance of even headways is a more appropriate proxy for service quality than is schedule adherence. Hence the control actions are analyzed in terms of rebalancing headways rather than correcting schedule deviations per se.

Holding a Train

Holding a train is the simplest operations control action, consisting of delaying a train in a station, usually when there is a short preceding headway and a long following headway. This reduces the headway variance and hence reduces passenger waiting time at all stations down the line. Within the

Green Line central subway, Park Street Westbound is the most common holding point because it is a double-tracked station with very heavy boardings. Because most of the Green Line is one track per direction, holding a branch train within the central subway at stations other than Park Street is likely to delay following trains of other branches, negating any benefit.

Holding selected inbound trains just before entering the central subway may be beneficial, especially in the p.m. peak (low inbound volume, high outbound volume) and avoids any inter-branch–line effects.

Short-Turning

Short-turning is the decision to turn a train before it reaches its terminus with the aim of reducing headway variance in the reverse direction by filling in a large headway gap (*3*). The ideal scenario for a short turn is to select a train with a low passenger load, a low preceding branch headway, a high branch headway further up the line (the large gap to be filled in the reverse direction), and a low following headway. In this situation a few passengers will be negatively affected by the short-turn (primarily those passengers forced to transfer to reach their destinations), but their additional waiting time will be small, and the benefit to riders in the reverse direction will be large. Short-turning, of course, can occur only where special turnback or crossover tracks exist. In the case of the Green Line, short-turning is the principal form of operations control with most short-turns involving northbound B and D line trains destined for Government Center being turned one stop early at Park Street.

Expressing

A decision to express a train reduces the number of stops for this train and hence also reduces running time and preceding headway beyond the express segment (*4*). Before expressing, affected passengers must be notified and allowed time to alight. The ideal scenario for an expressing decision is to have a long preceding headway, a short following headway, and high passenger load past the end of the express segment. In the case of the Green Line, expressing decisions are made occasionally, principally involving westbound trains in the central subway, such as from Park Street to Kenmore, but also on the surface portions of the network.

Deadheading

Deadheading (also known as running light) is similar to expressing except that no passengers are carried over the deadhead segment. To avoid forcing passengers to alight, deadheading is typically initiated at a terminus when there is a long preceding headway and a short following headway. Its principal advantage over expressing is that it does not require notifying passengers at the beginning of the deadhead segment, thus potentially reducing dwell time and passenger confusion.

CURRENT OPERATIONS CONTROL STRATEGY

In this section the current operations control strategy is described for short-turning, expressing, and deadheading. Holding is also used, principally at Park Street westbound, but is not documented and thus is hard to evaluate.

Short-Turning

The decision whether to turn trains at Park Street has traditionally been a "judgment call" by the Boylston inspector. Inspectors have not been expected to apply strict criteria, and different inspectors may make decisions differently, following their own sense of what will best maintain service quality. A skillful inspector will develop an ability to notice and keep track of several relevant pieces of information simultaneously and may or may not be able to explain his or her decision process. Years of practice result in a complex view of the problem that may not be easily reduced to a statement of the formal decision process.

According to Deckoff (*3*), "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 bunched together over the course of their inbound trip and have a large headway gap preceding them, the Boylston inspector may short-turn one of them to reduce the size of the gap, thereby producing more even headways on the B Line outbound.

It takes some skill to achieve this objective. Even so, many of the passengers waiting on the outbound platform at Park Street will be destined to other stations within the central subway (63 percent in the morning peak period and 39 percent in the afternoon peak). These passengers will not be concerned about the branch line headway because they can take any train to reach their destination. Hence, a short-turn decision that benefits branch line passengers may not provide much benefit to passengers traveling only within the central subway. In addition short-turning reduces the level of service for passengers traveling in either direction between Park Street and Government Center stations. Thus between 10 percent and 24 percent of passengers on a short-turned train are likely to be forced to transfer at Park Street (the remainder would have alighted at Park Street in any case), while some passengers at Government Center westbound will have a longer wait.

Analysis of a week's worth of data recorded by the Boylston inspector in March 1989 showed that of 1,956 B and D line trains observed, 270 (16 percent) were short-turned at Park Street. In most cases short-turning resulted in reduced overall passenger delay (measured in total passenger minutes), but 26 percent of short-turns actually increased passenger delay. In other words, under the current decision process—which varies from inspector to inspector—one in four short-turn decisions leads to poorer system performance based on total passenger minutes.

Expressing and Deadheading

Like the short-turn decision, expressing and deadheading decisions are generally made by an inspector on the station platform, and the decision is based on his or her judgment without formalized rules. Although inspectors at fixed locations such as Park Street keep a record of their control decisions, express or deadhead trips ordered by field inspectors on the branch lines are generally not recorded and thus not available for evaluation.

An analysis was made of 2 weeks of records from Park Street inspectors for weekday rush hours (both a.m. and p.m.) during June 1989 (*4*). Inspectors will sometimes express a train from Park Street to Kenmore Station, and trains may be deadheaded to intermediate stations. During this period 64 decisions were recorded to express or deadhead a train from Park Street Station. Only 10 of these actions were to express a train; the other 54 were to deadhead. B and D line trains are also on occasion deadheaded the one stop from Government Center to Park Street. It is not surprising that deadheading is preferred by inspectors over expressing, because expressing requires public address announcements and induces delay and general disruption as passengers sort themselves out once the announcement has been made.

Some patterns were found in the inspectors' decision making. First, when two (or more) trains on the same line arrived consecutively at Park Street, one of the trains was usually deadheaded to separate them. It could be surmised that one of the simultaneously arriving trains is likely to have been short-turned. Second, when the preceding branch headway was very long (16 min or greater), deadheading was not used; trains would either be expressed or no action would be taken. In these situations large numbers of passengers are likely to be waiting for service, which makes deadheading less attractive because of the associated reduction in line capacity. Control actions were about twice as likely to be taken during the p.m. peak period when more passengers are destined for the surface portions of the branch lines, than during the a.m. peak.

INFORMATION FOR OPERATIONS CONTROL

The ability to make good operations control decisions depends heavily on the availability of accurate real-time information. These decisions are sensitive to train length, train positions, passenger loads, and the expected future positions of trains with and without the intervention, and to a lesser extent, passenger volumes at various stations, occurrences of delays or breakdowns, train schedule adherence, and train congestion at track switches (*3,4*).

The information needed can be obtained from a variety of sources, including direct observation, radio and telephone communication, computerized information systems, and, if necessary, analyzed historical data. Although using predicted values based on historical data is less desirable than using real-time data, it is possible, with careful attention to the resulting uncertainty, to generate information from historical data that closely matches actual data and is substantially superior to random guessing (*3,4*).

In the past Green Line operations control decisions have been based on communications among field personnel and personal observations, though more recently some of the analysis described in this paper has been used to formulate decision guidelines (see Figure 2 for an example). However, additional improvements in decision making are expected to result from the installation of a new automatic vehicle identification (AVI) system on the Green Line (*2,5–8*). This system, which is now operational, performs automatic routing of trains through track switches, records detailed information on train movements, and drives a model display board in the MBTA operations control center (OCC).

Green Line AVI System

The AVI system transmits train identification information from 33 detectors located at various points along the network to the MBTA control center (*6–8*). The information is transmitted from transponders mounted at each end of every vehicle, to the wayside detectors, to the central control computer, and then to both video terminals (text display) and colored lights on a model board.

When a train passes a detector, the central computer records the car number(s), route number, destination, detector location, and the time of detection. This information can be viewed on a video terminal and is used to indicate approximate train positions, color-coded by branch, on the model board.

Using AVI for Operations Control

The original intent of the AVI system was to provide automatic switching at track junctions and, to a lesser extent,

B Line - During the AM Peak and Midday periods:

- Both the preceding headways on the line are short: ≤ 1 minute each (i.e., three trains appear in a row -- turn the third one), or
- The preceding headway is ≤ 1 minute, but the second preceding headway was between 8 and 10 minutes, or
- The second preceding headway was 10 minutes or longer and the inspector can see the candidate train (in other words, after a ten minute gap, two trains show up at once -- in this case turn the second of the two), or
- The preceding headway is ten minutes or longer and the candidate's follower is not in sight. Note that in this case many passengers would be dumped.

B Line - During the PM Peak Period:

- The preceding headway ≤ 1 minute and the second preceding headway ≤ 3 minutes, or
- The preceding headway ≥ 8 minutes.

B Line - During the Evening Period:

- The first preceding headway is ≤ 3 minutes and the second preceding headway ≤ 1 minute, or
- The first preceding headway is ≤ 3 minutes and the second preceding headway is between 10 and 12 minutes, or
- After a 12 minute gap two trains show up at once, in this case turn the second train, or
- The first preceding headway ≥ 12 minutes and the follower is not visible.

D Line - During the AM Peak, Midday or PM Peak Periods:

- Short-turn if the previous headway ≥ 8 minutes.

D Line - During the Evening Period:

- Short-turn if the previous headway ≥ 10 minutes.

FIGURE 2 Proposed short-turning decision rules.

collect maintenance data. Although the system works as designed quite reliably, for other uses, such as operations control, the system lacks some features that might be helpful and possibly worth adding in the future. For example, the number of detectors is adequate for train routing, but not really sufficient for effective operations control. With the short headways on the Green Line, accurate train position information is needed to ensure good decisions, but the 33 detectors cannot provide the necessary resolution.

Secondly, the video display terminals show only sorted and filtered AVI transmissions, rather than information derived from the data, such as headways, which must be manually calculated. This restricts the ability of OCC personnel to monitor headways at multiple keypoints and anticipate problems. Lastly no related information is provided, such as schedule data, run number, or operator badge number, that might be helpful when analyzing, either manually or automatically, the AVI data for operations control purposes.

Although these factors limit the maximum use of AVI data for operations control, additional features could be added in the future to overcome these limitations. In addition the new AVI system does give OCC personnel a broad system level view of the Green Line and, through voice communications, assists existing line personnel with operations control decision making. Although future enhancements will likely expand the AVI system's role in operations control, current decision making will still rely heavily on direct observation and voice communication, but with the added element of the AVI-provided system level view.

APPLICATIONS

Green Line operations control is evolving from a decentralized, direct observation-based system to a more centralized, AVI-directed system, but for many reasons, including those discussed above, the transition will be gradual. Although more information is usually better than less, good decision making still can be achieved with many different levels of information as long as the accuracy and meaning of the information is well understood.

In this section the potential benefits of improved operations control, based both on applying decision rules with current limited information and decision making with more complete AVI information, are illustrated for the short-turn and express decisions.

Short-Turning

The short-turn decision of whether to turn, at Park Street, an inbound train destined for Government Center is made by the Boylston inspector based on experience and judgment without strict criteria being applied. Deckoff (*3*) investigated different decision rules for this short-turning decision with an objective of minimizing total passenger minutes of travel time, including both wait time and ride time, weighted equally. From examining a week's worth of Boylston inspector records, estimates of the passenger time effects resulting from a decision to short-turn or not to short-turn were made for each observed train, and these results were generalized to identify conditions under which an inspector could be confident that a short-turn decision would result in a net decrease in total passenger minutes.

Four groups of passengers are affected by a short-turn decision:

- Skipped segment alighters—those passengers bound for Government Center who would be dumped off a short-turning train (passengers destined beyond Government Center are not counted because they would need to transfer in any case);
- Short-turn point boarders—passengers waiting at Park Street for Government Center who would have boarded the short-turned train had it continued;
- Skipped segment boarders—passengers who, if the train had not been short-turned, would have boarded it at Government Center for a westbound trip, including passengers destined to the surface portions of the B or D lines who must wait for a train running on the appropriate line, as well as those with central subway destinations who can take any train; and
- Reverse direction passengers—those traveling westbound including both branch line and central subway riders.

The last group benefits from a short-turn decision, whereas the first three groups are inconvenienced. Because passengers bound for different destinations face different choices of trains, each group was further divided by destination. Headways were calculated between successive trains, and passenger accumulations for each group were estimated using accumulation rates derived from data collected in 1985 by the Central Transportation Planning Staff (CTPS). For each trip, passenger minutes of delay were calculated twice for each of the affected groups, once assuming that the train (and only that train) was short-turned, and the second time assuming that the train followed its regular route. A great deal of care was taken to account for cases in which vehicle capacity would be exceeded and passengers delayed until the following train.

Among the model inputs required to compute the passenger minutes saved (or lost) in short-turning each train are the various passenger accumulation rates, the headways of outbound C and E line trains, train lengths of the C and E line trains, and the number of minutes saved by short-turning. Not all these inputs are known by the Boylston inspector at the time the short-turn decision must be made for each train; the other variables are, from the inspector's point of view, essentially random. Therefore, the model uses randomly generated, normally distributed values for the unknown variables, based on observed values.

The most crucial and available items of information available to the Boylston inspector for determining the suitability of a particular train for short-turning are the headways preceding the candidate train on the same line. Passenger minute effects from the model were grouped according to the headways preceding each candidate train to determine the circumstances under which a train can be short-turned with roughly a 95 percent confidence that aggregate passenger travel times will improve. Given only the first and second branch preceding headways, it is proposed that trains should be short-turned in the circumstances shown in Figure 2.

These short-turning guidelines differ by line and by time period because of different passenger flow rates and different line service frequencies. For example, on the B Line in the morning peak and midday periods, a majority of outbound passengers are headed to destinations within the central subway, whereas during the afternoon peak and evening more passengers are bound for the surface portions of the line. Because it is the branch line passengers who benefit most, more liberal use of short-turning is justified when the branch passengers predominate.

In the morning peak period on the B Line, of the 146 cases examined, applying the proposed criteria, only 32 short-turns would have been performed as opposed to the 44 trains turned by the Boylston inspector during the week examined; yet the number of passenger minutes saved by short-turning was estimated to increase from 9,400 to 13,000 despite the smaller number of short-turns. Likewise, the "success rate," or the percent of short-turns that cause a reduction in passenger delay, was estimated to increase from 73.8 percent to 93.6 percent using the guidelines.

With implementation of an enhanced AVI system, additional information on which to base short-turn decisions would be available. Specifically knowledge of both C and E line outbound headways and of headways following the candidate inbound train should enable short-turn decisions to be made with greater confidence about the outcome. However, even in this case the outcome will still depend on unknown factors and unpredictable future events, and so there will still be a non-zero probability of a negative outcome. The analysis showed that incorporating this increased information would allow a greater use of short-turning than that suggested by the proposed criteria. Specifically during the a.m. peak for the week analyzed, some 43 short-turns would have been made, almost the same number as those actually made by the Boylston inspector, but with a much higher expected success rate (92.7 percent) and higher estimated passenger minutes saved (17,200 versus 9,400 min).

Thus in the case of short-turns it appears that although the existing real-time decision making based on limited information and experience results in substantial net passenger benefits, these benefits could be increased by about 40 percent through the application of more consistent decision guidelines without additional information and further increased by a similar amount through the use of more comprehensive AVI data.

Expressing

Macchi (*4*) developed a set of mathematical models to determine which strategies for expressing trains would result in minimizing total passenger travel time, again expressed in passenger minutes. These models were applied to the expressing decision in the p.m. peak period westbound from Park Street with the express segment ending at Kenmore.

Again, four distinct groups of passengers are affected by an expressing decision:

- Expressed passengers—those who remain on an expressed train—these passengers will have a reduced travel time,
- Passengers waiting downstream who will benefit if headway variance is reduced,
- Passengers skipped—this includes passengers who would have boarded the train had it made all stops, both those waiting at the station where expressing is initiated and those waiting at intermediate stations, and
- Passengers dumped—those passengers already on the train and bound for stations in the express segment—they must leave the train and wait for another.

Given passenger accumulation rates for each set of passengers (again based on 1985 CTPS data), preceding and following headways, and an expected time savings as a result of expressing, a set of equations were developed to predict the cost and benefit in passenger minutes that would accrue to each group because of a decision to express a train. By summing the effects on the four groups, total net benefits to passengers of a decision to express were calculated.

The expected time savings is defined as the express segment travel time if the train is not expressed minus the express segment travel time if it is expressed. Both travel times include station dwell times. Because the time savings is defined as a travel time difference, if the travel time for the nonexpressed train would have been longer than usual [as a result of long dwell times as passengers squeeze on and off the crowded car and jam into the door wells (*9*)], the time savings from expressing can, in fact, be greater than the preceding headway.

Assuming a 1.5-min preceding headway (the headway between the express candidate train and the nearest preceding train) and a 2-min time savings for expressing, the model indicated that expressing would produce net benefits over a 250 passenger minute threshold on the B Line in the p.m. peak period in the circumstances indicated in the top half of Figure 3. Assuming instead a preceding headway of 3 min and a 4-min time savings, the model shows expressing to be beneficial for almost any above average preceding branch headway, given that the following branch headway is not greater than average (see bottom half of Figure 3). Comparing the net benefit tables produced by the expressing model under these two sets of assumptions shows the staircase pattern in the latter table to be steeper, indicating that confidence of a good decision increases when the preceding any-line headway is longer and the time savings is increased.

The same model was applied to the C and D lines during the same period and under the same two sets of assumptions. Again the net benefit tables formed a staircase pattern that was steeper in the case in which the previous headway was longer and time savings greater, but the benefits produced by expressing were greatest on the B Line, and least on the C Line, with the D Line in between—roughly proportional to the passenger volumes on each line.

Initially, the expressing models did not account for limited passenger capacity on any train, although given a long preceding branch headway, a train is likely to be crowded if not crush-loaded. In this case the cost of expressing to passengers waiting at intermediate stops is zero, because, as a result of capacity limitations, they could not have boarded the train even if it had made all stops. Likewise, the number of passengers who can ride the express train is limited to available capacity.

Incorporating capacity constraints into the B Line model, when the previous branch headway exceeds 12 to 16 min, beneficial expressing decisions can be made with significantly longer following branch headways than before, and expressing will virtually always be beneficial when the previous branch headway exceeds 18 min. The results indicate that expressing based on expected values may be warranted when train capacity is likely to be constraining, and it will not always be necessary to know the following headway to almost guarantee that the express decision will be beneficial.

The subject of deadheading trains was investigated only briefly, but the trade-offs are relatively straightforward. Deadheading a train, rather than expressing it, results in less delay and confusion for passengers and is easier for inspectors. But it shifts one group of passengers from being positively affected to being negatively affected: those who would have benefitted by riding the express train must instead wait for the next train as do skipped passengers.

The results of the expressing model were compared with current practice as observed from 2 weeks of Park Street inspectors' reports for weekday a.m. and p.m. peak periods during June 1989. As described earlier, 64 control actions were taken by inspectors during this period: 54 trains were deadheaded and 10 expressed. Of these, 10 were likely to have been good decisions according to the expressing model, 12 were likely to have been bad decisions, and the remainder

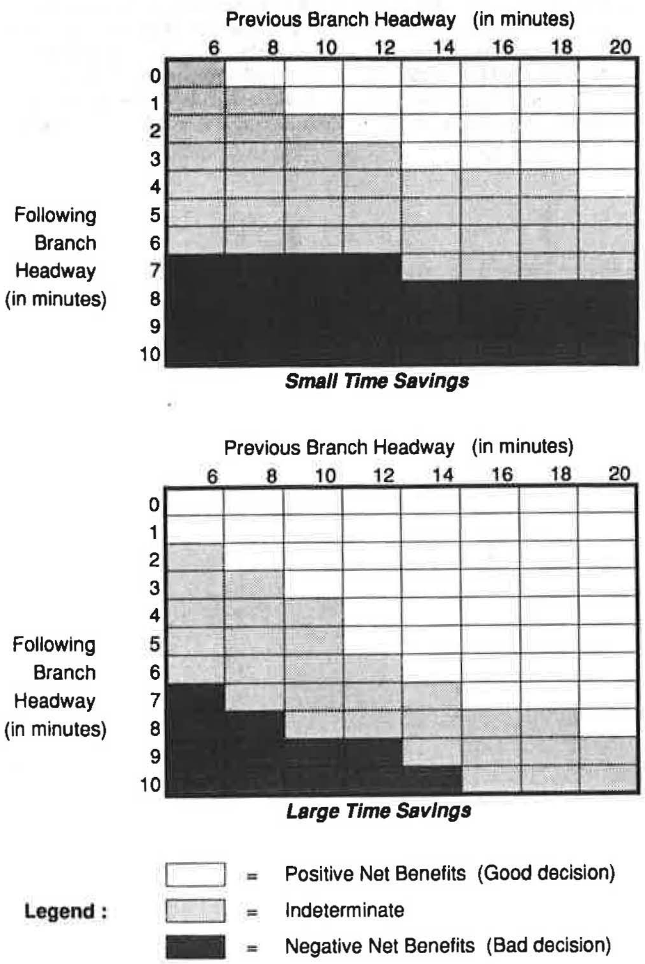

FIGURE 3 Benefit regions: B Line p.m. peak express decision—small and large time savings.

(42) were probably slightly beneficial. A decision to deadhead a short-turned train that arrived simultaneously with another train on the same branch line, given an average (or less) preceding branch headway, would be an example of the "slightly beneficial" category. Looking at expressing actions separately, of the 10 express actions taken, 4 were probably good decisions, 4 probably bad, and 2 slightly beneficial. The bad express decisions were typically characterized by 5- to 8-min preceding branch headways possibly with blocking trains ahead, and an average following headway. It is not clear why these actions were taken.

Again using the same 2 weeks of data, there were 45 instances in which a B, C, or D line train entered Park Street with a 12-min, or greater, preceding branch headway. In these instances, inspectors took action in eight cases, sending three trains light and five express. All of these actions would have been recommended by the expressing model. In addition, the model would have strongly suggested one more express trip and moderately recommended taking action in 31 other cases. So although the situations in which action was taken were also situations in which the model most strongly recommended action, the model suggests greater use of expressing in some more marginal cases in which the preceding branch headway is long. But of the 45 trips with preceding headways exceeding 12 min, 10 had following branch headways of 6 to 9 min, so the risk of a bad decision is not insignificant.

As with short-turning, express decision making could be greatly improved with the information that would be available given full AVI system implementation. The express decision is sensitive to the time savings and the neighboring headways, and AVI could provide the headways and an estimation of the probable time savings. Much of the ambiguity in the model analysis of the 45 instances of headways of at least 12 min results from the uncertainty of the external conditions—the records kept do not provide a complete and precise picture. By using the AVI system as the source of the important variables, much improvement could be made in decision making. In fact the AVI system, by recording the running times from Park to Kenmore of expressed trains, could be used to derive an empirical formula for time savings estimation, which in turn could be used in future express decisions.

The AVI system could be used not only to help make decisions, but to make them sooner, such that when a B or D train is at Government Center, passengers there could be notified that the train will be expressed from Park, minimizing annoyance. More importantly, Government Center passengers waiting for a B or D train could be told to take any train to Park, when a combination short-turn and express is planned. To do this properly, significant coordination is required: short-turn decision at Boylston, Government Center passengers notified to travel to Park, and passenger notification and coordination of other trains at Park Street. This requires both a central line controller to coordinate personnel and an information system to relieve the controller of time-consuming data analysis. Only with a very effective AVI system is such a scenario possible.

CONCLUSIONS

Currently the MBTA uses a decentralized operations control system on the Green Line, relying principally on the judgment and experience of field inspectors to decide when to hold, short-turn, express, or deadhead trains. The outcomes of these decisions are subject to great uncertainty because of lack of information about some critical inputs, most notably following headways. Analysis of short-turning and expressing decisions suggests that although most current decisions are beneficial, a minority result in worse overall performance. Decision guidelines were developed that can be applied with the current limited information and to improve the operations control function significantly.

An AVI system has now been implemented on the Green Line and holds the promise to improve substantially the information base for operations control. Although the initial AVI system will have some significant shortcomings as an operations control instrument, particularly in terms of processing the AVI data into information suitable for a controller to assimilate, the additional information will eventually result in better real-time control decisions, and better service to passengers.

The type of analysis presented here would be directly applicable to other high-frequency transit systems that routinely experience headway variability. Examples that come readily to mind are the branching light rail networks in San Francisco and Philadelphia. Analyses can be used both to evaluate the effectiveness of current operations control practices and to estimate the benefits of installing an AVI system in terms of improved operations control.

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