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**Bus Transit Operations Control:
Review and an Experiment Involving Tri-Met's
Automated Bus Dispatching System**

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Introduction

An operations plan contains information on the provision of transit service, including intended service levels, vehicle availability, and driver schedules. Agency resources would be utilized efficiently if the operations plan could be executed without disruptions in service. When service disruptions occur, the aim of operations control is to optimize system performance given the current state of the system (Wilson et al., 1992). This typically involves actions intended to either return service to schedule or restore headways separating vehicles. Disruptions in service impose costs on transit providers in the form of reduced productivity and on passengers in the form of increased in-vehicle travel time, longer waiting time at stops, and greater uncertainty.

This paper has two overall purposes. First, it provides a review of operations control principles and practices reported in the literature. Second, it reports the results of an operations control experiment whose objective was to maintain headways, or the time separation between buses on a route. The experiment was developed to explore a possible application of the automated Bus Dispatching System (BDS) recently implemented by Tri-Met, the transit provider for the Portland, Oregon, metropolitan region. The main components of Tri-Met's BDS are as follows:

- Automatic vehicle location (AVL) based upon global positioning system (GPS) technology, supplemented by dead reckoning sensors;
- Voice and data communication within a pre-existing mobile radio system;
- On-board computer and a control head displaying schedule adherence to operators, detection and reporting of schedule and route deviations to dispatchers, and two-way, pre-programmed messaging between operators and dispatchers;
- Automatic passenger counter (APC) technology;

- Computer-aided dispatch (CAD) center.

The BDS recovers very detailed operating information in real-time, and thus enables the use of a variety of control actions that would potentially yield substantial improvements in service reliability. The growing deployment of BDS technology in the transit industry is timely, given that worsening traffic congestion in most urban areas has made schedule adherence increasingly difficult.

Operations Control Research

Overview

In order to understand how operations control can be effective in reducing variability in system performance, it is first necessary to discuss the causes of unreliable service. Woodhull (1987) classifies the causes of unreliable service according to whether they are internal (endogenous) or external (exogenous) to the system. Exogenous causes include such factors as traffic congestion and incidents, traffic signalization, and interference with on-street parking. Endogenous causes include such factors as driver behavior, improper scheduling, route configuration, variable passenger demand, and inter-bus effects. Turnquist and Blume (1980) make a distinction between service planning and real-time control strategies. Service planning strategies can address problems of a persistent nature through route restructuring and schedule modification. This is in contrast to real-time control strategies, which focus on immediate responses to sporadic service problems. Abkowitz (1978) suggests that there are three basic methods to improve transit service reliability, categorized as priority, control, and operational.

Priority methods involve the special treatment of transit vehicles apart from general vehicular traffic. Examples of this type of strategy are exclusive bus lanes and traffic signal prioritization. Operational methods take place over a longer period of time and include such strategies as schedule modification, route restructuring, and driver training. Control methods take place in real-time and include vehicle holding, short-turning, stop skipping, and speed modification.

It is important to distinguish between low and high frequency service when discussing operations control strategies. For routes characterized by long headways, schedule adherence is the most important operations objective. Passengers will attempt to time their arrivals with that of the bus based upon a given probability of missing the departure (Turnquist, 1978; Bowman and Turnquist, 1981). In these circumstances average wait times are less than one-half of the scheduled headway. Schedule adherence is also an important objective at timed transfer locations. Alternatively, for routes that operate at headways of 10 minutes or less, headway maintenance is the most important operations objective. This is because passengers do not find it advantageous to time their arrivals with that of the schedule, and are thus assumed to arrive at stops randomly. The aggregate wait time of passengers is minimized when buses are evenly spaced on routes operating at high frequencies.

First Generation Operations Control Research

Early research on operations control involved the design and evaluation of vehicle holding strategies. Most of the studies relied on either analytical or simulation techniques in the absence of data on actual transit operations. A common thread in many of these early studies is that the models were based upon rather restrictive assumptions. Osuna and Newell (1972) developed a model to determine the amount of time needed to hold a bus in order to improve

service regularity. A hypothetical route was analyzed consisting of one stop and either one or two vehicles. The objective of the model was to minimize the average wait time of passengers. The authors concluded that control should be implemented following service deterioration rather than in anticipation of a potential problem, and that control should be applied sparingly to prevent service deterioration beyond a tolerable limit. Barnett and Kleitman (1973) developed a model building on the research of Osuna and Newell. Their analysis involved a hypothetical bus route with one vehicle and several stops. Vehicle holding was allowed at one of two possible control points. The study sought to devise a holding strategy that would minimize the average wait times of passengers. The authors concluded that holding was most effective when trips returned unusually early, and that the location of the control point proved crucial. Barnett (1974) later developed a more detailed model that analyzed a hypothetical multi-stop route with one control point. The objective of the model was to determine the optimal interval at which vehicles should be dispatched from a control point. The problem attempted to minimize aggregate passenger wait time relative to holding costs imposed on passengers already on board the vehicle. The optimal strategy was dependent upon the mean and variance of the headway distribution, the ratio of passengers on board the bus at the control point to those waiting downstream, and the correlation between successive vehicle arrival times at the control point. Bly and Jackson (1974) designed a simulation model that looked at the effects of holding buses at a control point until a threshold headway was reached. Under a threshold-based holding strategy, an early bus is held until the preceding headway reaches a prescribed value. The results of the study showed that holding resulted in reduced passenger wait times at the expense of longer running times. Koffman (1978) developed a simulation model analyzing four different control strategies for a simplified bus route. The strategies consisted of holding, stop skipping,

priority signalization, and reducing dispatching uncertainty. The model is noteworthy in that it took into account traffic signalization, different boarding and alighting rates, acceleration/ deceleration delay, and variable passenger demand. Similar to the finding by Bly and Jackson, Koffman concluded that holding produced very small improvements in wait times at the expense of longer passenger travel times. Turnquist and Blume (1980) developed a set of equations seeking to determine upper and lower bounds on the expected benefits of threshold-based holding. They showed that the optimal control point along a route is located where relatively few passengers are on board the vehicle and many are waiting at subsequent stops. The authors point out that control should be implemented as early along the route as possible because headway variability tends to increase with running time. An important result of the study was that the authors discovered cases where headway control was unlikely to produce benefits and could actually prove detrimental to transit operations.

The general contribution of the first generation of operations control studies can be summarized as follows:

- Holding imposes costs on passengers already on board vehicles in the form of increased travel time.
- Holding imposes costs on transit providers in the form of increased running time.
- The selection of an appropriate control point is crucial for minimizing aggregate wait times.
- Headway control is most effective when passenger loads at the control point are light and demand immediately following the control point is heavy.
- Holding is most effective at reducing wait times at stops immediately following the control point.

- Headway variability begins to increase again following control.
- Holding may prove detrimental to transit operations in some situations.

Second Generation Operations Control Research

The primary distinction between first and second generation operations control studies is that the latter are empirically validated with data on actual transit operations. Turnquist and Bowman (1980) developed a model using data from a bus route in Evanston, Illinois to address schedule-based holding. Under a schedule-based holding, early vehicles are held to their scheduled departure time. The authors found that schedule-based holding was an appropriate control strategy for routes characterized by large headways. A study by Abkowitz and Engelstein (1984) analyzed headway-based holding strategies in detail. The study employed a simulation using data from Cincinnati, Ohio, with the results later validated with data from Los Angeles, California. An algorithm was developed to identify the locations where the greatest reductions in passenger wait times would occur for specific threshold headways. The authors found that the optimal control point is sensitive to the ratio of passengers on board the bus to those waiting downstream and that the main benefits of control are realized by passengers immediately downstream from the control point. A later study by Abkowitz, Eiger, and Engelstein (1986) found that headway variation does not increase linearly along a route, but instead increases sharply at low values of running time variation, then tapers off once bunching occurs.

Both schedule-based and headway-based holding were analyzed by Turnquist (1982) in a report focusing on strategies to improve transit service reliability. The study was based on a simulation later validated with data from Evanston, Illinois and Cincinnati, Ohio. The author

analyzed two types of headway control strategies. The "Single Headway" strategy requires information about the current headway only and consists of holding a vehicle to the until the scheduled headway is reached. The "Prefol" strategy, consists of holding a vehicle until the preceding headway is as close as possible to the following headway. The Prefol strategy requires more information than the Single Headway strategy in that prediction of the arrival time of following vehicle is necessary. Turnquist found that the Single Headway strategy performs less well than the Prefol strategy when vehicle arrivals are largely independent from one another. As headways become more correlated, the effectiveness of the Single Headway strategy begins to approach that of the Prefol strategy.

According to Turnquist (1982), the headway control strategy that would maximize wait time savings would require that all headways be known in advance. Both the Single Headway and Prefol strategies are near-optimal solutions in that they neglect to consider the effects of holding on other vehicles serving the route. Turnquist found that the various holding strategies are sensitive to three characteristics of the control point: 1) the current level of unreliability; 2) the amount of correlation between successive headways, and 3) knowledge of the percentage of passengers on board the bus at the control point relative to those downstream.

A study analyzing the benefits of operations control was undertaken for the MBTA Green Line in Boston, Massachusetts by Wilson et al. (1992). Their study considered four types of control actions: 1) holding; 2) short-turning; 3) expressing, and 4) deadheading. The major operational problem on the Green Line consisted of headway variation. Field supervisors implemented control actions based upon direct observation, communication, and intuition. The authors found that some control actions actually increased aggregate passenger wait times, while others were not implemented when justified. The reason for such a wide variation in the

effectiveness of operations control was attributed to the lack of timely information available to field supervisors (Wilson et al, 1992). One of the more interesting aspects of the research was that the authors developed a set of location and condition-specific decision rules for control actions.

The study by Wilson et al. (1992) addressed several types of control actions that have not been extensively addressed in the literature. For example, stop skipping is a strategy that involves skipping one or more stops as a vehicle moves along a segment. Stop skipping serves to reduce running time on the vehicle of interest while shortening its headway. In essence, this represents a transformation from regular to limited service in real time. The benefits of stop skipping are reduced running time on the vehicle of interest, shorter wait times for passengers already on board the vehicle, and lower wait times for downstream passengers. These benefits are at the expense of increased wait time for persons at stops that have been passed by and passengers who are forced to alight early and take the next vehicle. The ideal scenario for stop skipping is to have a long preceding headway, a short following headway, and high passenger demand beyond the segment where skipping is implemented (e.g., on the vehicle's subsequent trip). Only two studies have analyzed stop skipping in detail, with one viewing it as a reasonable control action and the other recommending that it be avoided completely because of adverse effects on certain passengers (Wilson et al, 1992; Lin et al, 1995). A less disruptive variant of stop skipping that avoids forcing passengers to alight early is to limit stops to drop-offs of on-board passengers.

Short-turning involves turning a vehicle around before it reaches the route terminus, with the goal of reducing headway variance in the opposite direction by filling in a large gap in service. The ideal scenario for short-turning is to select bus with a light passenger load, a low

preceding headway, a low following headway, and a high headway further up the route (i.e., the large gap). Similar to stop skipping, short-turning adversely affects passengers on board the vehicle who are forced to alight and transfer to the subsequent bus. Short-turning primarily benefits passengers traveling in the opposite direction because of reduced headway variation. Deadheading is similar to expressing except that no passengers remain on board the vehicle. The ideal scenario is to deadhead a vehicle where there is a long preceding headway and a short following headway. One of the drawbacks to deadheading is that all passengers are forced to alight at the control point, including some passengers who would have benefited from an expressed trip. The practices of stop skipping, deadheading, and short-turning are not viewed as desirable control actions by many transit agencies because they force passengers to transfer to other vehicles, and they also degrade service for persons who are passed up.

Abkowitz and Lepofsky (1988) analyzed headway-based reliability control on two bus routes in Boston, Massachusetts. Control was exercised on both routes during the a.m. period in the inbound direction and on one route during the p.m. period in the outbound direction. Of the three experiments, only one was found to significantly reduce headway variance and run time variability. This proved to be a radial through route that intersected downtown. The study was hampered by manual data collection problems and the failure of field supervisors to adhere to holding instructions consistently. For the two experiments where control proved to be ineffective, it was discovered that field supervisors were only holding a portion of the buses when action was justified (Abkowitz and Lepofsky, 1988). This again highlights the fact that human factors can reduce the effectiveness of headway control strategies if they are not implemented properly. Although the results of this study were mixed, it is important in that it

sets the stage for evaluating context-specific control experiments based upon the use of actual operations data.

Signal priority is a mechanism for reducing delays to transit vehicles at signalized intersections. A number of researchers have found that signalized intersections are an important contributor to unreliable service (Welding, 1957; Abkowitz and Engelstein, 1983). Signal priority typically involves changing the phase of a signal to green or extending the duration of the green phase when a bus approaches an intersection. While it is not the intent of this paper to discuss signal control strategies in detail, it is important to note why this strategy is finding favor within the transit community. In contrast to holding, which always causes delay to some passengers and also results in increased running time, signal prioritization reduces running times and decreases delay for all passengers (Khasnabis et al., 1999). However, signal prioritization also imposes additional costs on general motor vehicle traffic, and it may also adversely affect operations on intersecting bus routes. An optimal signal timing control system would incorporate real-time information on transit operations and general traffic conditions, and would be able to respond to changing operating conditions while minimizing disruptions to traffic flow (Lin et al, 1995).

The relevance of the second generation studies of operations control can be summarized as follows:

- Holding is likely to be more effective at earlier points along a route.
- Human factors play an important role in the success or failure of operations control practices.
- Decision rules should be developed to assist field supervisors in making choices to implement control or not.

- Control actions should be analyzed using data from actual transit operations.
- Short-turning, stop-skipping, and deadheading are second best solutions because passengers are forced to transfer to other vehicles.
- Signal prioritization does not impose adverse costs on passengers or transit operators, but does impose costs on general motor vehicle traffic and may impose costs on intersecting bus routes.

The Next Generation Of Operations Control Research

Two areas that need further study are the evaluation of passenger waiting time and the incorporation of vehicle seating capacity in operations control models. Previous studies have assumed that the utility function for wait time is linear, implying, for example, that the disutility of one 5 minute delay is equivalent to five 1 minute delays. Additionally, in-vehicle and out-of-vehicle times have often been treated equally in evaluating the benefits of control. Research has shown that travelers value time spent waiting at stops much higher than time spent in motion (Kemp, 1973; Lago and Mayworm, 1981; Mohring et al., 1987). Incorporating different weights for wait time and in-vehicle time will likely influence the identification of the optimal control point location.

Another important aspect of headway-based reliability control concerns seating availability. Abkowitz and Tozzi (1987) found this to be an important omission in previous studies. This is because limited seating availability results in pass-ups whereby passengers are forced to wait for a subsequent bus. The main issue is that passenger benefits may be incorrectly determined, resulting in incorrect control actions being applied. The MBTA study by Wilson et al (1992) is the only known analysis to take seating capacity constraints into account.

Automatic Passenger Counter (APC) technology has not been fully exploited for operations control. This is because APC systems in North America do not produce reliable passenger counts in real-time (Levinson, 1991). APC data are typically subject to a considerable amount of post-processing before they are considered reliable enough for service planning and scheduling. The ability to generate accurate passenger load information in real-time would provide decision makers with one of the key parameters needed for estimating the potential benefits of control. In order to develop estimates of the number of passengers waiting at downstream locations, archived APC and operations data can be used to construct boarding and alighting profiles at specific stops for specific trips.

Pilot projects are underway in Chicago and Paris for AVL systems that generate real-time information on vehicle headways. A display connected to an on-board computer shows drivers the amount of headway delay from the preceding bus. This system allows drivers to make small changes in driving behavior in order to keep bunches from forming or becoming progressively worse. This is an example of a preemptive strategy in that it does not wait for system instability to set in before control decisions have to be made. This idea is consistent with Welding (1957), who argues for the need to identify the onset of irregularity and the need to restore service to normal as soon as possible, and also with Turnquist (1982), who argues that one of the purposes of operations control is to keep bunches from forming in the first place.

It is noteworthy that schedule adherence, rather than headway regularity, is the dominant operational objective on high frequency transit routes. This is somewhat perplexing given that average wait times would be minimized if headway regularity were maintained. Both Welding (1957) and Hundenski (1997) note that, in principle, schedules are largely irrelevant for routes that operate at high frequencies. At San Francisco MUNI, schedules on certain routes were

disregarded in favor of a policy of headway maintenance. This approach was originally supported by both operators and patrons, but was later discarded because subsequent checks revealed that headways were not being maintained and that bunching still posed a problem. Hundenski (1997) claims that these two problems stem from MUNI's high level of missed service rather than flaws in the basic concept. This idea will likely surface again in the future as advancements in real-time technologies make headway maintenance more feasible. One of the main arguments against headway maintenance policies is that timed transfers must be met. While it is probable that schedule adherence, as opposed to headway maintenance, would minimize wait time for passengers at timed transfer points, this it has never been empirically tested on routes operating at high frequencies. For uncoordinated transfers, it is likely that the average wait time of transferring passengers would be reduced if buses were evenly spaced.

Additional research is needed to determine which policy would be more appropriate for minimizing passenger wait times at transfer locations under different service frequencies.

- The immediate future of operations control practices can be summarized as follows:
- Incorporating distinct values of wait and in-vehicle times will produce more realistic evaluations of the costs and benefits of operations control actions.
- Vehicle capacity constraints need to be included in models in order to fully capture passenger wait time costs.
- Real-time APC technology will provide valuable information to decision makers on the number of passengers on board vehicles likely to adversely affected by holding.
- Archived APC and operations data can be used to construct boarding and alighting profiles at various locations to estimate the number of persons likely to be waiting at downstream locations.

- Providing drivers with real-time headway information will allow for a passive form of headway maintenance. Real-time vehicle headway information will also prove useful to decision makers in deciding whether or not control is justified.
- For high frequency routes, it may prove beneficial to disregard schedule adherence policies in favor of headway maintenance.
- Additional research should be undertaken in order to determine whether schedule adherence or headway maintenance results in less wait time for passengers at transfer points on high frequency routes.

Operations Control at Tri-Met

Following the recent implementation of its BDS, operators at Tri-Met are now aware of schedule deviations from the “minutes late” display on their vehicle control head. When possible, drivers modify vehicle speeds to better adhere to schedule. Another form of control that is emerging in the wake of the new system is the practice by some field supervisors of requesting recent BDS data to identify schedule deviation patterns, or “trouble spots.” Finally, although dispatchers have not taken on regular responsibility for operations control, the pre-programmed messaging feature of the new system has been heavily utilized. Both operators and dispatchers have thus become better informed about operating problems in real time, and this has most likely improved both dispatching and operating performance. Collectively, these changes following the implementation of the BDS have contributed to improvements in on-time performance and reductions in passenger travel time and bus running time (Strathman et al., 2000).

Headway Control: An Experiment

Despite the initial improvements in reliability, delay problems continue to threaten service quality. These problems are most pronounced for out-bound trips in the afternoon peak period, when service frequencies are increased by the addition of extra service buses (known as “trippers”). Aside from the normal challenges of maintaining service in a high frequency, heavy traffic environment, the coordination of trippers with regular service buses is complicated by traffic problems that trippers encounter in traveling to their staging points, which is compounded by the disruptions that regular service buses experience on their prior in-bound trips. In combination these problems frequently result in bus-bunching on out-bound trips, which negates effective utilization of the added capacity.

There are several possible solutions to this bus-bunching problem. The first would be to re-write schedules to expand layover times for regular service buses and to add staging time for trippers, which would make schedule maintenance more feasible. No control action would be required with this approach. But unless delay problems are recurrent, these adjustments will shift resources from revenue to non-revenue service and will not be cost effective. Schedule writers tend to be responsive to passenger and operator complaints about delays and thus, in the absence of active operations control, schedule adjustments can be considered a default solution.

Alternatively, headways can be maintained by holding buses at the departure point. This would not bring service back to schedule, but in short headway situations passengers tend to arrive at stops randomly and the main objective should be to keep service evenly distributed to respond to that passenger flow. Thus, holding buses to maintain headways is the focus of the experiment described below.

There are two additional features that guided the design of the holding experiment. First, Tri-Met coordinates its downtown service along directional, access-limited transit malls. Thus a number of routes share the same departure point and traverse the malls. A single dedicated field supervisor is therefore capable of controlling departures for multiple routes. Second, with the BDS, a dispatcher can identify delays on in-bound trips and communicate this information to the field supervisor. Communicating these delays allows the supervisor to employ Turnquist's (1982) "Prefol" strategy, or holding given buses to the mid-point of the time separating their leader and follower. As a final consideration, given the expectation by the dispatcher that a tripper or regular service bus will be delayed by more than the scheduled headway, the supervisor can be alerted to send the other in its place. Consideration of this "switching" action had to be factored into the design of the experiment, because some consecutive trips terminate at different locations (e.g., due to short-lining or routing permutations).

A list of the routes and scheduled trips involved in the headway experiment is given in Table 1. Nineteen regular service blocks and eleven trippers (identified in bold type) were selected for study. One consideration in the selection of the trippers was that they are dead-headed (i.e., not in revenue service) to the route origin and could thus be more easily staged at the downtown departure location.

[Table 1 about here]

One dispatcher and one field supervisor were responsible for making and implementing the control actions. These two individuals remained in radio contact. In instances where it was determined that the bus following the tripper was running less than one headway late the supervisor instructed the tripper operator to maintain a headway that was half the combined headway linking the lead and trailing bus. For example, if this difference was twenty minutes

and the tripper's scheduled headway was eight minutes, the supervisor would instruct the tripper operator to try and maintain a two minute delay on his or her vehicle control head.

Load checkers were also stationed at the maximum load points to recover passenger counts. This was done because the subject buses were not all APC-equipped, and there was some concern about the accuracy of the passenger counts recorded by this equipment. The reliance on manual load checking did affect the time frame of the study. Given that the BDS recovers actual headway and other operating data automatically, the baseline against which the effects of the control experiment can be compared already exists. With loads being counted manually, however, the baseline period was defined by the amount of time the load checkers were deployed prior to the implementation of the control strategy. This period covered 10 weekdays, extending from October 18-29, 1999. This was followed by a "treatment" period that covered 18 weekdays, extending from November 1-24, 1999.

Statistical Analysis

From a statistical standpoint, improvements in headway maintenance are represented by reductions in headway variance. A reduction in load variation would also be expected to correspond to a reduction in headway variability. As can be seen in Table 1, the scheduled headways of the trips involved in the experiment vary both within and between routes. It is thus necessary to standardize the headway measure to establish a consistent basis for comparison.

This is done by forming the ratio of observed to scheduled headway, as follows:

$$\text{Headway Ratio} = [(\text{Observed Headway}/\text{Scheduled Headway}) * 100]$$

A similar ratio could be constructed for passenger loads, but it is not needed because bus seating capacity does not vary.

Wonnacott and Wonnacott (1972: 180-182) explain the test for determining the significance of a change in variance using a C^2 statistic, which is a modified chi-square. Critical values from the distribution of this statistic are used to construct confidence intervals around the baseline and treatment sample variances to determine whether they can be significantly distinguished from each other. For example, the 95% confidence interval at 120 degrees of freedom is defined as follows:

$$\Pr (s^2/1.27 < \sigma^2 < s^2/.763) = 95\%,$$

where s^2 is the sample variance and σ^2 is the underlying population variance.

The BDS recovers headway data over the entire route. Thus it is possible to assess the consequences of headway control actions at the point where the actions are taken and at subsequent points on the route. This implies significance tests for three locational configurations: 1) at the control point; 2) progressively, at time points extending from the origin, and 3) over all time points. In the first case, the test would determine whether service regularity improved at the location where the control actions occurred. In the second case, one could determine how far an initial improvement (assuming that such an improvement occurred) was sustained along the route. In the final case, one could determine whether an overall improvement in service regularity was discernable.

Results

A summary of the control actions taken is provided in Table 2. Six actions were taken on regular service buses, including three holds, one swap and two short turns. For trippers there were sixteen actions taken, including seven holds and nine swaps. There were no opportunities for short-turning tripper buses, given that they were deadheaded to the departure point. Control

actions were taken on twelve of the eighteen days during which the experiment was conducted and were imposed relatively more frequently for trippers (9.6% of recorded trips) than for regular service buses (3.2% of recorded trips). Overall, the decisions by the dispatcher and field supervisor to implement controls can be characterized as conservative. This is not undesirable, given the finding by Wilson et al. (1992) of instances where control decisions were actually found to be counter-productive.

[Table 2 about here]

The impact of the control actions on headway ratio variances is reported in Table 3 for all time points on the affected routes as well as for the control point at which the actions were taken. Compared to their baseline values, headway ratio variances declined 3.8% overall and 15.8% at the control point. Two noteworthy items related to this outcome are 1) the improvement in headway regularity was substantially greater at the location of the control action, and 2) headway regularity generally tend to be better in the initial stages of trips. The change in headway variance was evaluated with the C^2 statistic. Neither of the reductions reported in Table 3 were found to be statistically significant at the .05 level.

[Table 3 about here]

The pattern of headway ratio variances for the baseline and control periods was also evaluated over the sequence of time points comprising the routes studied. These patterns are shown in Figure 1. Overall, the figure shows a pattern of increasing variance over the routes' time points in both the baseline and control periods, which is consistent with what has been observed in earlier studies (e.g., Abkowitz and Tozzi, 1987). Also, the figure indicates that the effect of the control actions (taken at time point one) in reducing headway ratio variation is

concentrated over the first three time points. The differences in headway ratio variance were tested by time point using the C^2 statistic, and none was found to be significant at the .05 level.

[Figure 1 about here]

Passenger loads were also evaluated to determine if their variation declined in correspondence with the improvement in headway regularity. Analysis of passenger loads was complicated by a number of missed assignments by load checkers. Fortunately, an effort was made to assign buses equipped with Automatic Passenger Counters (APCs) to the study routes during the control period, which provides a second source of passenger load data. However, it may not be appropriate to simply combine the load counts of APCs and manual checkers, given possible differences in way the two methods measure the same phenomenon. Wonnacott and Wonnacott (1970) provide a means of testing for the relative effects of measurement error in such cases. They suggest a regression of each variable on the other. If measurement error is present in either variable, it will have the effect of biasing its parameter estimate downward when it is specified as the independent variable.

These regressions were performed for the sample of 212 baseline and control period trips for which passenger loads were recorded by both APCs and load checkers. The results of these regressions are reported in Table 4. In the manual count regression, the APC passenger count serves as the independent variable. A 95% confidence interval is constructed around its parameter estimate of .932, and the result ranges from .85 to 1.01. We thus conclude that this parameter estimate is not significantly different from one and that manual counts can be estimated APC counts. Alternatively, in the APC count regression, manual counts serve as the independent variable, with an associated parameter estimate of .779. The 95% confidence interval around this estimate ranges from .71 to .84. Thus the parameter estimate is both

significantly less than one and it also falls below the range for the APC parameter estimate. The conclusions that can be drawn from these results are two-fold; 1) passenger load counts from the two sources should not be combined; 2) the manual count data is subject to a relatively greater level of measurement error than is the APC count data. As a result, the following passenger load analysis draws solely on APC data.

[Table 4 about here]

From the perspective of transit operations, improving headway maintenance should lead to more balanced passenger loads. This issue is examined for both load variation and average load levels in Table 5. In the baseline period the average load of regular service buses is 7.1 passengers greater than the average load for trippers, a difference that is significant at the .025 level, based on the student's t test statistic. During the control period, however, the average load of regular service buses declines by almost four passengers, while average tripper loads increase by nearly one passenger. As a result, the difference in mean loads shrinks to 2.7 passengers during the control period and is no longer significant. This outcome is consistent with an improvement in the spacing between regular service and tripper buses.

[Table 5 about here]

Turning to load variance, the composite effect of the various control actions contributed to a convergence of passenger load variability of regular service and tripper buses. The control actions, particularly holding, likely contributed to the increase in load variance for tripper buses, which were more than offset by the reduction in passenger load variance among regular service buses. Over all buses the improvements in service regularity contributed to a 16% reduction in passenger load variance. Although the differences in variances between tripper and regular service buses and changes between the baseline and control period are substantial, C^2 tests

indicate than none are statistically significant. This reflects the effects of the relatively small sample size of APC trips.

In summary, the statistical analysis of headways and passenger loads provides mixed evidence of the effects of the control experiment. Headway variation declined, but not significantly, while there was a significant convergence (leveling) of passenger loads. Given that the latter outcome relates to a principal motivation for engaging in operations control, we can conclude that the actions taken produced the desired effect. The analysis also indicates that small improvements in service regularity can potentially generate more substantial improvements in passenger load maintenance.

Conclusions

Most of the research and field experience to date on operations control has focused on headway-based holding. This reflects the fact that service regularity problems on high frequency routes affect more passengers, and that corrective actions will thus have larger effect on reducing aggregate wait times. Headway control is most effective on high frequency routes when passenger loads at the control point are light and demand immediately following the control point is heavy. The same holds true for schedule-based holding. As a general rule, control should be implemented as early along the route as possible because delay variation tends to increase as buses proceed further downstream. The main drawback to holding is that it imposes costs on passengers already on board buses.

A large body of useful information presently exists that can be used to design models capable of directing when and where to implement control actions and what the expected savings in wait time would be. The current trend is to implement and evaluate control actions using

actual operations data. Assuming that effective control points can be found, decision rules can be developed to aid in decision making. Advances in communications and transportation technologies such as real-time APC and AVL systems capable of displaying headway deviations will serve to increase prediction accuracy in the future.

The organization of operations control in the new BDS environment is evolving and somewhat uncertain. In the initial stage of BDS implementation it was thought that the role of dispatchers might grow to include some operations control responsibility. There is not much evidence that this has happened. Dispatchers say that they are paying attention to schedule adherence and bus spacing, but operations control has traditionally been managed in the field. Thus, greater improvements in operations control may occur from extending vehicle location and monitoring technology into the field, thereby improving the quality of information available to supervisors. The experiment reported in this paper represents an intermediate step, where supervisors are still reliant on dispatchers for real time information.

Finally, discussions among the participants of the control study reported here also indicate the need and opportunity for automating real time operations control actions. It was felt that a simple decision support system could effectively deal with vehicle holding decisions. The dispatcher in the control experiment noted that there was insufficient time to deal with some of the problems that developed, and that an automated decision support system would have been able to recognize and resolve such problems more effectively.

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Table 1

Routes and Scheduled Trips Selected for Headway Control
 (“Trippers” identified in bold type)

Route-Block No.	Scheduled Departure Time	Scheduled Headway (min.)
12 Sandy Blvd.		
1276	4:07	--
1288	4:10	3:00
1285	4:20	10:00
1275	4:22	--
1286	4:30	8:00
1277	4:37	7:00
1283	4:40	3:00
1294	4:50	10:00
14 Hawthorne		
1409	4:57	--
1417	5:02	5:00
1418	5:03	1:00
1407	5:08	5:00
96 Tualatin I5		
9677	3:50	--
9673	4:00	10:00
9679	4:08	8:00
9669	4:30	--
9675	4:35	5:00
9676	4:45	10:00
9668	4:55	--
9680	5:00	5:00
9671	5:05	5:00
4 Division		
438	4:43	--
459	4:50	7:00
436	4:57	7:00
9 Powell		
935	5:01	--
952	5:07	6:00
946	5:15	8:00
10 Harold		
1035	4:55	--
1046	5:02	7:00
1045	5:10	8:00

Table 2
Control Actions Taken

Action	Reg. Service Buses	Tripper Buses
Holds	3	7
Swaps	1	9
Short Turns	2	0
Total	6	16

Table 3
Baseline and Control Period Headway Ratio Variances*

Reference Point(s)	Baseline	Control Period	Change
All Time Points	.559 (1037)	.538 (1756)	-3.8%
Control Point	.234 (209)	.197 (356)	-15.8%

* Sample sizes are reported in parentheses.

Table 4

**Results for Manual and APC Load Count Regressions
(Standard errors in parentheses)**

	Dependent Variable	
	Manual Count	APC Count
Intercept	4.44 (1.1)	3.35 (1.0)
APC Count	.932 (.04)	--
Manual Count	--	.779 (.03)
R ²	.73	.73
SEE	7.75	7.09
N	212	212

Table 5
Baseline and Control Period Passenger Loads and Variances
(Sample sizes in parentheses)

Mean Passenger Loads			
	Baseline	Control Period	Change
Reg. Service Buses	29.0 (42)	25.4 (101)	-12.4%
Tripper Buses	21.9 (39)	22.7 (79)	3.7%
Overall	25.6 (81)	24.2 (180)	-5.5%
Passenger Load Variance			
	Baseline	Control Period	Change
Reg. Service Buses	239.3	165.9	-30.7%
Tripper Buses	135.4	167.0	23.3%
Overall	199.5	167.3	-16.1%

Figure 1
Baseline and Control Period Headway Ratio Variances By Time Point

