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Design and Implementation of Bus–Holding Control Strategies with Real-Time Information

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A systematic study is described to address various design and implementation issues associated with the problem of real-time bus holding control. Two holding control models have been investigated. The first model follows the conventional threshold-based control logic that determines holding times on the basis of headway to the preceding bus. The second model makes use of both preceding and following headways in identifying optimal control decisions with the assumption that real-time bus location information is available for estimating future bus arrivals at the control stop. An extensive simulation analysis is performed using a real-life bus route operated by the Grand River Transit of the region of Waterloo, Ontario. The simulation results have substantiated several conclusions and yielded new findings on various issues such as where to set the control point, how many control points should be used, what is the optimal control strength, and what is the value of real-time location information.

Bus operations in urban environments are often subject to significant variations because of a variety of complex factors such as dynamic and stochastic traffic congestion and passenger demand. These variations, if not offset by control actions, will cause bus bunching—a well-known phenomena contributing to increases in passenger wait time and uncertainty in bus arrival times (*1*). Controlling bus operations is a way to compensate and reduce the effect of such variations so that the planned headway and schedule can be maintained. Among many bus control strategies, holding control is one of the most effective and common strategies that can be used to regulate bus operations. By holding early-arriving buses, bus headways can be evened out and service reliability improved.

Bus–holding control strategies can be generally classified into two categories: one includes threshold-based control models in which buses are held at a control stop on the basis of the deviation of their headway from the desired headway (*1, 2*). Models in the second category determine holding times on the basis of a mathematical control formulation with an explicit objective function such as minimizing total passenger wait time (*3*). In this study, only those models in the first category are considered with a specific focus on headway-based transit services.

A number of studies have been devoted to the development and evaluation of threshold-based holding control models, and the majority of those studies addressed the following issues:

- Where should the control point be placed along a bus route?
- Would it be beneficial to use more than one control point?
- What control threshold values should be used to provide a desired balance between control benefits (e.g., reduced wait time) and control costs (e.g., increased in-vehicle time and bus travel time)?
- Would it be advantageous to consider bus location in holding control (or what is the value of real-time bus location information)?

However, past studies have not yet provided complete and consistent conclusions on these issues, as shown in Table 1. The main objective of this research is to provide some complementary evidence on the aforementioned issues, hoping to substantiate some of the existing conclusions and explain some of the conflicting findings. The following sections discuss the bus–holding control models analyzed in this study, the simulation model used in the analysis, and the simulation results.

HOLDING CONTROL MODELS

The main objective of a threshold-based holding control strategy is to regulate bus headways at the control stop, which is based on the following theoretical relationship between the expected wait time of randomly arriving passengers and the variation of bus headways (*1*):

$$E(W) = E(H)/2 + \text{var}(H)/2E(H)$$

where

$E(W)$ = average wait time,
$E(H)$ = average headway between buses, and
$\text{var}(H)$ = variance of headway.

The implication of this relationship is that a control strategy that reduces the variation of bus headway should also reduce passenger wait times at bus stops. The following section describes two control models that essentially follow this logic with the objective of minimizing headway variation at a control stop.

One-Headway-Based Holding Control

In this model, the preceding headway of the bus under control is compared with a threshold headway and the amount of holding time is determined accordingly. Consider that a request for a holding decision is made by bus *i* that is currently at the control stop and has just finished loading and unloading passengers, as shown in Figure 1. Denote H_0 as the planned service headway, and T_0 as the current time which would be the departure time of bus *i* if no holding control was applied.

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TABLE 1 Summary of Some Past Studies on Bus Holding Control (4–9)

Studies	Methodology	Design & Implementation Issues			
		Where to control?	What control threshold to use?	How many control points to use?	Value of real-time location information?
Osuna and Newell, 1972	Analytical: • a single stop route • one or two buses	Not analyzed	• Optimal threshold for one bus and two buses were derived	Not analyzed	Not analyzed
Koffman, 1978	Simulation • single control point	• Terminal	• Analyzed two threshold values ($0.75H_0$ and $0.65H_0$) • Higher threshold values corresponded to lower waiting time and higher bus travel time	Not analyzed	Not analyzed
Turnquist, 1978; Turnquist and Blume, 1980	Analytical: • single control point	• Stops with high boarding demand and low onboard passengers • As early along the route as possible	• Derived a formula for optimal threshold value that is related to the ratio of onboard passengers to the boarding demand at the stop	Not analyzed	Not analyzed
Abkowitz and Engelstein, 1984; Abkowitz, Eiger and Engelstein, 1986; Abkowitz and Lepofsky, 1990	Analytical + simulation: • single control point	• Just before a group of high demand stops	• Derived a formula for optimal threshold value • 0.6–1.0	Not analyzed	Not analyzed
Lin et al. 1995	Simulation: • all stops were controlled	Not analyzed	• 0.8–0.9	Not analyzed	Not analyzed
Eberlein et al., 2001	Analytical: • single control point	• Terminal	Not analyzed	• One control	• Useful

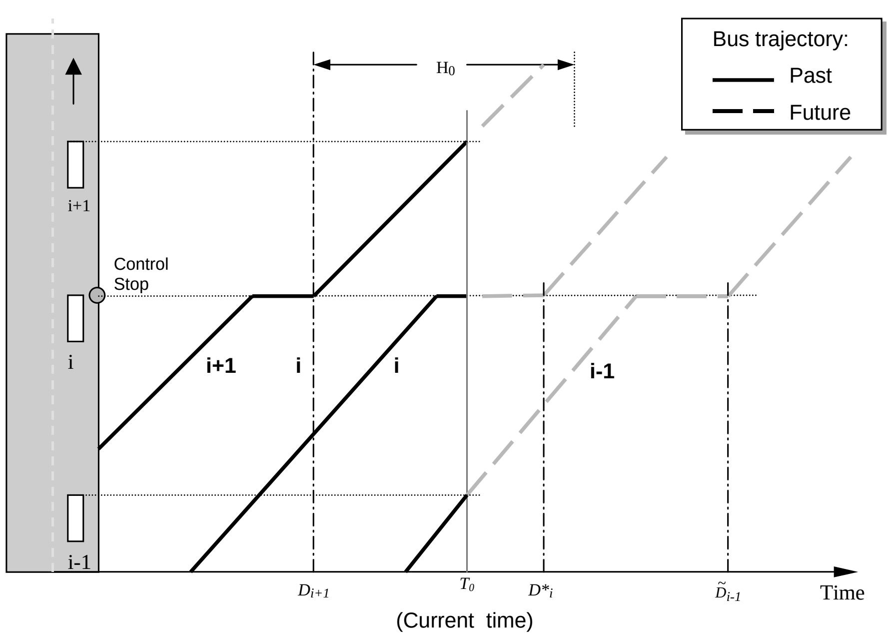

FIGURE 1 Space–time diagram of bus operations.

The optimal departure time of bus i, denoted by D_i^*, is determined as follows:

if

$$T_0 < D_i + cH_0$$

then

$$D_i^* = D_{i+1} + H_0$$

else

$$D_i^* = T_0$$

where c is the holding control parameter called control strength with values ranging from 0.0 to 1.0, and the product cH_0 is commonly referred to as threshold headway. By including this parameter, the control method tries to maintain the departure headway of each bus within the range (cH_0, H_0), or, only a headway of less than the threshold headway (cH_0) would invoke a holding action. Clearly, a c-value of 0.0 means no holding control will be exercised, and a c-value of 1.0 calls for full control—a situation in which a bus will be held whenever its headway is smaller than the planned headway.

The implementation of this control model is relatively simple; only the departure time of each bus at the control stop (D_i) needs to be recorded. The most common implementation in practice is based on field inspectors who monitor bus departures and estimate the hold times accordingly. A more sophisticated method would rely on a dispatch center to monitor bus operations and to calculate and send departure times to buses at the control stop.

Two-Headway-Based Holding Control

The one-headway control model determines the holding time for a bus only on the basis of its headway to the preceding bus and thus does not consider how close the following bus is. One potential problem of this model is that the resulting control actions may increase from one bus to the next when several buses arrive at the control stop closely following each other. A new holding control model is proposed called "two-headway-based holding control strategy," in which holding times are determined based on both the preceding headway and the following headway. This model assumes that an arrival-time prediction model is available for determining the estimated time of arrival (ETA) of the following bus at the control stop (Figure 1).

Denote the departure time of bus $i + 1$ by D_{i+1} (recorded in the past) and the estimated departure time of bus $i - 1$ by $\tilde{D}_{i-1}$. Note that the departure time of bus $i - 1$ at the control stop is the predicted departure time without holding, which depends on its ETA and the expected number of passengers boarding and alighting the bus. In this study, the following simplified equation was used to approximate the estimate:

$$\tilde{D}_{i-1} = t + b \cdot (t\lambda)$$

where

- t = travel time for bus $i - 1$ to travel from its current location to the control stop, which can be estimated based on the distance to the control stop and the average travel speed;
- λ = the average passenger arrival rate; and
- b = boarding time at the control stop.

Note that this approximation model does not consider passenger alighting time, which is often relatively small, to keep the need for real-time information at a minimum.

Define $\bar{H}$ as the average headway of bus i and $i - 1$, that is, $\bar{H} = (\tilde{D}_{i-1} - D_{i+1})/2$. The control logic of this model can then be formulated as

if

$$T_0 < D_{i+1} + H_0$$

then

estimate $\tilde{D}_{i-1}$ and then $\bar{H}$, and

if

$$\bar{H} > H_0$$

then

$$D_i^* = D_{i+1} + H_0$$

else

$$D_i^* = D_{i+1} + \left(\bar{H} + H_0\right)/2$$

else

$$D_i^* = T_0.$$

The intuitive advantage of this control model is that the resulting control actions could be less abrupt and would thus keep buses running more smoothly with reduced delay to the onboard passengers. However, implementing this model is a more challenging task as it requires a model for estimating bus departure times at the control stop.

SIMULATION ANALYSIS

The bus–holding control models discussed in the previous section are heuristic in nature and thus are not guaranteed to provide the expected performance benefit. In addition, each control model includes settings that need to be identified for specific operating environments. To evaluate the control strategies in a systematic manner, a bus simulation system called SimTransit has been developed to model bus operations with controlled operating conditions and dispatch models.

The simulation model includes three subcomponents: a dispatch module, a traffic module, and a geographic information system (GIS)-based animator. The dispatch module is used to represent a transit dispatch center with integrated functionality such as monitoring bus operating status, accepting dispatch requests from buses in service (represented by the traffic module), determining control actions according to a specified control strategy, and transmitting instructions back to the buses.

The traffic module is the component to replicate the operating process of each bus and its environment, including movements of buses and other vehicles, passenger flow (arriving, boarding, alighting), and signal control. Our current implementation does not explicitly model signal control and other traffic; instead, it considers the bus travel time (speed) on each road segment as a random variable with a distribution that can be specified externally. This modeling approach has been used in many other bus operations studies with the argument that, by selecting appropriate travel time distributions, the effects of signal control and traffic congestion should be able to be captured (*2, 10, 11*). Normal and lognormal distributions are commonly used to model bus travel times (*10, 11*); in this study, a normal distribution was assumed.

Furthermore, it is assumed that passenger arrivals at each bus stop follow a Poisson process. This assumption has been shown reasonable for modeling headway-based routes in which service headways are relatively small (e.g., less than 10 min) (*5, 9, 12*). Each passenger's destination stop is determined on the basis of a prespecified passenger origin–destination (O–D) distribution. Passenger boarding and alighting rates are assumed to be constant (*12, 13*).

The animation interface was implemented using Environmental Systems Research Institute, Inc.'s GIS control—MapObject—and the simulation system was coded in C++ as a Windows application program.

CASE STUDY

The simulation model was applied to a real bus route with the objective of evaluating the effectiveness of the control strategies with various assumed operating conditions and control options. The simulated bus route was a model of Routes 7C and 7D operated by Grand River Transit in the Kitchener–Waterloo area, Ontario, Canada, as shown in Figure 2. The route includes a total of 28 stops (after combining some of the low-demand stops in the original routes). The route starts from the transportation center located at the Kitchener downtown, via the University of Waterloo (a major O–D) and returns back to the transportation center. Two demand profiles were used in this analysis: the base demand profile is the afternoon peak passenger demand obtained through a passenger survey (see Figure 3); the second profile was created by doubling the demand rates of the base case to represent high-demand scenarios. Average passenger boarding and alighting times were assumed to be 4 s and 2 s per passenger, respectively. Travel times on individual links along the route were also available and found to have large variations with coefficients of variation (standard deviation to mean ratio) ranging from 0.21 to 0.53. In this simulation analysis an average coefficient of variation of 0.38 was used for all links. An operating headway of 5 min was used in all of our analyses and a total of 12 buses were assumed to operate on the route. For each scenario, the model was run for 6 h with the same passenger demand with the first hour removed as the warm-up period.

Five performance measures were used in comparing all control strategies: passenger wait time, passenger in-vehicle time, weighted passenger wait time, bus travel time, and control frequency. The weighted passenger wait time is the sum of the passenger wait time and the equivalent wait time of the in-vehicle time by assuming that 2 min of in-vehicle time is equal to 1 min of wait time. The control frequency is defined as the percentage of buses that are held at the control stop. All measures, except control frequency, are presented in relative values, that is, relative reductions as compared with the base case of no control.

Where to Control

Where to set control point constitutes an important decision when implementing a holding control strategy. This section presents the results of a set of simulation runs designed to address this decision. Bus operations with the two demand profiles were simulated with the one-headway holding control model ($c = 1.0$) applied to individual

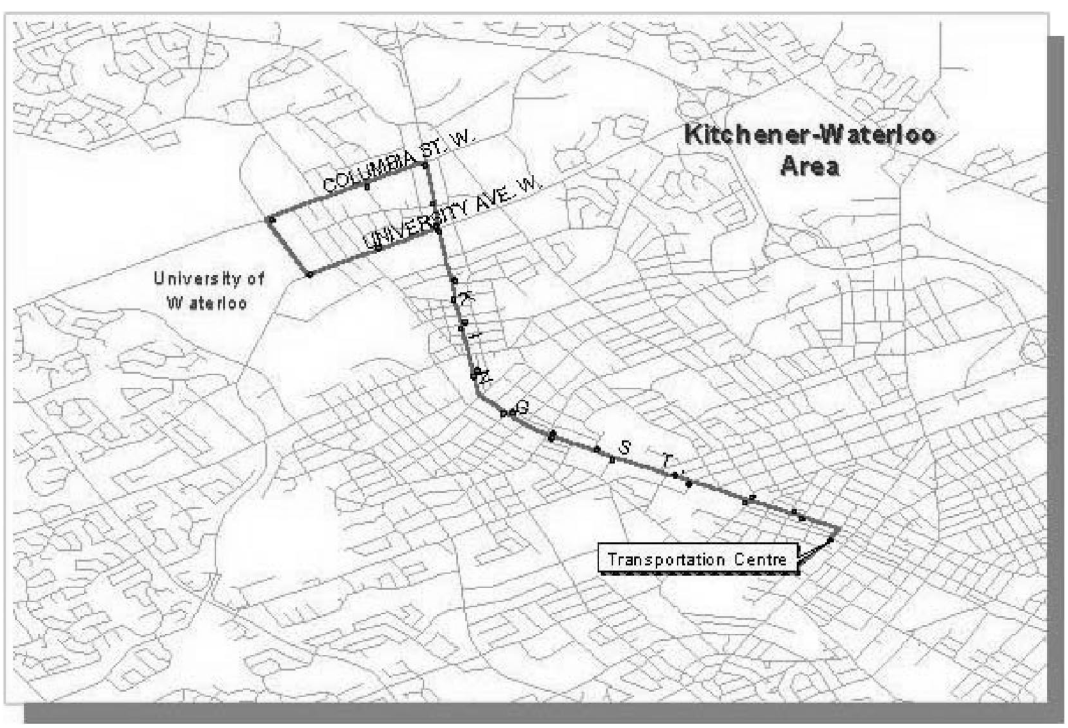

FIGURE 2 The bus route under study.

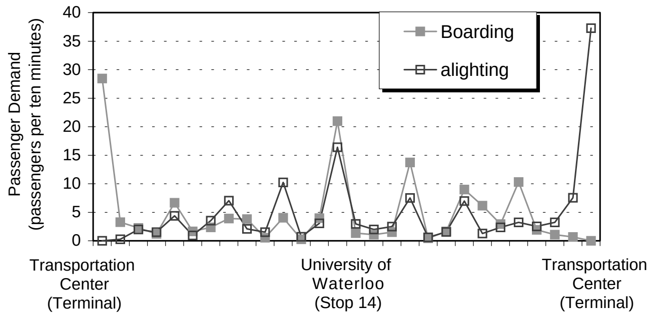

FIGURE 3 Passenger demand profile.

stops. The simulation results show that the effectiveness of holding control was strongly related to the passenger boarding demand at the control stop and at the location of the control stop. Figure 4 shows the relationships between the reduction in passenger wait time and the passenger boarding rate at the control stop and the distance from the control stop to the terminal. It can be observed that the higher the boarding demand at a stop and the closer the stop is located to the middle of the route, the more effective it was to use that stop as a control point. Similar patterns were also found for in-vehicle time and for both demand scenarios.

This finding is generally consistent with those of past studies. For example, Abkowitz and Englestein (*6*) concluded that the best control point should be the stop just preceding a group of stops with high levels of boarding demand, which, on the basis of our interpretation, is essentially the same as the first high-demand stop. Koffman (*2*), Turnquist and Blume (*5*), and Eberlein et al. (*3*) concluded that the terminal or the stop closest to the terminal should be the best point to implement holding control. However, our further simulation analysis on several additional cases with lowered demand at the terminal and varied levels of variation in dispatching headway indicated that this assertion cannot be generalized and is only valid when both the variation of dispatching headway and the boarding demand at the terminal are relatively high.

Optimal Number of Control Points

In the previous analysis, it was assumed that only one stop is implemented with holding control. In this section, the question of whether it is beneficial to apply holding control to more than one stop is addressed. Both demand scenarios were used in this analysis with three control scenarios: one-stop control (Stop 14), two-stop control (terminal + Stop 14), and all-stop control. The control strength was set to 1.0. In all-stop control, holding controls were applied to all 28 stops on the route. Figure 5 gives the simulation results of the high-demand case with regard to the relative reduction in passenger wait time, in-vehicle time, bus travel time, and control frequency with the three control methods. The following findings can be observed:

- The all-stop control reduced average wait time of passengers but resulted in significant increases in in-vehicle time, bus travel time, and control frequency.
- The two-stop control appears to be optimal with regard to all performance measures. It achieved a reduction in passenger wait time at a magnitude close to the all-stop control (34% versus 37%) while incurring no apparent increase in in-vehicle time and only a slight increase in bus-travel time and control frequency.

Optimal Control Strength

This section identifies the effect of the control parameter—control strength—on the effectiveness of the one-headway-based control model. Both demand scenarios were simulated to generate operating statistics with control strengths varying from 0.0 (no control) to 1.0 (full control). The one-stop control model with Stop 14 selected as the control point was applied. The simulation results of the high-demand case were given in Figure 6, which shows the relationships among the relative reductions in average passenger wait time, in-vehicle time, total weighted passenger time, and average bus travel time as functions of control strength. Three general conclusions can be obtained:

1. An increase in holding strength (tighter control) can reduce the average passenger wait time; a reduction as large as 24% was obtained in the simulated case. The relative benefit with regard to reduction in wait time, however, leveled off when the control strength was increased to a certain value (in this case, 0.6–0.8).
2. Holding control had no negative effect with regard to passenger in-vehicle time. Although the in-vehicle time of the onboard passengers at the control stop should increase, increased regularity of headways can reduce the in-vehicle time of the passengers at the following stops.
3. Tighter control also means higher bus travel time, which could imply higher operating costs.

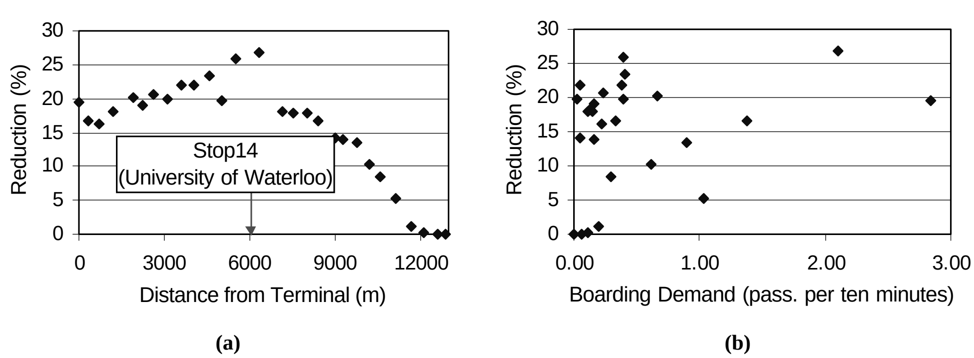

FIGURE 4 Control effectiveness versus (*a*) stop location and (*b*) boarding demand (pass. = passengers).

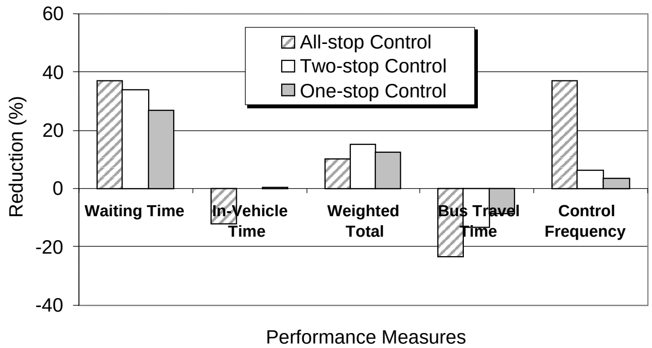

FIGURE 5 Control effectiveness with different numbers of control points.

4. Using lower control strength has another advantage of reduced control frequency. For example, when full control ($c = 1.0$) was used, the frequency was 90% (that is, 90% of buses arriving at the control stop were held), and the control frequency was reduced to 74% when a control strength of 0.6 (or 3-min threshold headway) was used.

It should be noted that the above conclusions are generally consistent with the results from several past studies. Abkowitz and Engelstein (*6*) developed an approximate model for determining the optimal threshold value for bus holding control and provide solutions to several cases of different demand profile. Interestingly, all optimal threshold values followed within the range of 0.6 H_0 and H_0. In a simulation study similar to ours, Lin et al. (*9*) concluded that the optimal control strength should consider a trade-off between passenger wait time and in-vehicle time. Although not directly provided in their study, their analysis would conclude that a control strength of approximately 0.8 would minimize the total weighted travel time if a wait-time to in-vehicle-time ratio of 2.0 were used.

Perhaps the most interesting finding from our simulation results (Figure 6) is that the threshold-based holding control strategy is fairly robust with respect to the control strength (or threshold headway). For example, a control strength of as small as 0.2 (or 1-min threshold headway) would realize approximately 70% of the total possible benefit that can be obtained from holding control with regard to reduction in wait time. The implication of this pattern is that it may not be necessary to calculate the control strength rigorously as long as a value that is not too small is used. This robustness may explain why field-inspector-based bus control, although approximate, works very well in practice.

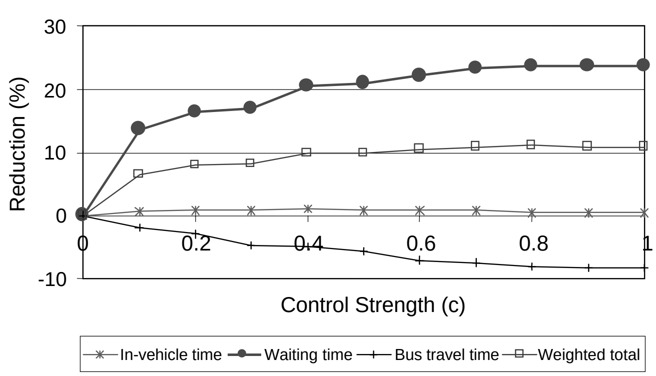

FIGURE 6 Effects of holding control versus control strength.

Value of Real-Time Information

This section addresses the question of whether a control strategy using real-time location information (two-headway-based model) would achieve better systemwide performance. First the high-demand scenario was simulated with the two control models applied to a single control point (Stop 14); it was found that there was no noticeable difference in performance between the two control models. Then the same scenario was simulated with the two control models applied to all of the stops; the results are shown in Figure 7. It can be observed that when all stops were implemented with holding control, system performance with regard to all performance criteria was improved. The main benefits were in passenger in-vehicle time and bus travel time. Compared with the first model, the reduction in passenger in-vehicle time was increased by more than 14.9%, and reduction in average bus travel time was increased by 16.5%.

CONCLUSIONS AND FUTURE WORK

Bus holding control is an effective means of stabilizing bus operating headways for improved service reliability and reduced passenger wait time. However, the effectiveness of this control is largely dependent on how the underlying control strategies are implemented. This research has carried out a systematic simulation study, aiming to identify the optimal settings by which a holding strategy should be implemented. The following general conclusions have been obtained from the simulation results:

- A control point should be placed at the bus stop that has a high level of boarding demand and is located close to the middle of the bus route.
- If possible, holding control should be applied to two points along the route, ideally one at the terminal and the other at a high-demand stop near the middle of the route. Little additional benefit can be attained by using more than two control points with threshold-based holding control strategies.
- Holding control is fairly robust with respect to the control parameter–control strength or headway threshold. The majority of the benefit with regard to reduction in wait time can be realized when the control strength used is greater than or equal to 0.4. The optimal control strength appears to be in the range of 0.6 to 0.8.
- Real-time bus location information has the benefit of reducing passenger in-vehicle time and bus travel time, but only when a number of control points are used. There appears to be small benefit with regard to passenger wait time.

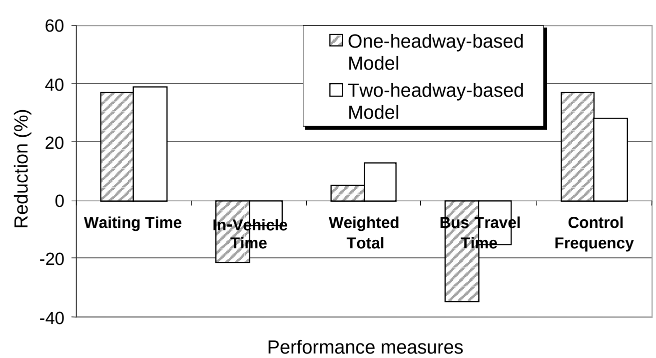

FIGURE 7 Effects of real-time location information.

Finally, it should be noted that the conclusion on the value of real-time information should be taken cautiously as the actual benefits probably depend on the implemented control model. Further research is needed to obtain a definite conclusion. Currently the authors are developing and testing several advanced bus control models and algorithms that can represent advanced technology options such as automatic vehicle location and automatic passenger counters and make maximum use of available real-time information.

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REFERENCES

1. Osuna, E. E., and G. F. Newell. Control Strategies for an Idealized Public Transportation System. *Transportation Science*, Vol. 6, No. 1, 1972, pp. 52–72.
2. Koffman, D. A Simulation Study of Alternative Real-Time Bus Headway Control Strategies. In *Transportation Research Record 663*, TRB, National Research Council, Washington, D.C., 1978, pp. 41–46.
3. Eberlein, X., N. Wilson, and D. Bernstein. The Holding Problem with Real-Time Information Available. *Transportation Science,* Vol. 35, No. 6, 2001, pp. 1–18.
4. Turnquist, A. M. Strategies for Improving Reliability of Bus Transit Service. In *Transportation Research Record 818*, 1981, pp. 7–l 3.
5. Turnquist, A. M., and S. W. Blume. Evaluating Potential Effectiveness of Headway Control Strategies for Transit Systems. In *Transportation Research Record 746*, TRB, National Research Council, Washington, D.C., 1980, pp. 25–29.
6. Abkowitz, M., and I. Engelstein. Methods for Maintaining Transit Service Regularity. In *Transportation Research Record 961*, TRB, National Research Council, Washington, D.C., 1984, pp. 1–8.
7. Abkowitz, M., A. Eiger, and I. Engelstein. Optimal Control of Headway Variation on Transit Routes. *Journal of Advanced Transportation*, Vol. 20, No. 1, 1986, pp. 73–88.
8. Abkowitz, M., and M. Lepofsky. Implementing Headway-Based Reliability Control on Transit Routes. *Journal of Transportation Engineering*, Vol. 116, No. 1, 1990, pp. 49–63.
9. Lin, G., P. Liang, P. Schonfeld, and R. Larson. *Adaptive Control of Transit Operations. Final Report for Project MD-26-7002*. University of Maryland, College Park, 1995.
10. Andersson, P., A. Hermansson, E. Tengvald, G. Paolo, and S. Tomba. Analysis and Simulation of an Urban Bus Route. *Transportation Research*, Vol. 13A, 1979, pp. 439–466.
11. Seneviratne, P. N., L. Tam, and M. Javid. Scheduling Fixed Route Bus Services Using Simulation. *Proc., International Conference on Microcomputers in Transportation,* San Francisco, Calif., June 1990, pp. 1042–1053.
12. Ding, Y., S. Chien, and N. A. Zayas. Simulating Bus Operations with Enhanced Corridor Simulator: Case Study of New Jersey Transit Bus Route 39. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1731*, TRB, National Research Council, Washington, D.C., 2000, pp. 104–111.
13. Li, Y., J. Rousseau, and M. Gendreau. Real-Time Dispatching of Public Transit Operations With and Without Bus Location Information. In *Computer-Aided Transit Scheduling Proceedings*, Lisbon, Portugal, July 1993.

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