RELIABILITY IMPROVEMENT IN SHORT HEADWAY TRANSIT SERVICES: SCHEDULE-BASED AND HEADWAY-BASED HOLDING STRATEGIES

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ABSTRACT

Improving service reliability is becoming a key focus for most public transport operators. One common operational strategy is holding. Holding vehicles can improve reliability, resulting in both shorter travel times and less crowding.
In this paper, both schedule-based and headway-based holding strategies are analyzed in short headway services. Despite a significant focus on holding in current literature, some important aspects have not been researched previously. The main, new, variables are the maximum holding time, the reliability buffer time and, in the case of schedule-based holding, the percentile value used to design the schedule. Both a real line in The Hague (tram line 9) and hypothetical lines are analyzed with various levels of running time variability. Both headway-based and schedule-based holding have the largest effect if deviations are high. When applying schedule-based holding and a maximum of 60 s. holding time is applied, the optimal value of the percentile value becomes about 65% for all lines analyzed. When no maximum holding time is applied, schedule-based holding is more effective, while there is no difference when the maximum holding time is set to 60s. This research also shows the effect of holding on crowding: An average level of irregularity of 20% could decrease to 15%, enabling either smaller capacity slack or less crowding.

1. INTRODUCTION

Improving service reliability is becoming a key focus for most public transport operators. The development of Automated Vehicle Location systems (AVL), Automated Passenger Counting (APC) and Computer Aided Dispatching systems (CAD) in the past two decades has facilitated research on and implementation of measures to improve reliability. While improved reliability can be achieved through changing the service plan (both network design and scheduling), the traditional approach in public transport practice focuses on the operational level. In (*1*) several options of this type are described. One common operational strategy is holding. Holding vehicles can improve reliability, resulting in both shorter travel times and less crowding.

Holding strategies can be designed in various forms with a major differentiating characteristic being how a holding action is triggered. Commonly either headway or schedule deviation is used to initiate holding. If the preceding headway of a vehicle is short or a vehicle is operating ahead of schedule, the vehicle will be held. The most commonly used method is a threshold strategy, whereby vehicles are held only if a certain threshold is exceeded (*2*). The next section reviews prior literature in this area.

While this research focuses on holding at a stop, holding at traffic lights is also a common strategy, for example conditional holding as analyzed by (*3,4*). The advantage of traffic signal strategies is that the traffic lights enforce holding, but the disadvantage is that waiting at the traffic lights does not enable passengers to board during the hold and priority for (almost) all vehicles may be preferable over conditional priority.

In this paper holding is presented as a measure to reduce travel time on a single line, but it can also be employed to ensure transfers, as explored by (*5*) and (*6*). Holding can also be very effective in restoring service after service disruptions have occurred, as described by (*7,8,9*).

This research, however, focuses on holding in normal operations. The focus is on short headway service, assuming random passengers' arrivals at stops. This means that headways can be used to calculate waiting times.

2. HOLDING STRATEGIES

In this section the main holding strategies and their associated key variables are explained. In section 3 the mathematical model is given, including the effect of holding strategies on waiting time for passengers.

When applying holding points, it is important to determine the location(s) of holding points. However optimizing the number and location of holding points is beyond the scope of this research. Rather the holding location is chosen in a pragmatic way: good holding points are where there are few through passengers are and many passengers boarding downstream (*10,11,12*).

2.1 Headway-Based Holding

Headway-based holding means that vehicles with headways shorter than scheduled are held to restore a tight headway distribution. No action is taken for vehicles with long headways because it is assumed that vehicles cannot be sped up. When applying headway-based holding the following variables are considered:

Holding factor

This factor determines how long vehicles are held relative to the difference between the actual and scheduled headways. A holding factor of 100% means that vehicles are held the full amount of time needed to achieve the scheduled headway. This means that even if only one vehicle experiences a delay, all following vehicles could also be held. A lower holding factor will reduce this effect.

Maximum holding time

Introducing a maximum holding time affects the maximum individual travel time. Maximum holding prevents anyone from experiencing extremely long travel times in order to achieve the optimum for all passengers. Experience has shown that in short headway service, holding times longer than 60 seconds are generally not acceptable to either passengers or drivers.

Figure 1 illustrates the headway-based holding strategy. Vehicle 1 is delayed and vehicle 2 is ahead of schedule, creating a short headway between them. At stop 3, the holding point, vehicle 2 will be held by an amount of time equal to either the maximum holding time or the product of the holding factor and the headway deviation. By holding vehicle 2, the headway between vehicle 2 and 3 also decreases, which could then also lead to the holding of vehicle 3 (depending on the trajectory of vehicle 3).

2.2 Schedule-based Holding

In contrast to headway-based holding, schedule-based holding involves analyzing only one vehicle at a time. At the holding point the vehicle's schedule adherence is checked and if the vehicle is ahead of schedule it is held for a certain time. The following variables are of importance.

Schedule percentile value
Because a comparison is made between the performance and the schedule of a specific vehicle, schedule design plays an important and direct role in this type of holding. For example, if scheduled trip times are very tight, few vehicles will operate ahead of schedule and little, if any holding is necessary. On the other hand, if the schedule is very loose, most vehicles will be ahead of schedule and will be held. To determine scheduled trip time, most transit operators use a percentile value of the cumulative distribution of the actual trip times from the previous period. Earlier research has investigated the effect of this choice on additional waiting time for passengers in the case of scheduled arrival of passengers (*1,12*). Note that this is not relevant in the case of random arrivals of passengers and headway-based holding.

Maximum holding time
Similar to headway-based holding, a maximum holding time is included to insure that the model results are acceptable.

Figure 2 illustrates the schedule-based holding, dealing with the variables mentioned above and showing both the 5- and 95-percentile values of trip 1. The actual trajectory of trip 1 is also shown. At the holding point, stop 3, a comparison is made between the scheduled and actual departure times. Depending on the percentile value, the actual trip is ahead of schedule or delayed. In this example the figure shows that the vehicle is ahead of schedule and is held for a certain time. The holding time is either the earliness or the maximum holding time. By holding the vehicle, the following headway will be shortened. However, the next vehicle is held only if its schedule adherence is negative, regardless of the value of the headway.

2.3 Literature Review
Several research papers on holding have been published (e.g. *13,14*). In (*15*), an overview of some earlier research on holding is provided most of which focus on headway-based holding. In (*11*) research on holding using thresholds is presented. The influence of different perceptions of waiting at the stop and inside the vehicle (due to holding) is shown. When the perception of waiting at a stop (as a ratio of waiting in the vehicle) increases, holding becomes more interesting. In (*16*) headway-based and schedule-based holding strategies are compared, concluding that headway-based control is more effective. Proportional holding, i.e. holding time as a fraction of the headway or schedule deviation, is also mentioned but results are not provided. Reference (*17*) deals with the holding problem for low-frequency services. Besides average travel time, also the budgeted travel time is considered. Reference (*18*) also deals with the phenomenon that travelers budget additional travel time ensuring on time arrival, referring to it as a Reliability Buffer Time (RBT). This indicator shows the effect of unreliability by taking into account the 95-percentile arrival time. Many passengers want to be on time for an activity at their destination and allow for this additional time required when planning their trip. In addition, (*17*) also considers the possibility of operators adding slack time into the schedule. This ensures that reliability will increase, although a trade-off clearly exists between reliability and travel time, due to additional scheduled trip time when slack is included. Other researchers (*19*) performed a real-life experiment, applying

threshold-based holding. They show positive results for headway-based holding and they state that the reported effect of holding may have been understated because human factors can greatly reduce the effectiveness of the holding strategy. (*20*) focuses on holding when real-time information is available, enabling better holding strategies. (*21*) shows research on schedule-based holding in high-frequency systems and explicitly accounted for the effects of schedule. One of the observations was that long holding times are hard to enforce in practice, supporting the introduction of maximum holding time. Finally, (*22*) presented research on schedule-based holding, also including scheduling issues, but assumed passengers arrive according to the schedule.

The literature review shows that not all the important variables (i.e. maximum holding time, schedule percentile value and RBT) have yet been taken into account in any single piece of research on holding. The maximum holding time is relevant for both operators and drivers and for passengers. The introduction of maximum holding accounts for the effect of holding on individual passengers. It makes it possible to optimize scheduling and holding strategies recognizing a minimum service quality for all passengers, i.e. a maximum additional travel time due to holding. Additionally, in the case of rail systems, limited capacity and shared use of tracks with other lines could force held vehicles to depart (before holding time is expired). Although leading to an optimum for all passengers on average, holding strategies without a maximum holding time are not likely to be acceptable if holding times exceeds 60 seconds (in the case of short headways). Experiences in The Hague show operators are not willing to adopt large holding times because of concerns about the acceptability to both passengers and drivers. (*21*) also states that long holding times are hard to enforce.

Due to the lack of research on the effect of introducing maximum holding time and little focus in the literature on the effect of schedule parameters on short headway service holding strategies, this paper focuses on these variables. The objective of this research is to assess the impact of the key variables on the optimal holding strategy (regarding travel time of passengers). Although headway-based holding is the main research topic in literature, this research deals with both headway-based and schedule-based holding. From a practical point of view, schedule-based holding may be interesting even if headways are short. Due to resource planning and workforce management concerns, schedules exist anyway and it is much easier to deal with schedules than with headways, which involves two vehicles. Another interesting phenomenon is the existence of branched networks all over the world, providing short headways on the trunk part, but on the branches headways could become large enough for many passengers to arrive at the stop based on the schedule. In this case, schedule adherence is preferred over headway adherence. Additionally, in most Western European countries, schedule adherence is similar to headway adherence, since schedules provide constant headways.

3. MODEL FORMULATION

To calculate the effect of holding strategies on passengers' travel time, a model has been developed. The main objective is to compute the additional waiting time, the time which is added as a result of service unreliability. In a perfectly regular service additional waiting time is zero per passenger.

First the variables used and the main assumptions made in the model are defined. Next the equations used to calculate additional travel time are presented. Finally, equations are given to calculate the effects of headway and schedule based holding on headways.

3.1 Variables and Assumptions

The variables in this research are:

- Number and location of holding points;
- Passenger boarding and alighting distribution;
- Standard deviation of total trip time;
- Percentile value used to determine scheduled trip time (schedule-based holding only);
- Maximum holding time;
- Holding factor (headway-based holding only);
- Scheduled headway.

This research focuses on short headway services, assuming random arrival of passengers at stops. In addition, cycle time is considered fixed (as in (*22*)). This results in longer layover times if lower percentile values are used for the scheduled trip time. However layover time is assumed to be long enough to enable punctual departures in the opposite direction. In addition, there is assumed to be no relation between headways and trip times (including dwell times), as in (*21*). Neither is a direct link considered between the holding time and the number of on-board passengers. Holding is applied at a stop and only the preceding headway is considered, because at the holding point, no information is assumed to be available about the following headway. The final assumption is that scheduled headways are constant.

3.2 Calculation of Additional Travel Time

To calculate the additional travel time per passenger due to unreliable service, both the waiting time at the stops and in the vehicle must be considered. Note that the latter only occurs when holding is applied. Equation 1 gives the average additional waiting time at a stop as a function of scheduled and actual headways (*23*). Equation 2 gives the average additional waiting time in the vehicle if holding is applied at stop h.

To calculate the additional (average) travel time per passenger on the line, equations 3 and 4 are used. Besides the average additional travel time, (*18,24*) argue that the reliability buffer time (RBT) is also important, reflecting the effect of unreliable services on passengers travel time budget. Equations 5-8 deal with the RBT which are also weighted per stop to calculate a line total. The 95th percentile value of waiting time is taken out of the actual trip data set and similar to (18,24) the RBT is calculated for the waiting time in the vehicle as well. Finally equation 9 assesses the total additional time using different weights for different components (compared to in-vehicle time).

$$T_j^{waiting\_stop} = \frac{H^{sched}}{2} * (c_v(H_j^{act})^2) \qquad (1)$$

$$T_j^{waiting\_vehicle} = \frac{\sum_{i=1}^{n_i} T_{i,j}^{waiting\_vehicle}}{n_i} \qquad j=h \qquad (2)$$

$$T^{Waiting\_stop} = \sum_{j=1}^{n_j} \alpha_j \; * T_j^{waiting\_stop} \qquad (3)$$

$$T^{waiting-vehicle} = \sum_{j=1}^{n_j} \beta_j \; * T_j^{waiting\_vehicle} \qquad (4)$$

$$RBT_j^{waiting\_stop} = T_{i,j}^{95\% waiting\_stop} - T_j^{waiting\_stop} \qquad (5)$$

$$RBT_j^{waiting\_vehicle} = T_{i,j}^{95\% waiting\_vehicle} - T_j^{waiting-vehicle} \qquad if\ j=h \qquad (6)$$

$$RBT^{waiting\_stop} = \sum_{j=1}^{n_j} \alpha_j \; * RBT_j^{waiting\_stop} \qquad (7)$$

$$RBT^{waiting\_vehicle} = \sum_{j=1}^{n_i} \beta_j \; * RBT_j^{waiting\_vehicle} \qquad (8)$$

$$T_{add} \approx \theta_{stop} * T^{waiting\_stop} + \theta_{in-vehicle} * T^{waiting\_vehicle} + \theta_{RBT} * (RBT^{waiting\_stop} + RBT^{waiting\_vehicle}) \qquad (9)$$

where:

i	= *index of vehicle*
j	= *index of stop*
$T_j^{waiting\_stop}$	= *Average additional out-of-vehicle waiting time at stop j*
$T_j^{waiting\_vehicle}$	= *Average additional in-vehicle waiting time at stop j*
H^{sched}	= *Scheduled headway*
H_j^{act}	= *Actual headway ahead at stop j*
c_v	= Coefficient *of variation*
n_i	= *number of trips observed*
α_j	= *Relative weight of boardings at stop j*
β_j	= *Relative weight of through passengers at stop j*
$RBT_j^{waiting\_stop}$	= *Reliability buffer time of waiting at the stop*
$RBT_j^{waiting\_vehicle}$	= *Reliability buffer time of waiting in the vehicle*
T_{add}	= *Additional travel time per passenger*

θ_{stop} = *Relative perception of waiting time at the stop*
$\theta_{holding}$ = *Relative perception of holding time in the vehicle*
θ_{RBT} = *Relative perception of Reliability Buffer Time*

a) Calculation of headway-based holding impacts
To calculate the additional travel time, the model calculates the effect of headway-based holding (at stop h) on headways. A change in headways will lead to a change in additional travel time (eq. 1-9). Equations 10 and 11 give the holding time and the effect on waiting time in the vehicle, while equations 12 and 13 show the effect of departure times and headways for the rest of the trip and the following trip. Note the effect of holding trip i on the holding choice process for trip i+1.

$$T^{holding}{}_{i,j} = Min(\gamma * (H^{sched} - H^{act}_{i,j}), T^{\max holding}) \quad if \quad j = h \text{ and } H_{sched}\text{-}H_{act,\, i,j} > 0 \qquad (10)$$
$$T^{holding}{}_{i,j} = 0 \quad j = h \text{ and } H_{sched}\text{-}H_{act,\, i,j} < 0$$
$$T^{holding}{}_{i,j} = 0 \quad if\ j \neq h$$

$$T^{vehicle}{}_{i,j} = T^{holding}{}_{i,j} \quad j \geq h \qquad (11)$$

$$D^{'act}_{i,j} = D^{act}_{i,j} + T^{holding}_{i,j} \quad j \geq h \qquad (12)$$

$$H^{act}_{i,j} = D^{'act}_{i,j} - D^{act}_{i+1,j} \quad j \geq h \qquad (13)$$

where:
$T^{holding}_{i,j}$ = *Holding time of vehicle i at stop j*
γ = *Fraction of headway deviation that vehicle is held for*
$T^{\max holding}$ = *Maximum holding time*
$D^{act}_{i,j}$ = *Actual departure time of vehicle i at stop j*
$D^{'act}_{i,j}$ = *New actual departure time of vehicle i at stop j (after holding)*

b) Calculation of schedule-based holding impacts
Equations 14 and 15 give the effect on waiting time in the vehicle in the case of schedule-based holding being applied at stop h. Equations 16 and 17 give the effect of holding on the portion of the trip downstream of the holding point. Note that equations 15-17 are similar with the headway based holding equations. In contrast to headway-based holding, schedule-based holding does not affect the holding decision process for the next trip: In equation 10, H is used, while equation 14 uses D. Regarding the next trip, the holding process only affects H.

$$T^{holding}{}_{i,j} = Min((D^{sched}_{i,j} - D^{act}_{i,j}), T^{\max holding}) \quad j = h \text{ and } D^{sched}_{i,j} - D^{act}_{i,j} < 0 \qquad (14)$$

$T^{holding}{}_{i,j} = 0$ $\quad$ $j = h$ and $D_{i,j}^{sched} - D_{i,j}^{act} > 0$

$T^{holding}{}_{i,j} = 0$ $\quad$ $j \neq h$

$$T^{vehicle}{}_{i,j} = T^{holding}{}_{i,j} \qquad j \geq h \qquad (15)$$

$$D_{i,j}^{'act} = D_{i,j}^{act} + T_{i,j<j}^{holding} \qquad j \geq h \qquad (16)$$

$$H_{i,j}^{act} = D_{i,j}^{'act} - D_{i+1,j}^{act} \qquad j \geq h \qquad (17)$$

where:

$D_{i,j}^{sched}$ = *Scheduled departure time of vehicle i at stop j*

4. ANALYSIS OF HOLDING STRATEGIES

To analyze the importance of the key variables and their effects on reliability and waiting time, the model is applied with actual data for both a real line as well as hypothetical lines. Analysis of hypothetical lines helps to set some design variables freely, which leads to insights helping the design of real lines. Analysis of actual lines on the other hand shows the practical benefits which could be used for theory development.

4.1 Case Study: Tram Line 9, The Hague

To assess the effect of applying different holding strategies in practice, tram line 9 in The Hague, operated by HTM, is analyzed. This line is the busiest line in the city, operating from the suburbs in the South West via the city centre to Scheveningen, a beach resort. Line 9 consists of 32 stops, is 14 km. long and operates at 5 min. headway. The standard deviation of total trip time is about 3.5 min. Figure 3 shows the passengers' travel pattern on line 9: both the percentage of boardings per stop and the percentage of through passengers are shown. They are shown as a percentage of total boardings on the complete line.

Figure 3 clearly illustrates that stops 14 (HS) and 18 (CS) are dominant. They are both major stations offering many connections to other local, regional and intercity rail services. The number of through passengers is low at these stops, which makes them interesting stops for holding. In this research, stop 14 (HS) is chosen as the holding point. At this point the through passengers ratio is 10%. The number of passengers boarding downstream is 60% of total boardings and 50% of total boardings are within 5 stops, maximally benefiting from holding.

4.2 Hypothetical Lines

Besides the analysis of an actual line, an assessment of the effect of holding strategies is also made for hypothetical lines. In this way, more insights can be developed regarding holding and the impact of several variables. The hypothetical line consists of thirty stops with scheduled trip time being constant between all adjacent stops. Three different standard deviations (σ) of total trip times are considered: 2 mins., 4 mins. and 6 mins.

The passengers' travel pattern is shown in figure 4. Both the number of through passengers and the boardings are illustrated as a percentage of total boardings on the line. Note that this passengers' pattern differs from that of line 9. Service frequency is 6 vehicles an hour.

Stop number 8 is chosen as the holding point. At this point, the number of through passengers is low (18%) and the number of downstream boardings is high (82%).

4.3 Results

For both the actual case and the hypothetical lines, both headway-based holding and schedule-based holding strategies are analyzed with the results given below. In this research γ is set to 0.75 and the values of θ are (according to *24*):

θ_{stop} = 2,
θ_{RBT} = 0.7

a) Headway-based holding results

For the three hypothetical lines and tram line 9, figure 5 shows the results of headway-based holding compared to the reference case without holding (i.e. maximum holding time is zero). Analysis is conducted on both one and two holding points and different values for the maximum holding time are used. The additional travel time is shown as a percentage of the waiting time in the case where perfect service is provided (i.e. average waiting time is half the scheduled headway).

Figure 5 shows that headway-based holding has a positive effect on the additional travel time: additional travel time has decreased compared to the no holding case, which is illustrated by the maximum holding value of zero. The decreasing effect increases with sigma. The optimal maximum holding time decreases with a decrease in sigma. The optimal value for the maximum holding time is about180 s. for σ=6, 100 s. for = 4, 40 s. for σ=2 and about 60 s. for line 9. The effect of introducing a maximum holding time of 60 s. is also shown in the figure. Actual holding times (σ = 4) are shown in figure 6 for both unlimited holding as well as a maximum of 60 s. Unlimited holding involves holding about 10% of the vehicles longer than 2 minutes.

Besides the scenario of applying one holding point, an analysis of adding a second holding point was also conducted. For line 9, the other main station on the line, CS (stop 18), is used, while for the hypothetical lines, stop 23 is chosen (see figures 3 and 4). Both stops have a relatively small number of through passengers (8% and 18%). The results in figure 5 show that in the hypothetical case the effect of adding a second holding point is negative: the additional travel is larger than when 1 holding point is applied. This is because there is no good second holding point on this line given the passengers travel patterns. No other point exists with both low numbers of through passengers and high numbers of downstream boardings. On line 9, however, such a point does exist, although the results show no significant benefit over a single holding point in terms of the additional travel time.

b) Schedule-based holding results

Figure 7 shows the effects of schedule-based holding on additional travel time which is again shown as a percentage of the average waiting time when service is perfectly on time and headways are equal. Results are shown for both the theoretical lines and line 9 for different percentile values chosen for scheduling and different maximum holding times (unlimited and 60 s.).

Figure 7 shows that holding has a positive effect, a decrease of additional waiting time, which increases with sigma. It also shows that the optimal percentile value (where additional travel time is minimal) decreases when sigma decreases. The optimal value, in the unlimited holding case, is between 70% (σ =2) and 90% (σ = 6). But when a maximum of 60 s. holding time is applied, the optimal value becomes about 65% for all lines.

Figure 8 shows an example of applied holding times (σ = 4) for both the unlimited holding strategy as well as a maximum holding time of 60 s. In each case the schedule percentiles values are set to their optimal values. Unlimited holding involves holding about 20% of the vehicles longer than 2 minutes.

c) Effect of holding on the level of crowding

All research on holding referred to in this paper focuses on the travel time effects of holding. However, improving reliability can also affect the level of crowding. Figure 9 shows the level of irregularity (actual headway deviation as a percentage of the scheduled headway) for both the reference case as well as two schedule-based and two headway-based holding cases. The cases are based on σ= 4. Both the average irregulartiy and the 95th percentile value are shown. The results differ per case, but in general the average irregularity decreases from 20% to 15% and in case of the 95th percentile from 55% to 40-45%. If uniform arrivals are assumed, this number is similar to the excess level of crowding for 50% of the vehicles. The other 50% will experience a lower level of crowding than the average value. Normally, during the process of determination of the number of vehicles, some slack is included with respect to the passenger capacity per vehicle. The results presented here illustrate that either this slack could be decreased (implying that fewer vehicles are needed) or the level of crowding could be decreased.

d) Headway-based holding vs. schedule-based holding

The previous sections showed results of both headway-based and schedule-based holding. If these two methods are compared it is clear that the schedule-based method can be more effective in reducing additional travel time. Figure 7 shows that additional travel can be more decreased by schedule based holding than headway-based (as shown by figure 5). The reason for this is that in that case, it is possible to set a loose schedule, which could be very reliable. Normally this implies a slow schedule as well, but when a small number of passengers travel over the holding point this effect is minimal. However, when maximum holding time of 60 s. is introduced, the effects of headway-based and schedule-based holding are similar.

5. CONCLUSIONS

This paper describes research on holding of transit vehicles to improve reliability. Both schedule-based and headway-based holding strategies are analyzed in short headway services. The objective is to reduce additional travel time for passengers, which is the additional time compared to a perfectly punctual and regular service. Despite a significant focus on holding in current literature, some important aspects have not been researched previously. The main, new, variables are the maximum holding time, the reliability buffer time and, in the case of schedule-based holding, the percentile value used to design the schedule. Both a real line in The Hague (tram line 9) and hypothetical lines are analyzed with various levels of running time variability. Both headway-based and schedule-based holding have the largest effect if deviations are high. When holding is headway-based, the optimal value for the maximum holding time is about 180 s. for σ =6 min., 100 s. for σ= 4 min., 40 s. for σ= 2 min and about 60 s. for line 9. Introducing an additional holding point on these lines does not result in further improvements in travel times. When applying schedule-based holding and a maximum of 60 s. holding time is applied, the optimal value of the percentile value becomes about 65% for all lines analyzed. When no maximum holding time is applied, schedule-based holding is more effective, while there is no difference when the maximum holding time is set to 60s. This research also shows the effect of holding on crowding: An average level of irregularity of 20% could decrease to 15%, enabling either smaller capacity slack or less crowding.

Although the results are useful in practice and research, some future research is recommended to further explore the effects of holding. The main issue is the choice of the holding point. The key variables would be schedule deviations, the number of through passengers and boarding passengers downstream of the holding point. It would be interesting to analyze the effect of different combinations of these values on additional travel time.

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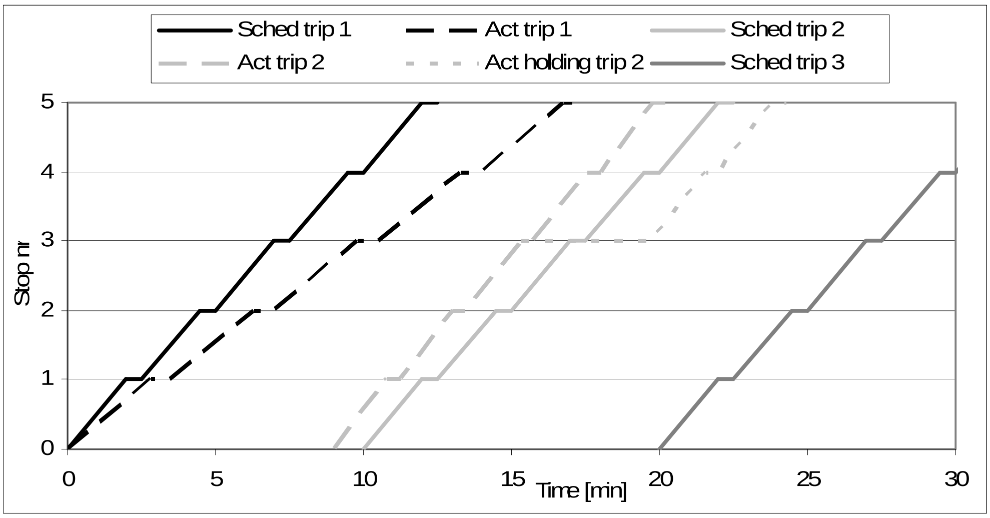

FIGURE 1 Headway-Based Holding.

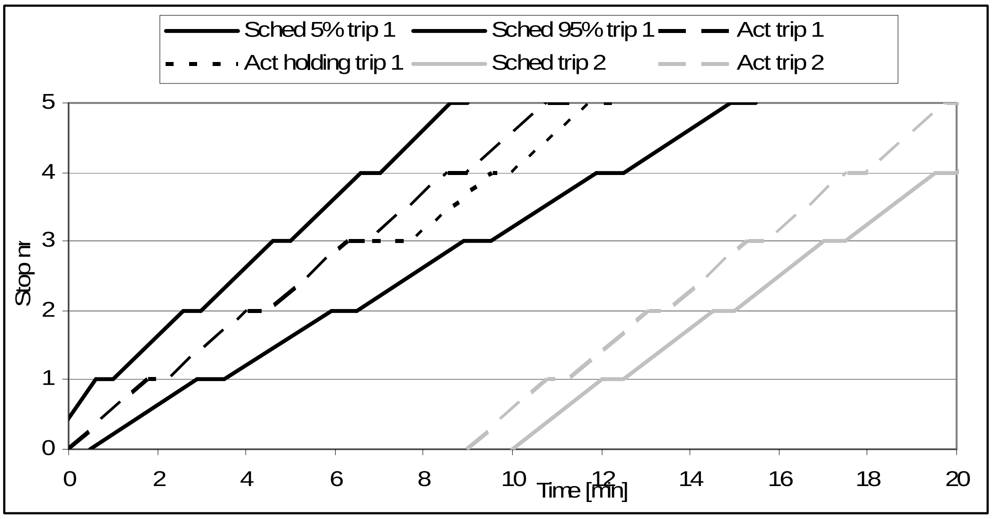

FIGURE 2 Schedule-Based Holding.

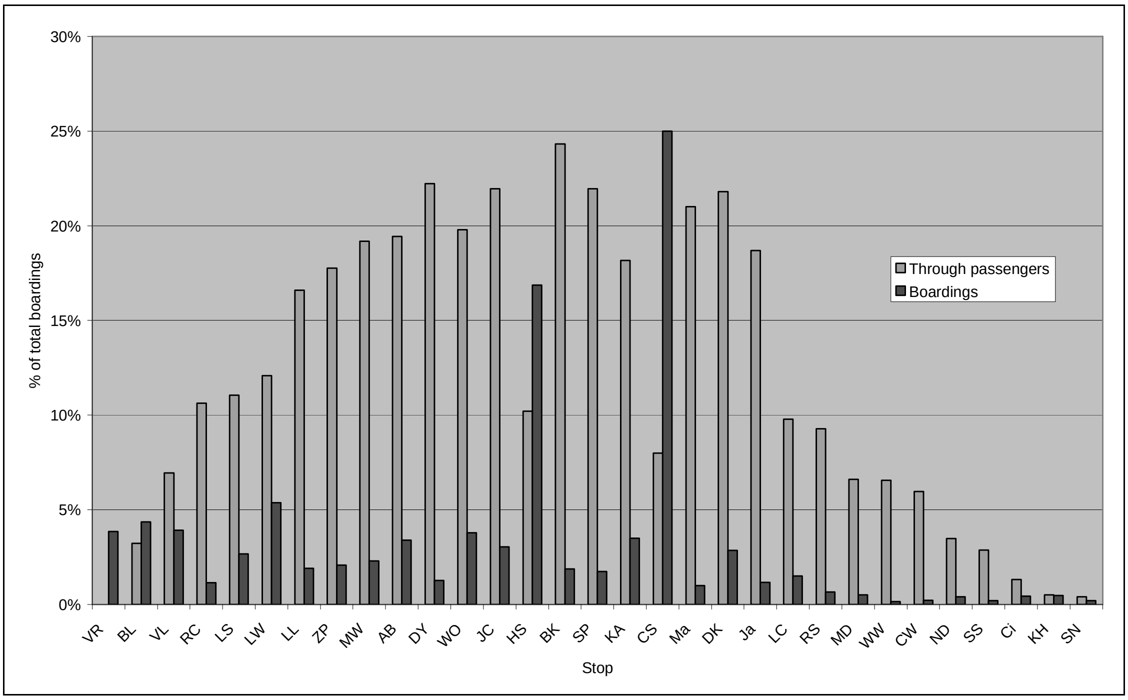

FIGURE 3 Percentage Boardings and Through Passengers per Stop (of Total Boardings) on Line 9.

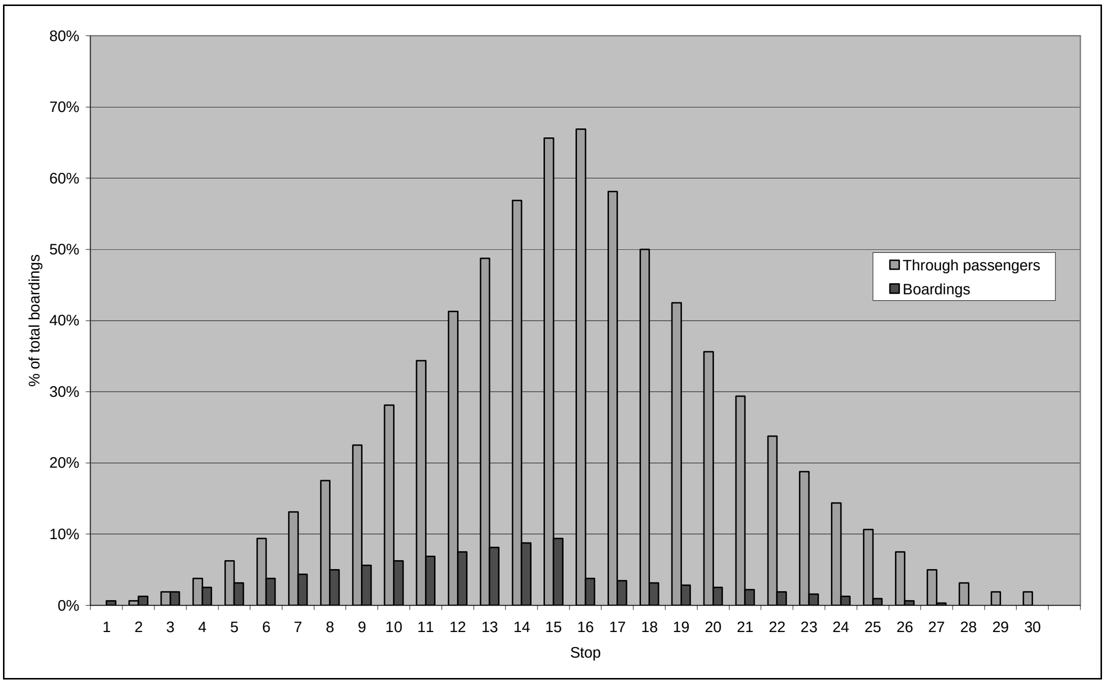

FIGURE 4 Percentage Boardings and Through Passengers per Stop (of Total Boardings) on Theoretical Lines.

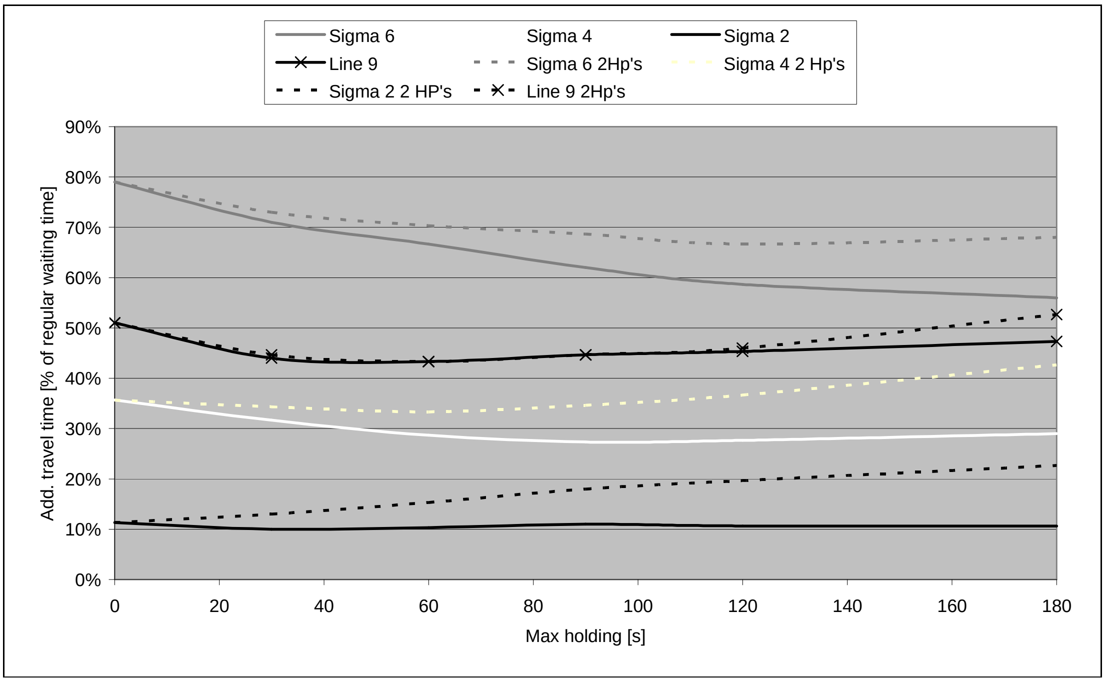

FIGURE 5 Effect of Headway-Based Holding on Additional Travel Time (HP = Holding Point).

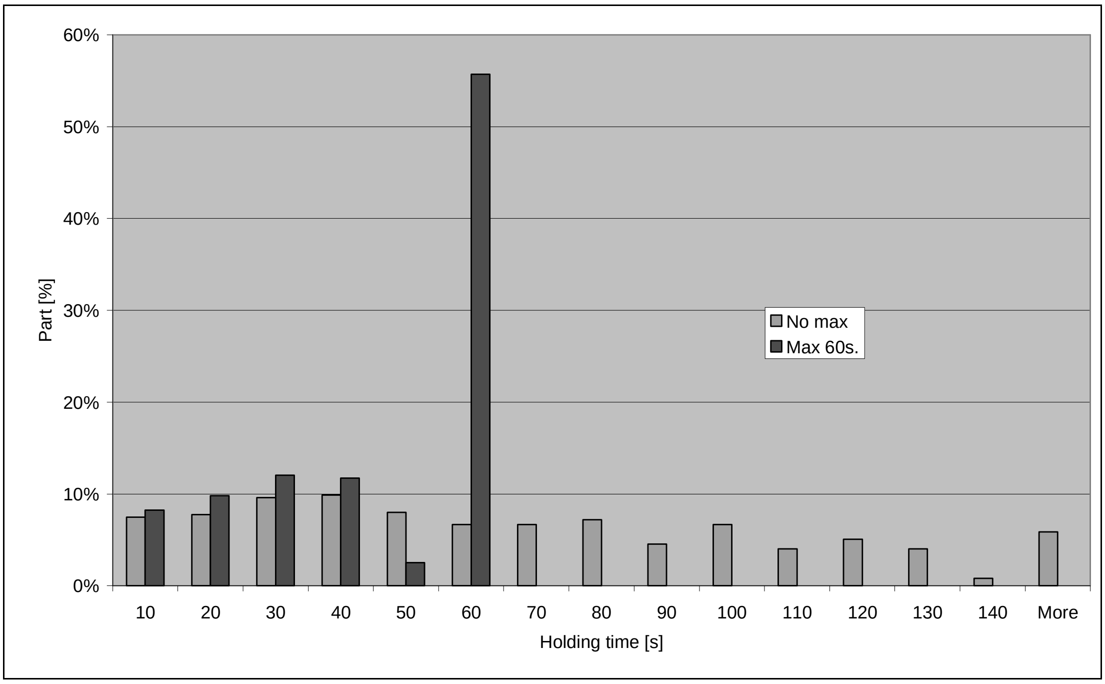

FIGURE 6 Holding Times, Headway-Based Holding (σ=4min).

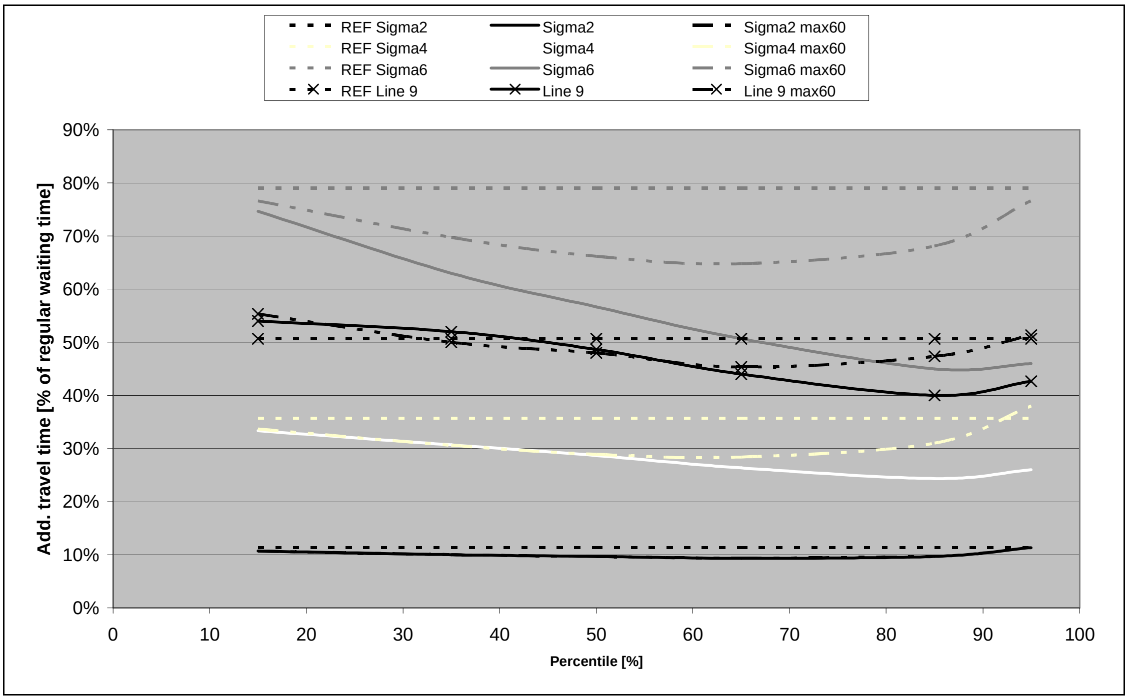

FIGURE 7 Effect of Schedule-Based Holding on Additional Travel Time.

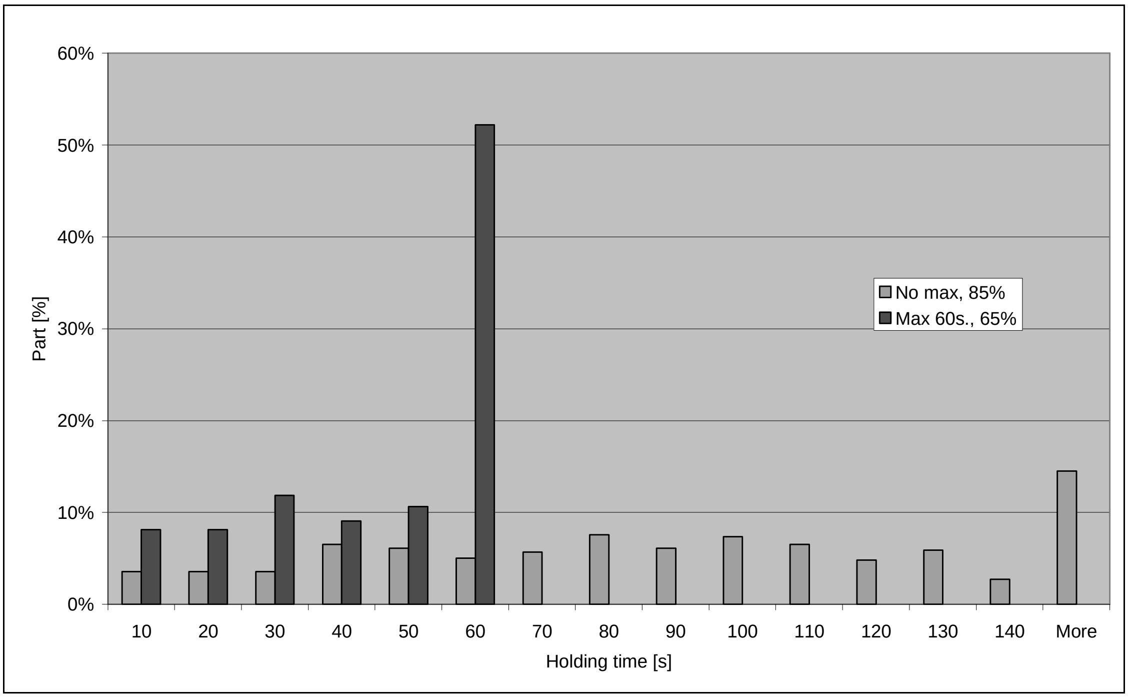

FIGURE 8 Holding Times, Schedule-Based Holding (σ=4min).

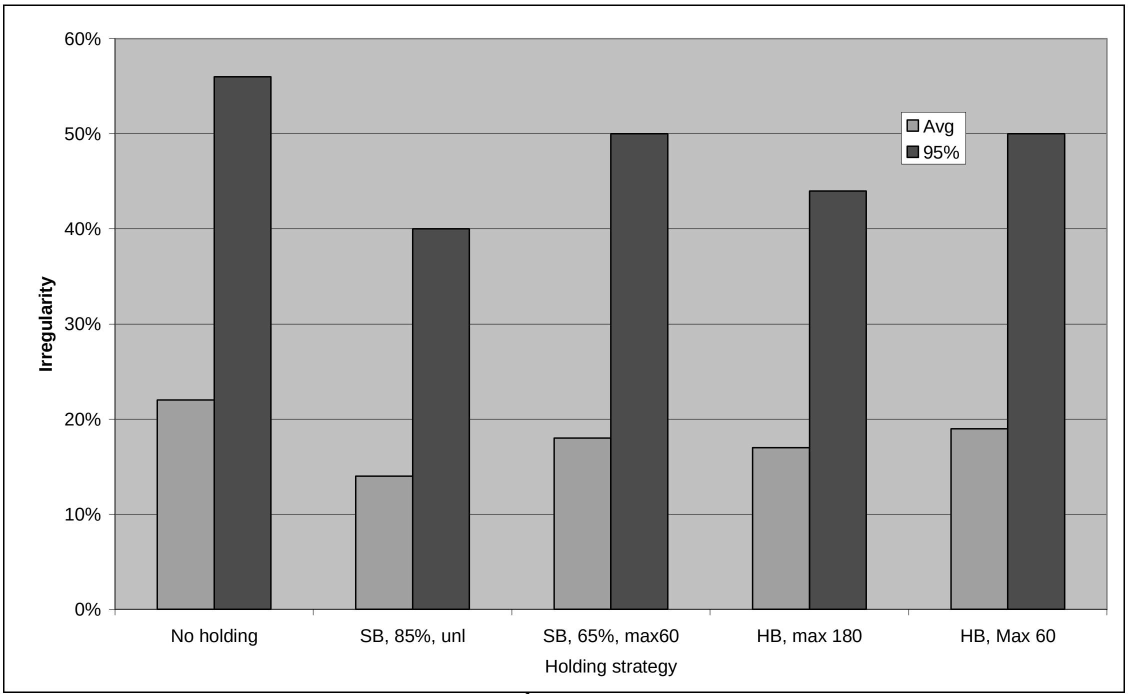

FIGURE 9 Irregularity (average and 95th percentile) for Different Scenarios.