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Impacts of Holding Control Strategies on Transit Performance: A Bus Simulation Model Analysis

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Abstract

Transit operators are interested in strategies to improve service reliability as it is an important measure of performance and level of service. One of the common practices aimed to reduce service unreliability is holding control strategies. The design of these strategies involves the selection of a set of time point stops and the holding criteria for regulating the departure time. In order to analyze the impacts of holding strategies on transit performance, it is necessary to model dynamically the interactions between passenger activity, transit operations and traffic dynamics. An evaluation of different holding criteria and number and location of time point stops was conducted using BusMezzo, a dynamic transit simulation model. The holding strategies were implemented in the model and applied to a high frequency trunk bus line in Stockholm. The analysis of the results considers the implications of holding strategies from both passengers and operator perspectives. The analysis suggests substantial gains from implementing holding strategy based on the mean headway from the preceding bus and the succeeding bus. This strategy is the most efficient in terms of passenger time savings as well as fleet costs and crew management.

Keywords: Transit Operations, Reliability, Simulation, ITS, Holding

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ABSTRACT

Transit operators are interested in strategies to improve service reliability as it is an important measure of performance and level of service. One of the common practices aimed to reduce service unreliability is holding control strategies. The design of these strategies involves the selection of a set of time point stops and the holding criteria for regulating the departure time. In order to analyze the impacts of holding strategies on transit performance, it is necessary to model dynamically the interactions between passenger activity, transit operations and traffic dynamics. An evaluation of different holding criteria and number and location of time point stops was conducted using BusMezzo, a dynamic transit simulation model. The holding strategies were implemented in the model and applied to a high frequency trunk bus line in Stockholm. The analysis of the results considers the implications of holding strategies from both passengers and operator perspectives. The analysis suggests substantial gains from implementing holding strategy based on the mean headway from the preceding bus and the succeeding bus. This strategy is the most efficient in terms of passenger time savings as well as fleet costs and crew management.

1. INTRODUCTION

Service reliability is one of the main objectives for transit operators. In the context of high-frequency urban services, unreliable service results in long waiting times, bunched vehicles, long delays and uneven passenger loads. In addition, having a more reliable transit performance can also imply lower operations costs and more efficient crew management. Transit operations involve several sources of uncertainty including dispatching time from the origin terminal, travel time between stops and dwell time at stops. Those stochastic factors are interrelated through the relation between the number of waiting passengers, headway between consecutive buses and dwell time as well as the propagation of delays through trip chaining.

Transit control strategies consist of a wide variety of operational methods aimed to improve transit performance and level of service. Advanced Public Transport Systems (APTS) are increasingly integrated into transit systems, enabling improved management and operation strategies that incorporate real-time information [1]. Holding strategies are among the most widely used transit control methods aimed to improve service regularity by regulating departure time from stops according to pre-defined criteria [2]. The strategy contains a set of rules that determine at which stops along the route departure times will be subject to regulation (those stops are known as time points) and which criteria are used for determining the departure time.

Evaluating the effects of holding strategies and assessing different holding designs requires a dynamic representation of complex interactions between stochastic processes, in particular when considering holding strategies that are based on real-time information. Many of the previous studies in the field assumed constant passenger arrival rates, dwell times or riding times, neglected capacity constraints or vehicle scheduling and did not take into account the interrelation among multiple time points.

The aim of this paper is to analyze and evaluate different holding control strategies for improving service reliability. This potential improvement is assessed by comparing level of service measures and passenger waiting and in-vehicle times. In addition, transit performance is also evaluated from the operator perspective by considering the impacts of holding strategies on fleet operations and crew management. The evaluation is based on BusMezzo, a mesoscopic traffic and transit simulation model [3]. The remainder of this paper is organized as follows: The following section discusses various holding control strategies and details associated with their implementation and evaluation. Section 3 provides a brief description of the transit simulation model. Several holding strategies were applied on a high-demand trunk bus line in Stockholm with a detailed representation of line characteristics based on empirical data. The case study analyzes the effectiveness of holding strategies from both passenger and operator perspectives. Finally, concluding remarks and recommendations are presented.

2. HOLDING CONTROL STRATEGIES

The implementation of holding strategies involves two key design decisions: selecting the set of time point stops and the holding criteria.

2.1 Number and location of time-points

Although hypothetically all stops can be defined as time points, departure times are usually regulated only at a small subset of stops along a bus line. Most typically, transit agencies define important transfer hubs with high capacity in terms of vehicles as time points. The optimal location of time point stops is the subject of on-going research efforts using both numerical and simulation studies. Several studies concluded that time points should be located at the beginning of every sequence of high-demand stops [4,5,6]. In addition, in order to minimize delays caused by holding passengers on-board, stops characterized by high levels of through passengers (passengers staying on board) should be avoided when considering time point layout [7].

In contrast, [8] concluded from a deterministic analytical model that searched for the optimum time point location that only the original terminal should be defined as a time point stop. [9] found that the relation between the standard deviation of the headway and the number of time points is a second degree polynomial. Therefore the author concluded that beyond a certain number of time points which depends on the specific line characteristics, the marginal contribution of an additional time point turns negative.

2.2 Holding criteria

Holding strategies are commonly classified into two categories: schedule-based strategies and headway-based strategies. A schedule-based holding strategy defines the earliest time that a bus can depart from a time point stop relatively to the schedule. This rule can be formulated as:

$$ET_{ijk} = \max\left(SET_{ijk} - s_{ij}, AT_{ijk} + DT_{ijk}\right) \tag{1}$$

Where ET_{ijk} is the exit (departure) time for line i on trip k from stop j, SET_{ijk} is the corresponding scheduled exit (departure) time and s_{ij} is a non-negative slack size defined for line i at stop j. AT_{ijk} is the actual arrival time and DT_{ijk} is the dwell time. Previous studies on the interaction between slack size and generalized passenger travel time concluded that the slack size should be set to zero [6,10]. This implies that buses that arrive early have to wait at time point stops until their scheduled departure time. Schedule-based strategies are useful for low-frequency services when passengers follow the timetable or when transfer coordination is an important issue [11]. [12] compared schedule-based holding strategies for improved schedule coordination at a transfer hub that rely on different levels of information. These levels ranged from static scheduled data at the specific stop level up to real-time Automatic Vehicle Location (AVL) and Automatic Passenger Counts (APC) data from all bus vehicles. They concluded that the optimal strategy is also the most demanding strategy is terms of data and technology requirements.

In contrast, headway-based holding strategies use headways between consecutive vehicles as their criterion for regulating departure times from time point stops. These strategies require real-time AVL information. If the headway-based strategy takes into account only the headway from the preceding vehicle, then the holding criteria is defined by a minimal headway requirement:

$$ET_{ijk} = \max\left(AT_{ij,k-1} + \alpha H_i^{k-1,k}, AT_{ijk} + DT_{ijk}\right) \tag{2}$$

Where $H_i^{k-1,k}$ is the planned headway between trips $k-1$ and k on line i, and α is a threshold ratio parameter. This parameter defines the minimum allowed headway relative to the planned headway. Both analytical and simulation-based studies that searched for the optimal threshold parameter found it to be in the range of 0.6 to 0.8 [4,13,14]. [15] proposed to choose the threshold value dynamically each time that holding strategy is triggered based on the number of passengers on-board.

Headway-based strategies can incorporate also the headway to the succeeding vehicle. This additional information can be utilized for keeping even headways by applying the following criteria:

$$ET_{ijk} = \max\left(AT_{ij,k-1} + \frac{(AT_{ij,k} - AT_{ij,k-1}) + (AT_{im,k+1} + SRT_{m,j} - AT_{ij,k})}{2}, AT_{ijk} + DT_{ijk}\right) = \max\left(AT_{ij,k-1} + \frac{AT_{im,k+1} + SRT_{m,j} - AT_{ij,k-1}}{2}, AT_{ijk} + DT_{ijk}\right) \quad (3)$$

Where m is the last stop that was visited by bus trip $k-1$ and $SRT_{m,j}$ is the scheduled riding time between stops m and j. This strategy implies that buses are held only if the headway from the preceding bus is shorter than the headway to the succeeding vehicle. Note that this holding strategy is independent of the planned headway. Nevertheless, [16] showed analytically for a similar adaptive control strategy that the deviations from the schedule and the planned headway are small and bounded under realistic assumptions. Furthermore, this strategy showed significant benefits when applied in a simulation model at terminals of urban rail service [17]. The implementation of this strategy at intermediate stops along the route requires real-time AVL data and vehicle-control centre communication network.

Headway-based strategies defined by equations (2) and (3) can be integrated to form a strategy that keeps even headways while restricting the maximum allowable holding time by the minimum headway:

$$ET_{ijk} = \max\left(\min\left(AT_{ij,k-1} + \frac{AT_{im,k+1} + SRT_{m,j} - AT_{ij,k-1}}{2}, AT_{ij,k-1} + \alpha H_i^{k-1,k}\right), AT_{ijk} + DT_{ijk}\right) \quad (4)$$

2.3 Evaluating holding strategies

The evaluation of holding strategies has to take into consideration their impacts on the level of service as well as implications on operation and management costs. Improved regularity has potential benefits for both passengers and operators, while longer travel times caused by holding buses at stops is the drawback of introducing holding control. Therefore, an analysis of holding strategies has to investigate the trade-off for both passengers and fleet management.

Improved service regularity is associated with shorter waiting times and reduced crowding conditions at stops and on-board. As service becomes more regular, passenger loads are expected to be distributed more evenly between bus vehicles. However, the implementation of holding strategies also imposes delays to passengers on-board. Hence, the evaluation of holding control strategies has to analyze the trade-off between the waiting time savings and the difference in travel times. Previous studies analyzed this trade-off by formulating a single compensatory objective function or by assessing multi-criteria analysis [5,15,18].

The application of holding strategies involves also a trade-off also from the operator perspective. Holding control strategies have the potential to improve fleet management certainty at the cost of longer total travel times. The result of these two factors in terms of fleet costs depends on the trip travel time distribution as holding strategies are expected to simultaneously increase the average value and reduce its variability. The common practice among bus operators is to use the 85^{th} or the 90^{th} percentile of trip travel time distribution when constructing their vehicle scheduling [19].

The level of service of high-frequency services depends mainly on headway regularity and therefore the main operational objective is to maintain even headways between consecutive vehicles. However, schedule-based strategy does not require real-time data communication and is also suitable for crew management. Some bus operators use driver schedules that include driver replacement at intermediate stops, also known as relief points. In case there are relief points along the line, this is an additional concern as it is especially important to have high schedule adherence at these stops.

3. TRANSIT OPERATION SIMULATION MODELS

BusMezzo is a transit simulation model developed on the platform of Mezzo, a mesoscopic traffic simulation model. The mesoscopic level of representation implies representing individual vehicles without modelling their second-by-second movements in detail. Travel times on links are determined by speed-density functions, while delays at intersections are modelled using a stochastic queue server for each turning movement [20]. While a detailed description of the transit-related object framework and simulation progress as well as model validation is presented in [3], we present here only the relevant features in brief.

BusMezzo is designed to enable the analysis and evaluation of transit performance and level of service under various transit operation conditions. The model represents the progress of bus trips in the traffic network following a pre-defined transit route. Dwell times at stops are determined as a function of passenger activity at stop, crowding on-board and physical stop characteristics (bay or in-lane, bus stop capacity), based on [21]. If the stop is defined as a time-point stop then the holding strategy determines the departure time based on the dynamic system conditions. Passengers arriving during the holding time can board the vehicle. Capacity constraints on bus vehicles are modelled explicitly as passengers unable to board due to overcrowded conditions have to wait for the next vehicle.

The interactions between different recovery time policies, fleet size and level of service can be directly assessed in BusMezzo. The model represents both service time-tables and vehicle schedules. Therefore trip dispatching is determined not only by the time-table, but also depends on the availability of the assigned vehicle from the preceding trips [22]. Passenger demand can be represented in several levels of detail depending on the application of interest and data availability.

4. CASE STUDY

4.1 Experiment description

Several holding strategies were implemented in BusMezzo and applied for bus line number 1 in Stockholm, Sweden. The line route connects Frihamnen, the main harbor in the eastern part of the city, the city center, a business district and western residential areas in Stora Essingen (see Figure 1). This high-demand line is one of four trunk bus lines operating in Stockholm inner-city characterized by high frequency, articulated vehicles, high level of signal priority and real-time arrival information at stops. The line includes 33 stops on the eastbound direction route (ER) and 31 stops on the westbound route (WR). Transit performance is analyzed for the afternoon peak period between 15:30 and 18:00. Figure 2 presents average passenger load profiles per trip for both directions for the peak afternoon time interval. Note that boarding and alighting bars refer to the axis on the left, while through passengers and passenger load curve refer to the axis on the right side. The dotted lines indicate the time point stops which are also the major transfer locations.

Figure 1

Figure 2

The operational characteristics of line 1 were analyzed in detail based on Automatic Vehicle Location (AVL) and aggregate passenger demand data in order to represent line 1 operations adequately in the simulation model. BusMezzo enables to model the progress of bus vehicles and their traffic dynamics as for any other vehicle. However, since the case study focuses on a specific bus line, travel times can be regarded as an exogenous process that results from time-dependent traffic conditions in the transport network. Empirical travel times between each pair of consecutive stops were analyzed. Travel times on all links were found to follow the Log-Normal distribution based on Chi-Square and Kolmogorov-Smirnov goodness-of-fit tests with a confidence level of 95%. The parameters that yielded the best goodness-of-fit for each link were given as input to the stochastic travel time generator in the simulation. As travel times between consecutive links are potentially dependent due to queue propagation and network topology, the correlation between travel times on each pair of consecutive links was calculated. All correlations were found to be less than 0.3, thus link travel times are regarded as independent stochastic processes.

The planned headway of bus line 1 is 4 to 5 minutes during the entire afternoon peak period. The real-world time-table was given as input to the simulation model. In addition, vehicle scheduling was simulated according to the actual trip chaining that is used by the operator. The coefficients of the dwell time function are based on values calibrated for local data by the metropolitan transit agency.

Passenger demand is represented in this case study in terms of arrival rates and alighting fractions. This level of representation enables to capture the interaction between passenger activity at stops and transit performance. It also allows the analysis of the impacts of various holding strategies on the level of service. Passenger arrivals follow a Poisson process since line 1 is a high-frequency line (e.g. [13]). There are three major transfer stops from the metro and bus systems that can potentially cause non-random arrival patterns along the route. However, service frequency in all cases is very high (more than 40 arrivals per hour) and therefore the passenger arrival process is assumed to be random at all stops. Time-dependent passenger demand rates were obtained from aggregated passenger demand and dwell time data. For each 30 minutes interval the corresponding passenger demand was estimated using the locally calibrated relationship between dwell time and the number of boarding passengers.

In summary, the case study represents in detail the bus line characteristics based on empirical data. This data is given as input to BusMezzo which simulates the interaction between time-dependent passenger demand, dwell time at stops, stochastic travel times between stops, holding strategies at time points, real-world time table and vehicle scheduling.

4.2 Scenario design

The case study evaluated different holding strategies by analyzing two schemes for selecting time points and three rules for defining the holding criteria. In line with the common practice of bus operators [23], bus lines in Stockholm are regulated using a schedule-based holding control. There are three time points along the route of line 1 where buses are being held if they arrive earlier than the scheduled time. In addition to the base case scenario of the current schedule-based holding strategy, two headway-based holding schemes were tested: a strategy based on a minimum headway requirement from the preceding bus (denoted by MH and defined by equation 2 with $\alpha = 0.8$) and; a strategy based on even headways between the preceding bus and the following bus (denoted by EH and defined by equation 4 with $\alpha = 1.0$).

Holding control is currently applied at three time point stops on each direction (stops 10,17 and 23 on ER and stops 10,17 and 24 on WR). Time point stops were selected based on network configuration by identifying the main transfer stops from the metro system (Figure 1). Alternatively, time points can be selected based on passenger demand and operational characteristics. As previous studies concluded, time points should be located at the beginning of a sequence of high-demand stops while avoiding stops characterized by high levels of through passengers (Figure 2). Moreover, since holding strategies aim to improve service regularity, it is useful to analyze the trend along the route for relevant measures (e.g. punctuality, variability of the headway) and identify critical points. These points may be associated with segments that experience high travel time variability, that contribute to service irregularity or have irregular passenger activity patterns. Applying those techniques and rules of thumb to line 1 yielded four candidate time point stops nicely distributed on each direction: stops (10,15,20 and 27) on the ER and stops (6,14,20 and 25) on WR.

The experimental design results in six holding scenarios based on the combination of three holding criteria and two sets of time point stops as summarized in Table 1. For each scenario 10 simulation runs of the afternoon peak period were conducted. Depending on the desired level of accuracy, different applications or output measures may require different number of replications. Using the standard deviation of the headway, an outcome of complex interactions between interrelated stochastic processes in the system, 10 repetitions yielded an allowable error of less than 8%. The total execution time for the 10 runs was less than 2 seconds on a standard PC.

Table 1

4.3 Results

BusMezzo enables to evaluate system performance and level of service at various levels from a specific trip or stop to overall system measures. The effect of time points on service irregularity as measured by the coefficient of variation of the headway is clearly evident in Figure 3. Service unreliability propagates along the route in line with previous studies that conducted empirical analysis of bus performance [24]. Headway variability decreases significantly immediately after a time point stop, restraining the continuous increase in service irregularity. The same pattern is obtained from implementing holding strategies at the alternative time point locations. Furthermore, the even-headway strategy (EH1) is the most efficient strategy yielding lower coefficient of variation of the headway at almost any given point along the route.

Figure 3

Table 2 presents several measures of performance at the system level for each scenario. Service regularity is evaluated by measuring headway variability, as for high-frequency services the main performance objective is to regulate headways and avoid bunching of consecutive buses. The coefficient of variation of the headway presented in the table is the mean value over all stops. Note that the mean headway value is constant across scenarios as the number of trips during the simulated peak period is independent of the holding strategy. As expected, headway-based strategies reduce headway variability substantially compared with schedule-based holding. In addition, the EH strategy performs better than the MH strategy and the proposed set of time points results in slightly better service reliability compared with the current time-point locations.

The improvement in service regularity results in shorter passenger waiting times which were calculated based on disaggregated output data. Following [21], the share of bunched buses is defined as the percentage of headways that are shorter or longer than the planned headway by more than 50%. This share decreased sharply when headway-based strategies were applied as these holding criteria prevent the bus bunching phenomenon by holding buses with short headways from the preceding bus. The corresponding regularity level of service was obtained. Furthermore, the lower headway variability under headway-based strategies led to more even passenger loads as indicated by the average standing time per passenger, an important comfort measure. This measure captures the inconvenient effect of over-crowdedness on the average passenger as it takes passenger-in-vehicle time into account. Moving from a schedule-based strategy to even-headway strategy resulted in 30% reduction in total passenger standing time on-board.

According to the metropolitan transit agency, bus arrival is considered as on-time if it arrives between one minute early and three minutes late compared with the timetable [25]. Interestingly, although EH strategy does not incorporate the schedule into the holding criteria, its implementation resulted in the same level of on-time performance as the schedule-based scenarios. Overall, there are no substantial differences in the proposed time point location scenarios with some improvements in service reliability and in particular in preventing bus bunching.

Table 2

The evaluation of holding strategies has to consider the trade-off between average passenger waiting times and the average increase in passenger on-board holding time. Figure 4 displays how each of the holding strategy scenarios performs on both passenger-time dimensions. The reference point for waiting times is the hypothetical case of perfectly even headways which imply average waiting time of half the planned headway. The graph illustrates the relative position of alternative strategies and enables the identification of dominated alternatives with respect to passenger time savings – alternatives which are worse than another alternative in one performance measure without being better than it in the other performance measure. It is evident that EH scenarios dominate MH scenarios regardless of time point locations. In the case of schedule-based strategy, the current layout dominates the proposed one.

Figure 4

Headway-based strategies resulted in shorter passenger waiting times in the cost of longer in-vehicle times compared with schedule-based holding. By constructing a compensatory objective function and assigning weights to time components, it is possible to determine which strategy is optimal with regards to passenger time savings. According to value of time studies, the ratio between waiting time and in-vehicle time is in the range of 1.5-2.0 [26]. The diagonal lines in Figure 4 represent level curves based on a ratio of 2 between waiting time and in-vehicle time components. Based on these values, the EH strategy results in substantial overall time savings compared with schedule-based strategy, as the weighted reduction in waiting time is 4 times higher than the weighted increase in in-vehicle time. In addition, in the case of MH strategy, the proposed set of time point stops outperforms the current one.

The effect of longer travel times imposed by headway-based strategies may be compensated by a reduction in total travel time variability. Figure 5 presents the total trip time distribution for WR direction, where according to the timetable the total running time is 3060 seconds. In order to study the effect of holding strategies on fleet assignment, we compare the 90th percentile of total vehicle cycle time (a bi-directional chain). On the one hand, the average total running time is slightly higher for headway-based strategies relative to schedule-based scenarios. This result is consistent with previous findings of [23] for a minimum-headway strategy. On the other hand, headway-based strategies also yielded a narrower travel time distribution. As a result, the total cycle time of the MH strategy has the same 90th percentile as schedule-based holding and therefore does not impose higher fleet requirements. Moreover, this planning criterion decreased by 1.6% when applying the even-headway strategy, indicating potential benefits in terms of operational costs. The reduction in total travel time with EH strategy has positive consequences for both operators and passengers. These findings reinforce the conclusions of [15] from an analytical study on a similar holding strategy.

Figure 5

Driver relief points may be a potential hindrance to applying headway-based strategies, as schedule adherence is the main concern for driver shifts scheduling. Figure 6 presents the delay distribution at the relief point on the WR, where the relief point is towards the end of the route and therefore subject to more uncertainty. Note that the relief point is also a time point stop in the current set of time points. While under scenario S1 the frequency of buses arriving less than one minute behind schedule is slightly higher than under EH1, the probability of a very late arrival (more than five minutes late) is more than double compared to EH1. Furthermore, when switching from schedule-based strategy S1 to headway-based strategy EH1, the average delay decreases by 18%. These results suggest that headway-based strategies can even improve the punctuality in the relief point, an important objective of crew management and fleet assignment and an important issue for labor unions.

Figure 6

5. CONSLUSIONS

In this paper several holding strategies were evaluated using BusMezzo, a dynamic transit and traffic simulation model, applied on a high-frequency trunk bus line in Stockholm. Detailed empirical data was used for replicating bus line characteristics in the simulation model. The evaluation considered passenger level of service measures as well as important aspects of operation and management. An analysis of the results highlights substantial potential benefits from implementing an even-headway strategy that regulates the headways according to both the headway from the preceding bus and the succeeding bus. Compared with the current schedule-based control, this strategy improves the service reliability substantially, leading to passenger time savings, reduced operating costs as well as better schedule adherence at the relief point. Therefore, the even-headway strategy is a very promising operation and management strategy. In addition an alternative time point location method was evaluated, but the results showed no substantial improvement over the current scheme.

Future research will investigate further the optimal number and location of time points stops. Moreover, such an optimization method can include a dynamic optimization of the holding times [18] to form an integrated dynamic control optimization tool that will support real-time control decisions. An additional future direction can focus on the potential benefits associated with schedule-based strategies for transfer coordination in the context of low-frequency services. This can be captured by representing individual passenger path choice decisions and their interaction with control strategies and real-time traveler information.

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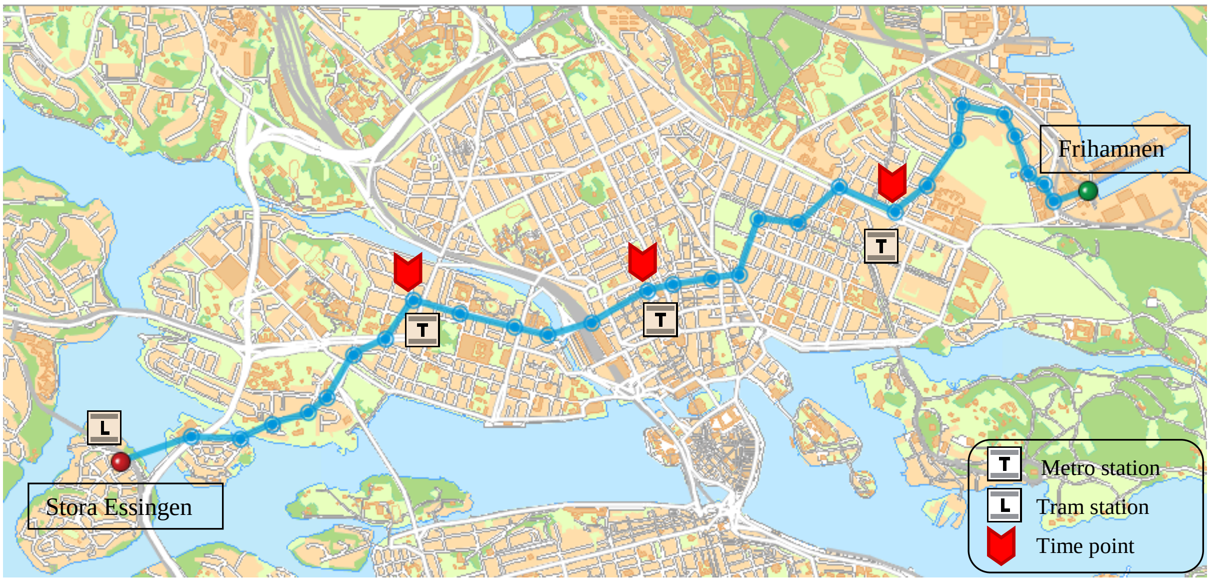


FIGURE 1 The route of bus line 1 in Stockholm inner-city.

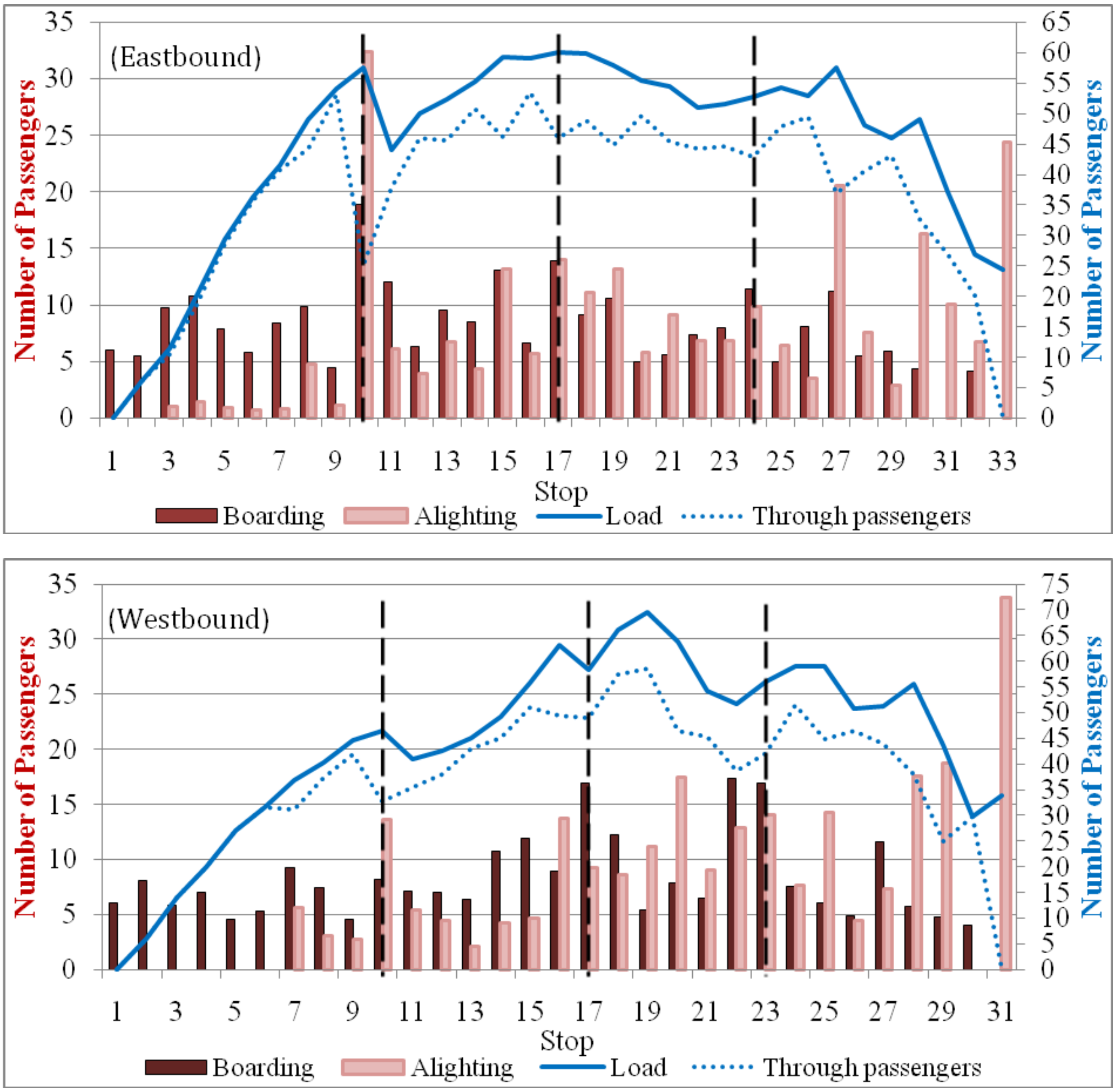


FIGURE 2 Load profiles of line 1 for ER and WR at the peak time interval (17:00-17:30).

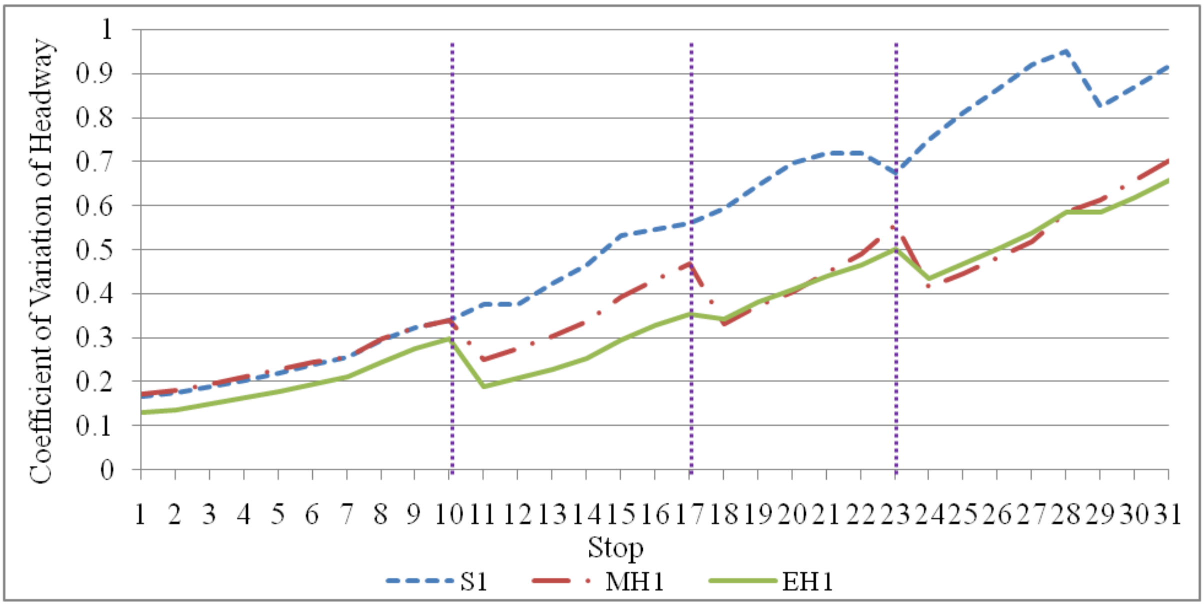


FIGURE 3 Coefficient of variation of the headway under various holding strategies.

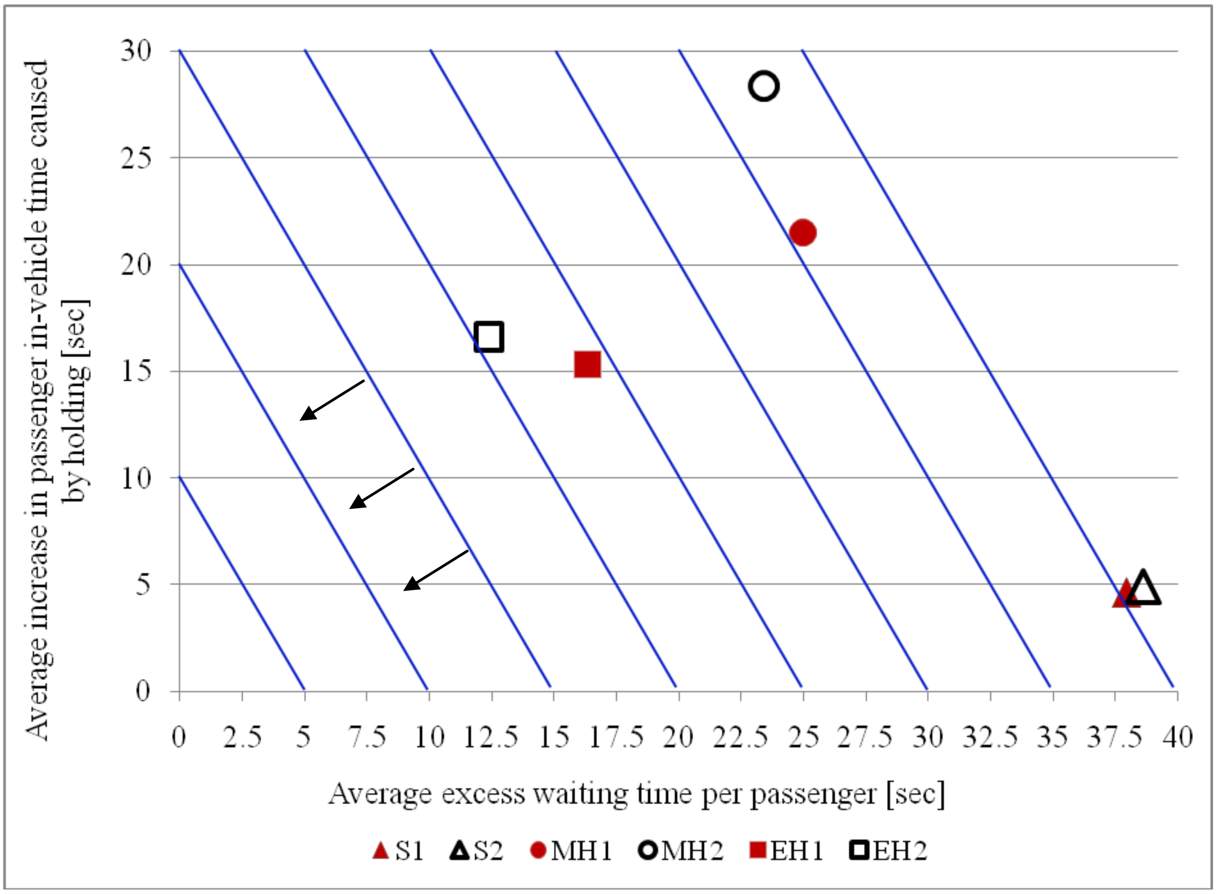


FIGURE 4 Trade-off between passenger in-vehicle delay and waiting time under various holding strategies.

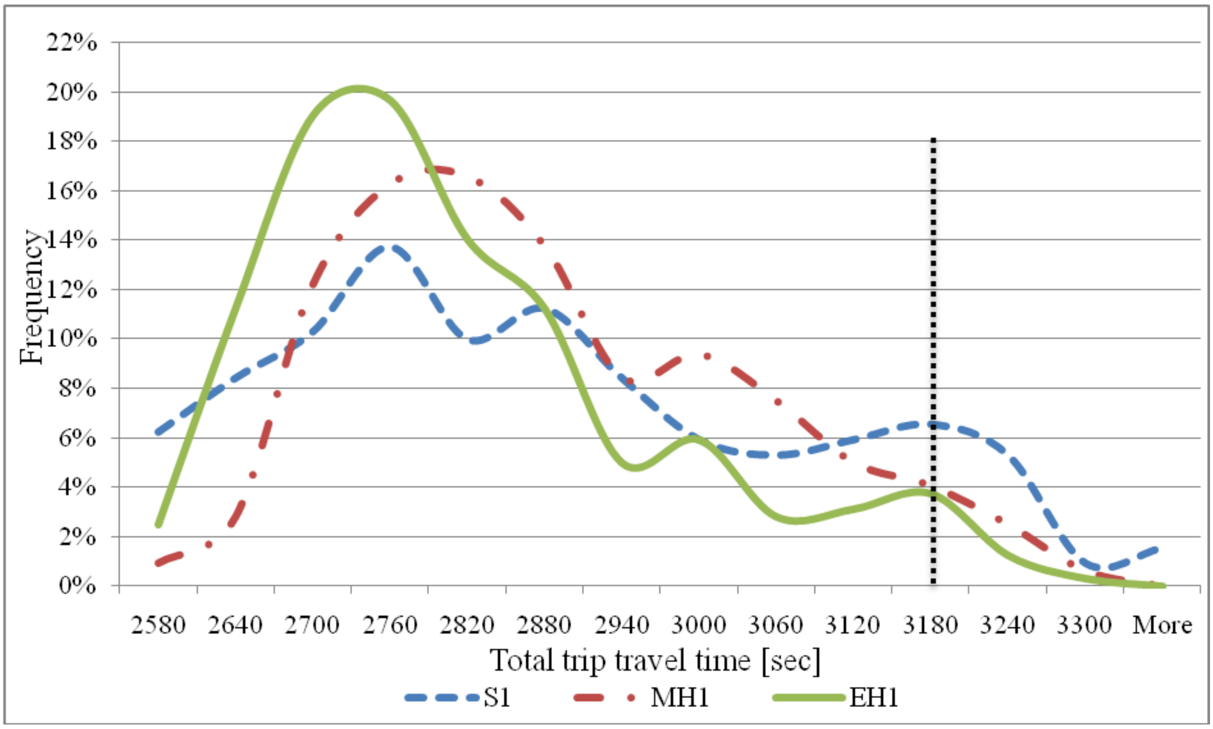
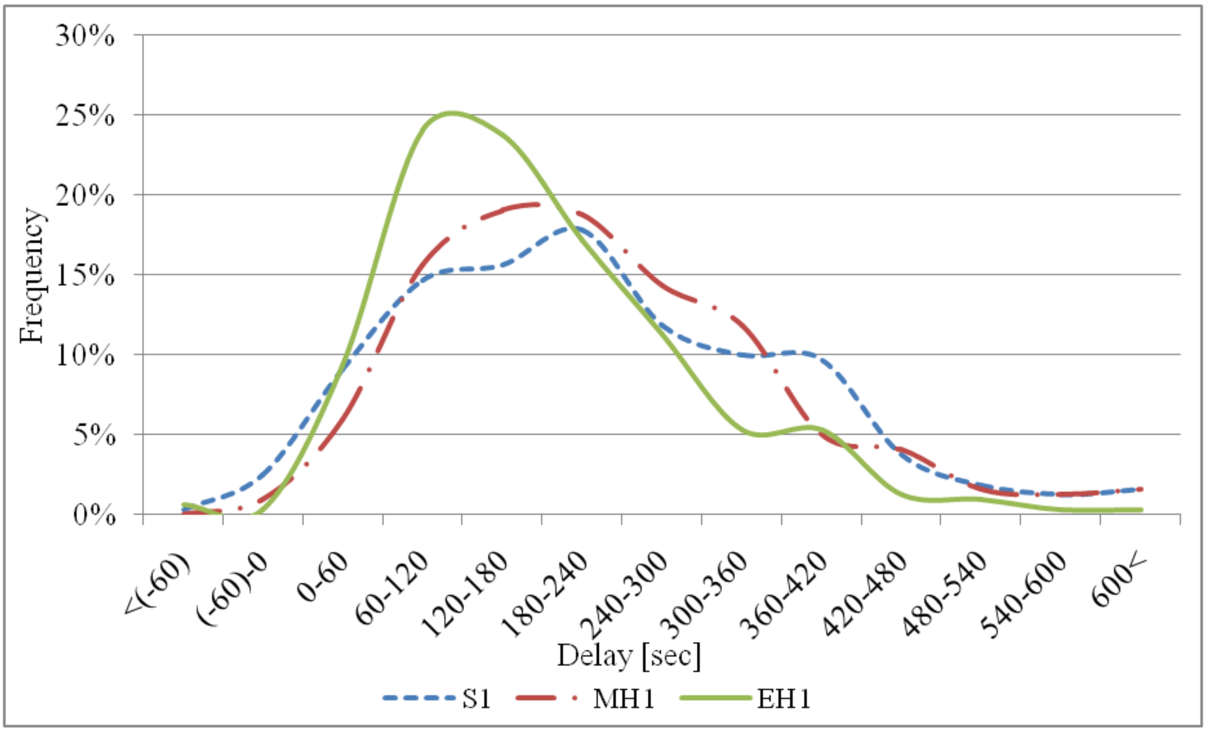


FIGURE 5 Total travel time distribution under various holding strategies.



FIGUIRE 6 Schedule adherence distribution at the relief point under various holding strategies.

TABLE 1 Experimental Design for Holding Scenarios

Holding criteria \ Time point locations	Schedule-based	Minimum headway-based	Even headway-based
Current	S1	MH1	EH1
Proposed	S2	MH2	EH2

TABLE 2 Service Measure of Performance under Various Holding Scenarios

Scenario	CV(h)	Average waiting time per Passenger (sec)	Bunching (%)	Regularity level of service	Average standing time per Passenger (sec)	On-time arrivals (%)
S1	0.54	172.94	30.26	D-E	79.62	79.24
S2	0.54	173.61	32.46	D-E	80.67	76.85
MH1	0.39	159.96	14.58	C	62.99	69.79
MH2	0.37	158.42	12.08	C	61.02	67.42
EH1	0.35	151.35	11.02	C	58.41	78.66
EH2	0.31	147.38	8.11	B-C	56.35	76.65