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Bus Holding Control Strategies: A Simulation-Based Evaluation and Guidelines for Implementation

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Abstract
Transit operations involve several inherent sources of uncertainty including dispatching time from the origin terminal, travel time between stops and dwell time at stops. Bus holding control strategies are among the prominent methods applied by transit operators in order to improve transit performance and level of service. The common practice is to regulate departures from a limited number of stops by holding buses until the scheduled time. An analysis of the performance of a high-frequency bus line in Stockholm based on Automatic Vehicle Location (AVL) data shows that this control strategy is not effective in improving service regularity along the line. It also indicates that drivers adjust their speed based on performance objectives. Implications of a control strategy that regulates departures from all stops based on the headways from the preceding bus and the following bus were evaluated using BusMezzo, a transit operations simulation model. The results suggest that this strategy can improve service performance considerably from both passengers and operators perspectives. In addition, it implies cooperative operations as the decisions of each driver are interdependent of other drivers with mutual corrections. The difficulties in realizing the benefits of the proposed strategy in practice such as dispatching from the origin terminal, driver scheduling and compliance are discussed. The implications of several practical considerations are assessed by conducting a sensitivity analysis as part of the preparations to a field experiment designed to test the proposed control strategy.

Keywords: Public transport; Operations; Simulation; Field experiment; Reliability

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ABSTRACT

Transit operations involve several inherent sources of uncertainty including dispatching time from the origin terminal, travel time between stops and dwell time at stops. Bus holding control strategies are among the prominent methods applied by transit operators in order to improve transit performance and level of service. The common practice is to regulate departures from a limited number of stops by holding buses until the scheduled time. An analysis of the performance of a high-frequency bus line in Stockholm based on Automatic Vehicle Location (AVL) data shows that this control strategy is not effective in improving service regularity along the line. It also indicates that drivers adjust their speed based on performance objectives. Implications of a control strategy that regulates departures from all stops based on the headways from the preceding bus and the following bus were evaluated using BusMezzo, a transit operations simulation model. The results suggest that this strategy can improve service performance considerably from both passengers and operator's perspectives. In addition, it implies cooperative operations as the decisions of each driver are interdependent of other drivers with mutual corrections. The difficulties in realizing the benefits of the proposed strategy in practice such as dispatching from the origin terminal, driver scheduling and compliance are discussed. The implications of several practical considerations are assessed by conducting a sensitivity analysis as part of the preparations to a field experiment designed to test the proposed control strategy.

1. INTRODUCTION

Service reliability is one of the main determinants of transit level of service. In the context of high-frequency urban lines, unreliable service results in long waiting times, bunched vehicles, long delays, uneven passenger loads and poor capacity utilization. In addition, more reliable transit performance can also imply lower operating costs and more efficient crew management. Transit operating environment is very uncertain. Sources of uncertainty include dispatching from the origin terminal, travel time between stops, and dwell times at stops.

Transit control strategies consist of a wide variety of operational methods designed to improve transit performance and level of service. Holding strategies are among the most widely used aiming at improved service regularity by regulating departure time from stops according to pre-defined criteria [1]. The design of holding strategies includes the stops where control is exercised, the conditions under which holding is used, and the amount of holding time. The stops where holding may take place are known as Time Points (TPS). Although hypothetically all stops might be defined as TPS, a typical bus line has only a few TPS (such as main transfer and central business district locations).

Although a number of studies [2,3,4] have indicated the benefits of holding strategies, a number of implementation studies have also shown that the benefits in practice some times are not realized. Previous reports on field trials of control strategies designed to improve service regularity shown limited results [5,6]. Pangilinan et al. [6] concluded that the main hindrance in the implementation was the workload in the control room. Carrel et al. [7] studied the control room dynamics and the main factors that influence controllers' decisions. An important observation was the dominancy of schedule adherence as a decision factor even when it introduces irregularities. Hence, the evaluation of various strategies should not be restricted to their impact on performance characteristics such as waiting time and crowding levels. It has to consider also the impacts on operators as well as overall robustness with respect to human factors, such as driver behavior and compliance in applying the proposed strategy.

This paper analyzes the performance of a high-frequency line under the current operation conditions based on detailed automatic vehicle location (AVL) data. The analysis reveals that the current control strategy does not improve service regularity along the line. Furthermore, an analysis of the speed pattern indicates that drivers adjust their speed continuously and that their driving pattern is sensitive to the TPS layout as they slow down when approaching a TPS. A holding strategy that is based on the headways from the preceding bus and the following bus can improve service performance considerably from both passengers and operator's perspectives [8]. The implications of applying this control strategy while treating all stops as potential TPS were assessed using BusMezzo, a transit operations simulation model. This control strategy implies cooperative operations as the decisions of each driver are interdependent of other drivers and executed simultaneously. The implementation of such a strategy involves practical considerations as scheduling constraints, driver display, driver compliance and control centre routines. This analysis was carried put as part of the preparations to a field experiment designed to test the proposed control strategy.

The remainder of this paper is organized as follows: Section 2 presents an analysis of the performance of a high-frequency line in Stockholm under current conditions. Section 3 describes the proposed holding strategy and its evaluation based on a simulation model including service regularity, operational considerations and issues related to strategy robustness. Section 4 discusses practical considerations and guidelines for the implementation of such strategies. Finally, concluding remarks are presented in Section 5.

2. ANALYSIS OF TRANSIT PERFORMANCE BASED ON AVL DATA

2.1 Line description

Bus line 1 was chosen as a case study. The backbone of the bus network in Stockholm inner-city consists of 4 trunk lines. These lines account for approximately 60% of the total number of bus trips in this area [9] and are characterized by high frequency, articulated vehicles, designated lanes at main streets, high level of signal priority and real-time arrival information at stops. Line 1 was chosen for a multi-perspective assessment of control strategies because it is a representative high-demand inner-city line that runs through the city centre. It runs with a planned headway of 5-7 minutes during most of the day and 4-5 minutes during the morning and afternoon peak periods. The line route connects Frihamnen, the main harbor in the eastern part of the city, the city centre, a business district and western residential areas (Figure 1). 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 (15:30-18:00). Holding control is currently applied at three TPS on each direction (stops 10, 17 and 23 on ER and stops 10, 17 and 24 on WR). The TPS were selected by SL, the regional transit authority, based on network configuration by identifying the main transfer stops from the metro system.One of the TPS is also as a relief point (10 on ER, 24 on WR) and hence late arrivals may affect succeeding trips on drivers' schedule.

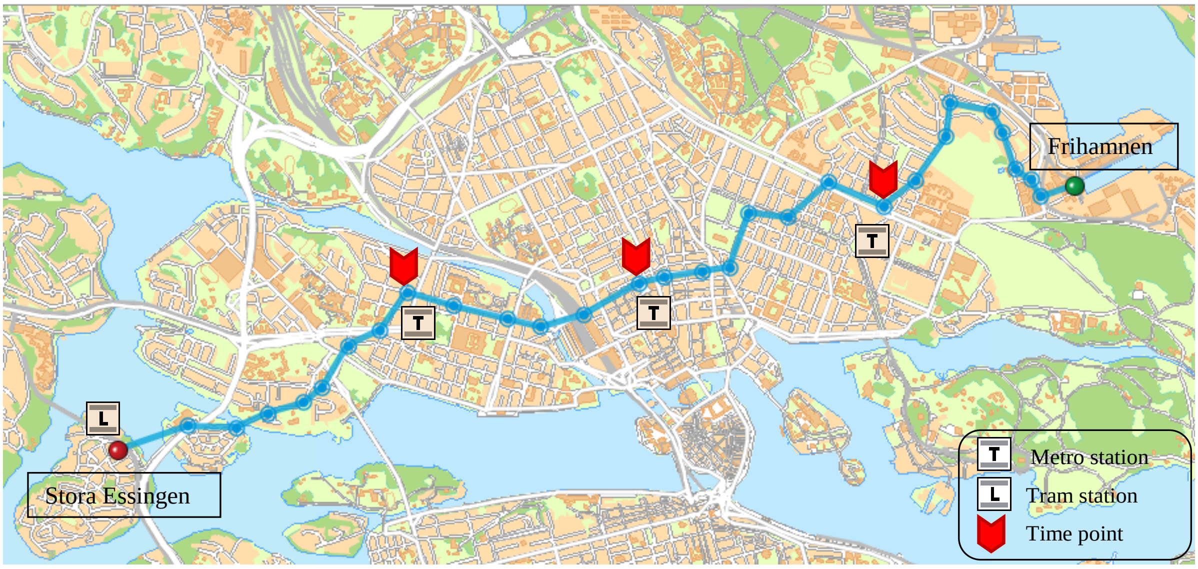
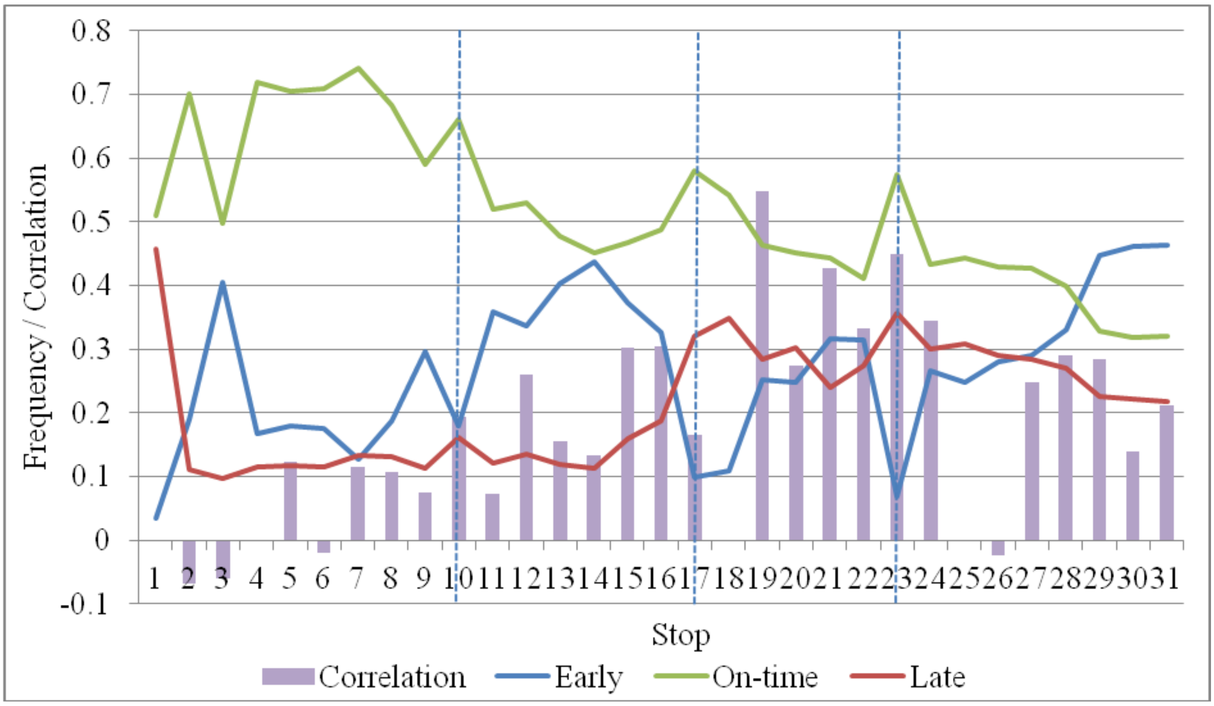


FIGURE 1 The route of bus line 1 in Stockholm

2.2 Performance analysis

The performance of line 1 was analyzed based on detailed and comprehensive AVL data for a week of regular operations in May 2008. Each bus that operates in Stockholm is equipped with a computer that is called BusPC and is located at the driver’s cabin. This system enables radio communication with the control centre, receiving text messages and the automatic display and recording of real-time information based on the AVL system. The software is provided and supported by INIT. The current display shows the three next TPS or terminals and the scheduled time at these stops. In addition, a measure of schedule adherence is shown continuously. It is calculated based on the actual location of the bus. A plus sign indicates that the bus runs ahead of the schedule and a minus sign indicates that the bus runs behind schedule. The scheduled adherence measure is given at the half minute level.

The contract between the regional transit authority and bus operators determines that the operator has to pay certain penalties, depending on the level of service offered and service punctuality is an important clause in the contract. On-time performance is defined as departing within the time window of 1 minute ahead of schedule and 3 minutes behind schedule [10]. Figure 2 shows the share of early, on-time and late departures based on the above definition from each stop along both directions with TPS indicated by dashed lines. The overall pattern is that the share of on-time departures deteriorates along the route from a level of above 0.7 down to 0.35. The share of early departures decreases at TPS due to holding of early arrivals. However, this affect does not last with an immediate increase in subsequent stops. Moreover, even at TPS a considerable share of the buses of 10-20% depart early. The share of late departures is not affected by TPS as the current control strategy does not handle buses that are behind schedule.



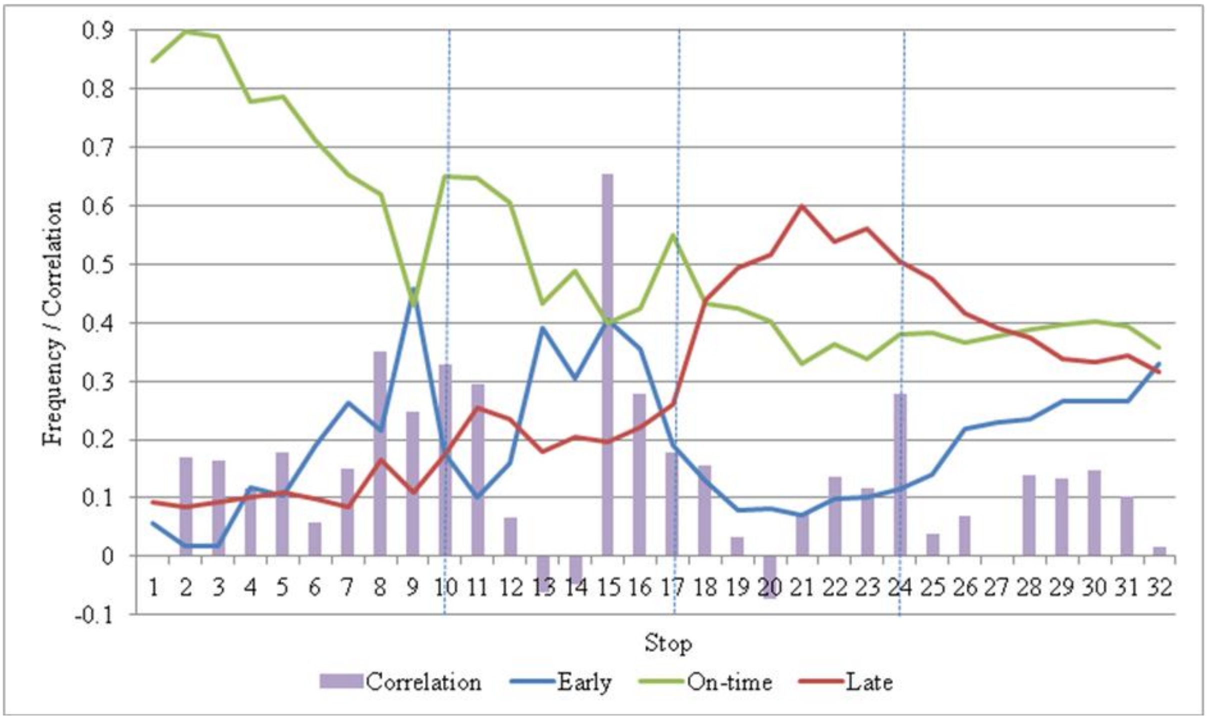


FIGURE 2 On-time performance and the correlation of speeds with schedule deviation along the WR (up) and ER (down).

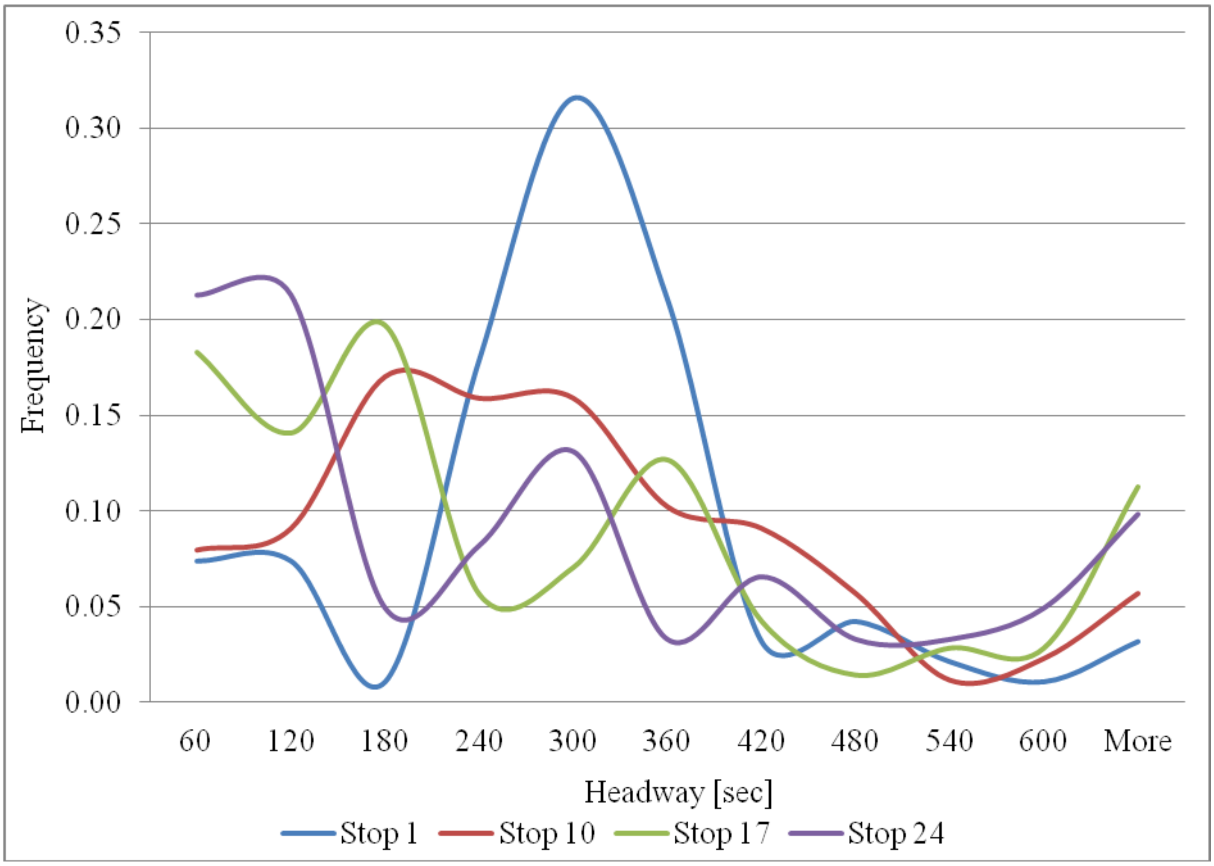
The AVL data facilitates the analysis of the speed profile along the line by considering the time interval between departure from one stop and arrival at the next stop. The average running speed is in the range of 7 to 40 km/h. As expected, the average speed is higher at both edges of route directions and lower at the middle part that runs through the inner city. Ingemarson [11] analyzed line 1 running times before and after the introduction of priority measures and congestion charge in Stockholm and found that running speeds remained unchanged.

The continuous display of the deviation from the schedule enables drivers to adjust their speed accordingly. In order to investigate the extent of these potential speed adjustments, the correlation between the average speed and the corresponding measure of schedule adherence that was displayed on the BusPC system was calculated between each pair of consecutive stops. The displayed measure was estimated by using the following formula:

$$OTD_{jk} = \lfloor ET_{jk} - ST_{jk} \rfloor_{30} \qquad (1)$$

Where OTD_{jk} is the on-time display for the driver on trip k when driving between stops j and j+1. The operator $\lfloor Y \rfloor_x$ indicates rounding down Y to the closest divider by x. ET_{jk} and ST_{jk} are the actual exit (departure) time and the scheduled exit time of trip k from stop j, respectively. The average speed is positively correlated with the schedule adherence measure on most route segments, as presented in Figure 2. The overall correlation is 0.2, suggesting that drivers adjust their speed between stops to reduce their deviation from the scheduled time, although speed adjustments are restricted by traffic dynamics, signals and speed limits. Moreover, stronger correlations tend to occur at segments preceding TPS (marked by dashed vertical lines). This observation suggests that drivers adjust their speeds just before approaching those stops in order to make it within the desired time window. Therefore, there are indications that drivers can and do adjust their speeds based on time-dependent service performance, although these adjustments depend on the TPS layout - locations where the performance is measured. Note that the speed on each segment contributes to the on-time performance downstream.

As a high-frequency line, the main determinant of level of service is service regularity. Figure 3 presents headway distributions at the origin terminal and the three TPS on both line directions based on the AVL departure times during the afternoon peak period. The distribution is narrowest at origin terminals with a central value that corresponds to the planned headway. However, even at the origin terminal there is a high variation in headways- 15-18% of headways less than 2 minutes and more than 10% longer than 7 minutes. The shares of very short and very long headway increase along the route, with no correction at TPS. The coefficient of variation of the headway doubles along the route from an already high level of 0.6 to 1.2 – indicating that service regularity deteriorates considerably along the route under the current control strategy.



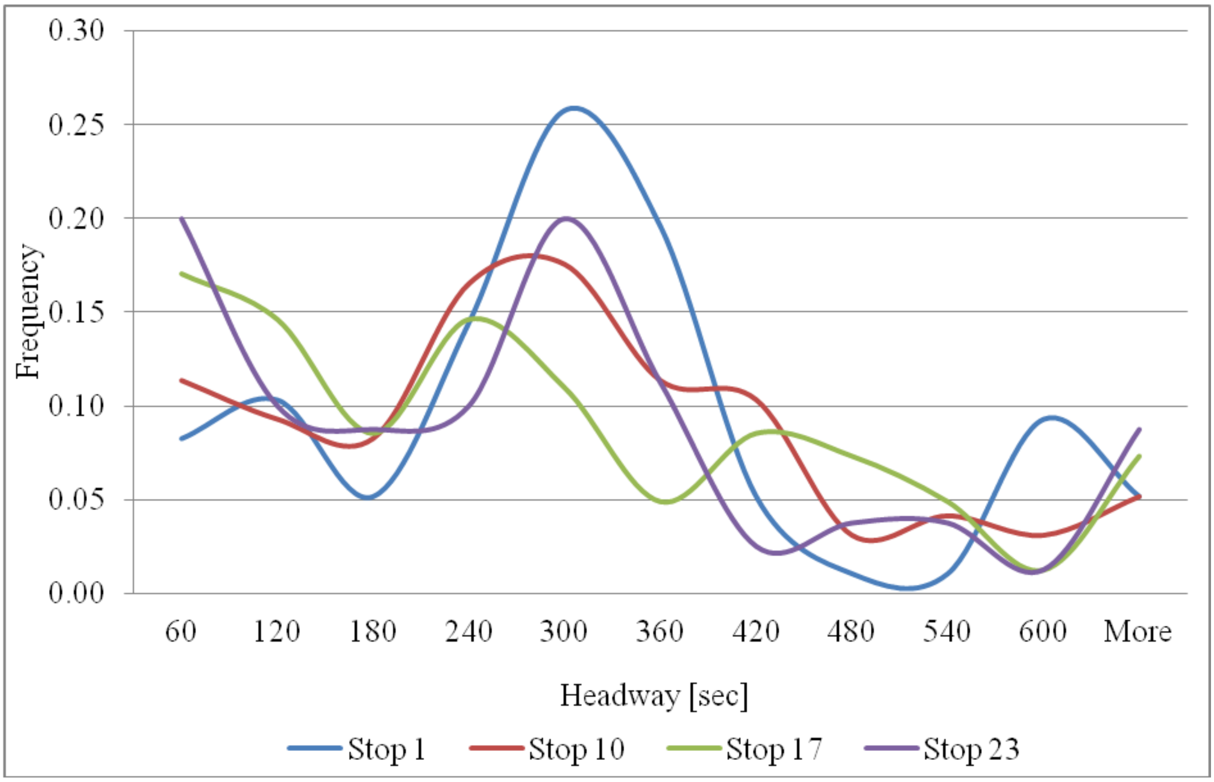


FIGURE 3 Headway distribution at terminals and TPS along the WR (up) and ER (down).

3. SIMULATION STUDY

The analysis of the AVL data suggests that the current control strategy does not prevent the deterioration of service regularity along the route. The evaluation of the performance under alternative control schemes can be estimated using a transit simulation model.

3.1 Simulation tool

BusMezzo, a transit simulation model, was used for the evaluation of various operations conditions. The transit model is completely integrated with Mezzo, a mesoscopic traffic simulation model [12]. The transit network layer includes routes, lines, stops and the corresponding timetables. Dwell time at stops can take different functional forms, with the default model based on TCRP [13]. Each stop can be defined as a TPS implying that the holding strategy determines the departure time based on the dynamic system conditions.

BusMezzo represents vehicle schedules and hence the potential propagation of delays from previous trips. Buses progress in the traffic network and enforce capacity constraints so that denied boarding passengers have to wait for the next vehicle. Passenger demand can be represented at several levels of detail depending on the application of interest and data availability. In all cases, passenger demand is time-dependent and agent-based. The mesoscopic level of representation enables to model the detailed interactions between control strategies, headways, passenger arrival process, dwell times, delays and trip chaining at the system level. A detailed description of the transit operations modelling in BusMezzo along with a validation is available in Cats et al. [14].

3.2 Experiment description

A previous simulation study of holding strategies evaluated several holding strategies using BusMezzo on line 1 [8]. Three holding strategies were evaluated: the current practice of schedule-based control (S); enforcing a minimum headway of 80% of the planned headway from the preceding bus (MH) and; a strategy based on even-headways between the preceding bus and the following bus (EH). The EH strategy is formulated as follows:

$$ET_{jk} = max\left(\min\left(AT_{j,k-1} + \frac{AT_{m.k+1}+SRT_{m,j}-AT_{j,k-1}}{2}, AT_{j,k-1} + \alpha H^{k-1,k}\right), AT_{jk} + DT_{jk}\right) \quad (2)$$

Where AT_{jk} and DT_{jk} are the arrival time and dwell time on trip k from stop j, respectively. m is the index of the last stop that was visited by bus trip k+1 and $SRT_{m,j}$ is the scheduled running time between stops m and j . $H^{k-1,k}$ is the planned headway between trips k-1 and k and α is a threshold ratio parameter.

Cats et al. [8] concluded that based on the current TPS layout, strategy (EH) is promising. An alternative TPS layout that was constructed based on recommendations from previous studies did not show substantial improvement over the current scheme.

The purpose of TPS is to control the deterioration of service regularity along the line. Although hypothetically all stops can be defined as TPS, departure times are usually regulated only at a small subset of stops along a bus line. The availability of AVL driver display on buses enables to instruct drivers continuously. Hence, each stop along the route can be defined as a TPS, where a bus can be potentially held. This layout can be useful to spread the control mechanism over the entire route and to prevent the propagation of discrepancies. Van Oort and Van Nes [15] reported the implementation of a schedule-based strategy at all-stops on a light rail line in the Netherlands, where it showed substantial benefits.

In order to investigate this possibility, a simulation study was carried out to evaluate the performance of holding strategies with an experimental design that consists of six scenarios based on the combination of the three holding criteria (S, MH and EH) and two sets of TPS – the current layout of three TPS versus all-stops (denoted by 3 and ALL). Dispatching from the terminal is schedule-based in all the scenarios. The case study represents in detail the bus line characteristics based on the empirical data described in Section 2 in order to represent them adequately in the simulation model. For each scenario 10 simulation runs of the afternoon peak period were conducted. 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. All of the reported results are the average of the 10 replications for each scenario.

3.3 Results and discussion

3.3.1 Service regularity

From the passenger perspective, holding strategies have the potential to improve service reliability, reduce waiting time and improve on-board comfort conditions. Headway-based strategies resulted in much narrower distribution with considerably lower probabilities for very short and very long headways than the schedule-based strategy (Figure 4). The distributions are composed from all the headways between successive buses at all stops during the simulated period. Interestingly, the headway distribution is essentially the same under schedule-based control regardless of the TPS layout. In contrast, for headway-based strategy, the TPS layout defines the headway distribution more than the headway strategy does as the distribution becomes much narrower for the all-stops layout.

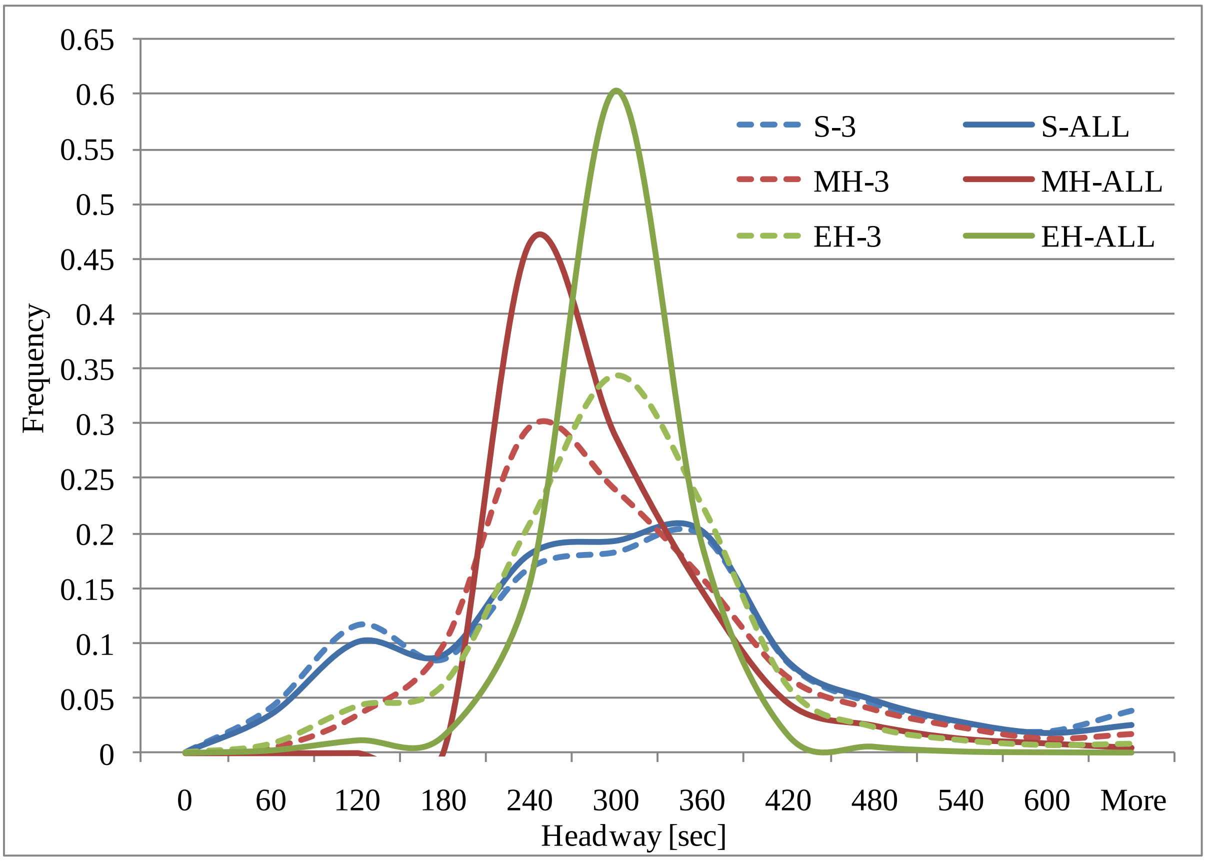


FIGURE 4 Headway distribution under various time point layout and holding strategies combinations.

Table 1 presents a number of measures of performance at the system level for each scenario. The coefficient of variation of the headway presented in the table is the mean value over all stops. Note that the average headway value is approximately the same across scenarios. The results reflect the headway distributions with the headway-based strategies reducing headway variability substantially compared with schedule-based holding and the EH strategy performing better than the MH strategy. Moreover, regulating at all stops improves the regularity considerably. In fact, the coefficient of variation of headways did not exceed 0.3 at any point under the EH-ALL strategy. The improvement in service regularity results in shorter passenger waiting times, which were calculated based on the disaggregate output data and take into account the extra waiting time caused when passengers are denied boarding due to capacity constraints. Furth and Muller [16] suggested that the total waiting time for high-frequency services corresponds to the 95th percentile of the headway distribution due to budgeted waiting time. As evident in the headway distribution above, the headway-based strategies result in substantial changes. EH3 yields a reduction of 40% in the 95th percentile value – from 558 seconds to 335 seconds - compared with the base case scenario (S1).

Two additional measures of service regularity were calculated based on the definitions given by TCRP [13]. The measure of bunching was calculated as the share of headways that deviate from the planned headway by more than 50% - either up or down. Very low bunching rates of less than 5% are obtained when applying headway-based control at all stops. A corresponding ordinal Level of Service (LOS) scale in terms of headway regularity was established by TCRP. The results suggest that moving from the current practice (S-3) to EH-ALL will improve the level of service from frequent bunching (LOS D-E) up to the level of clockwork performance (LOS A).

TABLE 1 Service measure of performance under various control scenarios

Scenario	CV (h)	Avg. wait time per pass. (sec)	Bunch-ing (%)	LOS	Avg. standing time per pass. (sec)	Avg. cycle time (sec)	Avg. holding time per vehicle run (sec)	90th perc. of cycle time (sec)	Avg. delay at relief point (sec)
S-3	0.54	173	30.3	D-E	80	5895	51	6269	222
S-ALL	0.50	165	26.5	D	87	5934	81	6226	181
MH-3	0.39	160	14.6	B-C	63	5944	173	6274	239
MH-ALL	0.26	146	4.0	B	65	6021	207	6306	215
EH-3	0.35	151	11.0	B-C	58	5874	130	6186	226
EH-ALL	0.18	141	2.6	A	58	5957	175	6078	220

Headway-based holding could also impact positively crowding conditions. A more regular service increases the probability of having an available seat since passenger load is distributed more evenly between buses, preventing the pairing of empty and overcrowded vehicles. The average standing time per passenger is used as the crowding measure and is a proxy for the level of comfort. It was estimated as:

$$AST = \frac{\sum_k \sum_j [RT_{jk} \cdot \max(0, L_{jk} - seats) + DT_{jk} \cdot \max(0, L_{jk} - A_{jk} - seats)]}{\sum_k \sum_j B_{jk}} \quad (3)$$

Where RT_{jk} is the running time from stop j-1 to stop j on trip k. L_{jk} is the passenger load on trip k when approaching stop j while A_{jk} and B_{jk} are the number of alighting and boarding passengers, respectively. seats is the number of seats on the vehicle type that is used for the operations of the line under consideration. Based on this calculation the average standing time per passenger was reduced by up to 30% when headway-based strategies were implemented.

3.3.2 Operational considerations

From the operator perspective, holding strategies have the potential to improve fleet management reliability at the cost of longer vehicle 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. Figure 5 presents the total trip time distribution for the ER where according to the timetable the total running time is 51 minutes. Headway-based strategies yielded a narrower travel time distribution. According to the simulation results, 80% of the trips were completed in less than the scheduled time under the strategy that is currently used (S-3). This percentage rises to 92% under EH with the current layout and to 99% when applying EH-ALL. The average total cycle time increases by 1-2 minutes when the MH strategy was implemented compared with schedule-based and EH strategies (see Table 1). This result is consistent with previous findings in Van Oort and Wilson [17] which compared a schedule-based and a MH strategy. Furthermore, holding at all stops prolonged the average cycle time by 0.5-1.5 minutes compared to the case of the same strategy and the current TPS layout. However, from a timetable and fleet schedule design point of view it is usually the 85th or 90th percentile of the travel time distribution that is used [18]. Hence, in order to study the effect of holding strategies on fleet assignment, we compare the 90th percentile of total cycle time (a bi-directional chain). The EH strategy reduces the cycle time variability with a reduction of 1.5-3 minutes for the 90th percentile value. This reduction of 3% in total cycle time has positive consequences for both operators and passengers. These findings reinforce the conclusions of Daganzo [4] from an analytical study on a similar holding strategy.

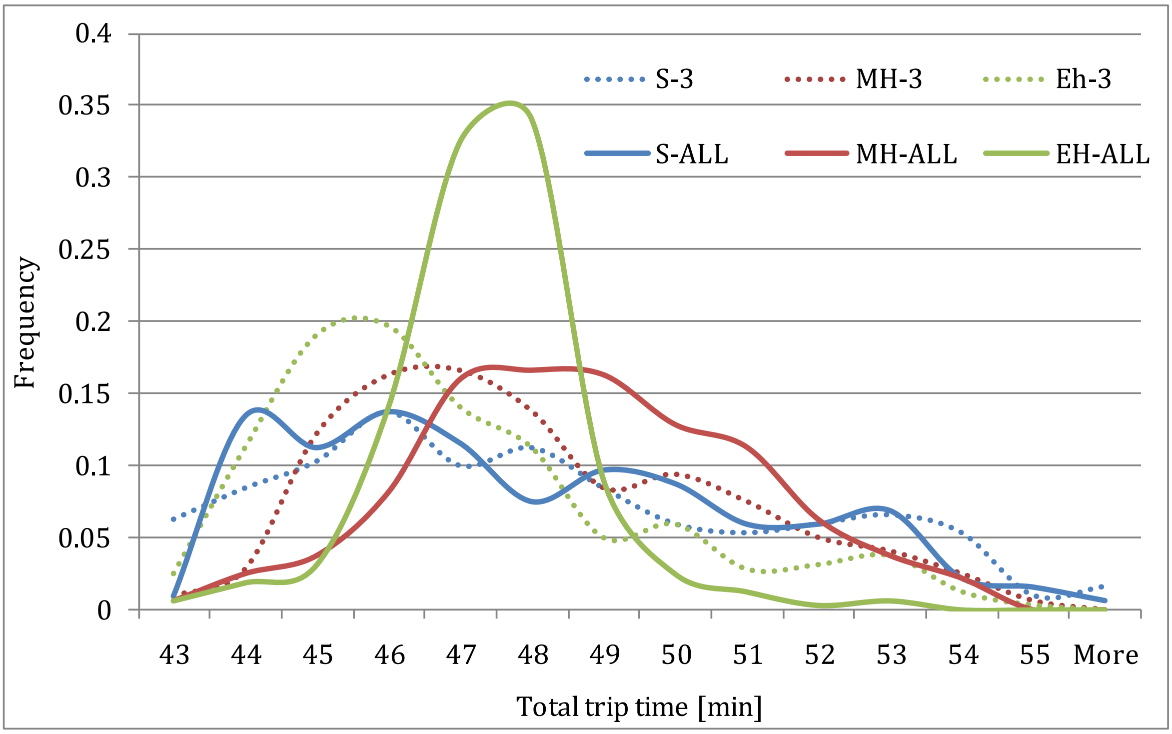


FIGURE 5 Total travel time distribution under various time point layout and holding strategies combinations.

Relief points are a potential concern when applying headway-based strategies, as schedule adherence is the main concern for driver shift scheduling. The distribution of the delay at the relief point (‘Fridhemsplan’) on the westbound route, towards the end of the route and therefore subject to more uncertainty, was obtained from the simulation output. The average delay defined as the deviation from the scheduled arrival time is the lowest under S-ALL, while the standard deviation of the delay is the lowest with EH-ALL. Interestingly, the headway-based strategies do not imply longer delays than the current schedule-based control of S-3 (Table 1). Furthermore, the standard deviation of the delay is significantly lower in the cases of headway-based control at all stops with lower probabilities for very late arrivals. These results suggest that headway-based strategies can even improve punctuality at relief points.

3.3.3 Robustness

The overall robustness of the EH strategy has to be considered with respect to human factors and BusPC design. The potential impacts of practical consideration for the implementation of the proposed strategy were evaluated using the simulation model for the peak hour only. The following factors were incorporated into the control strategy in BusMezzo: driver display preciseness – exact time difference in seconds vs. half minute level as provided by BusPC; compliance rate – the share of bus drivers that follow the control strategy with the remaining drivers assumed to consistently disregard the strategy and depart without holding; maximum holding time - an upper bound for the holding time at each TPS. These three factors were embedded in the EH control strategy as follows:

$$ET_{jk} = max\left(\min\left(AT_{j,k-1} + \left\lfloor\frac{AT_{m.k+1}+SRT_{m,j}-AT_{j,k-1}}{2}\right\rfloor_{30}, AT_{j,k-1} + \alpha H^{k-1,k}\right), AT_{jk} + DT_{jk}\right) \quad (4)$$

$$ET_{jk} = max\left(\min\left(AT_{j,k-1} + \frac{AT_{m.k+1}+SRT_{m,j}-AT_{j,k-1}}{2}, AT_{j,k-1} + DT_{jk} + \gamma_{max}\right), AT_{jk} + DT_{jk}\right) \quad (5)$$

$$ET_{jk} = \begin{cases} max\left(\min\left(AT_{j,k-1} + \frac{AT_{m.k+1}+SRT_{m,j}-AT_{j,k-1}}{2}, AT_{j,k-1} + \alpha H^{k-1,k}\right), AT_{jk} + DT_{jk}\right) & \delta_k = 1 \\ AT_{jk} + DT_{jk} & otherwise \end{cases} \quad (6)$$

Where $\gamma_{\max}$is an upper bound for holding time and δ_k is an indicator that equals 1 if the driver on trip k complies with the regulations at TPS.

The results of this experiment are presented in Table 2. Both EH-3 and EH-ALL were simulated with two imperfect compliance rates of 50% and 75% of the drivers complying with the applied headway strategy while the others simply ignore the BusPC display. The table shows the average coefficient of variation of headways along the line and the relative change compared with the base case of the same strategy with the ideal holding operations: perfect display preciseness, perfect compliance and no maximum holding time enforced. Both strategies are surprisingly robust with respect to driver compliance, presumably due to their cooperative nature where adjacent vehicles can correct for a non complying vehicle and mutual corrections. In an additional test of compliance error at the stop visit level (low awareness or stop-specific constraints that are not associated with a particular driver), the performance of EH-ALL was only negligibly affected as even the same vehicle can correct itself at the next stop if needed.

The introduction of maximum holding time comes at a higher price in terms of reduced service regularity. It is a practical constraint as long holding times cause inconvenience to passengers on-board. Moreover, the preciseness of the BusPC display adds another disturbance into the system that reduces the effectiveness of the holding strategy compared with the hypothetical case of ideal holding conditions. It is important to keep in mind that all these design factors hinder also the current operations and should be regarded as a sensitivity analysis. Furthermore, possible speed adjustments between stops were not modelled in the scenarios. Hence, the results may underestimate the benefits from the continuous cooperative nature of the proposed strategy.

TABLE 2: Effects of holding implementation on headway coefficient of variation

Strategy	Driver display preciseness	Compliance rate	Max holding time	CV(h)	Increase in the CV(h) compared with respective case (%)
EH-3	Perfect	1.0	None	0.35	+0
		0.75	None	0.35	+1
		0.5	None	0.37	+7
		1.0	1 min	0.42	+21
	30 sec	1.0	1 min	0.46	+31
EH-ALL	Perfect	1.0	None	0.18	+0
		0.75	None	0.19	+4
		0.5	None	0.19	+8
		1.0	1 min	0.21	+19
		1.0	5 min	0.20	+13
	30 sec	1.0	1 min	0.23	+26
		0.5	None	0.24	+34

4. IMPLEMENTATION GUIDELINES

The analysis of the simulation results highlights potential benefits from implementing the EH-ALL strategy. The analysis suggests that implementing this strategy on trunk line 1 will have positive impacts on reliability and hence on passenger waiting times, crowding levels, and fleet operations, while maintaining the schedule adherence in general, and at the relief points in particular. In addition, the underlying inter-dependent mechanism of the EH strategy can be useful in preventing the current speed pattern of slowing down just before approaching TPS that is reinforced by the schedule-based control strategy.

The findings of the analysis have led the local transit authority and bus operator to pursue an experiment to test the performance of this strategy in real-world conditions.The implementation of the proposed strategy could be facilitated by the capability of the BusPC to display a headway-based measure. The additional indicator refers to how far the bus is from being exactly in the middle between the proceeding and the succeeding buses. An indicator with a plus sign indicates that the bus is too close to the bus in front while a negative one means that the bus is too close to the bus behind. If the bus is exactly in the middle then the indicator displayed is zero. This measure can be embedded into the BusPC screen and is behaviorally consistent with the current practice as “plus” requires waiting or slowing down and “minus” to speed up.

The simulation model is a useful tool for assessing the impacts of potential control strategies. However, actual implementation of the design of the proposed control scheme involves complications that require careful consideration. The findings from the analysis of AVL data and the simulation study were discussed with the regional transit authority and the bus operator in order to design guidelines for its implementation. Some lessons can be drawn from previous field studies including an attempt to improve the regularity of line 1 in Stockholm which had limited results [5]. During the autumn of 2002, a dedicated dispatcher at the control centre instructed two mobile traffic controllers how to regulate the service with the objective of improving the regularity. The dispatcher was the only person that had access to real-time AVL data. Moreover, the control strategy was defined vaguely with no clear holding criterion. The report of the pilot study concludes that the headway control in addition to other measures that were introduced simultaneously led to small regularity improvement.

Important lessons can be draw from previous attempts to implement a headway-based strategy. A field study in Chicago reported by Pangilinan et al. [6] investigated a control strategy equivalent to the EH strategy. The trial was also based on a dedicated dispatcher at the control room and supervisors located at key stops along the route. Again, the supervisors passed on the dispatcher instructions to the drivers with only the dispatcher having direct access to real-time AVL data. The authors found that the dispatcher workload did not allow him to detect, not to mention respond to, every service regularity problem even after they simplified the conditions that require intervention. This was the underlying limitation that hindered their field study. Nevertheless, service regularity during the trial period improved compared with the previous unsystematic control scheme. In light of the conclusions of Carrel et al. [7] from their study on control room dynamics, it is important to modify the dynamic display at the control room so that it is consistent with the headway indicator. A dedicated dispatcher will monitor the performance, send reminders, communicate with drivers and initiate interventions in case of need. Of course the operator has to be assured that the current incentive scheme which is based on on-time performance will not apply during the trial period so that it will not result in high penalties on its expense.

According to the simulation results treating all stops as TPS (EH-ALL) have more significant gains in terms of service regularity than restricting holding to the current set of TPS (EH-3). Enabling to hold at each stop prevents the accumulation of irregularity instead of resolving it only at the next TPS downstream. Another advantage is that holding times are spread between more stops, hence requiring shorter holding time per stop as was the case when a schedule-based holding at all stops was applied on a light rail line in the Netherlands [15]. However, this approach may be difficult to implement due to local traffic dynamics, stop capacity constraints and the human factor. A possible compromise might be that drivers should keep an even headway at all stops by holding if necessary based on their judgment of local conditions while making sure that they fulfil the criteria at the three current TPS. A continuous control may also contribute to changing the current pattern of speed adjustments just before approaching a TPS.

Driver and vehicle scheduling are important constraints in an actual implementation of the proposed strategy. Regulating the dispatching from the origin terminal can potentially prevent some of the initial variability introduced already at the beginning of the route. The results of Pangilinan et al. [6] suggest that headway-based dispatching from the origin terminal plays an important role, an issue highlighted also by Van Oort and Van Nes [15]. However, transit lines do not operate as a closed system and headway regulation at dispatching may be complicated in real-world operation conditions since drivers and vehicles are circulated between lines. Hence, it may be worthwhile to treat the terminal as a TPS both in terms of schedule and headway. In other words, buses may depart later than the timetable in case the headway from the preceding bus is too short. This is aimed to prevent the departure of bunched buses from the origin terminal which is evident under the current control scheme (Figure 3).

5. CONCLUSION

Bus performance is impacted by various sources of uncertainty such as traffic conditions, passenger volumes, dwell times, operations at terminal, and driver behavior. A detailed analysis of AVL data combined with a simulation study showed that the current practice of schedule-based holding at a few key stops is an inefficient control scheme for a high-frequency bus service compared with alternative headway-based strategies. A headway-based control scheme that is based on holding buses to equalize headways has the potential to result in benefits from both passenger and operator perspectives. The results from the simulation study with all stops as potential TPS maintains a high level of service regularity. A sensitivity analysis shows that this strategy is also robust with respect to driver behavior.

An additional aspect that could be examined during the trial period is the potential reduction in running times between stops. The findings of Ingemarson [11] that running times on line 1 did not change due to the introduction of priority measures and congestion toll in Stockholm should be interpreted in the context of the current schedule-based control. Timetables are not merely a reflection of running times but rather an important determinant of running time. Under the current holding strategy, drivers follow the timetable both through holding at stops and speed adjustments between stops. Hence, as long as the timetables do not reflect the updated traffic conditions, buses will not exploit them. In contrast, under the proposed even-headway strategy running speeds are interdependent between adjacent buses and therefore the whole system is expected to get closer to the speeds enabled by the priority measures. So although running times are not an explicit objective of the proposed strategy, its implementation may prove beneficial to this aspect as well. Thus, it can help to resolve some conflicts between transit authorities and operators on the construction of timetables.

The assessment of the actual field implementation would be based primarily on before-after analysis of AVL and automatic passenger counts (APC) data. The comparison would be made for equivalent months that have similar traffic conditions and passenger demand levels. The integration of performance analysis and post-trial interviews will allow drawing conclusions on the applicability of the proposed scheme and possible refinements. Furthermore, the data collected during the trial would facilitate the validation of the transit operations modelling in BusMezzo.

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