

1 **Robust Control for Regulating Frequent Bus Services: Supporting the Implementation of Headway-based**
2 **Holding Strategies**

3
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1 **Abstract (245 words)**

2 Reliability is a key determinant of the quality of a transit service. Control is needed in order to deal with the stochastic
3 nature of high-frequency bus services and to improve service reliability. In this study, we focus on holding control,
4 both schedule- and headway-based strategies. An assessment framework is developed to systematically assess the
5 effect of different strategies on passengers, the operator and transport authority. This framework can be applied by
6 operators and authorities in order to determine what holding strategy is most beneficial to regulate headways, and thus
7 solve related problems. In this research knowledge is gained about what service characteristics affect the performance
8 of holding strategies and the robustness of these strategies in disrupted situations, by using scenarios. The framework
9 is applied to a case study of a high-frequency regional bus line in the Netherlands. Based on the simulation results, we
10 identified the line characteristics that are important for the performance of schedule- and headway-based strategies
11 and determined how robust different strategies are in case of disruptions. Headway-based control strategies better
12 mitigate irregularity along the line, especially when there are disruptions. However, schedule-based control strategies
13 are currently easier to implement, because it does not require large changes in practice, and the performance of both
14 strategies is generally equal in regular, undisrupted situations. In this paper, insights into what the concerns are for
15 operators with respect to technical adaptations, logistical changes and behavioral aspects when using a headway-based
16 strategy are given.

1. INTRODUCTION

Reliability is a key determinant of the quality of transit services. Irregular services are the result of variability in departure from terminals, vehicle running times and dwell times. A common problem for high-frequency bus services, caused by these types of variability, is vehicle bunching. The result of these factors is variability in the headway between buses, and thus a deterioration in service reliability (1). Control is needed to deal with the stochastic nature of high-frequency bus services and to improve service reliability (2).

In this paper, the focus is on holding control. There are roughly two categories of holding strategies: schedule-based holding and headway-based holding. In case the strategy is schedule-based holding, buses will be held up to the scheduled departure time. The second category is headway-based holding; vehicles will be held till a minimal headway requirement is fulfilled (3).

It is possible to examine service reliability in terms of both punctuality or regularity. For high-frequency bus services, regularity is more important than punctuality. When the frequency is high, passengers do not consult the schedule and arrive randomly at stops (4). The frequency is considered high in case the frequency of buses is equal or higher than 6 vehicle departures per hour (2, 5). Regularity is more important for high-frequency bus services than punctuality.

1.1. Related work

The absence of control strategies can lead to undesired behaviour of the system. Different control strategies have been proposed divided into station control, inter-station control and other control measures (6). Station control strategies and specifically holding strategies are the most common strategies applied in normal services to deal with variability and improve regularity (7). Therefore, the focus in this research is on this type of control. When devising a control strategy, three aspects are important. First the control points need to be determined; the stops where buses are held. The second aspect is the conditions under which holding will be applied: schedule- or headway-based. Finally, how long the bus will be held: the (maximum) holding time (4). These three aspects have been extensively discussed in literature.

Control points

Control points are commonly determined by the transit authority. These control points are in general the important transfer stops along the route (8). The number of control points and their locations has been the subject of several studies. In some studies, it was concluded that control points should be located before high-demand stops (9), at early points along a route (10), or at a stop in the middle of a route with a high-boarding demand (11), while others concluded that it is best to have only one control point at the original terminal (12). Cats, Rufi & Koutsopoulos (13) demonstrate that the selection of the control points can have considerable effects on service performance. In addition, the location of control points was found to be more important than the number of control points and that specific characteristics of a line are crucial for the choice of locations and number of control points.

Holding conditions

Schedule-based holding is the common practice to regulate buses by holding vehicles at control points until the scheduled departure time (3, 14).

Two types of headway-based holding conditions are predominantly discussed in the literature; the first one is realizing an a-priori headway, by determining the holding time based on the headway between the bus and its predecessor (9, 11, 15, 16, 17). Bartholdi & Eisenstein (15) discuss the disadvantages of this approach. According to the authors, the optimal achievable headway is not known in advance and can also change, due to changes in traffic conditions, driver behaviour and the amount of passengers boarding and alighting. In addition, control based on target headways is not able to react adequately to larger disruptions. In case of target headway control the successive bus should speed up, which is often not possible. Therefore, target headway control is vulnerable in the event of disruptions. This leads to the second type of headway-based holding condition; considering the location of successor and predecessor of a bus by communication between buses (3, 18, 19). With respect to the headway control strategy, Cats (3) also mentioned that in case of incidents it may be necessary to switch from headway-based control to schedule-based control. However, incidents were not taken into account in the simulation study performed in (8).

Following the promising outcomes of a simulation study (8), the even headway control strategy was put into practice in Stockholm (20). It should be noted that other measures were implemented simultaneously in the field study: infrastructural, route and passenger boarding procedure adaptations. With respect to the vehicle performance, the bus speeds along the routes increased and the service became more regular. However, the average dwell time slightly increased. The bus trip time, excess waiting time and in-vehicle time decreased (20).

1 *Holding time*

Maximum holding times could be taken into account to prevent that individual passengers experience very long travel times. It could be that, to achieve an optimum for the majority of the passengers, it can be advantageous to have extremely long holding times. However, in general, both passengers and drivers find it unacceptable for high-frequency services to hold longer than one minute (17). The location where vehicles are held also influences the acceptance of holding times. Closer to the final or transfer stop, less holding time will be accepted by passengers and drivers according to the bus operator (Arriva, personal communication).

9 **1.2. Problem definition**

In case of high-frequency transit services, it could be better to focus on regularity instead of punctuality. However, currently the focus of most bus operators worldwide is on punctuality. One of the causes is the design of key performance indicators (KPI), incentive schemes and in certain organizational contexts also in the form of a contractual requirements formulated in the concession between the authority and the bus operators. Operators are measured based on the punctuality, which makes it difficult to use headway-based control strategies.

Many different control strategies have been analysed in literature. Although different studies concluded that headway-based control strategies are advantageous, analysis of these strategies differ from each other in the method of analysis (i.e. simulation or field), the data used for the analysis (real-world data or not), the comparison with different strategies (schedule-based and headway-based holding), different operational conditions and different KPIs. Moreover, the effects of headway-based strategy in contexts outside of main transit corridors in the urban core remain unknown. This makes it more difficult to compare strategies, since every service has its own characteristics. Insights into how, under what conditions and where headway control should be implemented are thus missing in current research.

Another important aspect is the commonly perceived inadequacy of headway-based control in case of disruptions which is sometimes believed to potentially result in a ‘domino-effect’. Therefore the effects of headway-based control in the event of disruptions are explicitly studied in this research.

In literature, practical information for operators on how to implement a headway-based control strategy is missing. This includes key aspects in relation to the concession requirements; transport authorities do not have a consistent way in dealing with reliability (21) and most transport authorities do not include regularity in concession requirements.

31 **1.3. Research contribution**

In this research, an assessment framework was developed to assess the effect of holding strategies on the three most important stakeholders involved in transit services: passengers, the operator and the transport authority. This framework consists of the generation of different holding strategies, that subsequently can be tested on their performance based on different KPIs. Scenarios are also generated in order to test the robustness of the holding strategies in case of disruptions. The framework can be applied by operators or authorities to systematically determine what strategy could be most beneficial in order to regulate headways, and with that solve related problems. The assessment framework is applied to a case study and based on these results, knowledge is gained about what line characteristics are important for the performance of schedule- and headway-based strategies. From the application of the framework, also knowledge is gained about the robustness of headway-based holding strategies, with respect to disruptions. Line 400 (Leiden-Zoetermeer, The Netherlands, operator: Arriva) is used in this research as a case study. Special attention is given to technical adaptations, logistical changes and behavioural aspects when using a headway-based strategy. Insights into the difficulties when including regularity in the concession requirements can contribute to the discussion on how to implement regularity-based operations.

The paper outline is as follows; we first discuss the methodology of developing the framework. Subsequently the case study, followed by the simulation results are presented. Discussion on the results is provided in Section 5 and Section 6 discusses aspects important for implementing a headway-based control strategy. The final section provides conclusions and recommendations.

50 **2. DEVELOPMENT OF THE FRAMEWORK**

The objective of the proposed framework is to assess the effects of a holding-control strategy on passengers, operators and transport authority. The development of the framework can be divided into different steps:

- 53 1. Determination of holding control strategies: generating strategies, consisting of control points, holding condition and maximum holding time, that can be compared with each other. Additionally, scenarios can be generated to test the robustness of the strategies.

2. Testing (the robustness of) these strategies using the scenarios, by applying a simulation model. Next to a quantitative comparison, the results of the simulation will be presented to field experts, in order to determine aspects that are not considered in the simulation model (e.g. crew availability and driver behavior), consisting of, among others, bus drivers, managers, planners and concession grantors. This helps to distinguish the differences between the model and the social complex reality.
3. Determination of the objectives of the different stakeholders leading to KPIs to assess different strategies.

With these three steps holding strategies can be assessed and compared.

2.1. Holding strategies and scenarios

A holding control strategy consists of three aspects: holding conditions, control points and holding time. For every strategy a choice for these aspects should be made. Together these aspects determine the departure time of a vehicle at a stop.

Schedule-based holding is the current practice; vehicles will be held up to the scheduled departure time. When it is known whether a stop is a control point (J_C), and what the maximum holding time (α) is, the following schedule-based holding rule (Equation 1) is applicable in order to determine the departure time of a vehicle at a stop (DeT_{ijk})(8). It should be noted that stops are defined as J , consisting of two types of stops; stops that are control points ($J_C \subseteq J$) and stops that are not a control point ($J_{NC} \subseteq J$).

$$DeT_{ijk} = \begin{cases} \max(\min(SDeT_{jk}, AT_{jk} + \alpha - DwT_{jk}), AT_{jk} + DwT_{jk}), \forall j \in J_C \\ AT_{jk} + DwT_{jk}, \forall j \in J_{NC} \end{cases} \quad (1)$$

where:

- DeT_{ijk} = Departure time of trip k from stop j
- $SDeT_{jk}$ = Scheduled departure time of trip k from stop j
- AT_{jk} = Actual arrival time of trip k at stop j
- DwT_{jk} = Dwell time of trip k at stop j
- α = Maximum holding time

In case of headway-based holding, vehicles will be held at control points until a minimal headway requirement is fulfilled. Cats et al. (8) concluded, based on a simulation study and a field experiment, that the mean headway control strategy, a combination of the forward and backward headway, is the most promising strategy in terms of both passenger time savings and fleet costs. Therefore, it is chosen to investigate only this headway-based holding strategy. The determination of the minimal headway requirement consists of the average headway of the successor (and predecessor (equation 2)). The departure time follows from the minimal headway requirement or the maximum holding time (equation 3). The following rule is applicable in case of the mean-headway-based holding, in order to control a service (8):

$$\overline{h}_{jk} = \frac{(AT_{jk} - AT_{j,k-1}) + (AT_{m,k+1} - AT_{jk})}{2} \quad (2)$$

$$DeT_{jk} = \begin{cases} \max(\min(AT_{j,k-1} + \overline{h}_{jk}, AT_{jk} + \alpha - DwT_{jk}), AT_{jk} + DwT_{jk}), \forall j \in J_C \\ AT_{jk} + DwT_{jk}, \forall j \in J_{NC} \end{cases} \quad (3)$$

where,

- \overline{h}_{jk} = Mean headway for trip k at stop j
- $AT_{j,k-1}$ = Actual arrival time of trip $k-1$ from stop j
- $AT_{m,k+1}$ = Expected arrival time of trip $k+1$ at stop m
- AT_{jk} = Actual arrival time of trip k at stop j
- DwT_{jk} = Dwell time of trip k at stop j
- α = Maximum holding time

1 *Scenarios*

2 In addition to the regular differences between the planned and actual performance of a bus service, also disruptions
3 occur. Therefore, different scenarios have to be devised, to test the robustness of control strategies. Scenarios should
4 be included to test how sensitive a control strategy is with respect to disruptions, consisting of larger schedule
5 deviations than in regular operations. We devise the scenarios so that they pertain to aspects that are difficult for the
6 operator to control.

7 The aspects that affect travel times can be included in the model by simulating an incident or by modifying
8 travel times of specific route sections. The choice of including incidents or modifying travel times should be done in
9 consultation with the operator so that they are comparable to real world disruptions.

11 **2.2 Simulation model**

12 To be able to test different strategies and scenarios, a simulation model is used. The simulation model used in this
13 research is BusMezzo, being a mesoscopic, dynamic, stochastic transit operations model. It simulates individual
14 vehicles and passengers, without representing their second-by-second movements in detail. Uncertainties in bus
15 services, such as traffic conditions, vehicle capacity, dwell times, vehicle schedules and service disruptions, can be
16 included in the model. BusMezzo has been used in order to support the implementation of control and management
17 strategies, including holding strategies (3). Previous studies have shown that BusMezzo can reproduce bus bunching
18 (22) and crowding effects (23), attesting to its suitability for this research. A detailed description of modelling in
19 BusMezzo is available in (22).

21 **2.3. Key Performance Indicators (KPIs) for various stakeholders**

22 The KPIs that are important for the three main stakeholders are hereby specified, based on literature and interviews.
23 These KPIs are used to assess holding strategies.

24 First, the objective for the operator is to keep the costs low (mainly operational costs) and the revenues as
25 high as possible (passenger revenues). Variability is important, because it hinders the operator to make efficient use
26 of resources, which could lead to higher costs (24). It is also essential to meet the concession requirements. This leads
27 to the following KPIs for the operator as included in this research in order to assess a holding strategy:

- 28 - Holding time per trip
- 29 - Cycle time (80th-percentile value)
- 30 - Variation in cycle time (Difference between 50th- and 80th-percentile value)
- 31 - Service reliability (Coefficient of Variation (CoV) of the headways)
- 32 - Crowding variability (Average load deviation)
- 33 - Concession requirement: reliability (Punctuality or regularity)

35 Second, for passengers three aspects are of outmost importance: reliability, speed and comfort (25). Passenger
36 travel speed is determined by two aspects: waiting and in-vehicle time. In particular perceived times are important.
37 Reliability is measured in terms of the variation of these two time components (5). One of the important aspects
38 regarding comfort, is how crowded a vehicle is and whether one can find a seat. The average standing time per
39 passenger is used here as an indicator for comfort. Thus, the passenger aspects are:

- 40 - Perceived in-vehicle time
- 41 - Waiting time
- 42 - Variation in perceived in-vehicle time
- 43 - Variation in waiting time
- 44 - Average standing time

46 Third, to guarantee a minimum quality of public transport and trying to increase the usage of public transport is
47 one of the important tasks of the transport authority. The additional KPIs for the authority, are thus:

- 48 - Service reliability
 - 49 • Punctuality (Arrival and departure schedule adherence)
 - 50 • Regularity (CoV of the headways)
- 51 - Probability of finding a seat (Percentage of passengers that can find a seat)

53 It should be noted that some of the quality aspects are the same for the stakeholders, e.g. the quality aspects important
54 for passengers are also of importance for the other two stakeholders. The focus in this paper is on the service reliability
55 (CoV of the headways). More detailed results with regard to other KPIs are available in (26).

56

3. CASE STUDY

The assessment framework proposed in the previous chapter is applied to a case study. This section explains the characteristics of this case study, followed by the experimental setup.

3.1. Characteristics of line 400



FIGURE 1 Geographical overview line 400
(Source: 29)

Line 400, a high-frequency bus service between Leiden (123.000 inhabitants (27)) and Zoetermeer (124.000 inhabitants (27)) in the Netherlands, is used as a case study (see Figure 1). The analysis is based on the situation and timetable of the morning peak in 2015-2016. The line is approximately 14 km long, with 11 stops. The frequency in the study period is 10-12 buses per hour. The scheduled cycle times are in general 27 min in the southbound direction and 29 min in the northbound. There is a turnaround time of 2 minutes at Zoetermeer Centrum West, and 4 minutes at Centraal Station (Leiden). Smartcard data is available (2015-2016), consisting of tap-in and tap-out records providing insights into the travel patterns and most important origin-destination relations. More insights into the Dutch smartcard system and data is available in (28). Most passengers travel from begin terminal to end terminal implying that the stops between the cities of Leiden and Zoetermeer are less important with respect to passenger demand.

3.2. Experimental set-up

Line 400 exhibits reliability problems, caused by variability in running times and passenger demand, also resulting in crowding. In this section the experimental simulation set-up is explained, including the generation of strategies and scenarios.

Strategies

As explained in section 2.1., different choices can be made to generate strategies: holding criteria, control points and holding

time. The combination of these different choices leads to a large number of combinations. In consultation with the operator, nine strategies are analysed in this research, as shown in Table 1.

Two options related to the number of control points are included in this research; either 3 or 9 stops are control points. When there are 3 control points, the stops Leiden Centraal, Station Lammenschans and Zoetermeer Centrum West (ZCW) are control points, because these three stops are the most important boarding- and alighting-stops along line 400. In case 9 control points are used, all stops of line 400 are control points, except the Korevaarstraat and Breestraat, since it is physically impossible to hold buses here, due to limited space and multiple lines serving the stop.

TABLE 1 Overview of the nine strategies

Strategy	Holding condition	Control points	Holding time
1 Schedule-3-no max	Schedule-based	3 Stops: Leiden Centraal, Lammenschans, ZCW	No max
2 Schedule-9-no max	Schedule-based	9 All stops, excl. Korevaarstraat & Breestraat	No max
3 Hw-3-no max	Headway-based	3 Stops: Leiden Centraal, Lammenschans, ZCW	No max
4 Hw-3-300	Headway-based	3 Stops: Leiden Centraal, Lammenschans, ZCW	Max 300 sec
5 Hw-3-60	Headway-based	3 Stops: Leiden Centraal, Lammenschans, ZCW	Max 60 sec
6 Hw-9-no max	Headway-based	9 All stops, excl. Korevaarstraat & Breestraat	No max
7 Hw-9-300	Headway-based	9 All stops, excl. Korevaarstraat & Breestraat	Max 300 sec
8 Hw-9-120	Headway-based	9 All stops, excl. Korevaarstraat & Breestraat	Max 120 sec
9 Hw-9-60	Headway-based	9 All stops, excl. Korevaarstraat & Breestraat	Max 60 sec

1 By testing these nine strategies, it is possible to analyse the difference between the holding criteria, the choice of more
2 or less control points, and also the influence of maximum holding time.

3 *Scenarios*

4 Different scenarios are designed, in order to test the robustness of the control strategies. The generation of scenarios
5 is based on disruptions (i.e. incidents and modification of trip times). The choice of including incidents or modifying
6 travel times is done in consultation with the operator and based on Automatic Vehicle Location (AVL) data.

7
8 Two disruption scenarios are examined in this study:

- 9 1. The opening of the bridge on the route of line 400: 'Lammebrug'.
- 10 2. A detour between the stop Korevaarstraat and stop Station Lammenschans, in Leiden, resulting in longer trip
11 times
12

13 *Simulation model*

14 The input for the simulation model BusMezzo consists of the abovementioned strategies and scenarios. In addition, it
15 is important to use real-world data when analysing control strategies (30) and this is due to the development of real-
16 time information technologies possible (2). Specific case related input for the model, consisting of the network, routes,
17 fleet and demand, is based on AVL and smartcard data.
18

19 **4. APPLICATION AND RESULTS**

20 By simulating different strategies and scenarios, using AVL and passenger data of line 400, the holding strategies are
21 assessed based on the selected KPIs. This section first elaborates on the results of the normal (undisrupted) situation.
22 In this paper the focus is on the service reliability. Effects on other KPIs are described in less detail. More detailed
23 results are available in (26). The results of the simulation with the scenarios is described in section 4.2. In section 4.3
24 a brief reflection is given.
25

26 **4.1. Normal situation**

27 This section explains the results of the nine strategies in more detail, considering the perspective of the operator, the
28 passenger and the transport authority
29

30 *Operator*

31 The control strategies are used in order to control the service variability along the line and to provide a regular service.
32 Therefore, first the Coefficient of Variation (CoV) of the headways is investigated, which is one of the KPIs of the
33 operator. More control is expected to lead to a lower CoV of the headways, and thus to a higher quality of the service.
34 In a situation without control, the variation of headways propagates along the route. Applying a control strategy, this
35 propagation will be mitigated at each control point.
36

37 In Figure 2 the development of the CoV along the line per scenario is shown. In the southbound direction,
38 the first control point is Korevaarstraat and therefore holding is only possible after this stop. It can be seen that the
39 CoV increases towards this stop. After this stop the CoV of the headway consequently decreases. After that stop, the
40 CoV is within the range 0.12-0.25.

41 In the northbound direction, two observations are highlighted. First, the CoV of the headway for the schedule-
42 based strategy starts low, but increases substantially between Meerpolder and Stompwijk. At Stompwijk, 98% of the
43 vehicles arrives on-time, so no holding is needed. The CoV of the headways of buses departing at Zoetermeer Centrum
44 West is 0.18, while the CoV of the arrival headways at Leiden Centraal is 0.45, implying 'irregular headways with
45 some bunching' (31).

46 The other aspect that should be mentioned is that the CoV for the headway-based strategies fluctuates less,
47 compared to the CoV of the schedule-based strategy. So, although the average CoV of the headways for the different
48 strategies is comparable, the development of this CoV along the line is very different.

49 The strategies with more control points perform better on reliability aspects. However, the schedule-based
50 and headway-based strategies perform more or less equally well. This is the result of the fact that for this line, vehicles
51 arrive in general early at control points, suggesting excessive buffer times in the timetable design. Consequently, the
52 variation at the origin terminals is low to start with. The headway-based strategy could perform better when variation
53 at the origin stops can be decreased. It is not possible in BusMezzo to control vehicles at the terminal, using the mean-
54 headway-based strategy. In practice however, it is possible to control vehicles at the terminal by generating predictions
55 on arrival times of future trips and this is expected to contribute to service performance, because it leads to a lower
56 CoV of the headways at ZCW.

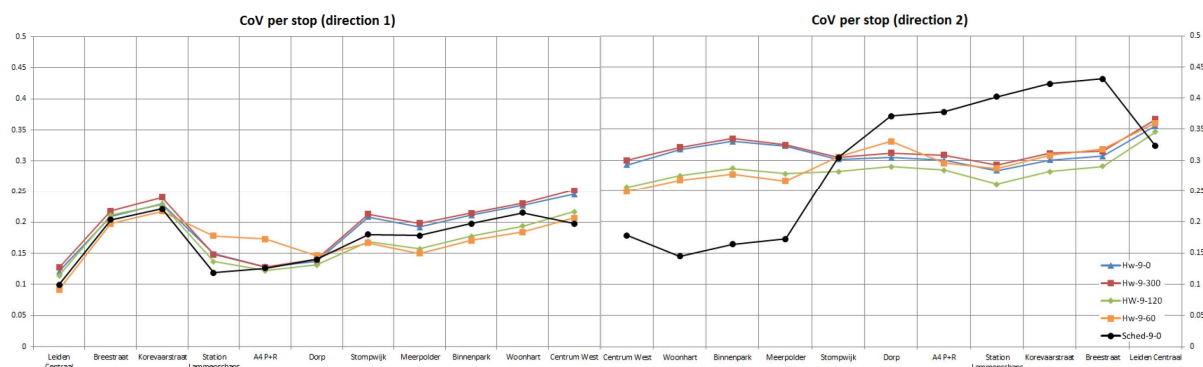


FIGURE 2 Development of the CoV of the departure headways along the case study line (left: southbound direction, right: northbound direction)

The more control is executed, the longer the cycle times, but the variation of the cycle times decreases. In the southbound direction the vehicles arrive in general early, which makes holding possible. In that case, when the strategy is schedule-based, the headways are thus the scheduled headways. This means that there is less headway and trip time variation. In that case, when vehicles arrive early, schedule-based control is equivalent to headway-based control, and slightly performs better in terms of the number of control actions, average holding time per trip and cycle times.

However, in case vehicles do not arrive early, schedule-based control is not an effective control anymore. This is the case in the northbound direction. Then headway-based control performs better. The cycle time increases slightly, as a result of the longer average holding times per trip, but no extra buses are needed. The variation in cycle time decreases and the CoV of the headways stays relatively stable along the route. Headway-based control at all control points is able to mitigate service irregularity along the line, regardless of the timetable.

In conclusion, “hw-9-60” is the best strategy for the operator. This strategy copes best with service variability along the route, without the need of a timetable. Notwithstanding, the differences compared with “sched-9-0” are relatively small.

Passengers

From a passenger perspective there are several promising strategies, mainly based on the in-vehicle and waiting times and variation of these times resulting in a total experienced travel time. Differences between schedule- and headway-based strategies are small, e.g. waiting times and in-vehicle times decrease between the 0-4% when using a headway-based strategy. There is also no strategy that performs best in both directions. In the southbound direction the strategy “hw-3-0” is the best performing strategy, while this is one of the worst performing strategies in the northbound direction. A trade-off should be made, since it would be difficult to use two strategies for one line. In that case, strategy “hw-9-60” is the strategy that performs relatively well in both directions. Therefore, from the passenger perspective this strategy should be selected. However, differences are minimal; maximum gains of 20s compared to a schedule-based strategy, which is approximately 1% of the total experienced travel times.

Note that passengers are assumed to arrive randomly at stops in the simulation model. However, in case a connecting light rail vehicle arrives at ZCW, more passengers can be expected to board, even when the headway is short. This could influence service performance in reality.

From a passenger perspective, the headway-based strategies with only 3 control points are the worst performing strategies. The variation of the perceived average in-vehicle time, the excess waiting times and the average standing times are all higher than when using the other strategies.

Authority

The arrival punctuality norms are met for the headway-based strategies with 3 control points: more than 85% of the trips arrive on-time (within 3 minutes after the time specified in the timetable). Trip times are relatively short, and vehicles therefore do not arrive late at the stops. In case a shift will take place to headway-based control, punctuality requirements should be replaced by regularity requirements, because in that case vehicles often arrive late: in northbound direction 43-83% of the vehicles arrive on-time. The arrival punctuality norms set by the transit authority are thus not met ($\geq 85\%$).

4.2. Scenarios

In this study, two scenarios are discussed: 1) trip time extension caused by a detour and 2) a disruption caused by the opening of a bridge. For the first scenario an actual detour is simulated; the modification of the trip times is based on actual AVL data from a detour in the first three weeks in March 2016. The distribution of the trip times, due to a detour, are used in the simulation model. On average the times on this route section were 1.5 and 3 times longer in the southbound and northbound directions, respectively. In the second scenario, the disruption is caused by the opening of a bridge, the Lammebrug; a bridge located between the stops Station Lammenschans and A4 P+R.

Disruption: travel time

The scheduled slack in the timetable, in order to compensate variation in trip times, is insufficient to compensate for the extra time caused by this disruption, resulting in more irregularity. As a consequence, the average waiting times increase. In addition, the variation in vehicle loads is also higher, and there were, thus, also more crowded vehicles.

The holding times were longer in order to regulate the irregularity on the line, resulting in longer cycle times (+5%), but the variation in cycle times decreased, leading to a regular service. When using the schedule-based strategy, the average CoV of the headways were high, implying 'frequent bunching', while headway-based control leads to lower CoV implying 'vehicles often off headway' (31).

The perceived times were relatively low. As a result of the lower irregularity, the waiting times were also shorter. The passengers were also more evenly spread over the vehicles. In conclusion, the schedule-based control strategies are not able to control the situation caused by the longer travel times, with drawbacks for the passengers. The headway-based strategy, in contrast, is able to deal with this disruption, resulting in savings in experienced travel times between the 5-20 %.

Disruption: bridge

The impact of smaller disruptions (the bridge blocked the road for 4 minutes) can be effectively mitigated. The headway-based strategy is able in reposition vehicles in order to resort again to a regular service. Bus bunching occurs, which is almost unavoidable in case there is a disruption of 4 minutes on such a high-frequency service, but can be solved by the cooperation of the vehicles along the line. Bus bunching cannot be solved by the schedule-based strategy, as visible in Figure 3.

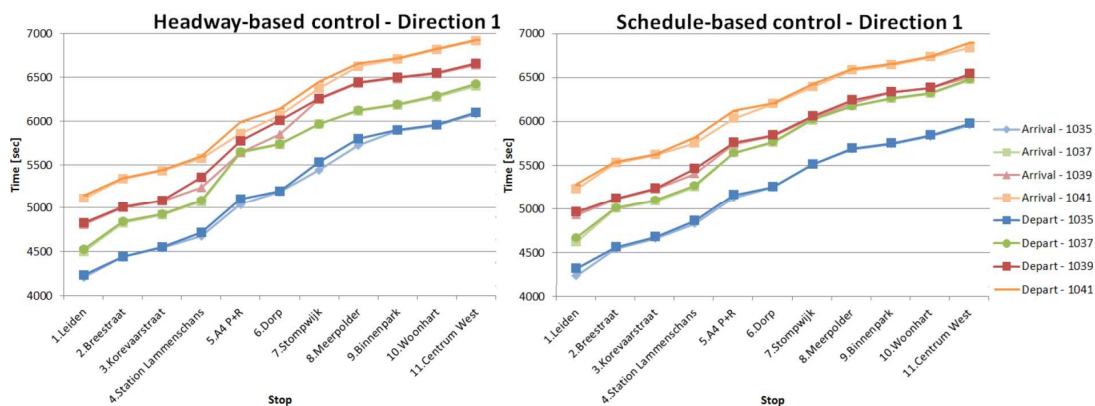


FIGURE 3 Trajectories of four buses for both headway- based control (left) and schedule-based control (right) after the opening of the bridge

It is therefore concluded that the headway-based strategy is also better able to deal with major disruptions. Hence, not only that the headway-based control does not result with a snow ball effect in the event of a disruption, but rather vice-versa, it is effective in preventing it. Both the travel time and crowdedness in the vehicles are more advantageous for passengers in case the headway-based strategy is used.

5. DISCUSSION

Based on the simulation results, schedule-based and headway-based holding could improve service regularity in the context of a high frequency regional service. Holding strategies are theoretically suitable to control a transit service, but in practice there are several challenges that needs to be dealt with. These challenges can be divided into the

1 execution of a headway-based holding strategy and contractual agreements between the operator and authority. These
 2 challenges will be briefly described in section 5.1. In section 5.2. insights are used to generalize the results.

3
 4 Inevitably, a simulation study involves making simplifications, e.g. driver behavior, that may influence the
 5 outcomes of the model. Notwithstanding, the model should be used as indication of the possibilities of strategies,
 6 because the model outcomes could be different than the outcomes when a strategy is put into practice.

8 **5.1. Implementation of holding strategies**

9 In case the operator decides to shift into a regularity-driven operation, fundamental changes have to be made, related
 10 to technical, logistical and behavioural aspects. These aspects cannot be simulated and therefore a pilot study is needed
 11 to test the working of headway-based control in practice.

12 Practical challenges with respect to the implementation of headway-based control may hinder the shift to a
 13 headway-based strategy. The following operational difficulties are identified:

- 14 - Technical: internal (board computer) and external (passenger information systems) data information flow
 15 may need to be adjusted.
- 16 - Logistical: more dynamic vehicle and crew planning is needed. Also, information for traffic controllers is
 17 required so that they are able to interfere.
- 18 - Behavioural: drivers need to adapt their current working style and traffic controllers need to know what
 19 decisions they have to make considering service regularity.

20 Next to the operational challenges for the operator, also authorities may experience them. Gradually authorities
 21 in The Netherlands will include regularity in their concession requirements. Although reliability is a very important
 22 quality aspect, transport authorities do not have a consistent way in dealing with reliability (21). There is a need to
 23 introduce suitable incentive schemes to improve the quality. Goals should be determined that lead to incentives that
 24 stimulate the operator to improve the quality, after the current performance of regularity of a line is analysed, as
 25 proposed in (4). In addition, the performance of services perceived by passengers can be taken into account, instead
 26 of the performance of vehicles. Also, for the authority it would be beneficial to organise a pilot. In that case, the
 27 authority can determine what the effect is on passengers or whether other requirements need to be applied.

29 **5.2. Generalization**

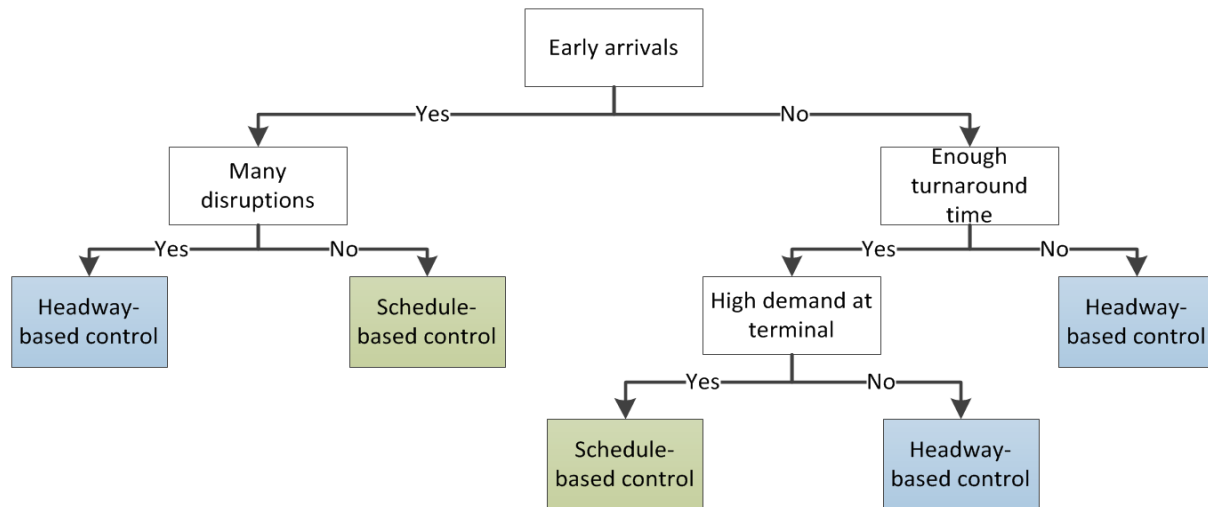
30 Based on the simulation results of the case study, headway-based control strategies better mitigate irregularity along
 31 the line, especially when there are disruptions. The headway-based control is effective in preventing a snow ball effect
 32 in the event of a disruption. However, the improvements in normal situation where relatively small compared to the
 33 schedule-based strategy.

34 We hereby sketch the most promising preconditions for introducing headway-based control. The aspects that
 35 influence the performance of a strategy, are:

- 36 - Occupancy along the line
- 37 - Punctuality of a service along the line
- 38 - Regularity of a service along the line
- 39 - Schedule quality (slack time and turnaround time in the timetable)
- 40 - Frequency and severity of disruptions

41
 42 In conclusion, if it is assumed that control is needed in order to mitigate the irregularity of a service, several
 43 aspects could determine what type of holding is best suitable. Figure 4 shows an overview of the characteristics of a
 44 transit service that leads to favourable holding strategies. It should be noted that the exact holding strategies depends
 45 on specific situations. In this figure, only an indication of the types are indicated.

46



1
2 **FIGURE 4 indication of the favourable holding strategy given different line characteristics**
3

4 In general, in case there are early arrivals, schedule-based control could also yield regular headways. Another
5 case where schedule-based control performs also relatively good, is when most passengers board at the terminal, and
6 there is enough slack time at this terminal in order to solve delays from previous trips. It is important to notice that it
7 is expected that headway-based control performs better compared to schedule-based control, but the differences
8 between the two types will probably be less when the line has these characteristics. Since these are the characteristics
9 of the case study line, the benefits of introducing headway-based control is limited. In case a line is relatively irregular
10 and when the occupancy increases along the line headway-based control is the preferred strategy. Headway-based is
11 also preferred after disruptions. Whether there are 'enough early arrivals', 'many disruptions', and 'enough turnaround
12 time', is dependent on specific situations. Further research is needed to determine these aspects in quantitative terms.
13

14 6. CONCLUSION AND RECOMMENDATIONS

15 The main objective of this research is to develop a calculation and evaluation framework to systematically assess the
16 effect of different holding control strategies in (un)disrupted situations, while taking into account the perspective of
17 passengers, the operator and the transport authority. This framework consists of generating holding strategies and
18 scenarios, that are tested on their performance based on different KPIs. Additionally, difficulties with respect to
19 implementing regularity-driven operations are identified and discussed.

20 Operators are interested in supplying a high-quality bus service at the lowest possible costs. Aspects related
21 to the cycle times are therefore of importance for the operator. Holding vehicles lead to longer cycle times that could
22 also require a larger fleet size. However, based on our analysis the effects of holding on the total cycle time do not
23 lead in general to the need of more buses. With respect to the reliability of a trip, the headway-based control strategies
24 offer a more stably reliable service along the line and are also more robust with respect to disruptions.

25 For the passenger, the effect of holding strategies is that the in-vehicle time increases in case more holding is
26 applied. However, the waiting times decreases, as a result of more regular services. Also, the variation of these time
27 components is reduced. However, the average impact on passengers highly depend on the load pattern along the line.
28 The differences between different holding strategies are minimal in case most passengers board at the terminals since
29 both strategies could facilitate regular departures.

30 For the transport authority, the most important aspect is that the service is reliable. Headway-based holding
31 regulates better the vehicles along the line. In case headway-based holding is the preferred strategy, the authority
32 should change the punctuality requirement in the concession towards a regularity requirement.

33 Headway-based control strategies are better able to regulate irregularity along the line, especially when there
34 is a disruption. However, at this moment, schedule-based control strategies are easier to implement in practice, and
35 the effect is generally the same when there is enough slack time in the timetable.

36 Future research should examine the network related impacts of headway-based holding. More knowledge is
37 required on how exactly to include regularity requirements in contracts and how to combine these with a bonus-malus
38 scheme that works as a proper incentive for the operator. Moreover, additional research is needed with respect to
39 service characteristics in order to be able to indicate candidate services for either schedule- or headway-based holding.

1 One of the possibilities to obtain information and test the holding strategies in practice is to conduct systematic pilot
2 studies.

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7 8 **CONTRIBUTION**

9 The authors confirm contribution to the paper as follows:

10 Data collection: Van der Werff; Modelling: Van der Werff, Cats; Analysis and interpretation of results: Van der
11 Werff, Van Oort, Cats; Author: Van der Werff; Draft manuscript preparation: Van Oort, Cats, Hoogendoorn;
12 Supervising: Van Oort, Cats, Hoogendoorn. All authors reviewed the results and approved the final version of the
13 manuscript.

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