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Robust Control for Regulating Frequent Bus Service: Supporting the Implementation of Headway-Based Holding Strategies

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Abstract

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

Reliability is a key determinant of the quality of transit services. Irregular services are the result of variability in departure from terminals, and 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. When 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 until a minimal headway requirement is fulfilled (*3*).

It is possible to examine service reliability in relation to 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 when the frequency of buses is equal or higher than six vehicle departures per hour (*2, 5*). Regularity is more important for high-frequency bus services than punctuality.

Related Work

The absence of control strategies can lead to undesired behavior of the system. Different control strategies have been proposed, divided into station control, inter-station control, and other control measures (*6*). Station control

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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*), whereas others have concluded that it is best to have only one control point at the original terminal (*12*). Cats et al. demonstrate that the selection of the control points can have considerable effects on service performance (*13*). In addition, the location of control points was found to be more important than the number of control points, and 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 realizes an a priori headway, by determining the holding time based on the headway between the bus and its predecessor (*9, 11, 15–17*). Bartholdi and Eisenstein discuss the disadvantages of this approach (*15*). According to the authors, the optimal achievable headway is not known in advance, and can also change because of changes in traffic conditions, driver behavior, 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 the 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: taking into account the location of the successor and predecessor of a bus by communication between buses (*3, 8, 18, 19*).

Following the promising outcomes of a simulation study (*8*), in which the minimal headway and even-headway control strategies were combined, 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*).

Holding Time

Maximum holding times could be taken into account to prevent individual passengers experiencing very long travel times. It could be that, to achieve an optimum for the majority of the passengers, it may 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 1 minute (*17*). The location in which 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).

Problem Definition

In the case of high-frequency transit services, it may 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 of this is the design of key performance indicators (KPIs), incentive schemes and, in certain organizational contexts, also the form of contractual requirements formulated in the concession between the authority and the bus operators. Operators are measured based on punctuality, which makes it difficult to use headway-based control strategies.

Many different control strategies have been analyzed in the 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 the headway-based strategy in contexts outside of main transit corridors in the urban core remain unknown. This makes it more difficult to compare strategies, as 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 the 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 the 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.

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 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 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, knowledge is also 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 behavioral 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: the authors first discuss the methodology of developing the framework. Subsequently the case study and the simulation results are presented. Discussion on the results is then provided, and the next section discusses aspects important for implementing a headway-based control strategy. The final section provides conclusions and recommendations.

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:

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. In addition, 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, 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 complex social 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.

Holding Strategies

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 to determine the departure time of a vehicle at a stop (DeT_{ijk}) (*8*). A vehicle will be held up to the scheduled departure time ($SDeT_{\mathrm{ijk}}$), but not longer than the maximum holding time (including the dwell time $\alpha - DwT_{\mathrm{jk}}$) or shorter than the needed dwell time (DwT_{jk}). 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 ($J_{\mathrm{NC}} \subseteq J$).

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

where:

DeT_{ijk} = Departure time of trip k from stop j

$SDeT_{\mathrm{jk}}$ = 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 the case of headway-based holding, vehicles will be held at control points until a minimal headway requirement is fulfilled. Cats et al. 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 relation to both passenger time savings and fleet costs (*8*). Therefore, it was 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, to control a service (8):

$$\overline{h_{\mathrm{jk}}} = \frac{(AT_{\mathrm{jk}} - AT_{j,k-1}) + \left(ET_{j,k+1} - AT_{\mathrm{jk}}\right)}{2} \tag{2}$$

$$DeT_{\mathrm{jk}} = \begin{cases} \max\left(\min\left(AT_{j,k-1} + \overline{h_{\mathrm{jk}}}, AT_{\mathrm{jk}} + \alpha - DwT_{\mathrm{jk}}\right), AT_{\mathrm{jk}} + DwT_{\mathrm{jk}}\right), \forall j \in J_C \\ AT_{\mathrm{jk}} + DwT_{\mathrm{jk}}, \ \forall j \in J_{\mathrm{NC}} \end{cases} \tag{3}$$

where,

$\overline{h_{\mathrm{jk}}}$ = Mean headway for trip k at stop j

$AT_{j,k-1}$ = Actual arrival time of trip k-*1* from stop j

$ET_{m,k+1}$ = Expected arrival time of trip $k + 1$ at 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

Holding Scenarios

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

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

Simulation Model

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

KPIs for Various Stakeholders

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

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

- Holding time per trip
- Cycle time (80th-percentile value)
- Variation in cycle time (difference between 50th- and 80th-percentile value)
- Service reliability (coefficient of variation [CoV] of the headways)
- Crowding variability (average load deviation)
- Concession requirement: reliability (punctuality or regularity)

Second, for passengers three aspects are of outmost importance: reliability, speed, and comfort (*25*). Passenger travel speed is determined by two aspects: waiting and in-vehicle time. In particular, perceived

Figure 1. Geographical overview line 400 (Source: Maartens [*30*]).

times are important. Reliability is measured in relation to the variation of these two time components (*5*). One of the important aspects regarding comfort is how crowded a vehicle is and whether one can find a seat. The average standing time per passenger is used here as an indicator for comfort. Thus, the passenger aspects are:

- Perceived in-vehicle time
- Perceived waiting time
- Variation in perceived in-vehicle time
- Variation in perceived waiting time
- Average standing time

To be able to compare different strategies from the passenger perspective, the average experienced travel time is calculated. This is done by summing up the experienced time components, in which the waiting time is weighted 1.5 as high as the in-vehicle times (*26*).

Third, guaranteeing a minimum quality of public transport and trying to increase the usage of public transport is an important task of the transport authority. The additional KPIs for the authority are thus:

- Service reliability
  - Punctuality (arrival and departure schedule adherence)
  - Regularity (CoV of the headways)
- Probability of finding a seat (percentage of passengers that can find a seat)

It should be noted that some of the quality aspects are the same for the stakeholders; for example, the quality aspects important for passengers are also of importance for the other two stakeholders. The focus in this paper is on the service reliability (CoV of the headways). More detailed results with regard to other KPIs are available elsewhere (*27*).

Case Study

The proposed assessment framework is applied to a case study. This section explains the characteristics of this case study, followed by the experimental set-up.

Characteristics of Line 400

Line 400, a high-frequency bus service between Leiden (123,000 inhabitants [*28*]) and Zoetermeer (124,000 inhabitants [*28*]) 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 min at Zoetermeer Centrum West (ZCW), and 4 min at Centraal Station (Leiden). Smartcard data are 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 are available in Van Oort et al. (*29*). Most passengers travel from start terminal to end terminal, implying that the stops between the cities of Leiden and Zoetermeer are less important with respect to passenger demand.

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.

Table 1. Overview of the Nine Strategies

Strategy		Holding condition	Control points		Holding time
1	Schedule-3-0	Schedule-based	3	Stops: Leiden Centraal, Lammenschans, ZCW	No max.
2	Schedule-9-0	Schedule-based	9	All stops, excl. Korevaarstraat & Breestraat	No max.
3	Hw-3-0	Headway-based	3	Stops: Leiden Centraal, Lammenschans, ZCW	No max.
4	Hw-3-300	Headway-based	3	Stops: Leiden Centraal, Lammenschans, ZCW	Max. 300 s
5	Hw-3-60	Headway-based	3	Stops: Leiden Centraal, Lammenschans, ZCW	Max. 60 s
6	Hw-9-0	Headway-based	9	All stops, excl. Korevaarstraat & Breestraat	No max.
7	Hw-9-300	Headway-based	9	All stops, excl. Korevaarstraat & Breestraat	Max. 300 s
8	Hw-9-120	Headway-based	9	All stops, excl. Korevaarstraat & Breestraat	Max. 120 s
9	Hw-9-60	Headway-based	9	All stops, excl. Korevaarstraat & Breestraat	Max. 60 s

Note: excl = excluding; max. = maximum; ZCW = Zoetermeer Centrum West.

Strategies. As explained earlier, 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 analyzed in this research, as shown in Table 1.

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

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

Scenarios. Different scenarios are designed to test the robustness of the control strategies. The generation of scenarios is based on disruptions (i.e., incidents and modification of trip times). The choice of including incidents or modifying travel times is done in consultation with the operator and based on automatic vehicle location (AVL) data.

Two disruption scenarios are examined in this study:

1. The opening of the bridge on the route of line 400: "Lammebrug"
2. A detour between the stop Korevaarstraat and stop Station Lammenschans, in Leiden, resulting in higher travel times

Simulation Model. The input for the simulation model BusMezzo consists of the abovementioned strategies and scenarios. This paper will not elaborate in detail on modeling in BusMezzo; a detailed description of modeling in BusMezzo is available elsewhere (*22*). In addition, it is important to use real-world data when analyzing control strategies (*10*), and this is possible because of the development of real-time information technologies (*2*). Specific case-related input for the model, consisting of the network, routes, fleet, and demand, is based on AVL and smartcard data.

Application and Results

By simulating different strategies and scenarios, using AVL and passenger data for line 400, the holding strategies are assessed based on the selected KPIs. This section first elaborates on the results of the normal (undisrupted) situation. In this paper the focus is on the service reliability. Effects on other KPIs are described in less detail. More detailed results are available elsewhere (*27*). The results of the simulation with the scenarios are first described, then a brief reflection is given.

Normal Situation

This section explains the results of the nine strategies in more detail, taking into account the perspective of the operator, the passenger, and the transport authority.

Operator. The control strategies are used to control the service variability along the line and to provide a regular service. Therefore, first the CoV of the headways is investigated, which is one of the KPIs of the operator. More control is expected to lead to a lower CoV of the headways, and thus to a higher quality of the service. In a situation without control, the variation of headways propagates along the route. Applying a control strategy, this propagation will be mitigated at each control point. The strategies with only three control points score also

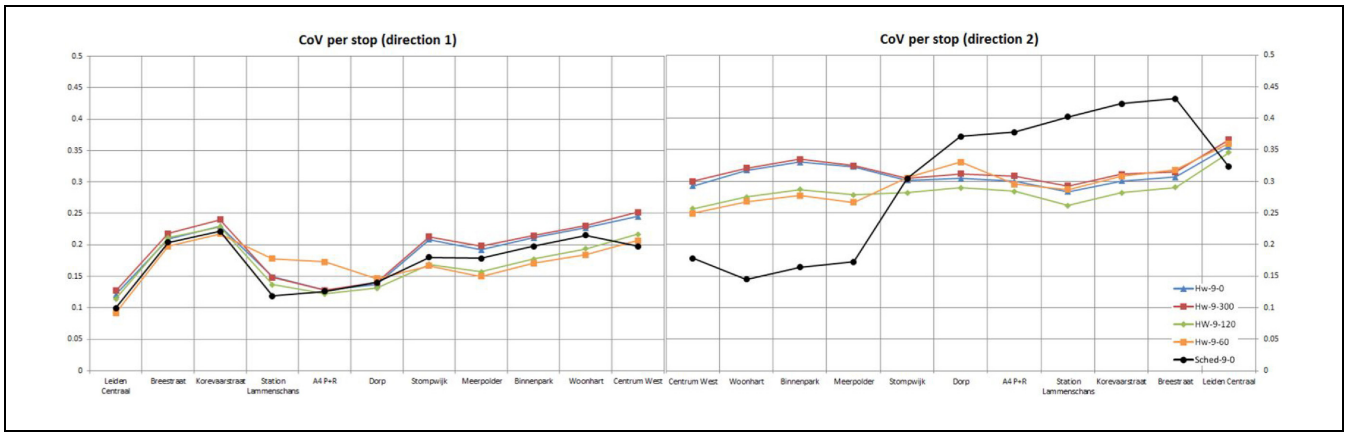

Figure 2. Development of the CoV of the departure headways along the case study line (left: southbound direction; right: northbound direction).

less with respect to the variation of headways, because fewer control possibilities are available.

In Figure 2 the development of the CoV along the line per scenario is shown, focusing on the strategies with nine control points. In the southbound direction, the first control point is Station Lammenschans and therefore holding is only possible at this stop. It can be seen that the CoV increases toward this stop. After this stop the CoV of the headway consequently decreases. After that stop, the CoV is within the range 0.12–0.25.

In the northbound direction, two observations are highlighted. First, the CoV of the headway for the schedule-based strategy starts low, but increases substantially between Meerpolder and Stompwijk. At Stompwijk, 98% of the vehicles arrive on time, so no holding is needed. The CoV of the headways of buses departing at ZCW is 0.18, whereas the CoV of the headways increases along the line to approximately 0.43 implying "irregular headways with some bunching" (*26*).

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

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

Another important aspect for the operator is the cycle times. The more control is executed, the longer the cycle times, but the variation of the cycle times decreases. In the southbound direction, in general the vehicles arrive 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 performs slightly better in relation to the number of control actions, average holding time per trip, and cycle times.

However, when vehicles do not arrive early, schedule-based control is no longer an effective control. 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; for example, waiting times and (perceived) in-vehicle times

Table 2. Average Experienced Travel Time of the Best Performing Strategies

	Headway-based			Schedule-based	
	CP: 3	CP: 9		CP: 3	CP: 9
	No max.	Max. 120	Max. 60	No max.	No max.
Strategy→	Hw-3-0	Hw-9-120	Hw-9-60	Sched-3-0	Sched-9-0
KPI					
Total experienced travel time (min:s)—southbound	22:38	23:24	23:08	23:24	23:26
Total experienced travel time (min:s)—northbound	32:48	29:27	29:40	29:46	29:33
Differences compared with sched-3-0 (min:s)—southbound	–00:46	00:00	–00:16	–	00:02
Differences compared with sched-3-0 (min:s)—northbound	03:02	–00:19	–00:06	–	–00:13

Note: KPI = key performance indicator; Max. = maximum.

decrease between the 0 and 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, whereas this is one of the worst performing strategies in the northbound direction. A trade-off should be made, as 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 a passenger perspective this strategy should be selected. However, differences are minimal: maximum gains of 20 s compared with a schedule-based strategy, which is approximately 1% of the total experienced travel times (Table 2).

Note that passengers are assumed to arrive randomly at stops in the simulation model. However, if 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 three control points are the worst performing strategies in the case that the schedule-based holding strategy is unable to control when vehicles are late. 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.

For the passengers, the differences between the three strategies are very small when comparing the experienced travel time. Schedule-based control is, in general, able to ensure even headways at terminal stops, as long as there is enough turnaround time at the terminal stops. As a result of this turnaround time, vehicles that are late can be on time again. As a consequence, the vehicles can depart according to schedule, which leads to even headways. Therefore, scheduled-based control performed relatively well compared with differences between the two types of strategies in other research. In addition, when holding and regulating vehicles at ZCW, the irregularity at this station will decrease. However, BusMezzo cannot hold vehicles at the terminal in the case of headway-based strategies, and therefore cannot control the vehicles at the first station of a trip. This affects the performance of the headway-based strategies, especially as most passengers board at these terminals. This leads in this case to small differences between schedule- and headway-based control. When the vehicles are regulated at ZCW, the performance of the headway-based strategy increased between 5 and 10% with respect to the average experienced travel time per passenger.

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

Scenarios

In this study, two scenarios are discussed: (1) trip time modification 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 3 weeks in March 2016. The distribution of the travel times resulting from 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, located between the stops Station Lammenschans and A4 P + R.

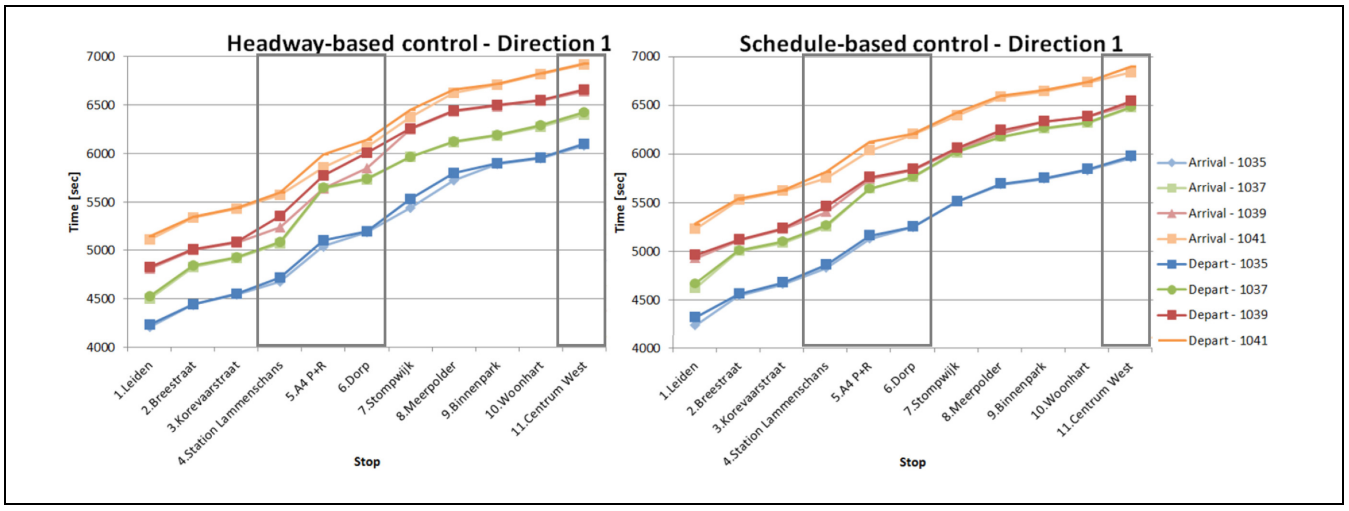

Figure 3. Trajectories of four buses for both headway-based control (*left*) and schedule-based control (*right*) after the opening of the bridge.

Disruption: Travel Time. The scheduled slack in the timetable to compensate for 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; thus, there were also more crowded vehicles.

The holding times were longer 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," whereas headway-based control leads to lower CoV, implying "vehicles often off headway" (*26*).

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 were not able to control the situation caused by the longer travel times, with drawbacks for the passengers. The headway-based strategy, in contrast, was able to deal with this disruption, resulting is savings in experienced travel times of between 5% and 20%.

Disruption: Bridge. The impact of smaller disruptions (the bridge blocked the road for 4 min) can be effectively mitigated. The headway-based strategy is able in reposition vehicles to regain a regular service. Bus bunching occurs, which is almost unavoidable when there is a disruption of 4 min 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 can be seen in Figure 3: bunching of the red and green vehicle (second and third vehicle).

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

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 need to be dealt with. These challenges can be divided into the execution of a headway-based holding strategy and contractual agreements between the operator and authority. These challenges will be briefly described, then the insights gained are used to generalize the results.

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

Implementation of Holding Strategies

When the operator decides to shift into a regularity-driven operation, fundamental changes have to be made, related to technical, logistical, and behavioral aspects. These aspects cannot be simulated, and therefore a pilot

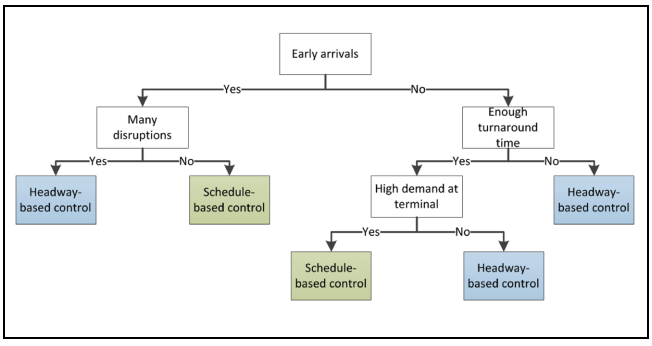

Figure 4. Indication of the favorable holding strategy given different line characteristics.

study is needed to test the working of headway-based control in practice.

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

- Technical: Internal (board computer) and external (passenger information systems) data information flow may need to be adjusted.
- Logistical: More dynamic vehicle and crew planning is needed. Also, information for traffic controllers is required so that they are able to intervene.
- Behavioral: Drivers need to adapt their current working style and traffic controllers need to know what decisions they have to make taking into account service regularity.

In addition to the operational challenges for the operator, authorities may also experience them. Gradually authorities in the Netherlands will include regularity in their concession requirements. Although reliability is a very important quality aspect, transport authorities do not have a consistent way in dealing with reliability (*21*). There is a need to introduce suitably inventive schemes to improve the quality. Goals should be determined that lead to incentives that stimulate the operator to improve the quality, after the current performance of regularity of a line is analyzed, as proposed elsewhere (*4*). In addition, passenger perception of the performance of the service can be taken into account, instead of the performance of vehicles. It would also be beneficial for the authority to organize a pilot; the authority could thus determine what the effect is on passengers or whether other requirements need to be applied.

Generalization

Based on the simulation results of the case study, headway-based control strategies better mitigate irregularity along the line, especially when there are disruptions. The headway-based control is effective in preventing a snowball effect in the event of a disruption. However, the improvements in the normal situation were relatively small compared with the schedule-based strategy.

An outline of the most promising preconditions for introducing headway-based control follows. The aspects that influence the performance of a strategy are:

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

In conclusion, if it is assumed that control is needed to mitigate the irregularity of a service, several aspects may determine what type of holding is most suitable. Figure 4 shows an overview of the characteristics of a transit service that leads to favorable holding strategies. It should be noted that the exact holding strategies depend on specific situations. In this figure only an indication of the types are indicated.

In general, when there are early arrivals, schedule-based control could also yield regular headways. Another case in which schedule-based control performs relatively well is when most passengers board at the terminal, and there is enough slack time at this terminal to solve delays from previous trips. It is important to note that it is expected that headway-based control performs better compared with schedule-based control, but the differences between the two types will probably be less when the line has these characteristics. As these are the characteristics of the case study line, the benefits of introducing headway-based control is limited. When a line is relatively irregular and when the occupancy increases along the line, headway-based control is the preferred strategy. Headway-based control is also preferred after disruptions. Whether there are "enough early arrivals,""many disruptions," and "enough turnaround time" is dependent on specific situations. Further research is needed to determine these aspects in quantitative terms.

Conclusion and Recommendations

The main objective of this research is to develop a calculation and evaluation framework to systematically assess the effect of different holding-control strategies in (un)disrupted situations, taking into account the perspective of passengers, the operator, and the transport authority. This framework consists of generating holding strategies and scenarios that are tested on their

performance based on different KPIs. In addition, difficulties with respect to implementing regularity-driven operations are identified and discussed.

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

For the passenger, the effect of holding strategies is that the in-vehicle time increases when more holding is applied. However, the waiting times decrease, as a result of more regular services. Also, the variation of these time components is reduced. However, the average impact on passengers highly depends on the load pattern along the line. The differences between different holding strategies are minimal when most passengers board at the terminals, as both strategies are able to facilitate regular departures.

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

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

Future research should examine the network-related impacts of headway-based holding. More knowledge is required on exactly how to include regularity requirements in contracts, and how to combine these with a bonus-malus scheme that works as a proper incentive for the operator. Moreover, additional research is needed with respect to service characteristics to be able to indicate candidate services for either schedule- or headway-based holding. One of the possibilities to obtain information and test the holding strategies in practice is to conduct systematic pilot studies.

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Author Contributions

The authors confirm contribution to the paper as follows: Data collection: EvdW; modeling: EvdW, OC; analysis and interpretation of results: EvdW, NvO, OC; author: EvdW; draft manuscript preparation: NvO, OC, SH; supervising: NvO, OC, SH. All authors reviewed the results and approved the final version of the manuscript.

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