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Master thesis

Assessing holding control strategies for high-frequency bus lines

An application to R-net line 400

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ARRIVA a DB company

TU Delft

Assessing holding control strategies for high-frequency bus lines

An application to R-net line 400

by

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This thesis is confidential

Preface

This thesis is the result of my graduation work, to conclude the Master Transport, Infrastructure and Logistics at the Delft University of Technology. The topic of this research is the assessment of different holding control strategies for high-frequency bus lines. This study was conducted at the public transport operator Arriva, but the general framework and the insights gained in this research are also applicable to other public transport operators.

I would like to express my gratitude to everyone who helped me during my master thesis, who gave information and were interested in this research. Particularly, I would show my gratitude towards my graduation committee. Niels van Oort, thank you for initially arranging the contact with Arriva. In addition, your critical review helped to keep me on the right track and also your support during the process was really helpful. Wijnand Veeneman, thank you for your critical comments on simulation models, but also for the discussions we had about governmental aspects. Oded Cats, thank you for your feedback and help with Busmezzo; I really appreciate your time and effort. Serge Hoogendoorn, thank you for your critical comments and feedback during the official meetings. I also would like to thank Ivo Schunselaar, for your practical feedback and your encouragement to see more of Arriva.

Second, I would like to thank Arriva, for giving me the opportunity to conduct this research. In particular my colleagues in Leiden for the warm welcome I received. I was always free to ask, and you always took time to answer my questions.

Last but not least, I would like to thank my parents. Although you expected me to write this, I am really grateful for your support and patience during my entire study. Furthermore, I would like to thank my brother Luc, for his help and distraction when I needed it. Also Menno, thank you for your support and trust. In addition, I would like to thank my friends for the encouragements, calls and messages, and for helping me relax.

Ellen van der Werff
Delft, 2017

Executive summary

Reliability is a key determinant of the quality of a public transport service. Irregular services are the result of variability in terminal departure, trip times and dwell times. Control is needed in order to deal with the stochastic nature of transit services. The focus of this research is on holding control strategies; schedule-based and headway-based. By schedule-based control, buses are held till the scheduled departure time, while in case of headway-based control vehicles are held till the minimal headway requirement is fulfilled.

Regularity is more important for high-frequency bus services than punctuality. However, punctuality is one of the main quality requirements in concessions in the Netherlands. Therefore, operators focus on punctuality. Additionally, in different situations and for different service characteristics, the effects of regularity control are unknown.

The objective of this research is to develop a framework to systematically analyse the impact of different holding-control strategies, and to assess the strategies based on different key performance indicators (KPIs) for operators, passengers and transport authorities. Additionally, difficulties with respect to headway-based control are discussed and advise is given on how to implement regularity-control.

The main research question is as follows:

How could holding control strategies be assessed and implemented, and what is the effect of different holding-control strategies, with respect to the operator, passengers and the transport authority?

In this research, an assessment framework is developed in order to assess different holding-control strategies.

Assessment framework

An assessment framework is developed to analyse the effects of different holding control strategies. In this framework key performance indicators (KPIs) of the three main stakeholder are incorporated (Figure 0.1). Holding strategies need to be defined, consisting of three main aspects: the criteria (headway- or schedule-based holding), selection of control points and maximum holding time. The choice for strategies depends on demand characteristics and infrastructural aspects of the bus line, and could therefore differ per service. Scenarios help to test the robustness of strategies and are related to disruptions and compliance rates of drivers. Once the strategies and scenarios are designed, the performance of strategies under different scenarios can be tested and assessed, by using results of the simulation model BusMezzo and the established KPIs. These outcomes can be presented to experts (bus drivers, managers, planners and grantor of concessions) in order to determine aspects that are not taken into account in the simulation model. This additional step can help to distinguish the differences between the model and the complex reality.

KPIs:
Operator
- Holding time per trip - Cycle time - Variation in cycle time - Service reliability - Crowding variability - Concession requirements
Passenger
- Perceived in-vehicle time - Waiting time - Variation in perceived in-vehicle time - Variation in waiting time - Average standing time
Authority
- Service reliability - Probability of finding a seat

Figure 0.1 Overview of determined KPIs per actor

Case study

A case study tested our framework. The case study is line 400; a high-frequency line between Leiden Centraal and Zoetermeer Centrum West operated by Arriva. The scheduled headway is 5-6 minutes during the morning peak. Different problems are identified; variation in headways caused by variation in terminal departure, trip times and passenger demand, which increase even more upstream of the route. In general the headway between two buses is between the 3.5 and 6.5 minutes. Variation in headways results in an increase of approximately 15% of the average waiting time per passenger.

The direction from Zoetermeer to Leiden is the busiest direction in the morning peak. Most passengers board at the terminal and alight at the final stop. Variation in passenger demand is caused by irregularity of the service, but also by external aspects such as the arrival of the Randstadrail for example.

A selection of strategies and scenarios were designed and simulated using BusMezzo. Different scenario tested the robustness of strategies; the opening of a bridge, disruptions along the line and driver compliance rate of 50%. Table 0.1 shows these strategies and which were tested under different scenarios.

Table 0.1 Overview of the simulated strategies and scenarios

Strategy		Criteria	Control points	Holding time	Scenarios?
1.	Sched-3-no max	Schedule-based	3. LC, Station Lammenschans, ZCW	No max	X
2.	Sched-9-no max	Schedule-based	9. All, excl. Korevaarstraat & Breestraat	No max	X
3.	Hw-3-no max	Headway-based	3. LC, Station Lammenschans, ZCW	No max	
4.	Hw-3-300	Headway-based	3. LC, Station Lammenschans, ZCW	Max 300	
5.	Hw-3-60	Headway-based	3. LC, Station Lammenschans, ZCW	Max 60	
6.	Hw-9-no max	Headway-based	9. All, excl. Korevaarstraat & Breestraat	No max	X
7.	Hw-9-300	Headway-based	9. All, excl. Korevaarstraat & Breestraat	Max 300	X
8.	Hw-9-120	Headway-based	9. All, excl. Korevaarstraat & Breestraat	Max 120	X
9.	Hw-9-60	Headway-based	9. All, excl. Korevaarstraat & Breestraat	Max 60	X

Results

Base situation

The differences between the strategies are relatively small. Therefore a top-3 best strategies is made: hw-9-120, hw-9-60 and sched-9-0.

One of the main differences between these strategies is the development of the irregularity along the line; the average Coefficient of Variations of the headways (Cov [h]) are equal, but the development is different (see Figure 0.2). For schedule-based strategies, the Level of Service (LoS), based on the regularity, varies between LoS A (very regular service) and D (irregular headways, with some bunching). The headway-based strategies varying between LoS A (very regular service) and B (slightly off headway).

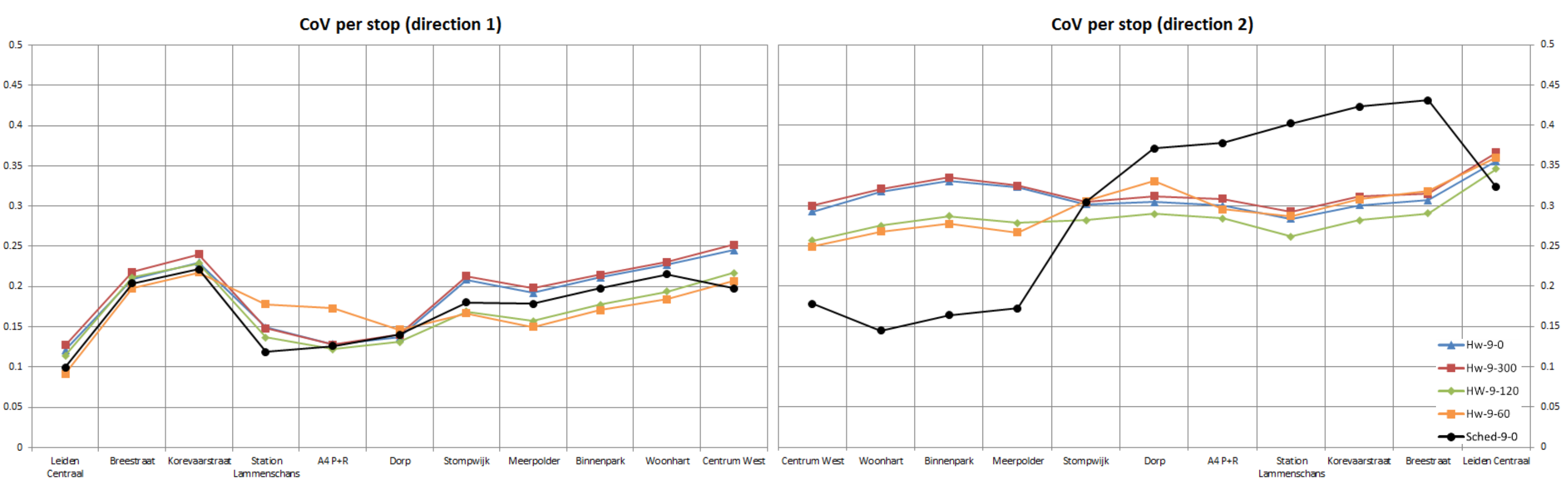

Figure 0.2 Development of the coefficient of variation of the departure headways

determines the performance of strategies. For passengers, strategy hw-9-120 is the most promising, because it does not influence direction 1 negatively. Strategy hw-9-120 would lead to a decrease of the experienced travel time per passenger of approximately 20s in direction 2, while the experienced travel time per passenger will be the same in direction 1.

Finally, for the authority hw-9-120, hw-9-60 and sched-9-0 are also the best strategies, because they lead to the highest level of reliability and the highest probabilities of finding a seat. Since the irregularity along the line increases in case of schedule-based strategies, the authority would prefer a headway-based strategy.

Scenarios

Headway-based control strategies are less sensitive to scheduled times. In case of a tight schedule, schedule-based control is not able to control the system. In addition, these strategies are also better able in dealing with smaller disruptions. Headway-based strategies are able to reposition vehicles in order to create a regular service again. The impact of smaller disruptions (for example the opening of a bridge for 4 minutes) can be solved. Bus bunching occurs, which is unavoidable in case there is a disruption of 4 minutes at such a high-frequency line, but can be solved by the cooperation of the vehicles along the line. In case of schedule-based control, bus bunching cannot be solved. In the event of a disruption, everything collapses until the final stop, while in case of headway-based control the service is more robust. Headway-based strategies are also less sensitive to (non-)compliance of drivers. Non-complying drivers are presumably corrected by the other drivers, as a result of the cooperativity of the headway-based strategy. Finally, it can also be concluded that the headway-based strategy is also better able to deal with larger disruptions. In direction 1, the strategies hw-9-120, hw-9-60 and sched-9-0 could save travel time per passengers compared to the current used strategy sched-3-0, with respectively 105, 60 and 45 s. The headway-based control strategies could save up to 5 minutes average experienced travel time per passengers, compared to the schedule-based strategies, in direction 1.

Overall conclusion

In Figure 0.3 the main results are shown, for both the operator, the passenger and the authority.

	Normal situation					Disruption			
	Headway-based			Schedule-based		Headway-based		Schedule-based	
	CP: 3	CP: 9	CP: 9	CP: 3	CP: 9	CP: 9		CP: 3	CP: 9
	no max	max 120	max 60	no max	no max	no max	max 300	no max	no max
KPI Strategy→	Hw-3-0	Hw-9-120	Hw-9-60	Sched-3-0	Sched-9-0	Hw-9-120	Hw-9-60	Sched-3-0	Sched-9-0
CoV [h] - 1	0.24 (B)	0.17 (A)	0.17 (A)	0.23 (B)	0.17 (A)	0.36 (C)	0.43 (D)	0.58 (E)	0.55 (E)
CoV [h] - 2	0.45 (D)	0.28 (B)	0.30 (B)	0.32 (C)	0.30 (B)	0.39 (C)	0.49 (D)	0.68 (E)	0.63 (E)
Range of the LoS (based on CoV) - 1	A-C	A-B	A-B	A-C	A-B	C-D	C-E	D-E	E
Range of the LoS (based on CoV) - 2	C-E	B-C	B-C	A-D	A-D	C-D	D-E	E-F	E
# buses in case of turnaround of 60s	12	13	12	12	12	14	14	14	14
# buses in case of turnaround of 360s	13	14	13	13	13	15	15	15	15
Total experienced travel time [min:s] - 1	22:38	23:24	23:08	23:24	23:26	28:40	29:23	30:36	29:57
Total experienced travel time [min:s] - 2	32:48	29:27	29:40	29:46	29:33	37:19	40:06	45:30	44:48
Differences compared to sched-3-0 [min:s] - 1	-00:46	0	-00:16	-	+00:02	-01:56	-01:13	-	-00:39
Differences compared to sched-3-0 [min:s] - 2	+03:02	-00:19	-00:06	-	-00:13	-08:11	-05:24	-	-00:42

*LoS is the level of service based on the average CoV of the headways according to TCRP, 2013

Figure 0.3 Main results of the simulation

In the normal situation the preferred strategy would be the schedule-based control, because implementing this strategy would not require large changes. Especially since the differences are small compared to the headway-based strategies. However, hw-9-60 will also be a promising strategy, that is more robust to uncertainties and could in practice perform better than in the simulation, as a result of the possibility to control vehicles at terminals. When holding and regulating vehicles at Zoetermeer Centrum West, the irregularity at this station will decrease, resulting in a decrease of 5-10% of the average experienced travel time per passengers.

Characteristics that are important and could influence the performance of a holding strategy could be identified. These are: occupancy pattern on a line, punctuality of a service along the line, variation along the line and the schedule quality (slack time and turnaround time in the timetable).

In general, in case there are early arrivals, schedule-based control could also provide regular headways. Another case where schedule-based control performs also relatively good, is when most passengers board at the terminal, and there is enough slack time at this terminal in order to solve delays from previous trips. In case the line is relatively irregular or when regularity along the line is required, headway-based control is the preferred strategy. In Figure 0.4 an overview of line characteristic and the preferred holding strategy is given.

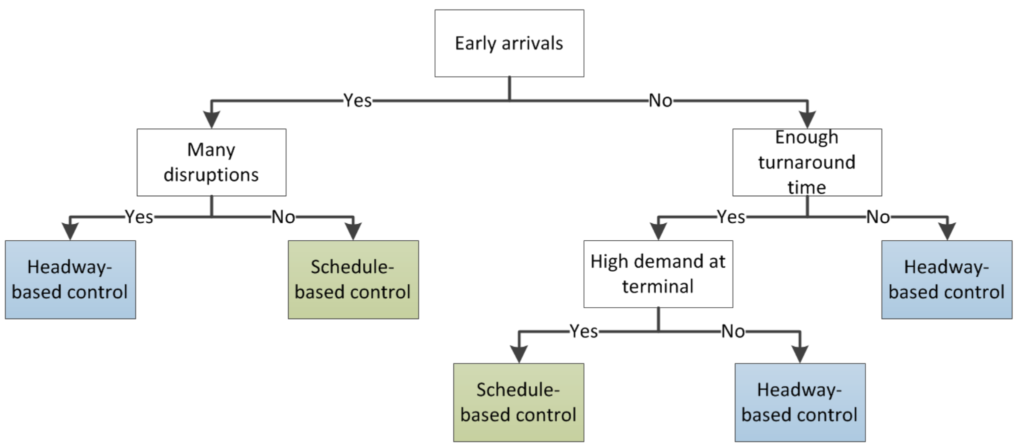

Figure 0.4 Indication of favourable holding strategies

Implementation

There are two aspects that bring uncertainty with respect to the implementation of headway control: aspects related to the execution of a headway-based holding strategy and contractual aspects. In case the operator decides to change to a regularity-driven operation, fundamental changes have to be made, related to technical, logistical and behavioural aspects. These aspects cannot be simulated and therefore a pilot study is needed to test the working of headway-based control in practice.

Authorities in The Netherlands include, gradually, regularity in their concession requirements. However, the requirements are incomplete and it can also be asked whether the penalties will work as incentive for the operator in order to improve the quality of the service. 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 analysed. In addition, the performance of a service perceived by passengers can be taken into account, instead of the performance of vehicles.

Main conclusions and recommendations

Operators are in particular 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 higher cycle times that could also lead to more buses. However, the effects of holding on the total cycle time do not lead, in general, to the need of more buses. With respect to the reliability of a trip; the headway-based control strategies are better able in offering a constant 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 in case more holding is applied. However, the excess waiting times decreases, as a result of the more regular service. Also the variation of the time-components is less. The average impact on passengers highly depend on the occupancy pattern on the line. The differences between different holding strategies are minimal, in case most passengers board at the terminals, where both strategies could facilitate regular departures.

For the transport authority, the most important aspect is that the service is reliable. Headway-based holding is better able in regulating the vehicles along the line. In case headway-based holding is the preferred strategy, the authority should change the punctuality requirement in the concession towards a regularity requirement. How to include a regularity requirement and combine this with penalties that work as incentives is one of the aspects that should be investigated.

Based on the simulations, and the current practice of Arriva, the best control strategy at this moment is sched-9-0; schedule-based control with 9 control points and no maximum holding time. Implementing this strategy does not require large changes and differences with the headway-based strategy are relatively small. However, hw-9-60 (headway-based control with 9 control points and a maximum holding time of 60s) will also be a promising strategy, that is more robust to uncertainties.

It is recommended to do additional research with respect to network related impacts of headway-based holding. More knowledge is also required for the transport authority with respect to regularity indicators and incentives for the operator. In addition, for practical implementation, additional research is needed with respect to service characteristics and other control strategies that are suitable in specific situations.

For Arriva, the main recommendation is to organise a pilot study in order to test holding strategies in practice.

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General abbreviations

AST	Average standing time
AWT	Average waiting time
CoV	Coefficient of Variation
CP	Control point
DT	Dwell time
EWT	Excess waiting time
LoS	Level of service
PAIVT	Perceived average in-vehicle time
PRDM	Percentage Regularity Deviation Mean
PT	Public transport
PWT	Planned waiting time
RBT	Reliability Buffer Time
St.dev	Standard deviation
SWT	Scheduled waiting time
Var	Variation

1. Introduction

In this section the problem is introduced. First the context of the research will be discussed, followed by a description of the problem. Thereafter the research objectives and questions will be presented. Subsequently, the scope and methodology will be defined. Finally, the overview of the report will be given.

1.1. Service reliability in general

Public transport services are essential and can contribute to a variety of social goals, such as improving the accessibility, liveability and the economic situation and development (Bakker & Zwaneveld, 2009). A quality improvement of transport services is needed in order to increase the share of public transport of the total mobility. One of the main factors that determines the quality of a public transport service, is the reliability of that service. Reliability is the extent to which the actual transit performance matched the expectations of the passengers (Van Oort, 2011).

Reliable bus services are important for both operators and passengers. For operators, variability in the services could cause efficiency losses. This can lead to higher operation costs. On the other hand, unreliability will decrease the quality of the service for passengers. The lower the quality, the more likely it is that less passengers will make use of the service (Uniman, 2009).

A common problem for bus services, that decrease the reliability, is vehicle bunching. Bunching is caused by the variability in trip time between stops and the variability in passenger demand. The result of these factors is variability in the headway between buses (Delgado, Munoz, & Giesen, 2012). In case a vehicle has an initial delay, the headway between that vehicle and its predecessor increases. As a result of this, the number of passengers at the next stop will also increase. The dwell time of the bus will increase, and this will create even more delay. The headway between the bus and its predecessor increases, but at the same time the headway between the bus and its successor decreases. Since this headway is smaller than planned, the number of passengers at stops are also lower. The dwell time of the successor is therefore lower, which decreases the headway even more. The result is clustered vehicles; some full while other vehicles are empty (Van Oort, 2011).

In order to improve service reliability, control stategies can be applied. In this research 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, it is analysed whether a bus is ahead of schedule or not. If a bus is ahead of schedule, that bus will be held for a certain time. This strategy aims at improving the reliability of the execution of the timetable. The second category is headway-based holding; vehicles will be held till a minimal headway requirement is fulfilled (Cats, 2011).

As mentioned before, reliability is important for both passengers and operators. It is possible to look at 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 pay attention to the schedule and arrive randomly at stops (Cats, 2014). The frequency is considered high in case the frequency of buses is equal or higher than 6 per hour (Oort, 2011; Ibarra-Rojas, Delgado, Giesen, & Munoz, 2015). In case regularity is more important for passengers than punctuality, it is questionable whether it is correct to base control on punctuality. In case the frequency of a bus service is high, it could be better to base control on regularity.

1.2. Problem description

This section discusses the problem, the knowledge gaps, the case study, the research objective and the main and sub questions in this research.

1.2.1. Problem definition

As mentioned in section 1.1, in case of high-frequency public transport services, it could be better to focus on regularity. However, currently the focus of bus operators is on punctuality. One of the causes is the concession between the authority and the bus operators. The concession between the authority and the bus operator determines the minimum level of service. One of the important aspects in this concession requirements is punctuality. Operators are accounted on the punctuality and this makes it difficult to use headway-based control strategies. However, for high-frequency lines punctuality is not the main determinant of level of service. Regularity is more important. Therefore it can be argued that regularity should be included in the concession requirements.

Additionally, the effects of regularity control are not known in different situations and for different service characteristics. Many studies have analysed headway control strategies. However, many of these strategies are not tested against field data, or implemented in the field. Especially in the Netherlands there are no examples found where headway control is used to control bus services. Although different studies concluded that headway control strategies are advantageous, different strategies are generally not compared to each other, based on the same field data. This makes it more difficult to compare strategies, since every service has its own characteristics.

Since there are three main stakeholders in the public transport, the effects of new control strategies also have influence on these three stakeholders. These three main stakeholders are: the transport authority, the transport operator and the passenger. The effects on these three stakeholders should be taken into account when analysing the effects of a new control strategy. To the best of the author's knowledge, the effect for the transport authority are not included explicitly in research.

1.2.2. Knowledge gaps

Although there are many studies about holding, some knowledge is missing:

- Overall assessment of different holding control strategies, based on the same field data, taken into account different key performance indicators (KPIs) for different stakeholders, including the effect of uncertainties (change trip time or disruptions). An systematic assessment framework to assess different holding control strategies is missing.
- Insight in how, under what conditions and where headway control should be implemented.
- Operators do not know how they should implemented headway control and authorities do not know how regularity should be included in the concession requirements. Practical information is missing.

1.2.3. Case study

When analysing control strategies, data from real-world public transport services should be used (Strathman, et al., 2000). Therefore a case study will be used in this research in order to test the approach used in this research. The transport service that will be used, is line 400. This is a high-frequency bus service between Leiden Centraal and Zoetermeer, operated by Arriva. In chapter 4 a detailed description of this case study will be given.

1.2.4. Research objective

The objective of this research is to develop a framework to systematically analyse the impact of different holding-control strategies, and to assess the strategies based on different KPIs. In addition, this research aims at discussing the aspects that should be taken into account when implementing regularity-control. With respect to this implementation, two main aspects will be discussed. First how to cope with the operational difficulties and second how the new strategy can be incorporated into the agreements between the transport authority and operator. It should be noted that line 400 will be used in this research as case study in order to test the framework.

As mentioned before, there are three important stakeholders that are generally involved in public transport service. These three stakeholders have different goals, which can lead to conflicting interests. These different interests should be taken into account when analysing the impact of a specific control strategy.

1.2.5. Research questions

The main research question is as follows:

How could holding control strategies be assessed and implemented, and what is the effect of different holding-control strategies, with respect to the operator, passengers and the transport authority?

In order to answer this question, several sub questions are formulated. First some general questions and after that case-related questions are defined.

General:

- What are different holding-control strategies?
- What are the key performance indicators (KPIs) of bus services for the transport authority, operator and passengers?
- What methodology could assess different holding-control strategies?
- What are the current concession requirements with respect to punctuality and regularity and what are the consequences in case regularity-control will be implemented?

Case-related:

- What is the current performance on R-net line 400 for both Arriva, Province of Zuid-Holland and passengers?
- What are possible holding strategies for R-net line 400, taken into account the current timetable, line characteristics and route constraints (bridge, traffic lights, etc)?
- What are the positive and negative effects of the control strategies on the different KPIs?
- To what extent will the problems be solved in case the service is regularity-driven and what new problems arise?
- How could headway-based control be applied to R-net line 400?
- What are the current concession requirements for Arriva and what are the consequences in case regularity-control will be implemented?

1.3. Scope

There are three types of decisions in the planning process of bus services. The highest is the strategic level, followed by the tactical level and finally the operational level. The time horizon of these levels is from long-term to short-term decisions.

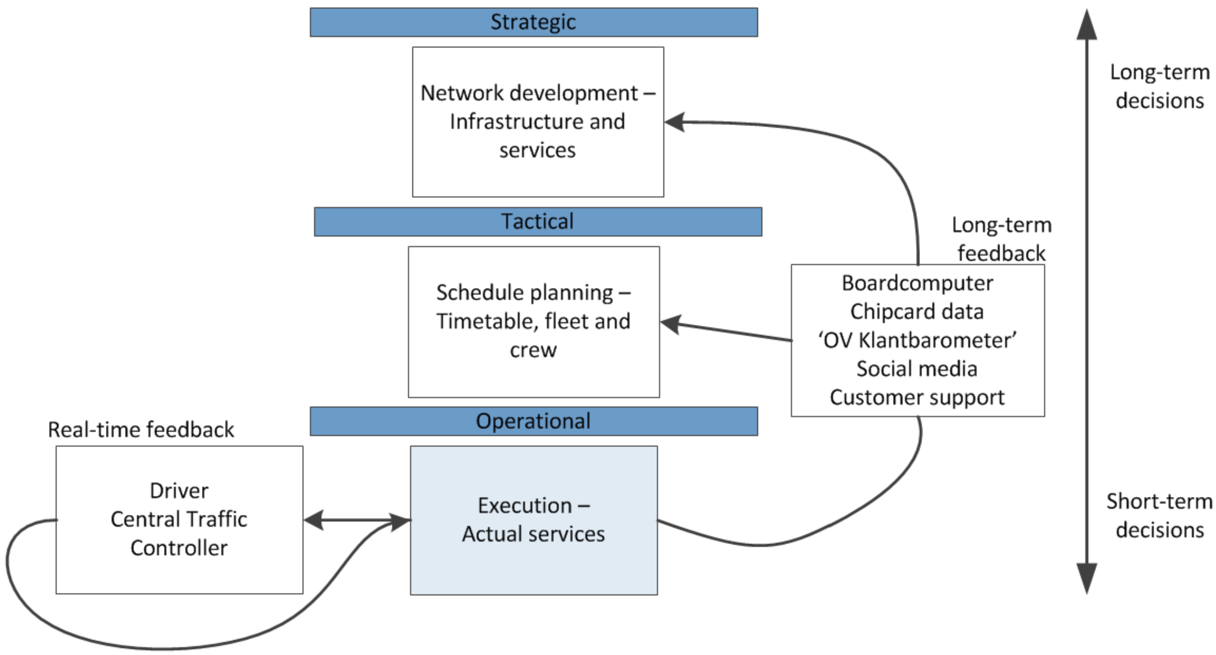

Figure 1.1 Planning framework, based on Van Oort, Ebben, & Kant (2015)

In this research the focus is on the short-term decisions, so the operational level. This also means that the current infrastructure design, service network design and frequencies are taken as given when analysing a new headway-control strategy. In addition, only headway-control measures will be analysed. Other control possibilities will be ignored.

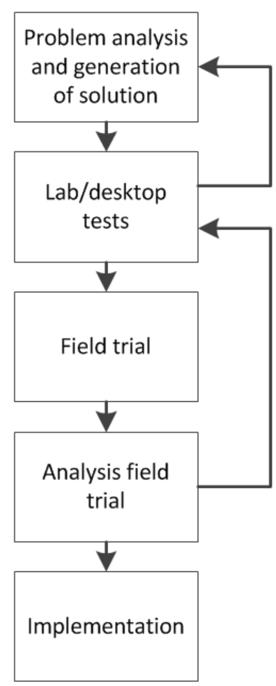

Figure 1.2 Implementation steps, based on Cats (n.d.)

Generally there are five steps that should be taken before an idea of a control strategy could be implemented, see Figure 1.2. First understanding the problem and idea generation in order to solve the problem. The second step is to make analyses and doing test of the control strategy. This can be done by making simulations for example. After this step, the new strategy can be put into practice; a pilot study can be performed. Data can be collected and analysed in the fourth step. The last step is the implementation.

There are also two feedback loops. First from the tests of the control strategy to the first step. This feedback loop is implemented in order to check whether the outcomes of the test make sense with respect to the in the first step determined problem. The second feedback loop is after the control strategy is put into practice in a pilot. After this pilot it can be concluded that the control strategy does not work or that some adaptations should be made. These changes can be, again, tested by simulations (Cats, n.d.).

Due to the lack of time for this research, it is not possible to do all the five steps. In this research only the first two steps will be done, with the purpose to provide recommendations concerning a field trial.

In order to evaluate the impact of new strategies, the KPIs of different stakeholders will be taken into account. As mentioned before, three stakeholders are considered: the transport authority, the bus operator (Arriva) and passengers. In addition, the focus of this research is on holding-control. Other control strategies will not be taken into account in this research.

In this research only line 400 is taken into account. Interactions with other lines and services are limited. In addition, when analysing new strategies, the input is based on the current situation, i.e. current timetable, buses and passenger demand. The time period that will be analysed, is the morning peak; from approximately 6:50 AM – 9:00 AM. This period is chosen, since during this time period the headway is 5 minutes. In addition, this is the busiest period with respect to passengers demand and the most problems occur during the morning peak.

1.4. Outline of the report

In Figure 1.3 a flow chart of the approach is depicted, including the related sub questions.

Chapter 2 discusses the performed literature study. In this review control strategies to reduce service variability will be discussed briefly, followed by more detailed description of the literature about holding control strategies. Finally, an overview of the research on concession requirements will be given. In chapter 3 the methodology will be explained: how can holding strategies be systematically assessed? After that, a performance analysis of line 400 will be discussed in chapter 4. Subsequently, chapter 5 describes the control strategies and the scenarios that will be simulated. In addition, the case study will be built in BusMezzo and this process will be described briefly. The results of this simulations will also be explained in chapter 6. After that chapter 7 discussed the limitations of the model, followed by the implementation difficulties for the operator. In addition, a generalisation of the results will be explained. Thereafter, in chapter 8, it is described how to include regularity control in concessions between operators and transport authorities. Finally, conclusions and recommendations will be given.

Figure 1.3 Structure of the report

2. Controlling public transport

This chapter discusses the context of this research. As mentioned in the introduction, service reliability is important. It will be explained briefly what the impact of unreliability is and what the causes of unreliable services are. Subsequently, section 2.2. describes how to deal with these variations by using control strategies. After that the focus will shift towards holding control strategies. The aim of this chapter is to gather information about different strategies. In addition, issues related to the design of holding strategies will be discussed.

2.1. Service variability

In the introduction it was mentioned that the service reliability is an important aspect of the quality of public transport. Service variability has impact on both the passenger and operator. The service reliability decreases in case the service variability increases. The quality of a service, perceived by passengers, is among others determined by the reliability. Unreliable services lead to longer average travel times, more travel time variability and lower probability of finding a seat (Van Oort, 2011).

Uniman (2009) summarized the effect of unreliability for the operator. Variability hinders the operator to make efficient use of resources. The operator has to take into account uncertainty when making a schedule. In case this uncertainty decreases, because the variation decreases, it is possible that less resources are needed to provide the same level of service. Leading to lower operation costs or possibilities to use these resources elsewhere. Another possibility is that the same amount of resources is needed for a more reliable service; the quality of the service could increase in that case.

Terminal departure time variability, driving times, dwell times and stopping times are the main determinants of service unreliability. It is important to understand the causes of this variability in the service. The causes of this variability can be divided into internal and external causes.

Some causes could be influenced by the operator or transport authority: the internal causes. Other aspects causes variation in the performance, but could not, or to a less extent, be influenced by the operator or authority. Internal aspects are vehicle availability, crew availability, schedule quality, infrastructure design, service network design, other public transport and vehicle design. External causes are weather conditions, other traffic, irregular loads and passenger behaviour (Van Oort, 2011).

All these causes lead to a mismatch between the schedule and the operations. In the next section possible control strategies will be elaborated.

2.2. Control strategies to reduce service variability

In the previous section it is shown that there are many causes that lead to a mismatch between the schedule and the operations. With other words, to an unreliable system. In order to deal with the stochastic nature of traffic flows and passenger demand, and to decrease this mismatch, control strategies are needed. The absence of control strategies can lead to undesired behaviour of the system. Different control strategies can be identified (Ibarra-Rojas et al., 2015).

Eberlein, Wilson, & Bernstein (1999) divided control strategies into three categories: station control, inter-station control and other control measures. In Figure 2.1 an overview of the divisions is shown.

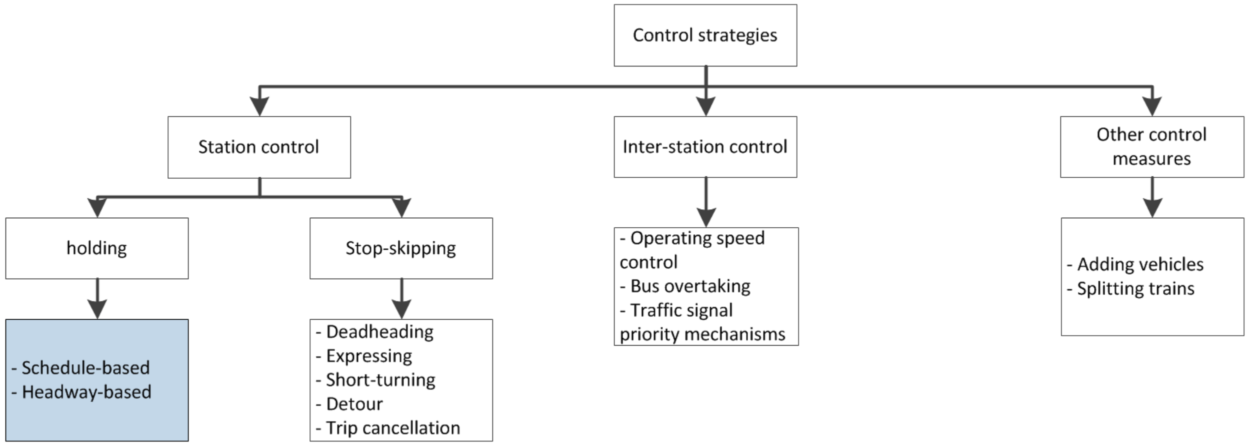

Figure 2.1 Division of control strategies (Eberlein et al., 1999)

Station control strategies can, subsequently, be divided into holding and stop-skipping. In case of holding, the dwell time at a specific stop can be determined and could vary from the planned dwell time. There are two types of holding: schedule-based and headway-based. These two types will be explained in more detail in section 2.2. Stop-skipping strategies are used to decrease the vehicle trip time by skipping stops. A disadvantage of this strategy is that passengers waiting at a stop that is skipped, experience longer waiting time of inconvenience as a result of alighting. In addition, the order of vehicles can change.

There are five main stop-skipping control strategies: deadheading, expressing, short-turning, detour or cancelling. Deadheading means that empty vehicles skip stations in order to return a late vehicle back to schedule. In case of expressing, stops will be skipped, while there are passengers in the bus. By doing this, the gap between the bus and its predecessor will decrease and the gap between the bus and the successor will increase. Bus bunching will be mitigated. Short-turning is when vehicles turns earlier, to run in the opposite direction. The final terminal will not be reached. In general, this control strategy can be applied in case there is a blockage. Detour is also a stop-skipping strategy. When there is a disruption along the route, buses can take another route and skip multiple stations. The final strategy that can be applied, is cancelling vehicles (Van Oort, 2011).

Where station control strategies were related to stops, inter-station control strategies are related to the space between stops. Due to the fact that bus operations are often executed in mixed traffic situations, these strategies are difficult to implement or do not lead to preferred results. Slowing down and speeding up, however, are often used for small adaptations. For example, to increase punctuality. Infrastructural aspects should allow speed adaptations. Overtaking another bus is also an control possibility, but infrastructural constraints make this control strategy often difficult to execute in practice. Finally, an example of inter-station control, is traffic signal priority mechanism. Traffic signals can give priority to buses and by that it could control the traffic flow (Eberlein et al., 1999; Van Oort, 2011).

The third category is 'other control measures'. The strategies in this category include adding vehicles and splitting trains (Eberlein et al., 1999). In case of bus services, splitting trains is not an option. However, adding vehicles is a strategy used more often. Adding an unscheduled trip can fill a gap, and add capacity. However, crew and material constraints make this strategy difficult. In addition, this leads to additional costs.

Among these discussed control strategies, station control strategies are mostly used. From these station control strategies, holding strategies are the most common strategies that are applied in normal service, to deal with the general service variability and to improve service regularity (Desaulniers & Hickman, 2007). Since service regularity is one of the most important aspect for high-frequency lines, the focus in this research is on holding strategies.

2.3. Holding strategies

As mentioned in section 2.1., there are two types of holding strategies: schedule-based and headway-based. Schedule-based strategies are commonly used for services that have long headways. Vehicles will be held in case a vehicle is ahead of schedule. In that case, that vehicle will be held for a certain time. This strategy aims at improving the reliability of the execution of the timetable (Cats, 2012).

Headway-base strategies can be used in case of high-frequency services, i.e. more than 6 vehicles per hour (Van Oort, 2011; Ibarra-Rojas et al., 2015). Vehicles vehicles will be held till a minimal headway requirement is fulfilled. Headway-based holding strategies are widely discussed in literature. When designing a control strategy, three aspects are important. First the control points need to determined. The control points are the stops where control is exercised. The second aspect is the conditions under which holding will be applied. Finally, how long the bus will be held. In other words, the holding time (Cats, 2014). Since the focus of this research is on high-frequency bus services, these three aspects for headway-based strategies will be discussed in more detail. In this section an literature overview will be given.

2.3.1. Control points

The control points are the stops where control is exercised. These control points are commonly determined by the transport authority. In addition, these control points are in general the important transfer stops along the route (Cats, Larijani, Koutsopoulos, & Burghout, 2011). The number of control points and their locations are still subject of many studies. In some studies it was concluded that control points should be located before high-demand stops (Abkowitz & Lepofsky, 1990), at early points along a route (Strathman, et al., 2000), or at a stop in the middle of a route with a high-boarding demand (Fu & Yang, 2002), while others concluded that it is best to have only one time point at the original terminal (Eberlein, Wilson, & Bernstein, 2001). Cats, Rufi, & Koutsopoulos (2014) concluded in their research that the selection of the control points should be done carefully, since this has considerable effects on the performance. In addition, the locations of time points is probably more important than the number of time points, since the performance is more sensitive for this. They also mentioned that the specific characteristics of a line are crucial for the choice of locations and number of control points.

By the location choice of a control point, three conditions should be considered. First, the number of through-passengers should be low, because these passengers do not have advantages of the holding times. The second condition is that the infrastructure allow buses to hold without delaying other transport users. Finally, back and forth should be the same control point, in order to keep it consistent and clear (Boterman & Van Oort, 2008).

2.3.2. Holding conditions

Another important design aspect is the condition under which control is applied: the strategy. One of the first study with respect to holding strategies, was of Osuna & Newell (1972). This study assumed a relatively simple network, using only one control point and based the model on only a limited number of buses. The objective in this study was to minimalise the passenger waiting time. Based on the proposed models, an optimal threshold value was derived. However, as a result of the simplifications, these models are, in general, not directly applicable in practice (Hickman, 2001).

One of the first real-life pilots with respect to holding strategies, was of Abkowits & Lepofsky (1990). Threshold-based holding was applied. Buses were held at specified locations along the route for a certain period of time. The objective was to minimise the total waiting time for passengers. This strategy was applied to two high-frequency lines of a transit network in the U.S. Headway-based control appears to be most beneficial on routes with the following characteristics: a cross-town route where passengers arrive randomly at stops. In addition, control points on the route depend on the boarding and alighting profile. The results of the research were positive, however, the effects may have been understated. Manual data collection problems and human failure had hampered the study. Street supervisors were instructed and coordinated to implement the design strategy into practice. However, not all the buses were held as they should have been. It turned out that human factors can reduce the effectiveness of the headway-based holding strategy.

Eberlein et al. (2001) proposed an optimization model in order to minimise the travel costs. Although the total passengers waiting times and the headway variability decreased, the effects of the strategy were not explored in detail. Variation in demand and travel times were not taken into account and also the effect of the strategy on the commercial speed was not explored systematically (Daganzo, 2009). In addition, the evaluation was based on data from a light rail system. Also how the system develops in case of disruptions is unclear.

Daganzo (2009) introduced an adaptive control scheme that dynamically determines the times that buses need to be held, based on real-time headway information about the previous bus. This approach focussed on achieving a predefined target headway. This study concluded that that this new strategy allows buses to travel faster, reduced in-vehicles passenger delays and increasing bus productivity. It is namely effective under smaller disturbances, since the control system can execute small corrections before problems grow large. In case of larger distrurbances, this method is ineffective.

All these studies about control strategy are based on realizing a-priori headways. However, Bartholdi & Eisenstein (2011) discuss the disadvantages of these approaches. According to them, the optimal achievable headway is not known in advance and can also change, due to 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. For example, in case a bus breaks down, there is a gap. In case of target headway control the successive bus should speed up, which is often not possible. Therefore, target headway control is vulnerable for disruptions.

In order to overcome these problems, Daganzo & Pilachowski (2010) proposed a method where buses communicate with each other. The cruising speed of buses can be adjusted, based on both the successor and predecessor of a bus. In this case regular headways can be yielded and at the same time faster bus travel can be achieved, compared to other control methods. However, evaluation was not based on real-world data.

Bartholdi & Eisenstein (2011) proposed a method where headways are self-equalizing by dynamically adjust the headway. The holding time in this strategy is based on the headway with the previous bus and can change continuously. This method can deal with large disturbances.

One of the studies that evaluated the effect of the strategies in more detail is executed by Cats et al. (2011). In this research, different strategies were taken into account. Both schedule-based and headway-based control strategies, with headways based on the preceding and/or succeeding bus, were simulated. For the headway-based strategies, the waiting time per passenger decreased, but the in-vehicle time inceased. In addition, the average cycle time increased as well, but the 90^{th}-percentile of the cycle time is lower compared to schedule-based control strategies. An evaluation was made based on different performance indicators for both the operator and the passenger (Cats, 2011).

West & Cats (2015) made a simulation and tested the effects of a headway-control strategy based on both the predecing and succeeding bus, while also simulating other control possibilities. The total dwell time, total bus trip time, trip time standard deviation and passengers travel costs did not improve compared to the base case (schedule-control). However, the regularity in terms of the regularity variation improved significantly. Moreover, there are probably synergy effect between this strategy and other control measures.

The most promising strategy was the one were both the preceding and succeeding bus were involved. According this research headway control has positive effects for both the operator and the passenger. Apart from different control strategies, also the impact when different time points were included, were analysed. It is concluded that there was no substantial difference between two chosen time point layouts. With respect to the even headway control strategy, Cats (2011) also mentioned that in case of incididents it may be necessary to switch from headway-based control to schedule-based control. However, incidents were not taken into account in the simulation.

As a result of positive outcomes of a simulation, the even headway control strategy was put into practice. A high-frequency bus line in Stockholm was controlled based on the even-headway strategy, because the current control strategy (punctuality based) was ineffective. The service was not regular and bunching was a common problem. 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. Also the travel time aspects were analysed. The bus trip time, excess waiting time and in-vehicle time decreased. The overall evaluation was expressed in monetary values. The overall benefit for both passengers and operator were approximately 15,300 euro per weekday (Fadaei & Cats, 2016).

Before this strategy can be implemented permanently, the agreements between the transport authority and the operator need to be revised. Incentives and penalties were based on punctuality, and this should be changed to regularity. This aspect will be explained in more detail in chapter 8.

2.3.3. Holding time

The holding time is the time that vehicles are held at control points. Maximum holding times could be taken into account in order to prevent that individual passengers experience very long travel times. It could be that, in order to achieve an optimum for the majority of the passengers, it is adventageous to have extremely long holding times. However, this is not desirable. In general, both passengers and drivers find it unacceptable if holding times are longer than one minute in case of a high-frequency service (Van Oort, Wilson, & Van Nes, 2010).

In addition, the location where vehicles are held also influences the acceptance of holding times. The closer to the final stop, or to a transfer stop, the lower the holding time that will be accepted by both passengers and drivers (Arriva, personal communication, 2016).

2.4. Sub conclusion

To deal with the stochastic nature of traffic flows and passenger demand at stops, control is needed. Otherwise, undesired behaviour of the system can be the result. Control strategies can be divided into three categories: station control, inter-station control and other control measures. One of the sub categories of station control, are the holding control strategies. These can be divided into schedule-based and headway-based. Headway-based control strategies are generally applicable for high-frequency public transport services. Three aspects are important when determining a headway control strategy: the location and number of control points, the strategy type and the holding time. With respect to the location and number of control points, there is no general rule. The best control point layout depends on the characteristic of the transport service.

There are many different control strategies analysed in literature. The analysis of the 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, different operational conditions and different KPIs. It can be concluded that there is no general rule under what circumstances what headway control strategy can be beneficial for different stakeholders. In Table 2.1 an overview of the discussed literature of section 2.3.2 is given.

Finally, very long holding times are unacceptable by both drivers and passengers. In case of a high-frequency services, holding times of maximum one minute should be taken into account.

The main knowledge gap that could be identified from this literature review is that there is no general rule for applying holding control strategies in order to regulate high-frequency bus lines. It is unknown what type of holding control strategy should be used under which circumstances and for what service characteristics. In addition, how strategies deal with disruptions is also an important aspect that is not always taken into account. Therefore, in this research, an assessment framework will be developed that can be used by decision makers in order to assess different holding control strategies.

Table 2.1 Control strategies: literature overview

					Evaluation		
Study	**Minimisation**	**Uncertainty**	**Solution method**	**Capacity constraints**	**Travel time components**	**Regularity components**	**Others**
Abkowits & Lepofsky, 1990	travel costs	deterministic	rule-based	no	x	x	passenger loading, vehicle running times
Bartholdi & Eisenstein, 2011	headway variation	stochastic	rule-based	no		x	
Cats, 2012	headway variation			yes	x	x	crowding, cycle times, holding times
Daganzo, 2009	headway variation	stochastic	rule-based	no	x	x	
Daganzo & Pilachowski, 2010	headway variation	stochastic	rule-based	no		x	
Delgado et al., 2009	travel costs	deterministic	Optimization	yes	x	x	crowding
Delgado et al., 2012	travel costs	deterministic	Optimization	yes	x	x	crowding, cycle times, holding times
Eberlein, 2001	travel costs	deterministic	Optimization	no	x	x	
Fu & Yang, 2002	headway variation	deterministic	Rule-based	no	x		control frequency
Hickman, 2001	travel costs	stochastic	Optimization	no	x		control frequency, holding times, crowding
Lizana et al., 2014	travel costs	stochastic	Optimization	yes		x	amount of fines, cycle times
Van Oort et al., 2010	travel costs	deterministic + stochastic	rule-based	no	x	x	holding times
Xuan et al., 2011	headway variation	stochastic	rule-based	no		x	cycle times

3. Methodology

This chapter discusses the methodology in order to generate and assess different holding-strategies. This methodology consists of different steps. First is to determine what aspects should be included in order to assess different strategies. Three different perspectives will be taken into account in this research: the passenger perspective, the operator perspective and the perspective of the transport authority. For these three different perspectives, the main objectives will be explained. These objectives lead to the most important KPIs for the passenger, operator and authority.

The second step of the methodology is to generate strategies that should be compared with each other. It will be explained how these strategies can be generated. In addition, the robustness of strategies could also be included in the assessment, by using different scenarios. Also the generation of scenarios will be explained in more detail in this chapter.

The next step is to test the strategies. This testing will be done by using a simulation model. In addition, the results of the simulation will be presented to field experts, in order to determine aspects that are not taken into account in the simulation model, consisting of, among others, bus drivers, managers, planners and concession grantors. This additional step can help to distinguish the differences between the model and the socially complex reality.

Finally, based on the model output and the determined KPIs, the performance of strategies under different scenarios can be tested and assessed. An overview of the methodology is shown in Figure 3.1.

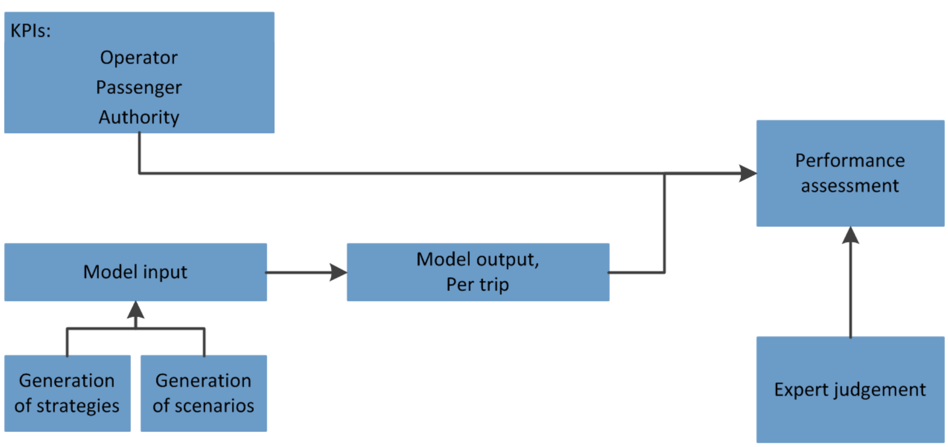

Figure 3.1 Overview methodology

In Table 3.1 an example of the assessment framework is presented.

Table 3.1 Example assessment framework

Scenarios →	Scenario 1		Scenario …		Scenario n	
Strategies → **Key performance indicators↓**	Strategy 1	Strategy n	Strategy 1	Strategy n	Strategy 1	Strategy n
KPI Passengers						
KPI Operator						
KPI Authority						

3.1. Determination KPIs

In order to determine what aspects are important when assessing bus services, objective trees are used. These objective trees define what actors want, which can be translated into measureable KPIs. An objective tree consists of multiple levels. The highest level is the general objective of an actor, and lower levels of the tree specify this high-level objective. The lowest-level objectives in the tree are the KPIs that can be used in order to assess and compare different strategies (Enserink et al., 2010).

As mentioned before, three perspectives are included in this research: passenger, operator and authority. For every actor an objective tree is made. Based on these objective trees, the KPIs are defined.

3.1.1. Operator

In Figure 3.2 the objective tree for the operator is shown.

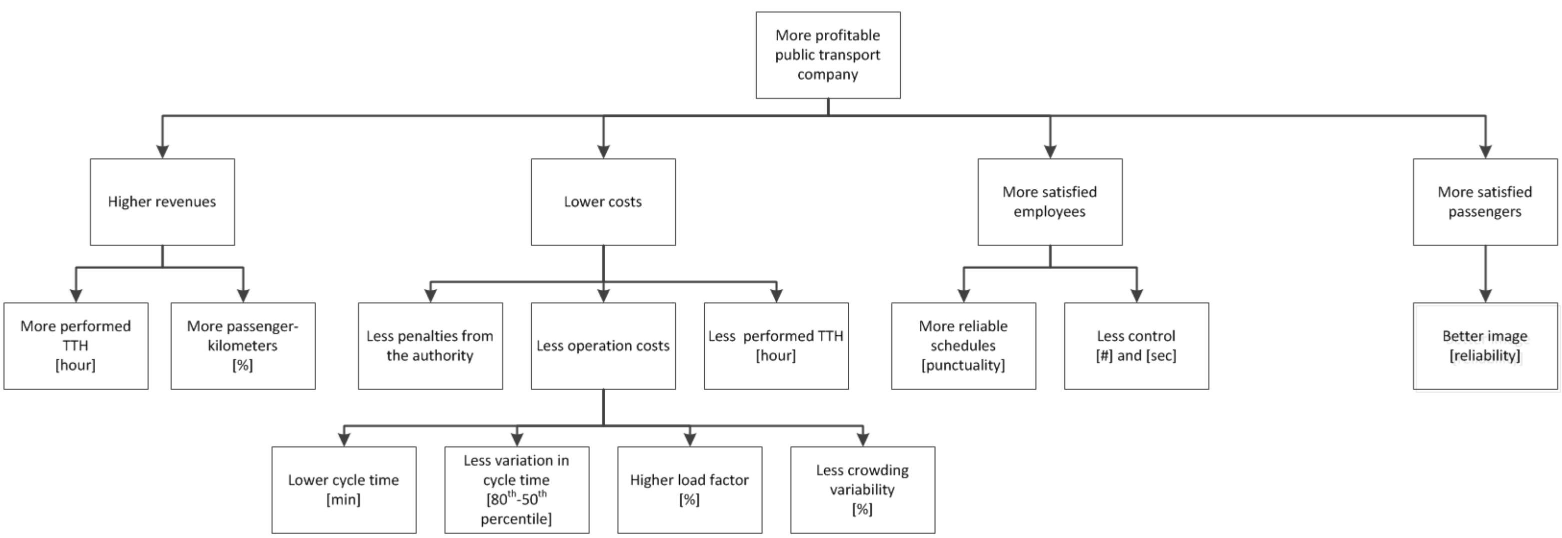

Figure 3.2 Objective tree operator

The main objective for the transport operator is to be profitable. In order to be profitable, the costs should be low and the revenues high. Additionally, the passengers and employees should be satisfied.

In order to get more revenues, more performed TTH (Time table hours, in dutch: dienstregelingsuren) are desired. The more TTH, the more revenues they receive from the authority. This holds for the maximum TTH in the concession. After that more TTH leads to more costs. Another aspects of generating more revenues: more passenger kilometres. More passenger kilometers are related to more satisfied passengers. Those two are two separate objectives for the operator. In order to continue being profitable, the operator wants more passengers, but also more satisfied passengers. More satisfied passengers will continue to use the bus. These objectives can be achieved by improving the quality for passengers. In addition, passengers' satisfaction is also an aspect included in the concession requirements. This is another incentive to increase passenger satisfaction. The aspects that are important for passengers will be discussed in section 3.1.3. Another aspect, related to satisfied passengers, is increasing the image of the operator. In general, public transport has the image of being unreliable. Therefore it is important to increase the reliability of a service.

The costs can be reduced by less penalties from the authority. Penalties are determined in the concession requirements. Also less operation costs reduce the total costs: lower cycle time, less variation in cycle time, a higher load factor and less variation in vehicle loads.

Satisfied employees are also important, since they are the appearance of the company. For drivers it is important that the schedules are reliable, since they care for example on being on time for their break. In addition, the less control they need, the more independent they are. Drivers do not want to wait at stops, especially not in case of punctuality requirements. Their main argument is that you do not know if you need this time anywhere else along the route.

In addition, the requirements imposed by the authority are also of importance for the operator. Currently these requirements, with respect to the quality of a bus service, are: transport duty, possibility of finding a seat, trip cancellation and punctuality. Passenger satisfaction is also part of the requirements, but no specific norms are included. In appendix A these concession requirements are explained in more detail.

In summary, the KPIs determined specifically for the operator can be divided into two categories. The first category is related to aspects that are important because of operational efficiency for the operator. The second category is related to the aspects that are required and imposed by the transport authority.

1.

- Control frequency (number of interventions per trip and the holding time of these interventions)
- Cycle time (minutes; 80-percentile value)
- Variation in cycle time (Difference between the 50^{th}- and 80^{th}-percentile)
- Load factor (%)
- Crowding variability (%)
- Coefficient of variation of the headways (CoV)

2.

- Transport duty
- Guarantee seats
- Trip cancellation
- Punctuality
- Passenger satisfaction

In appendix C an overview of all the KPIs are given, including an explanation of how these KPIs can be calculated. One of the important aspects is the CoV of the headways and will therefore be discussed briefly. The CoV of the headways is the standard deviation divided by the mean headway. This indicated the variability of the data. In addition, in TCRP (2013) an indication is given of the level of service (LoS) based on this CoV. This can be used in order to be able to compare strategies and to give a qualitative indication of the service quality.

3.1.2. Authority

The transport authority wants to improve the quality and effectiveness of public transport (Rijksoverheid, n.d.). Three aspects are important. First the monitoring possibilities should be high in order to check the operator. In order to be able to do this, the information have to be reliable and the requirements have to be measurable. Furthermore, requirements in the concession should ensure that operators behave as desired. Requirements that are ambiguous, cause undesired actions and decisions of the operator should be avoided.

The second aspect is related to guaranteeing the quality of public transport for passengers. A division can be made; speed, reliability and comfort are important for passengers, as will be discussed in section 3.1.3. In order to guarantee a basic level for passengers, requirements are included in the concession. First, with respect to the speed, the timetable should be realistic. Whether a timetable is realistic, will be reviewed by the authority. The reliability of a service will be reviewed by the three main requirements: trip cancellation, punctuality/regularity and passengers that cannot board. Guaranteeing seats in order to increase the comfort level is also included. Finally, in order to assess the overall quality, passenger satisfaction is measured by a survey. The third aspect is related to the cost coverage level. The costs for the authority should be low, which is related to the costs of the operator. In addition, more passengers are desired, to increase the revenues for the operator. In Figure 3.3 the objective tree for the operator is depicted.

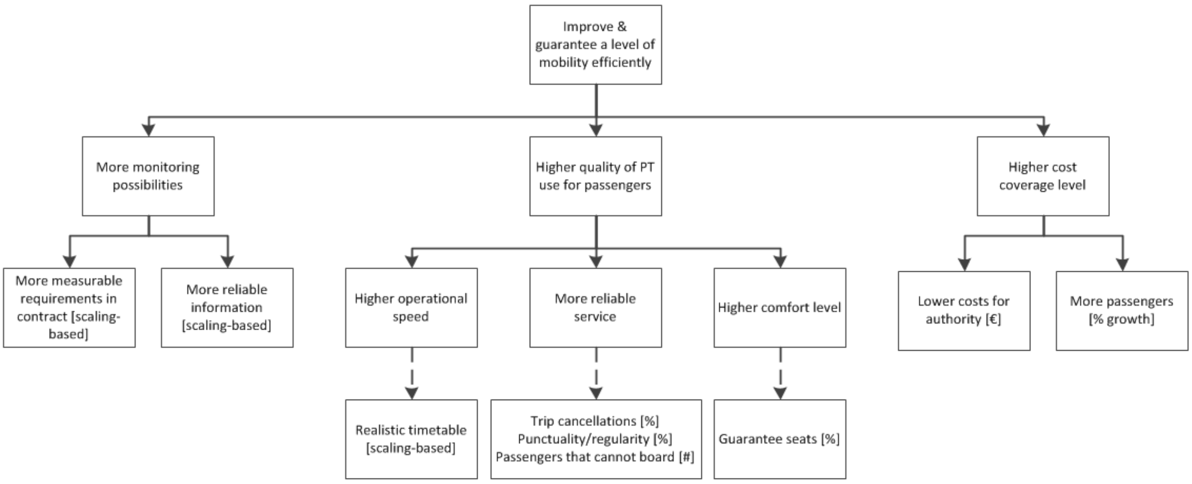

Figure 3.3 Objective tree transport authority

With respect to monitoring, these aspects cannot be included directly when assessing different strategies. A scale-based measurement is needed and these aspects should be analysed qualitatively. In addition, cost for the authority are related to the costs for the operator. The costs for the operator follow from the objective tree of the operator, discussed in the previous section. The quality aspects for passengers are also important, but can be determined from the objective tree of the passengers.

In conclusion, the KPIs for the transport authority, that will be included in the direct assessment of strategies, are:

- Trip cancellation
- Reliability: Punctuality [%] and regularity [CoV of the headway]
- Probability of finding a seat

3.1.3. Passengers

Whether a person decides to make use of a public transport service, depends on the service reliability, travel time, comfort, accessibility, image, information and price (Van Oort, 2011; CEN, 2002). The price of a trip will not be taken into account in this research, since the price of a trip will not change in case a different control strategy will be implemented.

Peek & Van Hagen (2002) prioritized the quality factors in the form of a pyramid (Figure 3.4). This prioritization is in accordance with the pyramid of Maslow. Safety and reliability form the basis of the pyramid. This are the minimal requirements for passengers. The second layer is speed; a fast and efficient trip is required. After that, the ease of travel is important. These three requirements are dissatisfiers, which means that in case these requirements are not met, passengers are not satisfied and are likely to avoid using public transpor services. After the dissatisfiers, there are two satisfiers: comfort and experience. Satisfiers are the aspects that satisfy passengers (Peek & Van Hagen, 2002).

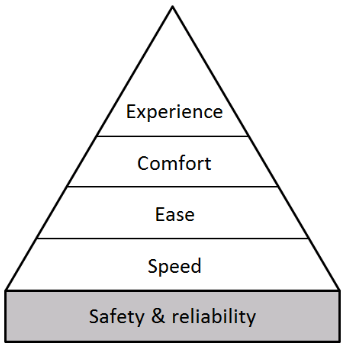

Figure 3.4 Prioritization quality factors for public transport services according to passengers (Peek & Van Hagen, 2002)

Although safety is one of the most important aspects, this will not be taken into account in this research. It is unlikely that the safety will change as a result of a changing control strategy. This is also the case for the factor experience. Experience-aspects such as available information, visual characteristics or additional services like access to internet, will stay the same in case the control strategy changes. It is possible that the experience of a trip change as a result of a changing control strategy, but it is assumed that these changes are captured in the other quality factors.

Ease of transport is also an important aspect for passengers. One of the aspects that is related to this ease, is transferring. It is important for passengers that there is a good connection, with not too much and not too little time to transfer. Although transfers are one of the concerns in case of headway-based control, this aspects will not explicitly taken into account in this research.

It can be concluded that the most important aspects for passengers are reliability, speed and comfort. Therefore, these three aspects are included in the objective tree in Figure 3.5. Travel times are divided into the waiting time and the in-vehicle time. The reliability of trips are therefore determined by the variation of these two aspects. For passengers one of the important aspects regarding comfort, is how crowded a vehicle is and whether they can find a seat. Therefore the average standing time per passenger is an indicator for comfort.

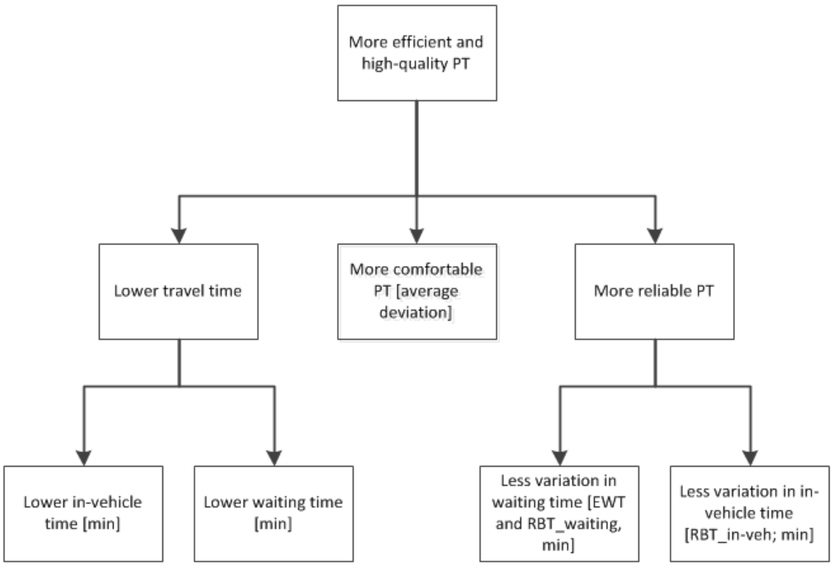

Figure 3.5 Objective tree passengers

The KPIs determined for the passengers are:

- Perceived average in-vehicle time (min)
- Average waiting time (min)
- Variation in waiting time (min; EWT and RBT-waiting time)
- Variation in-vehicle time (min; RBT_in-veh time)
- Average standing time per passenger (min)

Note that the variation in waiting time is expressed two time components (Cats, 2012); EWT and RBT_waiting time, which is the reliablity buffer time.

In order to give an total overview, the total average experienced travel time per passenger is calculated by summing up the weigted travel time components for passengers. In appendix C a detailed description of the KPIs and the calculation of these KPIs is given.

3.1.4. Sub conclusion

In previous sections the aspects for the three different stakeholders are discussed. Some of the quality aspects are the same for the three stakeholders. For example, passengers are important for both the transport authority and operator. Therefore, the quality aspects that are important for passengers are also of importance for the other two stakeholders.

The reason why passengers are important for the operator is as follows; in case the passenger is more satisfied, it will probably make more use of the bus. The more passengers make use of the bus, the more revenues the operator has. Moreover, in case the passenger is not satisfied, the operator will be accounted for this by the transport authority. The authority needs to guarantee the minimum quality level of a service and in addition tries to increase the use of public transport.

The KPIs that are important for the three main stakeholders are determined. These KPIs should be used to assess holding strategies. In the next section, the second step of the assessment framework will be explained; generating strategies and scenarios.

3.2. Holding strategies and scenarios

In this section the methodology of generating different holding strategies and scenarios will be discussed. First the holding strategies will be described. Subsequently, different scenarios will be built. The scenarios will be used in order to analyse the robustness of different strategies.

3.2.1. Holding strategies

A strategy can be characterised by a set of rules that are based on three aspects: the criteria that determine departure times, the location of the control points and the holding time (Cats, 2011). First all these three aspects will be discussed qualitatively. Finally, an overview of strategies will be given, including mathematical formulations.

Holding criteria

The holding criteria determines the departure times of buses. Two types can be indicated: schedule-based and headway-based holding.

The schedule-based holding strategies is commonly used. In case the schedule-based strategy is used, buses are held up to the scheduled departing time is reached.

The second type is headway-based holding. By headway-based strategies, vehicles are held in case a minimal headway requirement is not fulfilled. This minimal headway requirement could be based on the headway from the bus in front (forward headway) or the bus behind (backward headway). It is also possible to incorporate both headways, so that there are even headways on both sides. In that case the minimal headway requirement is based on the mean headway (Cats, 2011).The mean headway, a combination of the forward and backward headway, turned out to be the most promising holding control strategy (Cats et al., 2011). Therefore, it is chosen to include only this headway-based type.

In Figure 3.6 an schematic overview of different situations are depicted. Situation A is the desired situation; the headways between the buses are equal. However, in situation B vehicle 2 is too close to its predecessor. In case of schedule-based control, vehicle 2 will be held up to the scheduled departure time in order to achieve situation A again. In case of headway-based control, vehicle 2 will also be held, but based on the mean-headway; mean between vehicle 1 and 2 and vehicle 2 and 3. After vehicle 2 is held, situation A will be achieved again.

In situation C vehicle 2 is delayed. Schedule-based control could not regulate delayed vehicles. Bus bunching between vehicles 2 and 3 will be the result. In case of headway-based control, holding will be applied to vehicles 1, 3 and 4. The new situation is shown in situation D. The headway between the four vehicles is equal again, but they all shifted slightly.

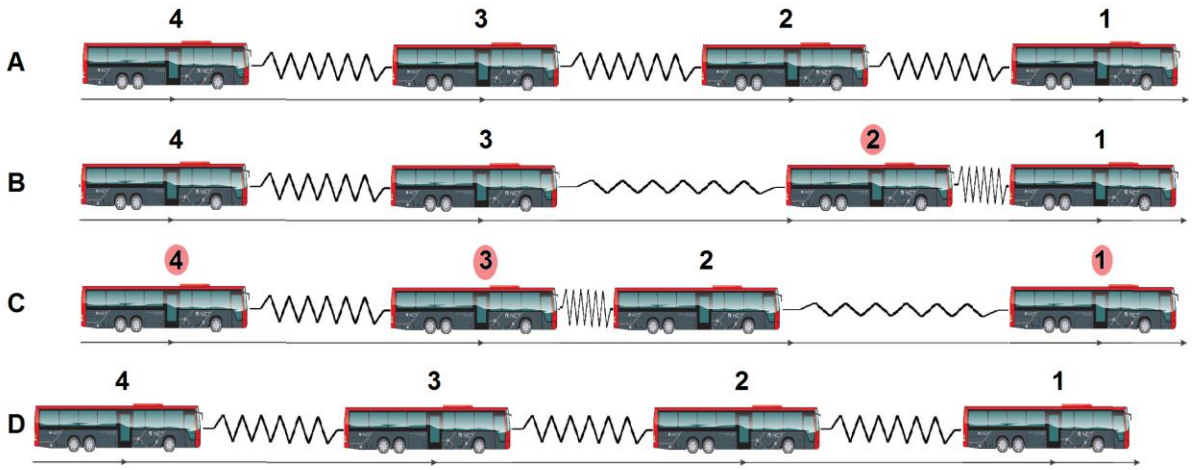

Figure 3.6 Schedule-based and headway-based holding; principle

Control points

The second aspect of the holding strategy, is the location of the control points. Control points are the stops where control is exercised. As mentioned in the literature study, it is unclear how many control points are optimal. In addition, there is also some uncertainty about the most ideal location of these points. Cats et al. (2014) concluded in their research that the selection of the control points should be done carefully, since this has considerable effects on the performance. In addition, the locations of time points is probably more important than the number of time points, since the performance is more sensitive for this. They also mentioned that the specific characteristics of a line are crucial for the choice of locations and number of control points. By the location choice of a control point, three conditions should be considered (Boterman & Van Oort, 2008):

1. The number of through-passengers should be relatively low
2. The infrastructure need to allow buses to hold without delaying other transport users
3. Back and forth should be the same control points

In this research different control point combinations are included:

- the first stop of a trip; minimum number of control points
- the main stops on a line; stops where 50% of all the passengers board and alight. However, every transit line has its own characteristics with respect to occupancy patterns, and whether a stop has a relatively low number of through-passengers should be based on that local situation
- all the stops on a line; Cats et al. (2010) concluded that that a strategy where all the stops where control points maintained a higher level of service regularity compared to the strategy where less control points where used. Therefore it is decided to include a strategy with all stops as control points.

It should be noted that in this research the focus is on holding vehicles at stops; control is only possible at control points by holding vehicles. Inter-station control possibilities that could help to regulate the headways, such as speed adaptations or traffic signal control, are not taken into account.

Holding time

The last important aspect of a control strategy is the holding time; the time the bus is held at a stop. Variations in holding times are included in order to analyse the effect of the differences. In order to analyse the maximum needed holding time, no maximum holding time should be determined. However, as mentioned in the literature study, a holding time of 1 minute is in general the maximum time for high-frequency services that is accepted by both passengers and drivers (Van Oort et al., 2010). In addition, in order to be able to analyse the result of longer holding times, a maximum holding time up to the scheduled headway is also included in this research. In case another maximum value is argued to be important to analyse, this could also be included.

Conclusion control strategies

In conclusion, the generation of control strategies should be based on the three aspects. The first aspect is the holding criteria, divided into two types. In addition, for every type the holding points and holding times should be determined. In Table 3.1 the options for the control points and maximum holding times are shown. The choice for control points and maximum holding times depends on the characteristics of a transit service. For every service the choice could be different. Therefore it is important to analyse the characteristics of a transit line, e.g. passenger pattern and infrastructural constraints. Based on these characteristics a choice could be made what options for control points and maximum holding times should be tested.

Table 3.1 Options for control strategies

Criteria	Control points	Max holding time
Schedule-based	First stop	1 min
Headway-based	Main stops	Up to planned headway
	All stops	No max
		Other

When it is known whether a stop is a control point, and what the maximum holding time is, the following rules are applicable. It should be noted that stops are defined as J, consisting of two types of stops; stops that are control points (J_C) and stops that are not a control point (J_{NC}).

In case of schedule-based holding:

$$ET_{ijk} = \begin{cases} max\left(min\left(SET_{jk}\ , AT_{jk} + \alpha - DT_{jk}\right),\ AT_{jk} + DT_{jk}\right) & ,\forall\ j\ \in J_C \\ AT_{jk} + DT_{jk} & ,\forall\ j\ \in J_{NC} \end{cases} \quad (3.1)$$

Where,

ET_{jk}	=	Exit time of trip *k* from stop *j*
SET_{jk}	=	Scheduled exit time of trip *k* from stop *j*
AT_{jk}	=	Actual arrival time of trip *k* at stop *j*
DT_{jk}	=	Dwell time of trip *k* at stop *j*
α	=	Maximum holding time

In case of mean-headway-based holding:

$$\overline{h_{jk}} = \frac{(AT_{jk} - AT_{j,k-1}) + (AT_{j,k+1} - AT_{jk})}{2} \quad (3.2)$$

$$ET_{jk} = \begin{cases} max\left(min\left(AT_{j,k-1} + \overline{h_{jk}}\ , AT_{jk} + \alpha - DT_{jk}\ \right),\ AT_{jk} + DT_{jk}\right) & ,\forall\ j\ \in J_C \\ AT_{jk} + DT_{jk} & ,\forall\ j\ \in J_{NC} \end{cases} \quad (3.3)$$

Where,

$\overline{h_{jk}}$	=	Mean headway for trip *k* at stop *j*
ET_{jk}	=	Exit time of trip *k* from stop *j*
$AT_{j,k-1}$	=	Actual arrival time of trip *k-1* at stop *j*
$AT_{m,k+1}$	=	Expected arrival time of trip *k+1* at stop *j*
AT_{jk}	=	Actual arrival time of trip *k* at stop *j*
DT_{jk}	=	Dwell time of trip *k* at stop *j*
α	=	Maximum holding time

In equation 3.2 the mean headway is calculated; the average headway of the forward and backward headway. The forward headway can be calculated since the arrival times of both trips is known and can be obtained by AVL data. The backward headway should be predicted, by estimating the arrival time of the succeeding trip at stop *j*. The estimation depends on the current location of the bus and the expected running time to stop *j*. When discussing the used simulation model, this estimation will be discussed in more detail.

In equation 3.3 the departure (exit) time is calculated, based on the mean headway, including a maximum allowable holding time.

3.2.2. Scenarios

There are differences between the planned performance of a bus service and the actual performance of a bus service. Therefore different scenarios have to be built, in order to test the robustness of control strategies. As mentioned in section 2.1, the main determinants of service variability are terminal departure time variability and trip time variability (Van Oort, 2011). Scenarios should be included in order to test how sensitive a control strategy is with respect to different aspects of uncertainty. The aspects that are included in the scenarios, are aspects that are difficult to control by the operator. The first aspect is longer trip times as a result of disruptions. Another aspect is driver behaviour.

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. By doing this, incidents or changes in travel times can be included that are comparable to real world disruptions. Real-world data should also be used.

Driver behaviour is an aspect that can affect the effectiveness of a control strategy. Compliance with the control strategy can influence the reliability of a service. The compliance rate of drivers can also be included in order to analyse how sensitive a strategy is for non-compliance of drivers. A compliance rate of 100% is the ideal situation. All the drivers behave as the theory expects. However, this is not realistic. Therefore, lower compliance rates should also be included. The complaince rate referes to the percentage of drivers that follow the holding rules. The other drivers do not follow the rules and depart without additional holding. Different rates could be chosen, but it is recommended to simulate at least the optimal situation (100% compliance rate) and the worst-case situation (50% compliance rate).

Conclusion scenarios

In conclusion, the generation of scenarios should be based on two aspects. In this research for every aspect different options are included, as shown in Table 3.2. Different combinations could be made. The choice of including incidents or modifying travel times should be done in consultation with the operator and by using real-world data.

Table 3.2 Options for scenarios

Disruptions	Compliance rate
Incidents	100%
Modification travel times	50%

3.3. Simulation model

3.3.1. BusMezzo

In order to be able to test different strategies and scenarios, a simulation model will be used. The simulation model used in this research is BusMezzo. In this model control strategies can be modelled, including different holding rules. These holding control strategies are important in this study. In addition, other studies have shown that BusMezzo can reproduce bus bunching (Cats et al., 2010) and crowding effects (Cats, West & Eliasson, 2016). This model is used in multiple studies in order to analyse holding control strategies. BusMezzo is a suitable tool for this research and it is, therefore, chosen to use this simulation model for testing different holding control strategies under different scenarios.

BusMezzo is a mesoscopic, dynamic, stochastic transit operations model. It simulates individual vehicles and passengers, without representing lanes specifically. Uncertainties in bus services, such as traffic conditions, vehicle capacity, dwell times, vehicle schedules and service disruptions, can be included in the model. BusMezzo can be used in order to support the implementation of control and management strategies, including holding strategies (Cats, 2011). In this section the aspects of BusMezzo that are relevant to this study will be discussed, particularly based on the BusMezzo input-output format written by Cats & Leffler (2017). In Figure 3.7 an overview is given of the required input and the output of BusMezzo.

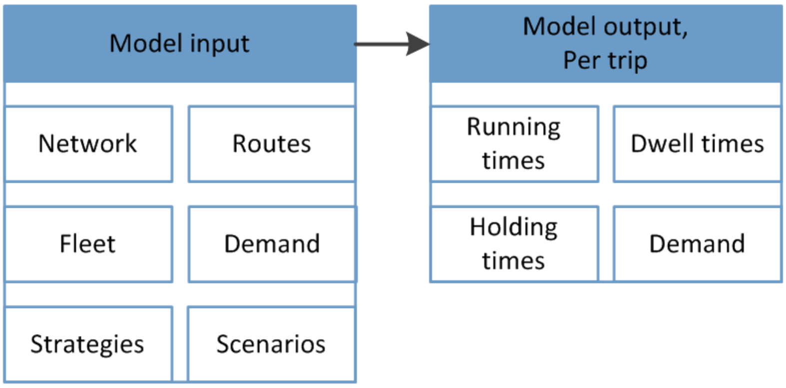

Figure 3.7 Input and output BusMezzo

The transit system is represented as follows. First the network is determined, by defining the stops, lines, trips, and travel-time disruptions. Subsequently, the transit fleet characteristics can be given. This includes dwell time functions, vehicle characteristics, and vehicle scheduling. Besides, the transit demand can be added by including an OD-matrix.

BusMezzo simulates individual buses. Every trip consists of two components: riding time between stops and dwell time at stops. The time between stops is determined by using empirical running times. A distribution function is estimated based on this empirical data. In the model, values are stochastically drawn from this distribution function. By using empirical data, congestion effects are included indirectly.

The second component is the dwell time at stops. Dwell time consists of the time needed for boarding and alighting passengers. Different dwell time functions could be included. The form and parameters should also be based on empirical data. The dwell time is a function of the number of passengers that want to board and alight at a stop, including specific parameters. Arriving passengers are based on the OD-matrix, based on empirical data. Another aspect that influences the number of passengers boarding, is the headway between buses. The higher this headway, the more passengers will board. Bus capacity is one of the vehicle characteristics, and can cause that passengers cannot board due to this capacity constraint.

It is also possible to include different holding strategies. These holding strategies determine the dispatching time of vehicles at stop, leading to holding times. Every stop could be defined as a control stop; stops where vehicles can be held.

Both scheduled-based holding and headway-based holding are holding strategies within BusMezzo. Headway-based holding is specified in different types: headway from preceding bus (forward headway), from bus behind (backward headway), or mean headway between bus in front and bus behind. In addition, different holding time constraints can be added; holding times up to the planned holding time or maximum holding times specified in absolute terms.

Since vehicle scheduling is represented in the simulation model, delays from previous trips are also taken into account. Both the schedule-based and mean-headway strategy make use of the timetable. The timetable can also be specified in BusMezzo.

Network specifications and line characteristics can be built in the model. In addition, different predefined holding strategies can be simulated. This is an advantage of BusMezzo; building the network, implementing holding strategies and including scenarios do not require advanced modelling skills.

However, this is also a side-effect, since some aspects are predefined and that makes it difficult to change settings. How these impact the outcome of the simulation, will be explained in more detail in chapter 7.

3.3.2. Holding control strategies in BusMezzo

In section 3.2 two control strategies are described. These two strategies are implemented in BusMezzo. In this section it will be explained how the prediction of the backward headway is estimated by the model.

In Figure 3.8 it is illustrated how BusMezzo calculated the mean headway. First the forward headway will be calculated: the actual arrival time of veh x minus the actual departure of the previous bus.

The headway with the next vehicle (backward headway), is estimated. This estimation makes use of the position of the vehicle and the scheduled running times between stops. The last stop that was visited by veh x+1 and the scheduled running time from that stop to stop j determines the estimated departure time of veh x+1 at stop j. Delays of vehicles are this taken into account. The interval with the next trip is therefore the difference between the actual arrival time of veh x and the expected arrival time of veh x+1. Equation 3.4 shows the calculation of the mean headway, based on both the forward and backward headway.

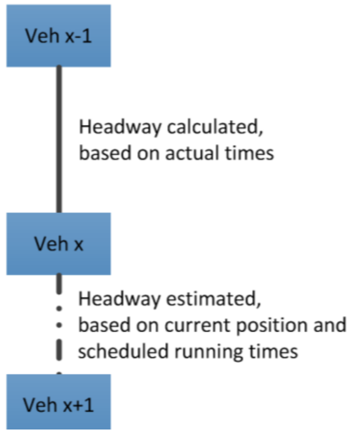

Figure 3.8 Schematic overview of the calculation of headways in BusMezzo

$$\overline{h_{jk}} = \frac{(AT_{jk} - AT_{j,k-1}) + (AT_{m,k+1} + SRT_{m,j,k} - AT_{jk})}{2} \quad (3.4)$$

Where,

$\overline{h_{jk}}$	=	Mean headway for trip *k* at stop *j*
$AT_{j,k-1}$	=	Actual arrival time of trip *k-1* at stop *j*
$AT_{m,k+1}$	=	Actual arrival time of trip *k+1* at stop *m*, which is the index of the last stop visited
$SRT_{m,j,k}$	=	Scheduled running time between stop *m* and *j for trip k*
AT_{jk}	=	Actual arrival time of trip *k* at stop *j*

Both the schedule-based and headway-based strategy use the scheduled riding time in order to determine the exit trip times. The scheduled running times are based on the 80th-percentile. This means that in 80% of all the trips, vehicles have enough time. However, there is variation in the actual running times.

It is explained how the scheduled running times are used for the estimation the backward headway. However, since the scheduled times are based on the 80th percentile, in general there is an overestimation of the interval with the next vehicle. This means that the average holding time is higher than needed. Sometimes a bus will even be held when holding is not needed, because the previous vehicle is further away than the next vehicle.

In case actual times will be used, instead of the scheduled times, more often no holding will be needed. The next trip is often faster than the scheduled time. In that case, it will also occur more often that the headway with the previous trip is larger than the trip behind. In that case holding is not needed. Therefore, less holding will be needed in practice.

In case there is no holding determined by the model, two explanations can be given. First, no holding is needed, because the bus is already positioned in the middle of its predecessor and successor. In particular when the time needed for boarding and alighting of passengers is longer, it is not possible to hold.

The second reason is when the headway between a bus and a predecessor is larger than the mean headway. In that case holding is not possible, and also not needed. In that case the bus should accelerate, if possible. Less holding will be needed, when it is possible for buses to accelerate. However, this is not possible in the model.

3.4. Sub conclusion

In this chapter the methodology is explained of how to assess holding control strategies. In Figure 3.9 an overview of the methodology is given.

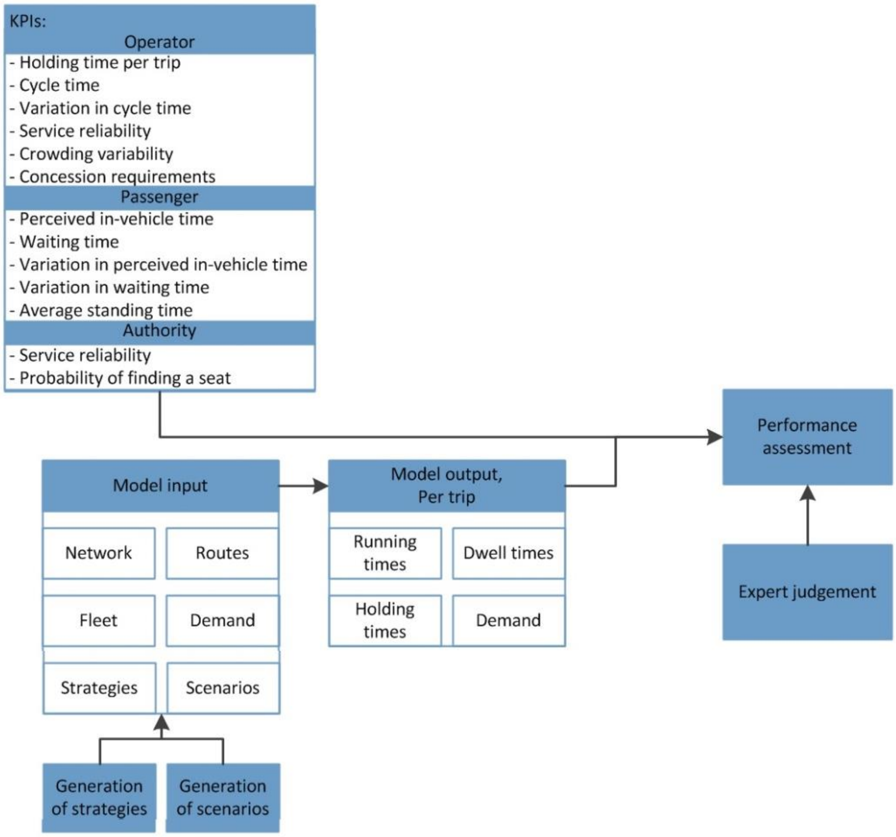

Figure 3.9 Overview of the methodology

4. Case study description

When analysing control strategies, data from real-world public transport services should be used (Strathman, et al., 2000). Therefore a case study will be used in this research in order to test the assessment framework that is explained in the previous chapter. The transport service that will be used is line 400; a high-frequency bus service between Leiden Centraal and Zoetermeer Centrum West, operated by Arriva. In this chapter, the general characteristics of this bus service will be explained in more detail in section 4.1. Additionally, in order to identify the current problems for both Arriva, the passengers and the transport authority, the current performance is analysed and will be discussed in section 4.2.

It is important to mention that this research is based on the situation and timetable of 2015-2016. In addition, the focus is on the morning peak.

4.1. Characteristics line 400

Line 400 is a R-net bus connection between Leiden Centraal and Zoetermeer Centrum West (Figure 4.1). R-net is an initiative in order to create high quality public transport in the Randstad. It is a collaboration between the public transport operators and authorities in the Randstad (Zuid-Holland, 2016). Short waiting times, service reliability and good connections to other public transport are important aspects for R-net.

Line 400 is one of the busiest lines of Arriva and is also their first R-net line. The number of passengers has grown and it is expected that this growth will continue. At this moment, there are approximately 6,000 passengers per day, from which almost 25% travels in the morning peak. Also the overall passengers' satisfaction is high (7.9/10). However, apart from the success, there are also some problems on this line. According passengers survey, the reliability of this line scores relatively low (6.8/10) (Sweers & De With, 2016). Bunching vehicles and capacity constraints are also common problems.

Figure 4.1 Geographical overview line 400 (Maartens, n.d.)

4.1.1. Line description

In total the line is approximately 14 km long, with 11 stops. In Table 4.1 characteristics of the route are shown. First the length of a route section is given. In addition it is shown whether there is a bus lane or not. In case there is a bus lane, the bus will be influenced less by other traffic. In case there is only one lane for both the bus and other traffic, the bus will be more affected. Finally, also traffic lights can have impact on the trip times.

There is also a bridge on the route of line 400: the Lammebrug, located between Station Lammenschans and Zoeterwoude A4 P+R.

Table 4.1 Route characteristics

Route section			Direction 1: to ZCW				Direction 2: to LC			
Leiden Centraal	-	Breestraat	1170 m		X		1550 m		X	
Breestraat	-	Korevaarstraat	390 m		X		230 m		X	
Korevaarstraat	-	Station Lammenschans	950 m	X	X	X	1010 m	X	X	X
Station Lammenschans	-	Zoeterwoude A4 P+R	2610 m	X	X	X	2620 m	X		X
Zoeterwoude A4 P+R	-	Zoeterwoude Dorp	1050 m		X		1030 m	X	x	
Zoeterwoude Dorp	-	Stompwijk	3350 m		X		3310 m	X	X	
Stompwijk	-	Zoetermeer Meerpolder	2510 m		X		2530 m		X	
Zoetermeer Meerpolder	-	Zoetermeer Binnenpark	440 m		X	X	390 m		X	X
Zoetermeer Binnenpark	-	Zoetermeer Woonhart	550 m	X	X	X	640 m	X	X	X
Zoetermeer Woonhart	-	Zoetermeer Centrum West	760 m			X	810 m			X

Length of the route section

Bus lane

Only one lane

Traffic light

4.1.2. Timetable

As mentioned before, this line 400 is a high-frequency service; during the morning and evening peak every 5-6 minutes a bus, during the rest of the day every 10 minutes a bus. Only before 6:00 AM and after 6:30 PM the headway is higher than 10 minutes. Since this line is a high-frequency service, it is suitable for this research.

The scheduled cycle times slightly differ per daily period. The scheduled cycle times for direction 1 differ between the 26 and 28 minutes, and for direction 2 between the 25 and 29 minutes. The scheduled times during the morning peak, the analysed period in this research, are in general 27 min for direction 1 and 29 min for direction 2. There is a turnaround time of 2 minutes at Zoetermeer Centrum West, and 4 minutes at Leiden Centraal.

4.1.3. Passenger demand

As mentioned before, line 400 is one of the busiest lines of Arriva, with respect to passengers. An overview of the twenty most important OD-pairs is given is Figure 4.2. This demand is based on the average demand in the morning peak during March 2016. The most important OD-pair is from Zoetermeer Centrum West to Leiden Centraal. In addition, from Zoetermeer Centrum West to Station Lammenschans and from the Korevaarstraat to Leiden Centraal are also important. From this figure it can be seen that direction 2 is the most important direction in the morning peak. However, from Leiden Centraal to Station Lammenschans and from Leiden Centraal to Woonhart are also frequently used OD-pairs.

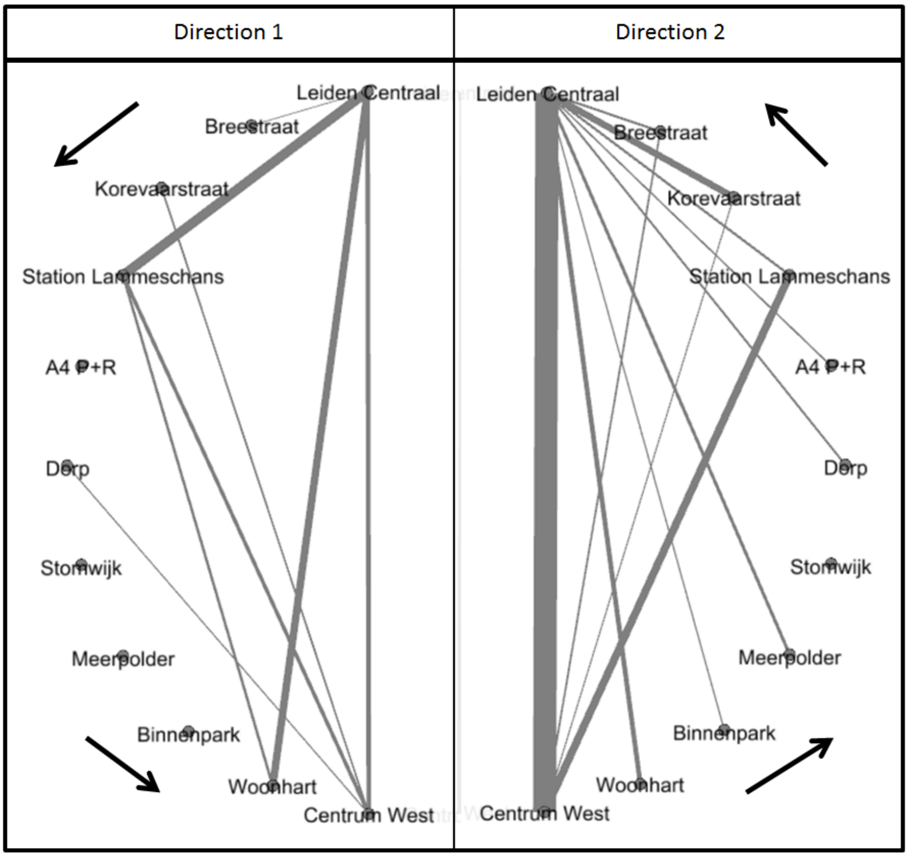

Figure 4.2 Demand representation peak period - top 20

It should be noted that the capacity of the R-net buses, used for line 400, is 80 passengers, of which approximately 40 persons can have a seat.

In direction 1 the most passengers board at Leiden Centraal, the Korevaarstraat and Station Lammenschans. The important stops for alighting passengers are Station Lammenschans, Woonhart and the final destination: Zoetermeer Centrum West. The highest average load is between the Korevaarstraat and station Lammenschans

In the opposite direction the average load is much higher, since this is the leading direction in the morning peak. It is remarkable that at the starting point of the trip, many passengers board. Zoetermeer Centrum West is the most important boarding-stop for direction 2. At every stop there is on average at least one boarding or alighting passengers.

Station Lammenschans is the first stop where many passengers alight. The third big alighting-station is the final destination. The highest average vehicle loads is between A4 P+R and Station Lammenschans.

4.2. Performance analysis: line 400

Section 4.2 (p.29-44) is confidential and therefore not visible in this version.

5. Application assessment framework

In chapter 3 an assessment framework is explained, in order to assess different holding strategies for a line. In chapter 4 the case study is introduced. At line 400 there are reliability problems, caused by variability in running times and passenger demand. In this chapter, the assessment framework will be tested by applying the framework to this case study. In Figure 5.1 the methodology is shown, highlighting the aspects that will be discussed in this chapter; the implementation of the assessment framework for the case study. First the generations of strategies and scenarios will be explained. After that, the case study will be built in the simulation model BusMezzo. In this chapter the specific data of line 400 is used as input for the model, and will be briefly explained. Finally, this chapter ends with the discussion of the model replications, model verification and validation.

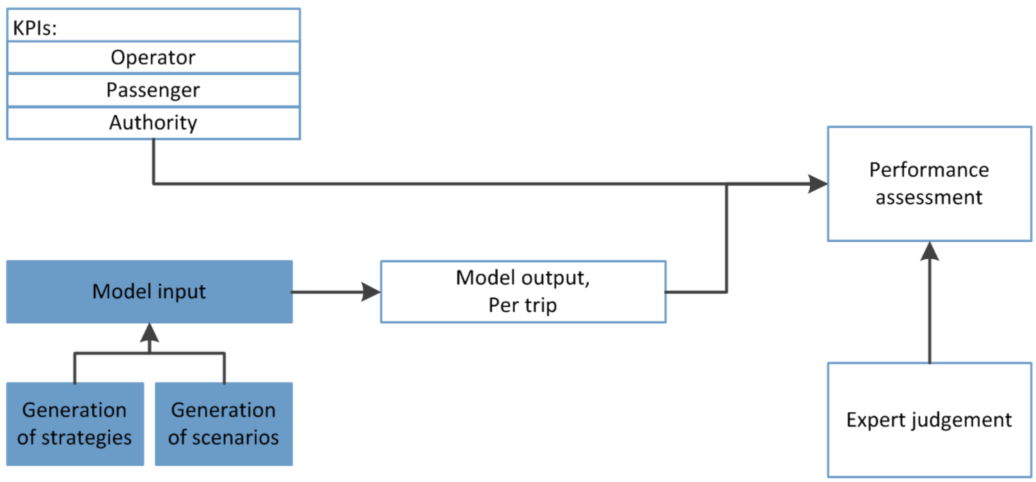

Figure 5.1 Schematic overview of the methodology

5.1. Generating strategies and scenarios

In section 3.2 it is discussed what aspects are important when generating strategies and scenarios. These aspects, for the strategy, are: the criteria, the control point(s) and the maximum holding time. The scenarios should be defined based on the options with respect to disruptions and compliance rates.

This section discusses the specific holding strategies and scenarios for the case study, line 400. A selection of strategies and scenarios is made, by choosing aspect that are of importance for line 400. The choices will be explained in this section.

Table 5.1 Options for strategy generation

Criteria	**Control points**	**Max holding time**
Schedule-based	First stop	1 min
Headway-based	Main stops	Up to planned headway
	All stops	No max
		Other

Table 5.2 Options for scenario generation

Disruptions	**Compliance rate**
Incidents	100%
Modification travel times	50%

5.1.1. Strategies

In this section the strategies applicable specifically for line 400 will be described. Choices for different options, as shown in Table 5.1 and Table 5.2, are made based on this specific situation and will be explained.

Criteria

The holding criteria determines the departure times of buses. Two types can be indicated: schedule-based and headway-based holding. Both types will be analysed in this research.

Control points

The second aspect, is the location of the control points. As mentioned before, three conditions should be considered when choosing the location of a control point. For the case study, these three conditions are examined. The first condition is that the number of through-passengers should be relatively low at control points. Every transit line has its own characteristics with respect to occupancy patterns, and whether a stop has a relatively low number of through-passengers should be based on that local situation. In this research 50% of the boarding and alighting passengers are indicated as main research stop.

The second condition is that it is physically possible to hold buses at the control stop. The stop needs to be a bay stop. Otherwise, other traffic will experience delays, because they cannot easily overtake the bus. Another aspect that is important is the possibility for buses to overtake another bus at the stop. This is crucial in case a stop is used by more bus lines.

The last condition for the selection of control points is that back and forth should be the same. This means that a selected stop should meet the first two conditions in both directions

Table 5.3 shows an overview of all the stops of line 400. Per stop it is indicated whether it fulfil the conditions mentioned above.

Table 5.3 Determining control points for line 400

Route section	Direction 1: to ZCW			Direction 2: to LC		
	Occupancy condition	Infrastrcture condition		Occupancy condition	Infrastrcture condition	
	Main stop	Bay	Other PT	Main stop	Bay	Other PT
Leiden Centraal		X			X	
Breestraat				X		
Korevaarstraat				X		
Lammenschans	X	X		X	X	
Ztw A4 P+R		X	X		X	X
Ztw Dorp		X	X		X	X
Stompwijk		X	X		X	X
Ztm Meerpolder		X	X		X	X
Ztm Binnenpark		X	X		X	X
Ztm Woonhart	X	X	X		X	X
Ztm Centrum West	X	X	X		X	X

When observing the passengers flow for route 400, it can be concluded that the most important alighting stops are Station Lammenschans, Woonhart and Zoetermeer centrum West for direction 1 and Station Lammenschans, Korevaarstraat and Breestraat in direction 2. Based on the first condition, the best control point should be at the first stop of the route. Another possibility can be at station Station Lammenschans or the Korevaarstraat, since the number of through-passengers decreases at this stop, because relatively many passengers alight here.

The second condition is that it is physically possible to hold buses at the control stop. For line 400, all the city-center stops in Leiden should be excluded: Breestraat and Korevaarstraat. It is not possible to hold buses at these stops, without delaying other traffic, because these stops are in-lane stops. Station Lammenschans is currently used as time point. Although it is a bay stop, it is not possible for buses to overtake another bus at this stop. This can cause problems, because other lines also stop here (line 3 and 45). The other stops, except from Leiden Centraal and Zoetermeer Centrum West, are bay stops, where overtaking is also not possible. However, these stops are only used by line 400 and will therefore not delay other traffic. Leiden Centraal and Zoetermeer Centrum West are also stops that are used by other bus lines, but at these stops it is possible for buses to overtake. Therefore, these stops can physically be control points.

The last condition for the selection of control points is that back and forth should be the same. This means that a selected stop should meet the first two conditions in both directions. It can be concluded that there are only two stops that meet all the three conditions: Leiden Centraal and Zoetermeer Centrum West, the first stop of every trip of line 400.

With respect to the demand pattern of line 400, Station Lammenschans could also be a possible control point. However, multiple bus lines make use of this stop and there is only place for 1 vehicle. Nonetheless, this stop is currently used by Arriva as control point.

In order to test the effect of all stops as control point, it is decided to include a strategy with all stops as control points. However, stops that have infrastructural constraints and cause delays to other traffic, are excluded: Breestraat and Korevaarstraat.

Holding time
Four options will be considered: no max, up to the planned headway and a maximum holding time of 1 and 2 minutes. In general, the planned headway is in the morning peak 5 minutes.

Conclusion: strategies
The combinations of the different choices, leads to 9 strategies, presented in Table 5.4. Some combinations are not taken into account in this research; this decision is made in consultation with the operator. It should be noted that a standard naming is applied to the strategies: 'criteria'-'control points'-'max holding time [s]'.

Table 5.4 Overview of the included strategies

Strategy		Criteria	Control points	Holding time
1.	Sched-3-no max	Schedule-based	3. LC, Station Lammenschans, ZCW	No max
2.	Sched-9-no max	Schedule-based	9. All, excl. Korevaarstraat & Breestraat	No max
3.	Hw-3-no max	Headway-based	3. LC, Station Lammenschans, ZCW	No max
4.	Hw-3-300	Headway-based	3. LC, Station Lammenschans, ZCW	Max 300
5.	Hw-3-60	Headway-based	3. LC, Station Lammenschans, ZCW	Max 60
6.	Hw-9-no max	Headway-based	9. All, excl. Korevaarstraat & Breestraat	No max
7.	Hw-9-300	Headway-based	9. All, excl. Korevaarstraat & Breestraat	Max 300
8.	Hw-9-120	Headway-based	9. All, excl. Korevaarstraat & Breestraat	Max 120
9.	Hw-9-60	Headway-based	9. All, excl. Korevaarstraat & Breestraat	Max 60

5.1.2. Scenarios
On order to test the robustness of a strategy, how sensitive a strategy is, different scenarios will be taken into account. In this section the choice for the scenarios will be explained. These choices follow from the problem analysis in chapter 4 or from conversations with drivers and planners.

One of the main points of concerns with respect to headway-based control, is how to deal with disruptions. Therefore, two disruptions will be taken into account: the opening of the Lammebrug and additional travel time at the route section between the Korevaarstraat and Station Lammenschans. It is chosen to simulate a disruption in the system caused by the opening of the bridge, because this is one infrastructural aspect that increases the unreliability at line 400. The average time the Lammebrug is open, is 4 minutes (Noordzij, n.d.). Therefore, a disruption for 4 minutes between stop Station Lammenschans and A4 P+R is included as a scenario. The opening of the bridge was one of the aspects drivers mentioned as disturbing factor on the route.

The second disruption is related to a detour that has taken place in March, as explained in section 4.2.1. Therefore, a modification of the travel time at the route section between the Korevaarstraat and Station Lammenschans will be included. This is decided in consultation with Arriva. The modification of these travel times are based on actual data; data from the first three weeks in March 2016.

The compliance rate of drivers can also be included in order to analyse the robustness of the strategies. Compliance of drivers is namely one of the concerns of planners. Two different levels are determined: 100% and 50%. A compliance rate of 100% is the ideal situation. All the drivers behave as the theory expect. However, this is not realistic. Therefore, a lower compliance rate is also included. A rate of 50% is chosen in order to explore the robustness of strategies. The complaince rate referes to the percentage of drivers that follows the holding rules. The other drivers do not follow the rules and depart without additional holding.

Conclusion: scenarios

In conclusion, 9 strategies are simulated. In addition, 3 different scenarios will be included in this research; the opening of bridge, the disruption between Korevaarstraat and Station Lammenschans and driver compliance rates of 50%. It should be noted that also different combinations are possible, but these combinations are not taken into acocunt in this research.

5.2. BusMezzo: model implementation

The input for BusMezzo consists of network, route, fleet and demand characteristics. These characteristics are specified for line 400. Actual data of March 2016 is used in order to determine line characteristics such as demand, dwell and running times. In appendix B the input will be explained in more detail.

After the case study was built in BusMezzo, it can be determined how many replications are needed. After that, model verification and validation will be discussed briefly.

5.2.1. Replications

In the simulation model different stochastic processes are included: running times, dwell times, passenger arrival and alighting processes. Therefore it is needed that the model runs multiple times in order to be able to analyse the output of the model. When multiple runs are used, an average performance can be analysed. In case only one runs is analysed, it is possible that it is accidently an extreme situation. In order to average out these extremes, multiple runs should be conducted (Cats, Burghout, Toledo, & Koutsopoulos, 2010).

It is determined that 100 replications are sufficient, based on an allowable error of 5% for the standard deviation of the line headway. In appendix C the calculation can be found.

5.2.2. Verification and validation

Verification and validation of the model is needed, before different strategies and scenarios can be implemented. In the verification step checks whether the model is built in the right way. Since BusMezzo itself is already verified, it is checked whether the case study is built in the right way. In the model every bus follows the determined path and stops at the defined stops along the line. There are no more buses than predefined. It can be concluded that the case study is built correctly in BusMezzo.

The next step is to compare the outcomes of the simulation to empirical data. This is the validation-step. Validation is done in order to analyse to what extent the behaviour of the model is comparable to the real system behaviour (Cats et al., 2010).

Empirical data is compared with outputs of the simulation. Different aspects are checked in order to determine whether the model accurately represent the real world system: the cycle times, the dwell times, headways and punctuality. In reality there is more variability than in the model, but the deviations are acceptable.

With respect to the cycle time, the model overestimates the times, with on average less than 5%. Also the average dwell times are comparable; 13 sec and 11 sec in respectively the real world and in the model. The distribution of the number of boarding and alighting passengers at the terminal stations is slightly different in the model, compared to the empirical situation. Leiden Centraal and Zoetermeer Centrum West are both train stations. The number of passengers will therefore be higher in case a train has arrived. Even when the headway between buses is very small. Therefore there is more variation is reality than showed by BusMezzo.

Headways are one of the most important aspect in this study. Therefore the distribution of the headways generated by BusMezzo should be compared to the distribution of headways in reality. This comparison can be seen in Figure 5.2. The distribution of the empirical data and the BusMezzo data are comparable. The difference is that in reality there is slightly more variation.

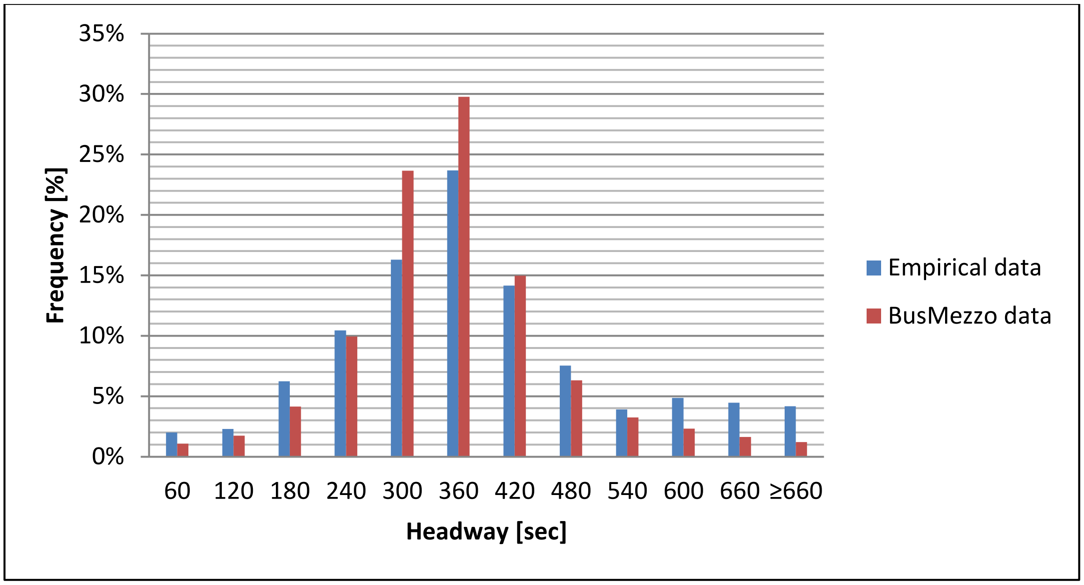

Figure 5.2 Distribution of headways for empirical and BusMezzo data

Overall, the model outcomes are comparable to the empirical data. One of the reasons why the outcomes of the model are slightly different compared the real world situation, is that driver behaviour is not included in the model. In appendix B a detailed overview of the validation can be find.

Next, the generated strategies and scenarios can be built in BusMezzo. In the next chapter the results of the simulations will be described.

6. Assessment of the holding strategies

This chapter discusses the results of the simulation of the different strategies and scenarios, as discussed in the previous chapter. The determined KPIs will be used in order to assess all the strategies. In addition, a division will be made between the different perspectives: operator, passenger and authority. Section 6.1 discusses the strategies without taking into account scenarios. The assessment of strategies, including scenarios, will be explained in section 6.2. Finally, this chapter ends by giving an overview of the main findings.

6.1. Assessing strategies: normal situation

This sections presents the results of the simulation

The discussion of the results will be divided into three sections: the operator, the passenger and the authority. First the KPIs belonging to the operator will be discussed. These KPIs are related to the supply-based performance. After it is explained what the effect of different strategies is on the performance of the bus service, based on the perspective of the operator, the effects for the passengers will be explained in more detail. Finally, the KPIs of the authority will be pointed out.

In appendix C an overview is given of all the KPIs and explained how the KPIs are calculated.

6.1.1. Operator

The control strategies are used in order to control the variation along the line and to provide a regular service. Therefore, first the CoV of the headways will be discussed, which is one of the KPIs of the operator (Table 6.1). As mentioned before, the level of service (LoS), based on the CoV, can be given in order to indicate the quality of a service with respect to regularity (TCRP, 2013). There are 6 levels; A is characterised as 'services provided like clockwork', while level F is characterised as 'most vehicles bunch'.

Table 6.1 Overview of the CoV [h] per strategy

	Headway-based							Schedule-based	
	CP: 3			CP: 9				CP: 3	CP: 9
	no max	max 300	max 60	no max	max 300	max 120	max 60	no max	no max
KPI / Strategy→	Hw-3-0	Hw-3-300	Hw-3-60	Hw-9-0	Hw-9-300	Hw-9-120	Hw-9-60	Sched-3-0	Sched-9-0
CoV [h] - 1	0.24 (B)	0.23 (B)	0.25 (B)	0.19 (A)	0.19 (A)	0.17 (A)	0.17 (A)	0.23 (B)	0.17 (A)
CoV [h] - 2	0.45 (D)	0.45 (D)	0.51 (D)	0.31 (C)	0.32 (C)	0.28 (B)	0.30 (B)	0.32 (C)	0.30 (B)
CoV[h] var - 1	A-C	A-C	A-C	A-B	A-B	A-B	A-B	A-C	A-B
CoV[h] var - 2	C-E	C-E	D-E	B-C	B-C	B-C	B-C	A-D	A-D

In direction 1 the LoS is relatively high; level A and B. The strategies with 3 control points have LoS B, while the strategies with 9 control points are able to provide a LoS A. In addition, the variation in LoS is also less: varying between LoS A and B, while the LoS varies between A and C when a strategy uses 3 control points.

In

direction 2 the LoS is lower, as result of more service variability. The best performing strategies are hw-9-120, hw-9-60, sched-9-0 (LoS B), followed by hw-9-0, hw-9-300 and sched-3-0. The worst performing strategies are the headway-based strategies with 3 control points (LoS D). Although the average LoS of sched-9-0 is relatively high, the variation along the line is higher than strategy hw-9-120 and hw-9-60.

In a situation without control, the variation of headways propagates along the route. This propagation will be interrupted after each control point. In case there are multiple control points, control is possible at every stop, adaptation is possible at every stop, leading to a lower CoV.

In Figure 6.1 the propagation of the CoV along the route is presented for every strategy with 9 control points, because these strategies have the highest LoS.

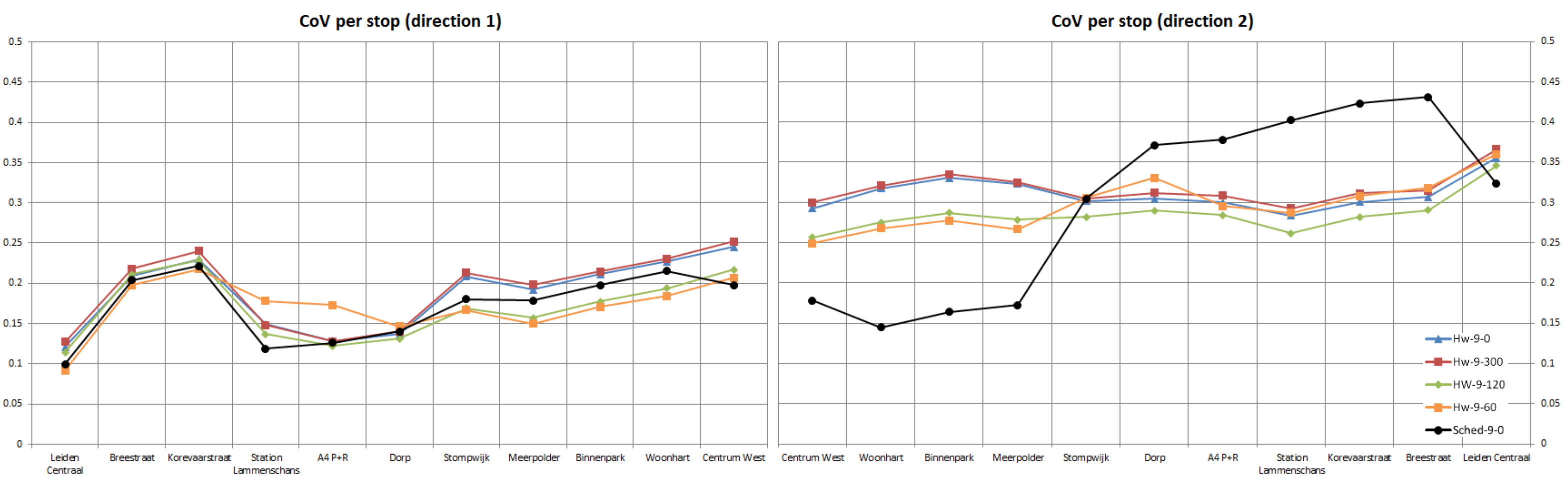

Figure 6.1 Development of the CoV of the departure headways along the line

In direction 1, holding is only possible after the Korevaarstraat. It can be seen that the CoV increases till this stop. After this stop the CoV of the headway decreases, as a result of the control possibility. After that stop, the CoV varies between the 0.12 and 0.25 (LoS A and B).

In direction 2, two things can be highlighted. First, the CoV of the headway for the schedule-based strategy starts low, but increases highly between Meerpolder and Stompwijk. At Stompwijk, 98% arrives on-time, so no holding is possible. The CoV of the headway at departure at Zoetermeer Centrum West is 0.18, while the arrival CoV of the headway at Leiden Centraal is 0.45. This is an increase from LoS A to LoS D; 'irregular headways with some bunching'.

The other aspect that should be mentioned is that the CoV for the headway-based strategies varies less, compared to the CoV of the schedule-based strategy. The CoV of the headway of headway strategy hw-9-0, hw-9-300 and hw-9-60 7 varying between LoS A and B. In addition, the initial CoV at Centrum West could be lower, in case the dispatching times at this station are also controlled.

So, although the average CoV of the headways for the different strategies are comparable, there development of this CoV along the line is very different.

The strategies with more control points score better on reliability aspects. However, the schedule-based and headway-based strategies are more or less equal to each other. This is the result of the fact that vehicles arrive in general early at control points. In addition, the variation at the origin terminals is lower for the schedule-based strategies. The headway-based strategy could perform better when the variation at the origin stops can be decreased. However, it is not possible in BusMezzo to control vehicles at the terminal, using the mean-headway-based strategy. In practice it is possible to calculate the position of the predecessor. In case the dispatch at Zoetermeer Centrum West is more controlled, the CoV of the headways will also be lower. In that case the CoV at Zoetermeer Centrum West will start with 0.1 instead of the initial CoV of 0.34.

However, although variation of headways is one of the KPIs of the operator, other aspects are also important. The other KPIs for the operator are shown in Table 6.2.

Table 6.2 Overview of the KPIs for the operator

	Headway-based							Schedule-based	
	CP: 3			CP: 9				CP: 3	CP: 9
	no max	max 300	max 60	no max	max 300	max 120	max 60	no max	no max
KPI / Strategy→	Hw-3-0	Hw-3-300	Hw-3-60	Hw-9-0	Hw-9-300	Hw-9-120	Hw-9-60	Sched-3-0	Sched-9-0
80th-percentile Cycle time [min:s] -1	27:22	27:19	27:11	28:45	28:55	28:27	27:58	27:40	28:03
80th-percentile Cycle time [min:s] -2	30:31	30:43	29:48	31:02	30:57	30:38	30:21	29:47	30:12
Cycle time variation [s] - 1	62	65	66	57	61	47	43	61	48
Cycle time variation [s] - 2	87	89	84	86	79	71	72	97	95
Average holding freq per trip [#] -1	1	1	1	3	3	3	3	1	2
Average holding freq per trip [#] -2	1	1	1	2	2	2	2	1	1
Average control time per trip [s] -1	53	51	33	137	140	123	99	74	116
Average control time per trip [s] -2	113	117	43	123	118	106	86	27	46
Average load deviation [# pas] - 1	3	3	3	3	3	3	3	3	3
Average load deviation [# pas] - 2	7	7	8	6	6	6	6	5	5

For the operator, one of the main aspects is the 80th-percentile cycle time, because this determines the number of vehicles needed for a certain level of service. Although there are differences between the 80th-percentile cycle times per strategy, almost all the strategies needs 12 buses in order to provide a service with headways of 5 minutes, taking into account at least 1 minute turnaround time at Leiden Centraal. Only hw-9-0, hw-9-300 and hw-9-120 need 13 buses. When using the currently used turnaround times of 2 minutes at ZCW and 4 minutes at Leiden Centraal, these strategies need 14 buses, while the others can provide a 5 min headway-service with 13 buses.

The variation in cycle times is also important, since less variation increases the efficiency for the operator. The variation in cycle times is, in general, lower for all the headway-based strategies, compared to the schedule-based strategy. Especially for direction 2. The best performing strategies, with respect to cycle time variation, are the strategies hw-9-120, hw-9-60 and sched-9-0, for direction 1. However, in direction 2, this schedule-based strategy has more variation in cycle times. In this direction less vehicles are early, resulting in less control possibilities. This leads to more variation.

The holding time is an important determinant of the cycle times. However, the longer the holding times, the more discipline is needed from drivers. On average, the holding time is less than 60 s per stop. However, in case of the strategies hw-3-0 and hw-3-300, the holding time is on average almost 2 minutes. This is not preferred by drivers.

Finally, the last aspect for the operator, related to efficient use of capacity: the average load deviation. In direction 1 there are no differences. Also in direction 2 the differences are small. The best performing strategies with respect to the load deviation are the schedule-based strategies. This is the result of the high regularity at ZCW. Most passengers board at this stop, and therefore more regularity at this stop lead to less load deviation at this stop, influencing the most important part of the occupancy rate of the bus.

Conclusion: Operator

In conclusion, more control per trip lead to a lower CoV of the headways, and this to a higher quality of the service. The cycle time increases as a result of the increased control, but the variation of the cycle time decreases. However, in direction 1 the vehicles arrive in general early, which makes holding possible. In that case, when the strategy is schedule-based, the headways are equal to the scheduled headways. This means that there is less variation. In that case, when vehicles arrives early, schedule-based control is comparable to headway-based control, and slightly performs better in terms of number of controls, average holding time per trip and cycle times.

However, in case vehicles do not arrive early, schedule-based control cannot control anymore. This is the case in direction 2. Then headway-based control performs better. The cycle time increases slightly, as a result of the longer average holding times per trip, but the variation decreases. In addition, the CoV of the headways stays relatively equal along the route. Headway-based control at all control points is able to control the irregularity at a line. It is able to control, regardless the timetable.

In addition, the performance, when using headway-based strategies, could be improved in case control at ZCW is possible. The quality of the service would increase from LoS A to B. Another aspect of holding strategies is that the calculated of the holding times needs estimation of the backward headway. There is always some uncertainty in this estimation, and therefore this holding time is not always optimal. Schedule-based strategies do not have this problem, since the schedule is a clear boundary.

Cycle times are important for the operator, because it determines the number of buses needed, in case the frequency of a line is predefined. The minimum required number of buses is in every strategy 12, except for hw-9-0, hw-9-300 and hw-9-120. In case the currently used turnaround time of 6 minutes is used, every strategy needs an extra bus in order to keep the headways at 5 minutes.

In direction 1 there is more slack in the timetable, compared to the opposite direction. In direction 1 the performance of strategies sched-9-0 and hw-9-60 are the same. In direction 2, these two strategies are also more or less comparable. However, there is more variation in cycle time when using strategy sched-9-0 (95 s compared to 72 s for hw-9-60). This is caused by less slack in direction 2.

In conclusion, hw-9-60 is the best strategy for the operator. This strategy is better able in dealing with variations along the route, without the need of a timetable. In addition, less buses are needed, compared to the other headway-strategies, since the cycle time is lower. However, this depends also on the needed turnaround time. However, it should be noted that the differences with sched-9-0 are small.

6.1.2. Passengers

Five aspects were determined to be important for passengers: the waiting time, the in-vehicle time, the variations of both times and the level of comfort. In appendix C an overview is given of these KPIS, including an explanation of every KPI. The CoV of the headways is also shown in the overview for the passengers. Although it is not directly important for passengers, this KPI can explain different KPIs.

Table 6.3 Overview of the KPIs for passengers

	Headway-based							Schedule-based	
	CP: 3			CP: 9				CP: 3	CP: 9
	no max	max 300	max 60	no max	max 300	max 120	max 60	no max	no max
KPI / Strategy→	Hw-3-0	Hw-3-300	Hw-3-60	Hw-9-0	Hw-9-300	Hw-9-120	Hw-9-60	Sched-3-0	Sched-9-0
PAIVT [min:s] - 1	13:09	13:09	13:12	14:02	14:02	13:54	13:42	13:25	13:47
PAIVT [min:s] - 2	18:11	18:17	18:03	18:17	18:16	18:04	17:53	17:34	17:41
AIVT [min:s] - 1	15:17	15:16	15:19	16:18	16:18	16:08	15:54	15:33	15:59
AIVT [min:s] - 2	19:15	19:25	19:01	19:48	19:43	19:37	19:25	18:55	19:06
EWT [s] - 1	5	5	5	6	6	5	4	8	8
EWT [s] - 2	26	26	30	12	12	9	10	16	16
Average standing per passenger [s] - 1	0	0	0	0	0	0	0	0	0
Average standing per passenger [s] - 2	7	7	9	4	4	4	2	3	3
RBT_in-veh [s] -1	150	155	157	175	177	169	167	163	162
RBT_in-veh [s] -2	311	322	307	239	246	212	232	236	228
RBT_waiting [s] - 1	54	57	57	53	53	46	45	60	51
RBT_waiting [s] - 1	107	108	119	84	87	76	78	82	77

When discussing the results of the simulation with respect to the passengers' perspective, direction 1 and 2 are discussed separately. There is more variation in direction 2, and also more passengers that will experience this variation. In direction 1 there is less variation, and also less passengers travelling in this direction. Therefore the results are different for the two directions. First direction 1 will be discussed, followed by direction 2. After that it will be explained what the best strategy is for passengers.

Direction 1

The perceived average in-vehicle time (PAIVT) is the lowest for the strategies with 3 control points. The trip times are lower, and the offered capacity is sufficient.

Another aspect that is important for passengers is related to the variation of the in-vehicle time. This variation is expressed in the budgeted in-vehicle time, which is the difference between the 50th- and 95th-percentile. The best scoring strategies are the headway-based strategies with 3 control points. Worst scoring strategies are hw-9-0 and hw-9-300.

Excess waiting time (EWT) is a KPI in order to indicate the extra waiting time passengers have to wait, based on the planned waiting time. The planned waiting time is 2.5 minutes, since the scheduled headway is 5 minutes. The EWTs of the schedule-based strategies are higher than the headway-based strategies. However, these differences are relatively low (varying between the 4 and 8 s).

Also the budgeted waiting time is calculated. The strategies with the lowest budget waiting times are the strategies hw-9-120, hw-9-60 and sched-9-0. The waiting times are related to the variation of headways, and therefore these results are comparable to the results of the CoV of the headways.

In order to be able to compare the strategies from a passenger perspective, the total experienced travel time is calculated, consisting of the weighted travel time components.

Table 6.4 Total experienced travel time per passenger - direction 1

	Headway-based							Schedule-based	
	CP: 3			CP: 9				CP: 3	CP: 9
	no max	max 300	max 60	no max	max 300	max 120	max 60	no max	no max
KPI / Strategy→	Hw-3-0	Hw-3-300	Hw-3-60	Hw-9-0	Hw-9-300	Hw-9-120	Hw-9-60	Sched-3-0	Sched-9-0
Total experienced travel time [min:s] - 1	22:38	22:47	22:53	23:55	23:56	23:24	23:08	23:24	23:26

For passengers, the best strategy, with the lowest experienced travel time, is hw-3-0. The headway-based strategies are in general better than the schedule-based strategies, expect from the strategies hw-9-0 and hw-9-300 (see Table 6.4).

Direction 2

In Table 6.5 the KPIs and the values for direction 2 are shown. First aspect that can be seen is that the headway-based strategies with 3 control points performs worse from passengers perspective: more in-vehicle times variation, longer waiting times, more variation in waiting times and longer average standing times. So, although the average trip times are lower using these strategies, the variation is more, which is also not desired by passengers.

In direction 2 crowding effects influence the PAIVT. In this direction more passengers board. Therefore it is more important to keep even headways, in order to distribute passengers equally over the vehicles. The schedule-based strategies have the lowest PAIVT. In particular caused by the lower variation at the terminal, which is the most important boarding stop. With respect to the EWTs, the headway-based strategies with 9 control points scores better than the schedule-based variants. The reason that the EWT in the schedule-based variants is lower, compared to the headway-based strategies with 9 control points, is the fact that the irregularity increases more along the line. Based on the variation in in-vehicle times and waiting times, the three best performing strategies are hw-9-120, hw-9-60 and sched-9-0. The average standing times are comparable; varying between the 2 and 4 s. Only the headway-based strategies with 3 control points score relatively high, as mentioned above.

Table 6.5 Overview of the KPIs for passengers - direction 2

	Headway-based							Schedule-based	
	CP: 3			CP: 9				CP: 3	CP: 9
	no max	max 300	max 60	no max	max 300	max 120	max 60	no max	no max
KPI / Strategy→	Hw-3-0	Hw-3-300	Hw-3-60	Hw-9-0	Hw-9-300	Hw-9-120	Hw-9-60	Sched-3-0	Sched-9-0
PAIVT [min:s] - 2	18:11	18:17	18:03	18:17	18:16	18:04	17:53	17:34	17:41
AIVT [min:s] - 2	19:15	19:25	19:01	19:48	19:43	19:37	19:25	18:55	19:06
PAIVT variation [s] -2	130	132	133	109	116	107	109	121	117
EWT [s] - 2	26	26	30	12	12	9	10	16	16
Average standing per passenger [s] - 2	7	7	9	4	4	4	2	3	3
RBT_PAIVT [s] -2	311	322	307	239	246	212	232	236	228
RBT_waiting [s] - 1	107	108	119	84	87	76	78	82	77

Also for direction 2 the total average experienced travel time per passenger is calculated, see Table 6.6. The worst performing strategies, from passengers' perspective, are the headway-based strategies with 3 control points. The best performing strategies are hw-9-120, hw-9-60, sched-3-0 and sched-9-0.

Table 6.6 Total experienced travel time per passenger - direction 2

	Headway-based							Schedule-based	
	CP: 3			CP: 9				CP: 3	CP: 9
	no max	max 300	max 60	no max	max 300	max 120	max 60	no max	no max
KPI / Strategy→	Hw-3-0	Hw-3-300	Hw-3-60	Hw-9-0	Hw-9-300	Hw-9-120	Hw-9-60	Sched-3-0	Sched-9-0
Total experienced travel time [min:s] - 2	32:48	33:07	33:08	30:27	30:40	29:27	29:40	29:46	29:33

Conclusion: Passengers

In conclusion, from passengers perspective there are different strategies that are the best. In direction 1 the strategy hw-3-0 is the best performing strategy, while this is one of the worst performing strategies in direction 2. Therefore 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 scores relatively high in both directions. Therefore, from passengers perspective this strategy should be chosen. However, the differences are minimal; maximum of 20s.

One important aspect that should be mentioned, is that BusMezzo generates passengers based on the headways. In case the headways are higher, more passengers will board and vice versa. However, in reality this is not always the only aspect that influence the number of boarding passengers. In case a train of the Randstadrail arrives at Zoetermeer Centrum West, more passengers will board, even when the headway is very low. This could influence the results.

From passengers perspective, the headway-based strategies with only 3 control points are the worst performing strategies. Especially in direction 2. 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.

6.1.3. Authority

Important aspects for the authority are trip cancellation, reliability (punctuality/regularity), probability of finding a seat, and denied boarding. These aspects are currently included in most of the concessions. First the denied boarding will be elaborated. Since all the passengers are able to board, irrespective of the strategy, this KPI will not be discussed any further. Also trip cancellation will not be taken into account, because the simulation model cannot take into account trip cancellation.

The punctuality, both arrival and departure, are presented in Table 6.7. In the concession requirements, only a few stops are taken into account in the calculation of punctuality. For line 400 this are the terminal stations: Leiden Centraal and Zoetermeer Centrum West. However, station Lammenschans is also an important transfer station. Therefore, although not explicitly mentioned in the concession, this station will also be reviewed with respect to punctuality.

The second aspect that in general is included as requirement, is guarantee seats to passengers. Despite the fact that peak hours are neglected when determining the share of passengers that are able to find a seat, this KPI is included in this research.

First some remarks about the punctuality in case of the schedule-based strategies. On-time departure at Station Lammenschans in direction 2 does not meet the norm of 85%. At least 17% of the trips depart late from this stop. However, more than 85% of the trips arrives on-time at Leiden Centraal-2. Another aspect that is remarkable, is that in case of schedule-based holding at all stops, the punctuality norm at Station Lammenschans – 2 will not be met.

The arrival punctuality-norms are met for the strategies with 3 control points. The trip times are relatively low and the trips will therefore not arrive late at the stops. However, the departure-punctuality is worse, because trips depart before the scheduled times.

For the strategies with more control points, the travel times are higher and therefore the arrival punctuality do not met the norms. Since there is no adaption to the timetable at Zoetermeer Centrum West, the trips with headway-based control do not meet punctuality norms in direction 2.

Based on this result, it can be stated that in case a shift will take place to headway-based control, punctuality requirements should be replaced by regularity requirements. In general the punctuality norms cannot be met, but this does not necessarily indicate a worse performing service. In chapter 8 this transfer from punctuality indicators to regularity indicators will be discussed in more detail.

Another aspect that is important for the operator, is guaranteeing seats for passengers. For direction 1 there are no differences between the strategies; all passengers will have a seat. The headway-based strategies with more control points are best able to guarantee seats, since the share of passengers that find a seat is the highest in these strategies.

Table 6.7 Overview KPIs transport authority

	Headway-based							Schedule-based	
	CP: 3			CP: 9				CP: 3	CP: 9
	no max	max 300	max 60	no max	max 300	max 120	max 60	no max	no max
Strategy→ KPI	Hw-3-0	Hw-3-300	Hw-3-60	Hw-9-0	Hw-9-300	Hw-9-120	Hw-9-60	Sched-3-0	Sched-9-0
On-time arrival [%]									
Leiden Centraal - 1	-	-	-	-	-	-	-	-	-
Station Lammenschans - 1	100%	100%	100%	99%	99%	94%	100%	100%	100%
Zoetermeer Centrum West - 1	99%	100%	100%	94%	93%	98%	100%	99%	99%
Zoetermeer Centrum West -2	-	-	-	-	-	-	-	-	-
Station Lammenschans - 2	87%	86%	89%	43%	44%	58%	70%	87%	82%
Leiden Centraal - 2	95%	95%	96%	83%	82%	91%	95%	98%	98%
On-time departure [%]									
Leiden Centraal - 1	100%	100%	100%	99%	99%	94%	99%	100%	100%
Station Lammenschans - 1	47%	39%	33%	50%	46%	39%	35%	100%	100%
Zoetermeer Centrum West - 1	-	-	-	-	-	-	-	-	-
Zoetermeer Centrum West -2	43%	39%	34%	78%	77%	78%	75%	99%	99%
Station Lammenschans - 2	65%	66%	53%	22%	21%	33%	55%	83%	76%
Leiden Centraal - 2	-	-	-	-	-	-	-	-	-
Probability of finding a seat [%] -1	100%	100%	100%	100%	100%	100%	100%	100%	100%
Probability of finding a seat [%] -2	96%	96%	96%	98%	98%	99%	98%	98%	98%
PRDM [%] - 1	19%	18%	20%	13%	14%	12%	13%	17%	12%
PRDM [%] - 2	35%	36%	41%	23%	24%	21%	22%	24%	22%

In conclusion, the authority prefers the strategies with 9 control points, because then the service is more regular and more passengers can find a seat. The best strategy, from the perspective of the authority, is hw-9-120. However, in that case the punctuality requirements needs to be replaced by regularity requirements.

One important aspect that can be highlighted, using average values for the irregularity on a line does not show the differences of the development of the regularity on a line. The average PRDM is equal between hw-9-120, hw-9-60 and sched-9-0, while the development is different.

In this section the different strategies are compared to each other. The normal situation is the basis. However, it is also interesting to know how robust strategies are with respect to different uncertainties. In the next sections, first the timetable will be adapted. The impact of the timetable on the performance of the strategies will be discussed in the next section. After that, several scenarios are implemented in the model and the strategies are again compared. Section 1.3. discusses the results of these scenario simulation.

6.2. Assessing strategies: lower scheduled running times

BusMezzo uses the timetable to calculate holding times. Since most trips arrive early (before the scheduled departure time), schedule-based holding is possible. In that case, schedule-based holding is comparable to headway-based holding, as showed in the previous section.

Also headway-based strategies make use of the timetables. As mentioned before, headway holding times are determined by calculating the mean headway between the bus in front and bus behind. The headway between a bus and its successor is estimated, based on the scheduled running times. Too loose schedule running times can lead to longer holding times than needed.

In order to analyse what happens in case the schedule is tighter, the running times in the timetable are adapted. Normally the 80^{th}-percentile times are used to determine the timetable times. An adaptation is made by taking the 20^{th}-percentile of the trip times between stops. Actual data of line 400 is used for this. In this section, the situation based on the 20^{th}-percentile trip times is referred to as 'new situation'. The 'initial situation' is the case where the timetable is based on the 80^{th}-percentile trip times.

Since it is expected that this change of the timetable influence the holding times, the average holding times will be compared to the initial situation. Per trip there is less holding, and also the holding time is lower. As expected, for the headway-based strategies, the holding time is lower, because of the underestimation of the headways with a bus behind. In case of the schedule-based strategies, less control is possible, because less vehicles arrive before the scheduled time at a stop. The highest decline in holding time per trip is for sched-9-0; 62% and 54% for direction 1 and 2. The cycle times, however, do not change excessive; average increase of 20 s with a maximum of 1 minute. A change is in particular visible in the variation in cycle times.

Table 6.8 Changes in control times, from initial situation to new situation

	Headway-based							Schedule-based	
	CP: 3			CP: 9				CP: 3	CP: 9
	no max	max 300	max 60	no max	max 300	max 120	max 60	no max	no max
Strategy→ KPI	Hw-3-0	Hw-3-300	Hw-3-60	Hw-9-0	Hw-9-300	Hw-9-120	Hw-9-60	Sched-3-0	Sched-9-0
Average control time per trip-1	-33%	-30%	-15%	-34%	-35%	-31%	-25%	-38%	-62%
Average control time per trip-2	-12%	-14%	-4%	-16%	-11%	-9%	-7%	-48%	-54%

More variation in the cycle times lead to more variation in headways. The CoV of the headways increases as well. Especially for the schedule-based strategies in direction 1. In direction 2 the variation increases less, because in the initial situation there was also less holding possible. However, in terms of Level of services, the LoS of the strategies hw-9-120 and hw-9-60 decrease one level. In direction 1 only sched-9-0 decreases from level B to C (see Table 6.9).

Table 6.9 CoV [h] in the new situation

	Headway-based							Schedule-based	
	CP: 3			CP: 9				CP: 3	CP: 9
	no max	max 300	max 60	no max	max 300	max 120	max 60	no max	no max
Strategy→ KPI	Hw-3-0	Hw-3-300	Hw-3-60	Hw-9-0	Hw-9-300	Hw-9-120	Hw-9-60	Sched-3-0	Sched-9-0
CoV - 1	0.26 (B)	0.26 (B)	0.26 (B)	0.20 (A)	0.19 (A)	0.19 (A)	0.18 (A)	0.29 (B)	**0.29 (B)**
CoV - 2	0.47 (D)	0.48 (D)	0.52 (D)	0.32 (C)	0.31 (C)	**0.31 (C)**	**0.32 (C)**	0.33 (C)	**0.33 (C)**

In Figure 6.2 the development of the CoV of the headways is shown, for both the new situation (Timetable based on the 20th-percentile running times) and the initial situation (timetable based on the 80th-percentile running times).

For most strategies the development in both situations is comparable. Only, for direction 1 the development of the CoV for the schedule-based strategies is really different. Buses arrives late at stops and holding is not possible. Therefore a continuous growth of the CoV is visible. As a result of the turnaround times, the variation at the terminal stops decreases.

The headway-based strategies are less sensitive to the timetable. Although the holding times are dependent on this, control is still possible at stops. Resulting in less variation of headways along the line.

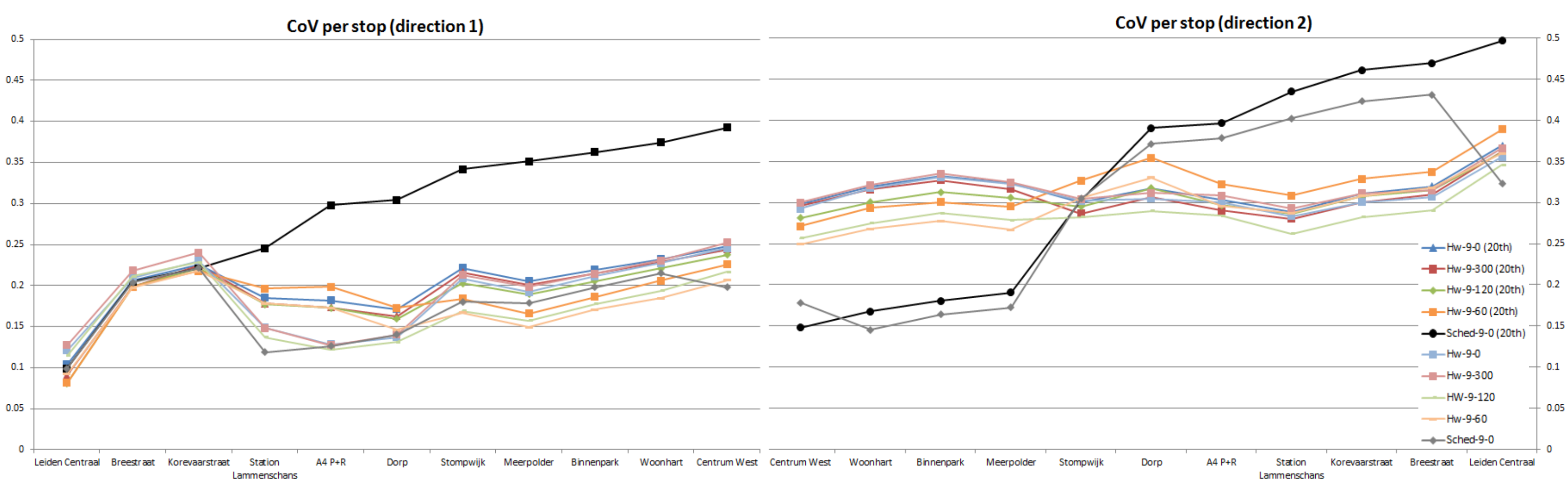

Figure 6.2 Development of CoV of the headways for both the new and initial situation

The development of the CoV of sched-9-0 is comparable in both situations, because in the initial situation vehicles also arrived late.

One important remark that should be made is as follows; in direction 1 the schedule-based strategy is not able in controlling the vehicles. However, this also leads to lower trip times, meaning that the turnaround time at ZCW is enough in order to reset the vehicles. So, although the variation increases along the line in direction 1, the turnaround time at ZCW could reset the buses. Subsequently, the vehicles can depart according to schedule, which is regular again. Since most passengers board at the terminal, the impact on passengers will not change heavily in this scenario (Table 6.10).

Table 6.10 Total experienced travel time per passenger: new situation

	Headway-based							Schedule-based	
	CP: 3			CP: 9				CP: 3	CP: 9
	no max	max 300	max 60	no max	max 300	max 120	max 60	no max	no max
Strategy→ KPI	Hw-3-0	Hw-3-300	Hw-3-60	Hw-9-0	Hw-9-300	Hw-9-120	Hw-9-60	Sched-3-0	Sched-9-0
Total experienced travel time [min:s] - 1	22:49	22:54	22:38	23:20	23:17	23:11	22:53	23:27	23:17
Total experienced travel time [min:s] - 2	33:45	33:18	33:23	30:36	30:17	30:08	29:58	29:54	29:00

In conclusion, the timetable is very important for schedule-control. If there is no slack in the scheduled times, control is not possible. As mentioned in the introduction, control is desirable with respect to the instability of the system. This instability is also visible in Figure 6.2 , since the irregularity increases along the line in case there is no control.

On the other hand, headway-based control is less sensitive to the timetable. However, headway-based strategies could probably be optimised in case actual travel times can be used, instead of scheduled times.

6.3. Assessing strategies: scenarios

In this section different scenarios are simulated in order to test the sensitivity of strategies. It should be noted that the timetable during this simulation, again, is based on the 80th-percentile trip times.

- A travel time disruption is included; the travel times between the stops Korevaarstraat and Station Lammenschans are higher
- A disruption caused by infrastructural constraints; the opening of a bridge between Station Lammenschans and A4 P+R
- Decrease of the compliance rate of drivers towards 0.5; 50% of the drivers do not comply with the holding rules.

The scenarios are only applied to the strategies with 9 control points. In the previous sections it appears that less control points cannot inadequately control the variability of running and dwell times. Therefore it is chosen to analyse only the strategies with more control points.

6.3.1. Disruption

First the scenario with the travel time disruption will be explained. The modification of the trip times are based on actual data. In the first three weeks of March 2016, there was a detour, as a result of construction works on the Jan van Houtbrug. The distribution of the travel times, due to this detour, are used in the simulation model. On average the times on this route section were 1.5 and 3 times higher in respectively direction 1 and 2.

Operator

First the consequences of a disruption for the operator will be discussed. In Table 6.11 the KPIs for every strategy is shown.

Table 6.11 KPIs operator: disruption

	Headway-based				Schedule-based	
	CP: 9				CP: 3	CP: 9
	no max	max 300	max 120	max 60	no max	no max
KPI / Strategy→	Hw-9-0	Hw-9-300	Hw-9-120	Hw-9-60	Sched-3-0	Sched-9-0
Average holding freq per trip-1	2	2	2	2	1	1
Average holding freq per trip-2	2	2	2	2	1	1
Average control time per trip [s] -1	174	176	156	127	74	84
Average control time per trip [s] -2	132	127	121	96	27	51
80th-percentile Cycle time [min:s] -1	31:17	31:19	30:45	30:14	29:16	29:11
80th-percentile Cycle time [min:s] -2	36:09	36:11	36:08	35:46	35:03	35:14
Cycle time variation [s] - 1	98	99	91	90	106	88
Cycle time variation [s] - 2	100	100	95	104	119	103
CoV [h] - 1	0.37 (C)	0.38 (C)	0.36 (C)	0.43 (D)	0.58 (E)	0.55 (E)
CoV [h] - 2	0.41 (D)	0.42 (D)	0.39 (C)	0.49 (D)	0.68 (E)	0.63 (E)
Average load deviation [# pas] - 1	6	5	3	6	13	19
Average load deviation [# pas] - 2	7	5	4	5	25	34

All the headway-control strategies have, on average, more holding time per trip. The schedule-based strategy can apply less control in direction 1. The disruptions starts before the first control point on the line. Less vehicles arrive early and therefore less control is possible. In the opposite direction there is a smaller change in holding time, compared to the initial situation. The disruption starts after the last control point in that direction. For the headway-based strategies there is more holding time, in both direction. The reason is that there is more variability and therefore more control needed.

The variation in headways increases for all strategies. However, the CoV of the schedule-based strategy increases the most.

In Table 6.11 an overview is given of the scores per KPI. With respect to the times, the scheduled-based strategy performs better: less control, resulting in lower cycle times. The schedule-based variants needs 13 buses in order to be able to provide a service with headways of 5 minutes, while the headway-based strategies would need 14 buses. However, since only 12 buses are available, resulting in higher headways and lower frequencies. The variation in cycle times is also slightly lower for direction 1.

However, with respect to controlling the irregularity on a route, headway-based strategies are better able to do that in case of a disruption. Figure 6.3 shows the development of the CoV of the headways along the line. The irregularity in case of the schedule-based strategy is very high. Also, the irregularity only increases along the line. The irregularity along the line in case of the headway-based strategies is also relatively high, compared to the initial situation. The reason is that there is no control at the terminal stops. In the model a headway of 5 minutes is used as regulation headway. However, as a result of this disruption, a headway of 5 minutes is not possible for all the buses, since there are nog enough buses for that frequency. The cycle time increases, and therefore the frequency has to be lower, because the number of buses cannot change. The headway control steers towards higher headways between buses.

The headway strategies are able to decrease the irregularity along the line; some better than others. The strategies with higher maximum holding times can better steer towards a more regular service in case of larger disruptions. The best strategy is hw-9-120. In both directions the LoS is C; ‘vehicles often off headway’. The LoS of the other strategies is at least one LoS higher. The LoS of the schedule-based strategies is E: ‘frequent bus bunching’.

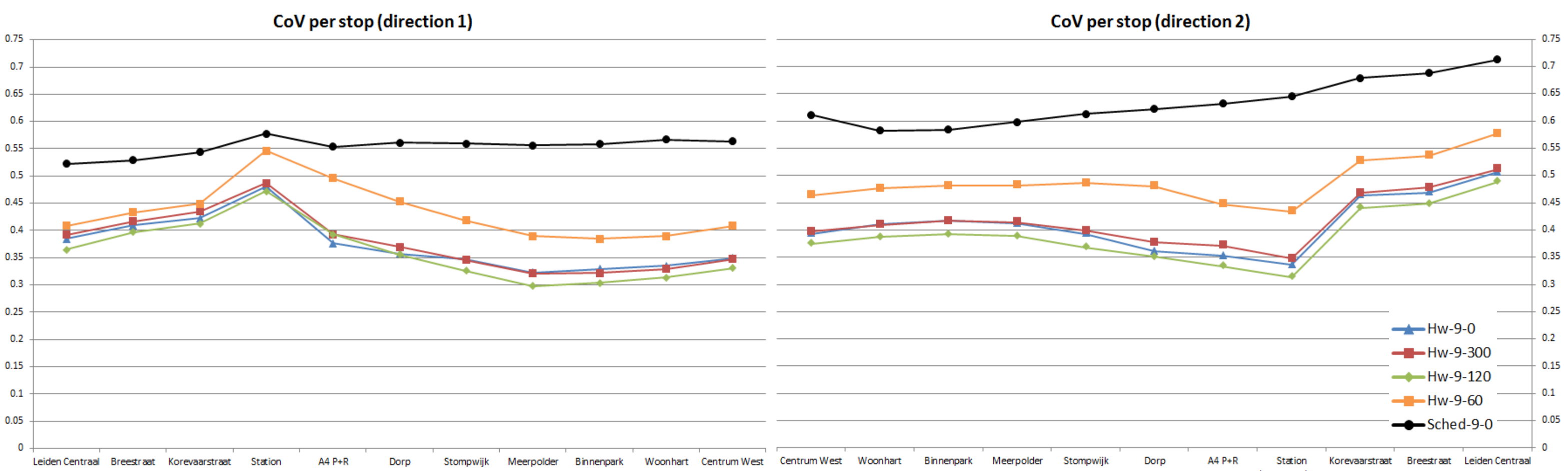

Figure 6.3 Development CoV of the headways per strategy: disruption

In conclusion it can be said that the headway-based strategies with more control points are best in regulating a disruption in the system. Particularly schedule-based strategies are not able to control the irregularity in case the disruption leads to late arrival times of vehicles at stops. The cycle times are lower in case of the schedule-based strategy. However, this is not beneficial for the operator, since the deviation of the planning is already high. The headway-based strategy is able to regulate the service, with the buses that are available.

Passengers

Next, the impact on passengers in case of disruptions. In Table 6.12 an overview of the KPIs for the passengers is given. The running times are an important determinant of the perceived average in-vehicle times (PAIVT). However, one remarkable aspect: the PAIVT in direction 1 is higher in case of schedule-based holding compared to the other PAIVTs in the same direction. This indicates that the vehicles are crowded. In particular since the AIVT is lower than those of the other strategies. The fact that it is more crowded can be confirmed by the high value of the average standing time (AST). The AST is much higher for the schedule-based variant, compared to the headway-based ones.

Besides the perceived in-vehicle times, the average waiting times is also lower in case of the headway-based strategies. The EWT in on average at least 1.5 and 2 times higher in case of the schedule-based strategies, compared to the headway-based variants.

Table 6.12 KPIs passengers: disruption

	Headway-based				Schedule-based	
	CP: 9				CP: 3	CP: 9
	no max	max 300	max 120	max 60	no max	no max
KPI / Strategy→	Hw-9-0	Hw-9-300	Hw-9-120	Hw-9-60	Sched-3-0	Sched-9-0
PAIVT [min:s] - 1	911	908	894	883	855	865
PAIVT [min:s] - 2	1330	1323	1322	1323	1347	1346
AIVT [min:s] - 1	17:27	17:22	17:08	16:56	16:19	16:30
AIVT [min:s] - 2	23:04	23:04	23:04	22:43	22:14	22:40
EWT[s]- 1	36	37	35	38	61	51
EWT[s]- 2	31	31	29	37	81	64
RBT_in-veh [s] -1	220	223	204	207	221	206
RBT_in-veh [s] -2	385	387	344	426	547	552
RBT_waiting [s] - 1	126	130	126	148	169	162
RBT_waiting [s] - 1	113	115	107	142	187	181
Average standing per passenger [s] - 1	0	0	0	0	1	0
Average standing per passenger [s] - 2	25	24	21	34	55	52

For passengers the schedule-based strategies performs worse compared to the headway-based strategies. In both directions, strategy hw-9-120 performs best. The total average perceived travel time per passengers is approximately 1 minute and 8 minutes lower than the schedule-based strategies, in respectively direction 1 and 2 as (see Table 6.13). This is in particular caused by the more even distributed passengers. The fact that the perceived times are higher than the actual times lead to the higher travel times for passengers in case of schedule-based holding.

Table 6.13 Total experienced travel time per passenger - disruption

	Headway-based				Schedule-based	
	CP: 9				CP: 3	CP: 9
	no max	max 300	max 120	max 60	no max	no max
KPI / Strategy→	Hw-9-0	Hw-9-300	Hw-9-120	Hw-9-60	Sched-3-0	Sched-9-0
Total experienced travel time [min:s] - 1	29:15	29:24	28:40	29:23	30:36	29:57
Total experienced travel time [min:s] - 2	38:22	38:22	37:19	40:06	45:30	44:48

Authority

In Table 6.14 an overview of the KPIs for the operator are given, in case of a disruption. As a result of this disruption, vehicles have longer trip times. Therefore, not surprisingly, punctuality norms will not be met. Since the delays are that large, turnaround times are insufficient in order to be able to be on time again for the next trip. For example, the turnaround time at Leiden Centraal is 240 sec, but 50% of the trip arrive more than 286 sec late. These trips will also depart too late.

With respect to the probability passengers are able to find a seat, the headway-based strategies scores better than the schedule-based strategy. Approximately 95% of the passengers are able to find a seat, compared to 91% in the schedule-based variant. This is caused by the fact that the irregularity on the line is higher.

Table 6.14 Overview of the KPIs for the operator in case of disruptions

	Headway-based				Schedule-based	
	CP: 9				CP: 3	CP: 9
	no max	max 300	max 120	max 60	no max	no max
KPI Strategy→	Hw-9-0	Hw-9-300	Hw-9-120	Hw-9-60	Sched-3-0	Sched-9-0
On-time arrival [%]						
401	-	-	-	-	-	-
404	59%	60%	58%	66%	87%	73%
411	32%	32%	39%	46%	73%	74%
2411	-	-	-	-	-	-
2404	6%	7%	9%	17%	61%	58%
2401	1%	1%	2%	3%	32%	25%
On-time departure [%]						
401	57%	58%	56%	63%	82%	81%
404	42%	41%	42%	43%	69%	69%
411	-	-	-	-	-	-
2411	27%	26%	31%	39%	74%	74%
2404	2%	3%	4%	8%	58%	55%
2401	-	-	-	-	-	-
Zitplaatsgarantie-1	100%	100%	100%	100%	100%	100%
Zitplaatsgarantie-2	94%	95%	95%	94%	91%	91%
PRDM [%] - 1	28%	29%	28%	33%	44%	42%
PRDM [%] - 2	33%	33%	31%	38%	53%	50%

Conclusion: disruption

In this section a disruption is simulated. The scheduled slack in the timetable, in order to compensate variation in trip times, is insufficient to compensate the extra time caused by this disruption. Therefore, the irregularity on the route increases. As a consequence, the average waiting times increases. In addition, the variation in vehicle loads is also higher, and there where, thus, also more crowded vehicles. The perceived average in-vehicle time per passengers was relatively high, as a result of this. In spite of the fact that the average in-vehicles times were lower.

The absolute cycle times in the headway-based strategies increased as a result of the higher holding times. These holding times were higher in order to regulate the irregularity on the line. Although the times were higher, the perceived times were relatively low. In addition, it was possible to slightly decrease the irregularity, by holding vehicles. As a result of the lower irregularity, the waiting times were also lower. The passengers were also more evenly spread over the vehicles and the vehicles were therefore less crowded.

6.3.2. Bridge

Another aspect that drivers often indicate as cause of disruption: the Lammebrug; a bridge located between the stops Station Lammenschans and A4 P+R.

Figure 6.4 shows what happens in case the bridge opens for 4 minutes for both headway- and schedule-based control. Four trips are shown (trip 1035, 1037, 1039 and 1041). Both the arrival and departure times are included in the figure.

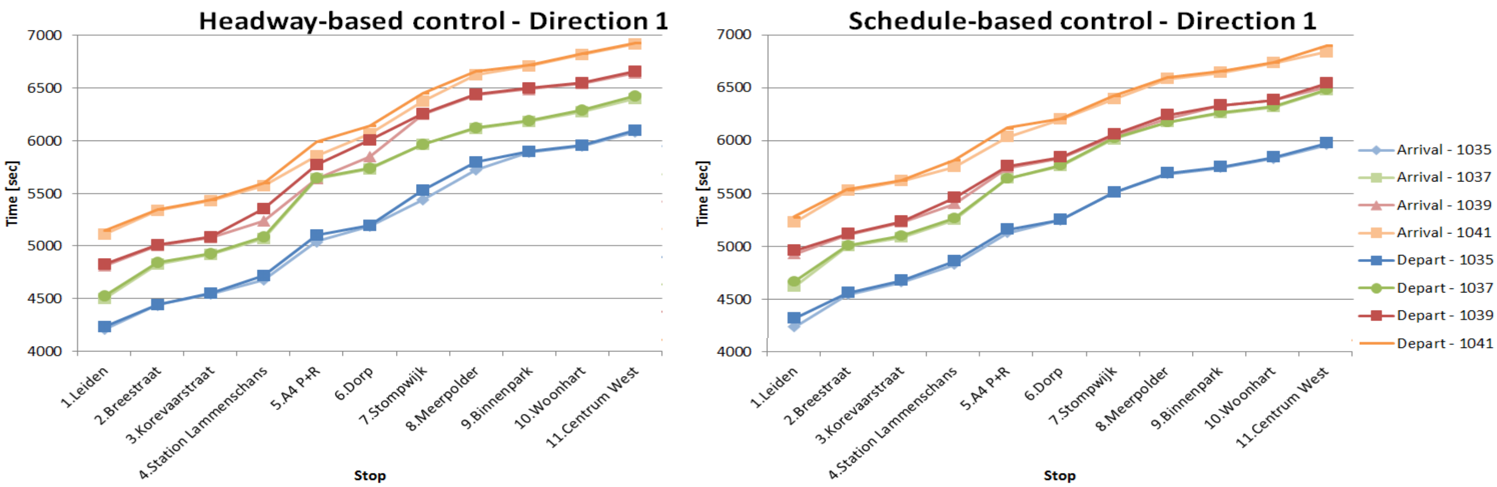

Figure 6.4 Trajectories for both headway- and schedule-based control: opening of the bridge

In case the bridge is open, buses have to wait, and it is likely that they arrive at almost the same time at the next stop. Both buses 1037 and 1039 arrive at almost the same time at A4 P+R.

In case of the headway-based control, bus 1037 departs immediately after the passengers are boarded and/or alighted. This bus will not be held at a stop, since it has to speed up in order to decrease the gap with bus 1035. Bus 1039 will be held at the stop, in order to create a gap between the two buses. However, bus 1041 also arrives at the stop. This bus will also be held. The holding times of the buses slightly decreases, as the mean headways decreases as well.

The bus before the delayed vehicles, bus 1035, will also be held in order to decrease the gap between the buses. The adaptions vehicles make, can be seen in the figure. As a result of the opening of the Lammebrug, irregularity has arisen. The headway-based control succeeds to regulate the headways; the trips have even headways again at Zoetermeer Centrum West.

In the schedule-based situation, bus 1037 and 1039 also arrives almost at the same time at A4 P+R. Bus 1037 is late, and will depart immediately after boarding and/or alighting passengers. However, bus 1039 is on time and will therefore depart as well, with bus bunching as result. Bus 1041 arrives ahead of schedule and will wait till its scheduled time. However, additional adaptations are not made. The bus before the opening of the bridge, bus 1035, is on time and therefore no control is needed. The result of this control strategy; bus bunching caused by the opening of the bridge cannot be avoided or solved

The question that arises; what is the impact on passengers? The average in-vehicle times of the passengers in the four trips in Figure 6.4 increases with approximately 2 minutes in case headway-control is applied.

However, the CoV of the headways along the line is 9% lower, meaning that there is less variation in headways.

In conclusion it can be stated that the headway-based strategy is able in reposition vehicles in order to create a regular service again. The impact of smaller disruptions (the bridge blocked the road for 4 minutes) can be solved. Bus bunching occur, which is almost unavoidable in case there is a disruption of 4 minutes at such a high-frequency line, but can be solved by the cooperation of the vehicles along the line.

6.3.3. Compliance rate

Headway-based strategies are better able to deal with drivers that do not follow the control rules. Other drivers are able to mitigate the irregularity. Schedule-based strategies are not able to deal with these drivers. This can be indicated from the CoV of the headways; in both strategies the CoV increases, but for the headway-control strategy this increase is higher. For example, the CoV of the headway of strategy hw-9-0 increases with 0.07, while the CoV of sched-9-0 increases with 0.13 in direction 1. This difference is less clear in direction 2; increase of 0.14 and 0.16 for respectively hw-9-0 and sched-9-0.

Also in this case the strategies with the higher maximum holding times are better able to correct and to minimise the irregularity on the line, compared to the other strategies.

Cats et al. (2011) concluded that headway holding strategies were robust with respect to the average CoV of the headways along the line. However, the differences between 100% compliance and 50% compliance were less compared to the differences in this study. The reason why there are differences between the two simulation results is unclear. Therefore it is recommended to analyse the cause of these different outcomes in more detail.

6.4. Sub conclusions: simulation results

Different holding strategies are simulated and the results are discussed in this chapter.

First it can be concluded that three control points are insufficient in order to control the irregularity along the route. The perceived travel times of passengers is higher when applying these strategies. Also the waiting times are longer. For passengers it is preferred to use more control points.

The differences between the other strategies are relatively small. Therefore a top three best strategies is made: Hw-9-120, Hw-9-60 and Sched-9-0.

For the operator the first two strategies are equal, with respect to the performance. The performance of strategy sched-9-0 is also comparable to the other two strategies. However, the difference between these two headway-based strategies and the schedule-based variant, is the variation of cycle time in direction 2, as a result of the irregularity on the line in that direction. Although the average CoV of the headways is the same, the development along the line is different. There is less irregularity along the line with this headway-control strategy, compared to the scheduled-variants.

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 turn-around time at the terminal stops. As a result of this turn-around time, vehicles that are late can be on-time again. As a consequence, the vehicles are reset and depart according to schedule, which leads to even headways. Therefore, scheduled-based control performed relatively good, compared to differences between the two type of strategies in other research.

With respect to the operator, the schedule-based strategy is less favourable, because of the increased irregularity along the line.

Scenarios

Headway-based control strategies are less sensitive to scheduled times. In case of a tight schedule, schedule-based control is not able to control the system. However, the performance of headway-based control could be optimized. The simulation make use of the scheduled times to estimate the headway with the bus behind. In case this estimation will be more accurate, it will probably increase the performance and its power to control.

Headway-based strategies are also better able to deal with smaller disruptions. Headway-based strategy is able in reposition vehicles in order to create a regular service again. The impact of smaller disruptions (for example the opening of a bridge for 4 minutes) can be solved. Bus bunching occur, which is unavoidable in case there is a disruption of 4 minutes at such a high-frequency line, but can be solved by the cooperation of the vehicles along the line. In case of schedule-based control, bus bunching cannot be solved.

In addition, headway-based strategies are less sensitive to (non-)compliance of drivers. Non-complying drivers are presumably corrected by the other drivers, as a result of the cooperativity of the headway strategy.

It can also be concluded that the headway-based strategy is also better able to deal with larger disruptions. In direction 1 the strategies hw-9-120, hw-9-60 and sched-9-0 could save travel time per passengers compared to the current used strategy sched-3-0, with respectively 1:45, 1:00 and 0:45 minutes. The headway-based control strategies could save up to 8 minutes average experienced travel time per passengers, compared to the schedule-based strategies, in direction 1. It can be concluded that an headway-based strategy is better able in controlling disruptions.

Overall conclusion

In the normal situation the preferred strategy would be the schedule-based control, because implementing this strategy would not need large changes. Particularly since the differences are small compared to the headway-based strategies. However, headway-based strategies are more robust with respect to disruptions and non-compliance of drivers. In addition, when holding and regulating vehicles at Zoetermeer Centrum West, the irregularity at this station will decrease. However, BusMezzo cannot hold vehicles at the terminal in case of headway-based strategies and therefore not able to control the vehicles at the first station of a trip. This has impact on the performance of the schedule-based strategies. Especially since most passengers board at these terminals. In case the vehicles are regulated at Zoetermeer Centrum West, the performance of the headway-based strategy increased between the 5 and 10%, with respect to the average experienced travel time per passenger.

Based on this simulation, and the current practice of Arriva, the best control strategy at this moment is sched-9-0. However, hw-9-60 will be also a promising strategy, that is more robust to uncertainties and could in practice performs better than in this simulation, as a result of the possibility to control vehicles at terminals. In addition, the hw-9-60 strategy will be best for the total reliability of the line The results are based on the current occupancy pattern of line 400. However, in case the total reliability along the route can be improved, which is the case when using headway-based control, the development of a different occupancy is possible. For example, stops where the regularity increases could attract more passengers. However, this indirect effect is difficult to specify and quantify.

In Table 6.15 an overview of the main results is shown.

Table 6.15 Main results of the simulation

	Normal situation					Disruption			
	Headway-based			Schedule-based		Headway-based		Schedule-based	
	CP: 3	CP: 9	CP: 9	CP: 3	CP: 9	CP: 9		CP: 3	CP: 9
	no max	max 120	max 60	no max	no max	no max	max 300	no max	no max
KPI Strategy→	Hw-3-0	Hw-9-120	Hw-9-60	Sched-3-0	Sched-9-0	Hw-9-120	Hw-9-60	Sched-3-0	Sched-9-0
CoV [h] - 1	0.24 (B)	0.17 (A)	0.17 (A)	0.23 (B)	0.17 (A)	0.36 (C)	0.43 (D)	0.58 (E)	0.55 (E)
CoV [h] - 2	0.45 (D)	0.28 (B)	0.30 (B)	0.32 (C)	0.30 (B)	0.39 (C)	0.49 (D)	0.68 (E)	0.63 (E)
Range of the LoS (based on CoV) - 1	A-C	A-B	A-B	A-C	A-B	C-D	C-E	D-E	E
Range of the LoS (based on CoV) - 2	C-E	B-C	B-C	A-D	A-D	C-D	D-E	E-F	E
# buses in case of turnaround of 60s	12	13	12	12	12	14	14	14	14
# buses in case of turnaround of 360s	13	14	13	13	13	15	15	15	15
Total experienced travel time [min:s] - 1	22:38	23:24	23:08	23:24	23:26	28:40	29:23	30:36	29:57
Total experienced travel time [min:s] - 2	32:48	29:27	29:40	29:46	29:33	37:19	40:06	45:30	44:48
Differences compared to sched-3-0 [min:s] - 1	-00:46	0	-00:16	-	+00:02	-01:56	-01:13	-	-00:39
Differences compared to sched-3-0 [min:s] - 2	+03:02	-00:19	-00:06	-	-00:13	-08:11	-05:24	-	-00:42

*LoS is the level of service based on the average CoV of the headways according to TCRP, 2013

The results of the simulation are discussed with experts in order to identify weaknesses in the simulation; differences between the model and the (social) complex reality. In addition, concerns of the operators with respect to implementing a headway-based strategy will be discussed. Finally, the insights obtained in this chapter, will be used by the generalization to other transit services.

7. Discussion

This chapter discusses aspects that are not included in the simulation model. A model is a simplified representation of the complex reality. Therefore, assumptions and simplifications are made in order to be able to make a simulation. In this chapter these model limitations will be discussed. After that it will be explained what operational difficulties are involved when implementing headway-based control. Finally, this chapter uses the insights from chapter 5 to make a generalization to other transit services.

7.1. Simplifications and model limitations

The model is a simplified representation of the complex real world. Although models can be used in order to estimate impacts, it is important to know what and where its weaknesses are. Persons involved in the planning and operational phase of the transit service are asked about the model and the results by conversational interviews. These interviews are conducted in an informal manner. Arriva employees who commented on the model and the results consist of planners (timetable, fleet, crew), managers, data analysts and drivers. An overview of the outcomes of the conversations are presented in this section.

7.1.1. General remarks

The model is built based on empirical data of the March 2016. Arriva uses this months also for trip time analysis for the timetable, because it is experienced as 'average month'. However, this also means that there could be differences of the model outcome in case other input data was used. Another aspect that could influence the results, it the choice of the control points. It is possible that other control points, or another control point selection could lead to different results.

One of the aspects that are not taken into account in this research, are other control possibilities. It could be that combinations of different control strategies leads to other results.

7.1.2. Terminal departure variability

Crew and vehicle availability is considered to have more impact on the performance of the holding strategies. Two aspects can influence the regularity at the terminal:

- A driver is delayed. Shifts can create departure delays, in case a driver is delayed as a result of a delayed previous trip. Delays of drivers that are already on line 400 are included in the model. However, shifts from other lines are not.
- A vehicle is delayed; vehicles are not ready to depart from the terminal, because they arrived too late from a previous trip of line 400. Also these delays are included in the model, since vehicle scheduling is part of the model input. It is also possible that vehicles are not ready to depart from the terminal, because they arrived too late from depot. These delays are not included in the model, because this variation is related to driver behaviour.

The fact that these aspects are not included in the model, resulted in an overestimation of the regularity at Leiden Centraal. Zoetermeer Centrum West is less impacted by this simplification, since there are no changes between drivers and/or vehicles.

For the headway-based strategies there is another aspect that influences the result; the possibility to regulate the dispatch of trips from the terminals Leiden Centraal and Zoetermeer Centrum West. As a result of this, the results are overestimated at Leiden Centraal and underestimated at Zoetermeer Centrum West. This is not caused by a simplification of the reality, but rather a disadvantage of BusMezzo. The dispatch time of a trip is an input aspect for BusMezzo. The dispatch should be determined beforehand, and could not change during the simulation. In case of headway-based control, the dispatch times will influence the results more. At Leiden Centraal the vehicles are partly regulated. The headway between the dispatch times of the first trip of a vehicle is 5 minutes, resulting in a departure of a vehicle every 5 minutes. However, controlling the other vehicles is more difficult, because the arrival time of that trip is unknown. In that case, the dispatch time is also every 5 minutes, but it could be that the vehicles arrives later from its previous trip. In that case, the regularity of the service is disrupted. Control is needed, but in the simulation this is not possible at the terminal. At terminal stops, the vehicle in front is driving in the opposite direction compared to the vehicle behind. However, in practice this problem can be solved.

At ZCW there is no control forced by regulating the dispatch time. At this stop, vehicles can depart after the required minimum turnaround time of approximately 30s. However, this leads to an underestimation of the results of headway-based control.

In summary, it is possible to control the dispatch of vehicles when it is the first trip of that vehicle. The model is not able to control headways by holding vehicles at terminals, because the vehicles in front drives in the opposite direction as the vehicle behind. The first and last trips of a service cannot be controlled by the mean-headway-based strategy. These model limitations could partly be solved in practice. This will be addressed later.

7.1.3. Trip time variability

Another aspect that was mentioned, is that running times in reality are more correlated than in the model. Running times in the model are drawn from a distribution. This distribution is based on actual running times from working days in march. Longer running times alternate shorter times. In practice there is more correlation between the running times of trips in the same daily period. For example, in case there is congestion on the road towards Zoetermeer, it is expected that a sequence of buses will have longer running times. In the model this correlation is less, as the result of the distribution.

Subsequently, dwell times that are very long, are not taken into account in the model. In practice it is possible that dwell times are relatively long, caused by other traffic at stops. For example, when there is a bus of another line at stop Korevaarstraat, the bus behind needs to wait, leading to higher dwell times. This is not taken into account in the model. In addition, extreme long dwell times, caused by passengers, are also not taken into account. There is some variation in the model with respect to dwell times, but extremes are not included.

Assumptions with respect to the passenger demand cause different patterns. In the model passenger demand is mainly influenced by the headway between buses. However, in reality the arrival of trains are also an important determinant of passenger boarding. In case a train arrives at Zoetermeer, it is likely that many passengers board, even though the headway with the bus before is low. Also, there is more variation between daily periods than included in the model. It is assumed that during the peak hours the passenger demand is equally distributed. Yet, the demand in the period between 7:30 AM and 8:00 AM is higher than the demand during the rest of the peak hour. Also these effects are not included, while it could impact the average standing times heavily. This could not always be influenced by even headways.

Another aspect is related to the holding times at stops. In the model, holding is possible at al stops, except at Breestraat and Korevaarstraat. However, in practice there are other limitations as well. For example, currently, holding is not always possible at Station Lammenschans. It is a bay-stop, so it does not hinder other traffic. However, the stop has only space for one vehicle. This is a problem, because multiple lines make use of this stop. In case a bus should hold, but another bus arrives from another line, the bus of line 400 has to depart. Another aspect with respect to holding at every stop; sometimes there are no passengers boarding or alighting at a stop. Drivers declared that holding in that case is not realistic.

7.1.4. Driver behaviour

The most important aspect mentioned by the experts: driver behaviour. Driver behaviour is difficult to include in models. Although driver behaviour lead to variability in terminal departure and trip time, this aspect will be discussed sepeartly, because it is an important simplification.

Different aspects of driver behaviour are mentioned:

- In practice drivers will adapt their speed based on the timetable. In case they are ahead of schedule, they will driver slower. In case they are behind schedule, they have the possibility to drive faster. To what extent this is possible, is dependent on different aspect: driving style, infrastructural possibilities etc. Speed adaptations are also possible in case of headway-based holding; instead of holding at stops, driving slower or faster is also possible.
- Drivers can decide to depart later from the a stop, in case they know the schedule is loose. In case the schedule is tight, or if there is much uncertainty, drivers tend to depart earlier than scheduled. This is in particular dependent on the experiences of drivers. For line 400, drivers experience much uncertainty, resulting in early departures along the line. The model does not take into account these aspects, resulting in an overestimation of the results of schedule-based control. In practice it could turn out that drivers are not waiting till the scheduled departure time. This effect will be less in case of headway-based control, because drivers do not have their own fixed arrival time.
- At Leiden Centraal, drivers sometimes depart later, without a clear demonstrable reason. In the model full driver compliance rate is assumed, while this is not the case in practice. The model results overestimate the effect of holding. In this research also lower driver compliance rates are taken into account in the simulation. However, in that case it is assumed that non-compliance of drivers means that they do not follow the holding rules. While in practice it is also possible that non-compliance means that drivers only partly follow the rules; waiting 1 minute instead of the required 3 minutes or depart later for example. In other words, assumptions are made with respect to driver behaviour, while it is uncertain if this is the actual driver behaviour. Driver behaviour is very uncertain and difficult to implement in models.

In conclusion, there are many simplifications made, that influence the outcomes of the simulation model. It is important to be aware of these deviation. In addition, the model should be used as indication of the possibilities of different strategies. There will always be uncertainty whether the model outcomes are comparable to the outcomes when the strategy is put into practice.

7.2. Implementation of holding strategies

Besides the model limitations, practical difficulties with respect to the implementation of holding strategies are also discussed with Arriva employees. These aspects will be explained in this section. Based on the simulation results, schedule-based and headway-based holding could improve the regularity on a line. Holding strategies are theoretical suitable in order to control a transit service, but in practice there are several challenges that needs to be dealt with. For Arriva, three main categories are important: technical aspects, logistical aspects and behavioural aspects. It should be noted that the main implementation difficulties are specifically related to headway-based control. However, in some cases, difficulties are discussed with respect to holding in general.

7.2.1. Technical aspects

In case a shift takes place towards a regularity-driver operation, there are also some difficulties for the operator, because this is a new method. The technical difficulties will be discussed in this section. Two technical aspects are of importance, related to the internal change and external change in case one shift towards a regularity-driver operation.

First the needed internal change will be discussed. Currently, the display inside the bus shows its punctuality with respect to the timetable. However, in case of headway-based control, it should show its regularity. It should show how far the bus is from being located exactly between its predecessor and successor. The buses in Stockholm are able to show this. The indicator in these buses are consistent with the current practice: in case a bus is too close to its predecessor, it shows a plus (meaning to slow down), and in case it is too close to its successor, it shows an negative value (meaning to speed up). In case the bus is exactly in the between, there is a zero visible (Cats, et al., 2012).

For Arriva it could also be possible to show this indicator in buses. Vehicles could communicate with each other by frequently sending their GPS-location to each other. Currently, the board computer (Albatros) calculates the punctuality of a bus, by comparing the actual location and time of the bus with the timetable. This should be changed. Albatros needs to adapt the punctuality indicator by the regularity indicator and show this on the display in the bus. Two aspects are important: the forward headway and the backward headway. The first part, the forward headway, can be calculated relatively easy, because these times are known and forecasting is not needed. The second part, the backward headway, is more difficult, because of the forecast. However, currently the punctuality of the bus for the next stop is also estimated. Therefore, it is expected that the same algorithm can be used for the backward headway. However, some situations needs additional research with respect to the calculation of headway:

- A bus is cancelled
- A bus is not on the line; bus departs from depot
- The first or last bus on the route; there is no forward or backward headway
- Required turnaround times at terminals

The change, from a board computer that gives the punctuality towards a board computer can show a regularity indicator, could not be made by Arriva. A software update is needed, meaning that the supplier of the board computer has to change this aspect. An extra difficulty is that on some lines there should be a punctuality indicator, while other high-frequency lines would require the regularity indicator. This could also change per period of day; during peak hours a regularity indicator, and during the off-peak a punctuality-indicator. Albatros should also be able to deal with this aspect.

The second aspect that needs to be changed is related to the external information flow. Vehicle data (GPS location and time) is sent to external parties. These parties organise, among others, information for passengers. Examples are the suppliers of the stop information displays at stops or the travel information apps. They should also change their systems in order to be able to work with regularity-driver operations.

In conclusion, it is expected that it is technical possible for Arriva to change to a regularity-driven operation, but some additional aspects needs to be investigated before such a regularity-based system can be implemented. The following technical related steps needs to be taken before shifting to a regularity-driven operation:

- The system within Albatros should be changed. The information is known: forward and backward headways. The combination between these headways needs to be made for every bus. How this should be done exactly needs to be investigated and is the responsibility of the supplier of the board computer. In addition, regularity is not used at every moment of the day and every line. It needs to be possible to use both a punctuality- or regularity-indicator, or to be able to change between these two types of indicators.
- External parties also have to change their systems in order to be able to deal with regularity-driver operations.

7.2.2. Logistical aspects

Another aspect that should be considered, are logistical aspect. Drivers and vehicle schedule are one of the constraints. However, during the pilot in Stockholm, it was experienced that punctuality remained at the same level, despite the fact that headway control was used. Therefore, vehicle and crew schedule was not affected heavily (Cats, 2013). However, it is expected that this is dependent on the amount of scheduled slack time. Arriva schedules 4 minutes turnaround time at bigger stations as Leiden Centraal and 2 minutes at Zoetermeer Centrum West. In addition, drivers have 8 minutes in case they have to change from one bus to another. The more slack, the less difficulties with transferring crew. However, more slack also costs more, as the crew and vehicle scheduling is less efficient.

Based on the simulation, the share of vehicles that are more than 8 minutes late at Leiden Centraal, relative to the current timetable, is less than 0.5%. Meaning that in less than 0.5% of the cases a shift towards another line will lead to delay at that line. The results match with the results from the pilot study in Stockholm; punctuality remained at the same level. How often buses needs to depart before schedule, could not be determined, because in the simulation there is no control at terminals.

Additionally, in the model no extra buses are available. However, in practice it is possible to have extra buses available to use when the headways are too large. This could be used when there is a larger disruption and the headways become too large. Note that the definition of too large depends on the requirements in the concession. 'Where' and 'when' are important questions that needs to be answered. These decisions should be made by traffic controllers. Traffic controllers are currently trained to deal with disruptions, taking into account the punctuality. However, they also need to be instructed how to deal with regularity; how to control regularity, when to intervene and how to act in different situations. They should be aware of the different systems: punctuality-based and regularity-based operations. Before and during implementing a regularity-driven operation, traffic controllers should be actively involved in the process. A pilot study could also be a good training and learning process for them, with respect to dealing with regularity-driven operations.

7.2.3. Behavioural aspects

Irrespective of the chosen control strategy, driver compliance is an important, and difficult, aspect. Drivers should be motivated to adapt their (drive) behaviour to the rules of the control strategy.

Departing on time, whether this means on time according to the schedule or according to the regularity, is an important aspect. Van Oort & Van Nes (2009) discussed the aspects that are of influence on the departure time from the terminal. Availability of the vehicle and the driver is one of the main aspect. First, there have to be enough slack in the timetable to ensure that drivers and vehicles could depart on time. In addition, the control whether drivers depart on time should increase. In case a driver is not on time, the traffic controller should be aware of this and should decide how to solve this (by contact the driver of use a spare driver for example). Continuously monitoring the on time performance and publish the performance to managers, traffic controllers and drivers, will probably increase the awareness. It is emphasized that the timetable should be achievable in order to prevent that drivers adjust their departure times to be on time at the last stop. It is important that drivers trust the schedule.

In order to increase the compliance of drivers, different aspects will be important:

- Clear rules; when and where to wait
- Control; monitor the performance and publish this to drivers
- Convesations: what are the consequences for passengers/Arriva when drivers do not follow the rules, why do drivers do not follow the rules, what should and could be improved? Mutual comprehension could improve the performance of a service

One important aspect when planning a pilot study, is to involve drivers as soon as possible. It is advisable to do the pilot with a selection of motivated drivers. In addition, in case these drivers are enthusiastic about the pilot, they can also help to motivate other drivers. Something that could be a problem when using holding control in general: waiting at stops could be difficult for drivers. Also with pressure from passengers inside the bus could it be difficult to wait at a stop. Especially at stops where nothing happens.

Another aspect related to headway-based holding; drivers continuously change between lines. Some lines require a punctuality-driver operation, while others a regularity-driver operation, and this could lead to confusion. Drivers need to adapt their working style to the system. How they deal with this, is unknown. It is therefore important to, at least, develop an indicator that required the same action of the driver. With other words, as explained in section 7.2.1., the same action in both the schedule-based and headway-based strategy in case of a positive value or a negative-value is shown.

Besides driver behaviour, passenger behaviour is also an aspect that could influence the performance. For example, at both Leiden Centraal and Zoetermeer Centrum West the flow of passengers is almost continuous. Drivers indicated that it is difficult to close the doors, in case they have to depart according their schedule, while there are still passengers that want to board. Now passengers could see what the departure time is, however in case of headway control this is not visible, since there is no clear departure time.

Another aspect that could cause problems in case of headway control: How to deal with transfers? Currently, the operator have thought about transfers, by guaranteeing transfers. However, when there is a shift towards headway-control, guaranteeing transfers is more difficult. Then passengers are expected to plan their trip, taking into account some delay as a result of holding.

7.3. Generalization

In chapter 5, different holding strategies are assessed for the used case study (Line 400). Insights gained in this chapter will be used to make a generalisation for other transit networks.

Although the headway-based strategies turned out to be the best strategies, for both the operator, passenger and authority, the improvements where relatively low. In this section the line properties that influence the performance of a control strategy will be reviewed. The most promising properties for introducing headway-based control will be discussed. In addition, an overview of the line properties and what decisions could be made with respect to the control strategy, will be shown.

Characteristics that are important and could influence the performance of a holding strategy, are:

- Occupancy pattern of a 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)
- Amount of disruptions

All these aspect will be discussed. Note that the punctuality and schedule quality are related.

The occupancy pattern on transit lines is one of the aspects that characterised a line. In Figure 7.1 examples of common used patterns are shown. The pattern is of importance to determine the impact of different holding strategies on passengers. The impact on passengers' waiting time is mostly dependent on the location where most passengers board. For situation 1, most passengers board at the first stop and alight at the end stop. In that case, regularity at the first stop is important. Increased irregularity on the line does not impact the waiting time of these boarded passengers.

In situation 2 passengers boards only at the first half of the line and alight in the second half. In that case, regularity should be high up to this first half. After that, the impact on passengers is less. Situation 3 is comparable to situation 2. Only in that case there is an increase in passengers load in the middle of the line. It is important that the regularity at this stop is high.

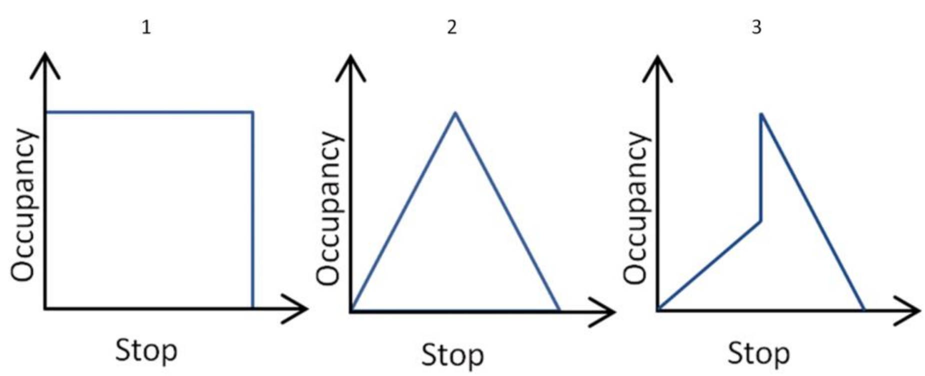

Figure 7.1 Example of occupancy patterns on transit lines (adapted from Van Oort, 2011)

The occupancy pattern of a line determines where high regularity is required. Regularity can be obtained by holding. However, what strategy is best able to ensure this regularity, depends on different characteristics. In general, headway-based control is able to provide regularity along the line. However, is some cases, schedule-based control is also able to provide a regular service. What service requirements are for schedule-based control, will be discussed.

The first characteristic that is important for the performance of a specific holding strategy, is the punctuality of a line, depending on the quality of the timetable and the regularity along the line. First the timetable will be discussed. It should be noted that the headway-based strategies do not require a timetable. However, the performance of a schedule-based strategy is highly dependent on the quality of a timetable. With the quality of the timetable it is meant whether it is a loose or tight schedule. In order to be able to control, the schedule-based control strategy needs a timetable that is relatively loose. Control is only possible if vehicles arrive too early. In case there is a relatively high amount of slack in the timetable, vehicles arrive early at stops and schedule-based control is possible. In that case the schedule-based control strategy can regulate the buses. Subsequently, vehicles depart according to schedule, which is in general regular.

The regularity along the line is also an important aspect. The irregular a line, the more slack is needed in order to be able to regulate the buses by the schedule-based control strategy. More slack, means more reliability, but also longer trip times. In case there is much variation, there are also many trips that have unnecessary longer trip times. In case a specific stop is more important than others, with respect to passenger demand (see occupancy patterns 2 and 3 for example), additional slack could be given in order to ensure a high level of regularity at these stops. It should be noted that the headway-based strategy do not need a timetable.

So far, the punctuality and regularity along the line are discussed. However, punctuality and regularity at the terminal is also important. Particularly when most of the passengers board at the terminal, which is the case in situation 1 of Figure 7.1. Schedule-based control is able to provide regularity, when there is enough turnaround time at the terminal in order to solve any delays from previous trips. In that case, vehicles are able to depart according to schedule, which is regular again. However, the longer the turnaround times, the longer the cycle times. A trade-off should be made by the operator, because a longer cycle time could lead to the need of extra buses. Slack in the timetable and turnaround time at terminals is an important precondition for schedule-based control to be effective.

The timetable is very important for the performance and control possibility of the scheduled-based control. However, there will always be uncertainty, for which you cannot plan. Headway-based control strategies are better able to deal with these uncertainties, compared to schedule-based control. Systems that have relatively many disruptions, are better suitable for headway-based control. Headway-based control is capable in keeping the regularity along the route at a relatively high level, without the need for a timetable. For passengers headway-based control is better, because the perceived travel time are on average lower, compared to the schedule-based control. This is in particular caused by the lower average waiting times and the more evenly distributed passengers. In case the disruption is larger than the slack in the timetable, headway-based control is preferred.

In conclusion, if it is assumed that control is needed in order to control the irregularity of a service, several aspects could determine what type of holding is best suitable. In Figure 7.2 an overview of the characteristics of a transit service that leads to favourable holding strategies. It should be noted that the exact holding strategies depends on specific situations. In the figure only an indication of the types are indicated.

An aspect that should be taken into account, is the level of irregularity on a line and to what extend slack time should be included in the timetable. More slack time leads to longer trip times, which could lead to higher costs for the operator and also the travel time could increase. It is possible that there is much irregularity on a line, while the schedule is loose and there are many early arrivals. In that case it is possible that headway-based control is better suitable and more efficient compared to schedule-based control.

However, this should be analysed in more detail in another research. Variation could be over days, but also between months. In case there is much variation, either between days or between months, it could be more difficult to make a high quality timetable that is not too loose or too tight.

In general, in case there are early arrivals, schedule-based control could also provide regular headways. Another case where schedule-based control performs also relatively good, is when most passengers board at the terminal, and there is enough slack time at this terminal in order to solve delays from previous trips. It is important to notice that it is expected that headway-based control performs better compared to schedule-based control, but the differences between the two types will probably be less when the line has these characteristics. In case a line is relatively irregular or when regularity along the line is required, headway-based control is the preferred strategy.

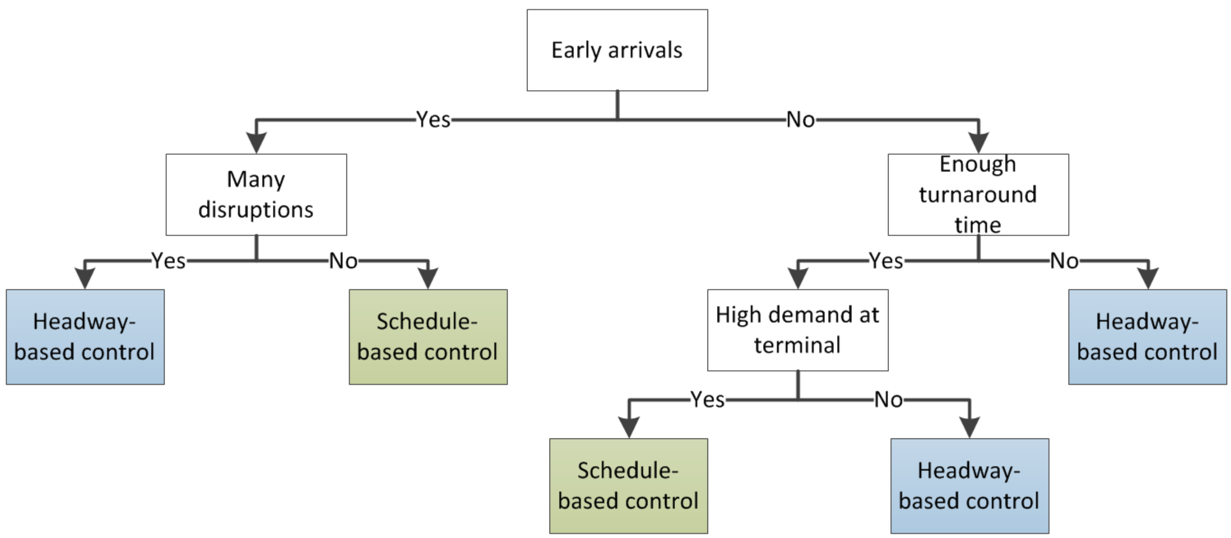

Figure 7.2 Indication of favourable holding strategies

Whether there are ‘enough early arrivals’, ‘many disruptions’, and ‘enough turnaround time’, is dependent on the specific situation. Based on this research these aspects could not be determined quantitatively.

8. Regularity in concessions

Difficulties for the operator with respect to implementing holding control strategies are discussed in the previous chapter. However, one of the main constraints for the operator to change to a headway-based driver operation, is that punctuality is currently of the main concession requirements. However, transport authorities gradually change from punctuality based requirements to regularity based requirements. The aim of this chapter is to discuss the current practice with respect to concession requirements, but also to explain what is needed to change to regularity-based concession requirements. First literature with respect to incentives schemes will be presented. After that, the focus will shift to the Dutch situation;. It will be discussed what the difficulties are with respect to including regularity in concession requirements and different concession requirements are analysed. Different contractual aspects will be discussed, but the focus will be on punctuality and regularity.

8.1. Contractual aspects

In the Netherlands, as in many other countries as well, public transport tendering is legally required. There are many different organisational forms in public transport, control by the authority or freedom for the operator, leading to different types of contracts. One important aspects included in every contract, is the quality of the bus service (KpVV, 2008). Although reliability is a very important quality aspect, transport authorities do not have a consistent way in dealing with reliability. This follows from research on how authorities deal with reliability in concession requirements (Van Oort, 2014). There are different reliability requirements in the concession. However, the focus in this section is on punctuality and regularity.

There are two main considerations authorities need to address (Leong, Goh, Hess, & Murphy, 2016):

- How to measure bus service reliability?
- How should reliability be included in the contracts in order to improve the service reliability?

Leong et al.(2016) proposed a similar incentives scheme as in London, based on reliability, measured in the EWT. Based on current performance and on line characteristics, every service has its own baseline. Based on this baseline, norms and penalties/bonuses are determined. Operators are penalised when the service regularity decreases and get bonuses when the regularity of the service improves.

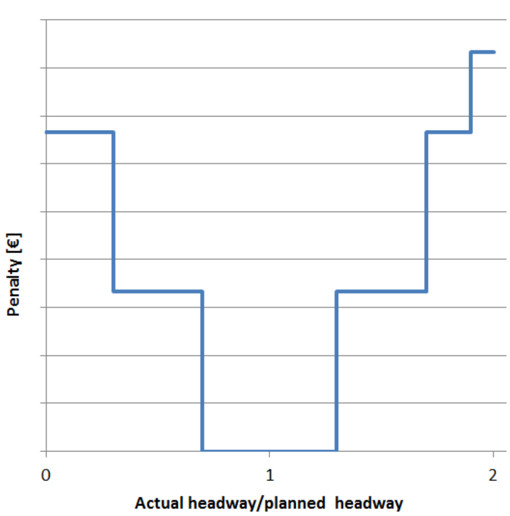

Figure 8.1 Possible penalty-system based on headways adapted from Cats (2014)

Cats (2014) argued that the indicator should be the ratio between the actual headway and the planned headway. A bonus/penalty system was proposed; bonuses and penalties depends on the share of headways that corresponds to a specific interval (actual headway/planned headway). In Figure 8.1 such a system is presented. The ratios and the corresponding penalties should be determined by the transport authority. This can replace the current penalty-system. In addition, because of the stepwise function, larger deviations from the planning leads to higher penalties. The headways could be measured continuously along the line, which has as positive effect that control at terminals and along lines will be promoted.

The ratios and penalties should be determined by the authority, as mentioned before. This choice should be based on current performance. Penalties can be used as incentives. In case the norms are too high, and cannot be met by the operator, the operator will not be stimulated to increase the quality of the service. This is the a problem, particularly in case there is a maximum on the total amount of penalties that can be imposed. Therefore, reasonable penalties should be asked, in order to stimulate the operator to increase the quality (Walters & Jansson, 2008).

8.1.1. Punctuality

In most of the current concession requirements, punctuality is one of the main KPI with respect to reliability. Punctuality is defined as the share of trips that departing or arriving on-time. However, research, based on an international survey, demonstrates that authorities do not apply an uniform method to measure service reliability. There are differences in the boundaries of the bandwidth, impacting the share of vehicles on-time. Also the (number of) stop locations are different. Altogether, there is no consistent way how different authorities deal with reliability. As a result of these differences, it is difficult to compare different bus services. The degree of reliability is dependent of the chosen definition of punctuality. In order to be able to compare different bus services, an unambiguous requirement should be used (Van Oort, 2014).

Beside the fact that there is no consistent approach in requiring service reliability, there are also other disadvantages in using punctuality as service reliability KPI.

Punctuality is a supply-oriented KPI. Rietveld (2005) argued that supply-oriented KPIs systematically overestimate the quality as experienced by passengers. In case quality performance is based on the experience of passengers, one could avoid situations where the operator is satisfied, while the passengers are not.

Rietveld (2005) also mentioned that supply-oriented KPIs could lead to counter-productive effects. Operators can improve performance based on the supply-oriented KPI, which could have a negative effect on demand-oriented KPIs.

Since punctuality is the share of buses that arrive or depart too late, it does not take into account to what extent buses are late. There is no difference in the calculation for buses that are 4 minutes late or 14 minutes late. KPIs defined in terms of thresholds always have this problem (Cats, 2014).

Punctuality also uses the timetable as reference point. However, the timetable is based on historical data. Timetables cannot be seen as a reflection of travel times. Timetables are based on the historical running times of bus drivers, while they adapt their speed to the timetable. The timetable, therefore, is an important determinant of the running times, instead of the other way around. Moreover, deviations from the schedule cannot always be attributed to factors that are under control of the operator (Cats, 2014).

Based on these aspects, it could be argued whether punctuality is a suitable KPI. For the transport authority it is important that they impose KPIs that helps to increase the reliability. In case of high-frequency lines reliability should be defined and measured in terms of regularity (Cats, 2013). There are some examples where regularity is used in order to measure the performance. These examples are shown in Appendix D. In the next section the difficulties related to regularity in oncession requirements will be discussed. After that, the Dutch situation will be discussed; several concession requirements are analysed and the main important insights will be discussed.

8.2. Regularity in concession requirements

There are many uncertainties with respect to the implementation of regularity control. Also for the authority it is not completely clear how regularity control will work in practice. Concession grantors were asked about the difficulties with respect to regularity in concession requirements. A list of persons who commented on this are included in appendix E. An overview of the outcomes of the conversations are presented in this section

8.2.1. Bandwidths and norms

A complete 100% regular service is not realistic, since there will always some variation, caused by other traffic or passenger demand. In addition, there can be cases of force majeure, such as congestion, which should be excluded from the performance. Currently, congestion is included in the contract and is part of force majeure. This could also be done for regularity, however it would be better to find a way to include this more directly in the contract. It is difficult for the operator to measure when there is congestion and buses are affected by this. The level of control would be very high in case congestion effects will be measured exactly. It is therefore not desired to exactly measure the cases of force majeure exactly. Therefore some slack for the operator is needed, resulting in a bandwidth and a belonging norm. There are two possibilities for the operator in case of congestion in order to provide even headways; increase the headway, or increase the number of vehicles. With respect to the first, efficient use of vehicles is important for the operator. Therefore, it is not preferred to have many extra vehicles available in order to be able to deal with congestions. In case of congestion the headway should be increased, in order to provide a regular service with the same amount of vehicles. Therefore a bandwidth is required.

The bandwidth, the range of the headways, could lead to strategic behaviour of the operator. In case the bandwidth is large, the operator could plan its service for the highest possible headway, because that leads to less buses needed. However, too large headways will be disadvantageous for passengers. In addition, it is expected that the operator will ensure that the supply of trips is large enough in order to be able to comply with the concession requirements of the transport duty and possibility of finding a seat.

Additionally, the norm prescribed by the operator should also be chosen carefully as mentioned in section 8.1. First, the norm should not be too high, because the norm should be realistic and achievable. Second, the norm should not be too low, because than the operator has no incentive in order to improve the service. Currently, authorities do not know exactly what the current performance of bus service is with respect to regularity. This makes it difficult to set realistic norms.

One important aspect is also the relation between trip cancellation and headways. In case a trip is cancelled, the headway of the bus behind is affected. In general, trip cancellation is penalised. In addition, the headway of bus behind will also increase and lead to a higher headway than acceptable. This will be discussed in more detail in section 8.2.2.

8.2.2. Data collection

In case regularity requirements will be used, it is needed to calculate the headways. This can also bring some difficulties. For every trip the arrival headway should be calculated, which is the difference between the arrival of trip a *k-1* and trip *k*. Data availability is an important aspect. Reliability of vehicle location data is essential. Data anomalies that could make it more difficult to calculate the headways are (Trompet, Liu, & Graham, 2011):

- Missing data: in case a bus failed to be recorded, while the bus ran, can be a problem. This can be either caused by a human error or technical error.
- Trip cancellation: in case a bus did not run.
- Breakdown of buses: bus ran but did not complete the trip due to technical problems.
- Overtaking: buses can overtake buses, which changes the scheduled sequence of buses.

Since the calculation of headways is based on two buses, it is a problem when data of one bus is missing. When a bus is cancelled, it leads to a larger headway between the bus in front of that bus and the bus behind that bus. In that case the large headway is also the headway experienced in practice. However, when bus data is missing, a larger headway is, wrongly, calculated. Therefore, it is important to know whether buses are cancelled or if data is missing. Currently, in case of punctuality calculations, missing data is of less importance. Breakdown of buses leads also to a gap between buses, leading to a larger headway. Also in this case it is important to determine whether there indeed was a breakdown, or data is missing.

In case of overtaking, the sequence of the buses changes, compared to the scheduled sequence. It is therefore important to sort the buses based on the arrival time at stops. Passengers do not know the scheduled sequence and therefore do not care which bus arrives first. In case the order of the buses is based on the arrival sequence at stops, there is no problem when calculating the headways.

As mentioned before, performance should be based on passengers. Therefore, passenger counts needs to be combined to vehicle data. To combine these sources of information could lead to new problems. In particular, in case data is missing. In order to be able to analyse passengers impact, the passenger counts and vehicle data should be coupled automatically.

In conclusion, there are some difficulties with respect to requiring regularity. A fully regular service is not realistic and therefore bandwidths, norms and penalties have to be determined. The choice for these aspects should be based on current performance. Penalties can be used as incentives. In case the norms are too high, and cannot be met by the operator, the operator will not be stimulated to increase the quality of the service. This is the a problem, particularly because currently there is a maximum on the penalty that can be imposed. Therefore, reasonable penalties should be asked, in order to stimulate the operator to increase the quality. In addition, how to deal with data deficiencies should also be taken into account when changing towards a regularity requirement.

8.3. Dutch concession requirements

It is discussed that regularity could be a better requirement for high-frequency services. In this section some Dutch concessions are analysed with respect to punctuality and regularity.

In most of the concession requirements in the Netherlands, punctuality is one of the most important KPI concerning reliability. However, regularity is also mentioned more often in concession requirements. In the 'Toolbox Beter Bestek', a tool for improving the quality of the concession requirements in The Netherlands, punctuality is indicated as a KPI. It also mentioned that regularity is more important than punctuality, in case of high-frequency services (CROW, 2011). MIPOV (Dutch: Model Informatieprofiel Openbaar Vervoer) is used by authorities and operators to determine what information needs to be exchanged. Giving guidelines for standardizing the information exchange between the operator and authority is one of the main purposes of MIPOV. In MIPOV-2008, both punctuality and regularity are included. The definition used in MIPOV, is the share of headways within an maximum acceptable bandwidth (KpVV, 2008). The indicator is known as headway adherence (HA): the share of buses that arrives within a given bandwidth (Cats, 2014).

Three examples are found where regularity is included in the concession requirements: Haarlem/Ijmond, Amstelland-Meerlanden (AML) and Drechtsteden, Alblasserwaard-Vijfheerenlanden (DAV). In these three concession requirements, the definition of high-frequency lines is: bus services with a frequency of 8 or more trips per hour. It should be noted that the there is no universal definition of high-frequency lines. This should be taken into account when comparing different high-frequency lines. In appendix D an overview of important parts of the concession are presented.

In Haarlem/Ijmond it is only mentioned that in case of high-frequency lines, the operator and transport authority can decide to change from punctuality towards regularity control. No specifications are given in this concession (Provincie Noord- Holland, 2014). In the concession Amstelland-Meerlanden more specifications about regularity are given, namely the boundaries of acceptable bandwidth, given a frequency: [planned headway – 1 min, planned headway + 1 min]. In addition, for specified sections in the network, a maximum headway is required (Stadsregio Amsterdam, 2016). However, it is not mentioned what the required share of buses within this bandwidth needs to be. Penalties are not mentioned in case the operator does not fullfill the requirements. Something that is remarkable, is how aspects are included in the requirements. Unambiguity is prefered. An example that can be given:

'A new application possibility of real-time information about the position and speed of buses is to improve the regularity of high-frequency buslines by accelerate the bus in case of delays or slowing down buses if they arrive too early at a stop' (Stadsregio Amsterdam, 2016).

This text is included in the AML concession requirements. However, it is unclear what is meant by 'arrive too early'. Too early with respect to the timetable or too early with respect to the minimal headway requirement.

In the concession requirements of DAV the same bandwidth is given as in AML. Additionally, it is mentioned what the penalty is in case headways are larger than the predefined bandwidth. The norm is 95%; minimal 95% of the headways should be within the predefined bandwidth of +/- 1min of the planned headway. In case this norm is exceeded, a penalty have to be paid per exceeded procent.

Discussion indicators

To the best of the authors knowledge, the DAV concession is the first concession in the Netherlands that has included regularity indicators, including norms and penalties in case that norm will be exceed. The quality of high-frequency lines are explicitly determined based on regularity instead of punctuality, because these lines are excluded from the calculation of punctuality. In Appendix D an list of requirements for KPIs is given. These requirements are used in order to discuss the suitability of headway adherence.

With respect to headway adherence; it can be interpreted and communicated relatively easily. The result of the calculation is a percentage. It is, however, a subjective indicator. Other authorities can set other norms and this will make it difficult to compare other services with each other. Variation over day and between routes, on the other hand, do not influence the outcome. It is still a supply-oriented indicator. Assessing progress is difficult, since there is no distinction made between the extent to which the norm will be exceeded. Although it is a regularity KPI, there are deficiencies. The question that arises, what is the most important objective for KPIs? KpVV (2008) mentioned that direct comparison is important. They mentioned that one should prevent that different regularities need to be measured. For example, regularity during the morning peak and during the rest of the day or different regularities between lines. Some of the problems that has been arisen, or aspects that are not clear from the DAV concession requirement, are:

- Where do you measure the headway; arrival headway or departure headway?
- How do you deal with strategic behaviour as a result of the fact that regularity is measured at some point along the route?
- How do you deal with different scheduled headways within one period?

The latter will be explained in more detail by giving an example. Currently, the scheduled headway in the peak hour for line 400 is in general 5 minutes. However, some trips have a scheduled headway of 6 minutes. The question that arises, taken into account the given regularity norms: differ the norms for these trips or do you use the same norms as for the trips with a scheduled headway of 5 minutes?

In conclusion it can be said that this regularity also has deficiencies; that are comparable to the deficiencies of the punctuality requirement. First, the degree of reliability is dependent of the chosen definition of regularity. Second, the focus is on the supply side, instead of the demand side. Also whether the bandwidth and norms work as incentives is unknown.

8.4. Sub conclusion

Currently, one of the main determinant of reliability imposed by the transport authority is punctuality. However, in case of high-frequency lines, regularity is more important. A shift has to be made to include regularity in the concession requirements, instead of punctuality. Currently, more operators in The Netherlands include regularity in their concession requirements. However, the requirements are incomplete and it can also be asked whether the penalties will work as incentive for the operator. In addition, the focus is on the supply side, instead of the demand side.

It is proposed to first determine the current performance of regularity. After that, goals can be determined and realistic incentives can be given to stimulate the operator to improve the quality. In addition, the possibilities to combine vehicle data and passengers data, in order to shift from supply to demand oriented performance. Currently, this combination is not made. In case this is possible, the performance of a service perceived by passengers can be taken into account, instead of the performance of vehicles. In addition, choices should be made about how to measure headways and when to include or exclude data.

Also for the authority it would be beneficial to organise a pilot. In that case, the authority ca determine what the effect is on passengers or whether other requirements could be applied. In addition, it could be analysed whether the determined bandwidth and norms are realistic. For the authority the following steps are important when organising a pilot:

- Analyse the current situation; a baseline measurement is needed in order to analyse the starting point. For line 400 a baseline measurement is executed in this research.
- What possibilities do you want to test? Different strategies could be tested in practice
- A control plan should be determined; what actor wants to know what aspect? The KPIs that are determined in this research could be used as basis. AVL and APC could be used for this.
- Passenger interviews should be done in order to know what their opinion is about different strategies.

9. Conclusions and recommendations

In this chapter conclusions and recommendations are formulated. First the main research question will be answered. In the next section some recommendations for Arriva are given. Subsequently, recommendations for further research will be the last part of this chapter.

9.1. Main conclusions

One of the main factors that determines the quality of a public transport service is the reliability of that service (Van Oort, 2011) In order to improve service reliability, control stategies can be applied. For high-frequency bus services, regularity is more important for the quality of a system than punctuality.

The main research question in this research was:

How could holding control strategies be assessed and implemented, and what is the effect of different holding-control strategies, with respect to the operator, passengers and the transport authority?

The main objective in this research was to develop a framework to systematically assess the effect of different holding control strategies, taken into account the perspective of passenger, the operator and the transport authority. Additionally, difficulties with respect to regularity-driven operations were discussed.

First a framework consisting of the KPIs for the three main actors was deceloped, in order to be able to assess strategies. Subsequently, hholding strategies were developed, consisting of three main aspects: the criteria (headway- or schedule-based holding), selection of control points and maximum holding time. The choice for strategies depends on demand characteristics and infrastructural aspects of the bus line, and could therefore differ per service. Scenarios were also generated to help to test the robustness of strategies. The assessment framework was applied on a case study, in order to test this framework, but also to get insight in the performance of holding strategies. Some general guidelines were derived from this application, indicating what service characteristics influence the effect of holding strategies. The case study that is used in this research is a high-frequency line between Leiden and Zoetermeer, operated by Arriva: line 400.

The current problems for line 400 can be summarised as follows:

- No punctual performance: relatively high amount of too early departures
- Variation in running times and dwell times; leading to variation in headways
- Crowded vehicles

The framework is applied to this case study. Effects of the holding control strategies on the different perspectives are as follows.

Operators are in particular 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 higher cycle times that could also lead to more buses. However, the effects of holding on the total cycle time do not lead, in general, to the need of more buses. With respect to the reliability of a trip; the headway-based control strategies are better able in offering a constant 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 in case more holding is applied. However, the excess waiting times decreases, as a result of the more regular service. Also the variation of the time-components is less. The effect of the two control strategies depend on two main aspects: the quality of the timetable and the occupancy pattern of a line. Schedule-based control can provide a regular service, if there is enough turnaround time at the terminal or if there is enough slack time in the timetable. Particularly the occupancy pattern on the line affects the average impact on passengers. In case most passengers board at the terminal, schedule-based control performs also good, because the effect on waiting times is comparable to the effect in case of headway-based control.

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

Based on the simulations, and the current practice of Arriva, the best control strategy at this moment is sched-9-0; schedule-based control with 9 control points and no maximum holding time. Implementing this strategy does not require large changes. Particularly since the differences are small compared to the headway-based strategies. However, hw-9-60 (headway-based control with 9 control points and a maximum holding time of 60s) will also be a promising strategy, that is more robust to uncertainties.

Based on this research it can be concluded that the most important service characteristics, related to the performance of a specific holding strategy are as follows. Headway-based holding is in general better for high-frequency lines, because this strategy can deal with variability along the route. However, in some cases, schedule-based control performs the same. The requirements for schedule-based control are: enough slack time in the timetable and enough turnaround time at terminals. In addition, in case most passengers board at terminals, schedule-based control also performs relatively good.

Practical problems with respect to the implementation of headway-based control makes it difficult to shift to aheadway-based strategy. The following operational difficulties are identified:

- Technical changes; internal (board computer) and external (passenger information systems) data information flow should be able to deal with regularity
- Logistical changes; more dynamic vehicle and crew planning is needed. Information for traffic controller
- Behavioural changes; drivers need to adapt their current working style and traffic controllers need to know what decisions they have to make taking into account the regularity on a the line and in a network

In addition, when operators would shift towards a regularity-driven operation, the punctuality requirements should be changed towards regularity requirements. For the transport authority there are also uncertainties. Currently, more operators in The Netherlands include regularity in their concession requirements. However, the requirements are incomplete and it can also be asked whether the penalties will work as incentive for the operator. In addition, the focus is on the supply side, instead of the demand side. It is proposed to first determine the current performance with respect to regularity. After that, goals can be determined and incentives can be given to stimulate the operator to improve the quality. In addition, it needs to be possible to combine vehicle data and passengers data, in order to shift from supply to demand oriented performance. Currently, this combination is not made automatically. In case this is possible, the performance of a service perceived by passengers can be taken into account, instead of the performance of vehicles. In addition, choices should be made about how to measure headways and when to include or exclude data.

In conclusion, the question how to include headway-based control cannot be answered directly. First the above mentioned aspects needs to be solved.

9.2. Main contributions

In this research an assessment framework is developed to assess the effect on passengers, the operator and the transport authority. This framework can be applied by operator or authorities in order to determine what strategy could be most beneficial in order to regulate headways, and with that solve related problems.

The assessment framework was applied to a case study and based on these results knowledge was gained about what line characteristics are important for the performance of schedule- and headway-based strategies. This knowledge is also useful for operators and transport authorities. From the application of the framework, also knowledge was gained about the robustness of headway-based holding strategies, with respect to disruptions and non-compliance. This robustness is important and valuable. One of the concerns of operators is that the system collapse in case of a disruption: the 'domino-effect'. In this research it was shown that this effect can be mitigated more easily with schedule-based control. This insight is important for operators, because headway-based control can increase the reliability of a service and is also able to deal with disruptions and other uncertainties.

In this research insight in what the concerns are for operators with respect to technical adaptations, logistical changes and behavioural aspects were discussed. This contributes to the discussion about implementing regularity-driven operations. More insights on this aspect help to be able to deal with the difficulties. Insight in the difficulties with respect to including regularity in the concession requirements can contribute to the discussion on how to implement regularity-based operations. At this moment the requirements included in concessions are incomplete and it can also be asked whether the penalties will work as incentive for the operator.

9.3. Recommendations

In this section the recommendations will be provided. The recommendations are divided into scientific and practical recommendations. Subsequently, the practical recommendations are subdivided into general practical recommendations and recommendations specifically for Arriva.

9.3.1. Scientific recommendations

It is recommended to apply the assessment framework on different lines. In this study it was concluded that some services are better suitable for headway-based control than others. However, only one line is analysed. Multiple lines should be assessed similarly. In that case it would be possible to better indicate candidate routes for either schedule-based or headway-based holding.

It is also recommended to do additional research with respect to network-related impacts of headway-based holding. It should be analysed how to deal with services that have partly the same route. An example is given in Figure 9.1. The assessment of a control strategy can be improved, in case network related impacts are included.

In this research the schedule-based strategy and the mean-headway based strategy are used. However, it is recommended to test also other holding

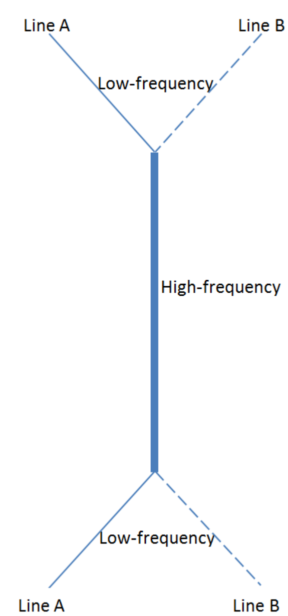

Figure 9.1 Example network

strategies. For example, holding strategies that incorporate passengers into the decision of holding. Holding time affect the in-vehicle time of passengers that are already in the bus. For these passengers holding is not desired. In order to analyse when and how the decision could be made, taking into account the number of passengers in the bus, is one of the aspects that is not analysed in this research. Subsequently, the focus in this research is on holding control strategies. However, to what extent other control strategies could solve regularity problems should also be subject of further research. Combinations of control strategies are also worth investigating. This could also be added to the assessment framework.

Also more knowledge is needed for the transport authority with respect to regularity indicators and incentives for the operator. How to include a regularity requirement and combine this with penalties that work as incentives is one of the aspects that should be investigated. In addition, research on the possibility to shift from supply-oriented requirements to demand-oriented requirements is recommended.

Another recommendation is related to an improvement of BusMezzo. One the main limitation of BusMezzo that has impact on the results in this research, is the fact that the simulation model is not able to control vehicles at terminals. It is recommended to investigate how to implement control at terminals in the model. In addition, terminal departure variability is one of the causes of service variability. An improvement of the model would be to include terminal departure distributions.

9.3.2. Practical recommendations

General

In this research a simulation model is used to test different strategies. However, one of the main limitation of simulation models are the behavioural aspects. Behaviour is difficult to simulate. Therefore, it is recommended to analyse the effect of different behavioural aspects, related to holding: traffic controllers and drivers. First, in case a change will be made towards a regularity-driven operation, the working style of traffic controllers probably needs to change. However, it is unknown how. In addition, in case two systems are applied to different lines (based on regularity- or punctuality), making decision will be more difficult. In general, traffic controllers currently base their decisions on, among others, keeping the punctuality as high as possible. However, how to be able to keep the regularity of a system as high as possible, requires a new way of acting. What the influence is of different actions is not known and should be investigated in more detail.

Also drivers needs to change their working style. It is important for them to understand why there are differences in control methods on different lines. In addition, it is important to explain how to deal with the different strategies; what actions are required in what case.

Arriva

The first recommendation for Arriva is to actively implement schedule-based holding control. This strategy could improve the service reliability, without the need of large changes. Clear rules should be defined on how drivers need to act. In addition, decreasing the variation in terminal departure is also important in order to improve the total service reliability. In general, driver compliance is an important, and difficult, aspect. Drivers should be motivated to adapt their behaviour to the rules of the control strategy. It could help to involve drivers more and show them the consequences of their actions. For example, show them what happens in case they depart early or late from a stop. In case they are more aware of the consequences of their actions, it could motivate them to make other decisions.

Headway-based control strategies are more robust with respect to disruptions than schedule-based control. Therefore it is recommended to analyse the effect of this holding strategy in practice. A pilot study could help to see how headway-control could improve performance. In addition, to what extent logistical, technical and behavioural aspects influence the control strategy and performance of other lines could then be investigated.

In order to be able to perform a pilot study, different actors have to be involved, including the operator, transport authority, passengers and external parties that are responsible for passengers information. For the operator, different persons within the organisation should be involved: drivers, planners, traffic controllers and managers. It is advised to make a detailed plan of action:

- Who should be involved in the process?
- What do the different actors want to know with respect to headway-based holding strategies?
- How could this be tested in practice and what changes need to be made?
- What do you want to measure in order to analyse the effects of the control strategy? Our assessment framework can be used.
- How do you want to measure the effects?

Finally, it is recommended to analyse the influence of other public transport in the region; train station Leiden Centraal and RandstadRail Zoetermeer Centrum West. It is expected that the differences in vehicle loads are not only caused by irregularity. It could be possible that other strategies are better suitable for solving the problems for this line.

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Appendix A. Program of requirements public transport

The case study is line 400 of Arriva. Line 400 is part of to concession Zuid-Holland-Noord. This concession started in December 2012. In this appendix it will be explained what the requirements are for Arriva, based on the concession requirements. Only the requirements with respect to the performance will be discussed. Other requirements, for example with respect to vehicles, crew and prices, will not be discussed, because it is assumed that these aspects do not have influence on the control strategy, which is the focus in this research.

Since line 400 is a R-net-line, additional requirements are also applicable; there are additional R-net-requirements. Also these requirements will be discussed in this section.

A1. Concession Zuid-Holland-Noord: Quality of performance

The following aspects, regarding the quality of the performance are included in the concession requirements (article 4.5) (Provincie Zuid-Holland, 2011):

1. Transport duty
    - The concessionaire is required to transport all the waiting passengers, who want to travel with a line that stops at that stop according the timetable. The waiting passengers need to be able to board at the first vehicle that stops at that stop.
    - The concessionaire has to match the offered capacity on the reasonably foreseeable demand for public transport.
2. Guarantee seats
    - The concessionaire needs to match the offered capacity with the foreseeable demand in order that at least 95% of the passengers will directly have a seat, outside the peak periods (Peak period: 6:30 AM-9:00 AM, 4:00 PM- 6:30 PM).
3. Trip cancellations and punctuality
    - All the trips included in the timetable needs to be performed closely, fully, adequately and in accordance with the timetable. Trip cancellation is only accepted if there are unavoidable consequences of collisions or calamities. The concessionaire needs to strive to offer alternative transport possibilities. The vehicle log-files are the basis of the registration of the cancellations.
    - Trips are not allowed to depart early, based on the timetable, from the first stop of a trip, nodes or time stops. These nodes and stops are also specified in the concession requirements.
    - At least 90% of all the trips needs to depart from the starting point within 2 minutes after the time specified in the timetable.
    - At least 85% of all the trips needs to depart from nodes and time stops within 3 minutes after the time specified in the timetable.
    - At least 85% of all the trips needs to arrive at nodes and time stops within 3 minutes after the time specified in the timetable.
    - Departing later than 3 minutes or arriving later than 3 minutes is only allowed if a trip experienced traffic congestion, impossibility to use the road or in case of serious incidents with public. As long as the concessionaire has made efforts to prevent the deficiencies.
    - A trip is a cancelled trip in case it is not or not completely performed, irrespective of the reason.

- The risk of trip cancellation is on behalf of the concessionaire. The grantor can subtract the cancelled trips from the contribution for the operation, except in case of force majeure (see 6).

4. Connections.
   - The concessionaire tries to realise all the in the timetable specified transfers.
   - It is allowed to delay a trip with more than 2 or 3 minutes, in order connect delayed trains/buses, as long as there are no consequences for other connections of that trip.
5. Central traffic controller.
   - The concessionaire has central traffic controllers with sufficient local knowledge to steer the operation in the right direction, in case of disruptions or calamities.
6. Force majeure.
   - With force majeure, all the events that hinders the concessionaire to keep to its duties and that are not his fault, are meant.

Passengers satisfaction is also included in the concession.

A2. Concession Zuid-Holland-Noord: Monitoring and financing

The grantor, the transport authority, needs to be able to monitor the performance of the public transport services. In order to be able to do this, he requires information. These requirements can be found in appendix M of the concession Zuid-Holland Noord (Provincie Zuid-Holland, 2011). In addition, in order to stimulate the concessionaire, the grantor also determines penalties in case the requirements are not fulfilled. In this section the required information will be discussed. In addition, the penalties will be discussed.

Information with respect to the quality of supply of public transport:

- Overview of all the lines and trips of the cases of denied boarding.
- Overview of lines and trip with more passengers than seats.
- Overview of all trips that were cancelled; trips that are not or not completely performed. Including the reason for the cancellation.
- Overview of the share of trips per line that departed too early from the specified stops, or arrived too late at the specified stops.
- Number of complaints.
- Number of incidents and calamities.

Information with respect to the demand of public transport:

- Number of passengers, per month, line, direction and daily period.
- Number of passengerskilometer, per month, line, direction and daily period.
- Occupancy rate of the vehicles.
- Overview of actual trip times, and deviations from the times according the timetable.

Penalties with respect to the performance quality, mentioned in appendix W of the concession (Provincie Zuid-Holland, 2011):

Table A.0.1 Requirements and belonging penalties

Requirement	Penalties	Measurement
Timetable does not meet the requirements included in the concession.	-	- Information provided by the concessionaire - Passengers complaints - Observations by the grantor
No connection although it was predefined in the timetable and/or a stop was skipped.	€50,- per shortcoming	- Information provided by the concessionaire - Passengers complaints - Observations by the grantor
Trip departs more than 2 minutes late from the first stops or time stops, based on the timetable and the share of these late trips is lower than 90%.	€5,- per minute later than 2 minutes	- Trip information system - Passengers complaints - Observations by the grantor
Trip departs more than 3 minutes late from node or time stop, based on the timetable and there were no situations that can be excluded from the punctuality determination (congestions, force majeures, etc). The share of these late trips is lower than 85%.	€5,- per minute later than 3 minutes	- Trip information system - Passengers complaints - Observations by the grantor
Trip arrives more than 3 minutes late at node or time stop, based on the timetable and there were no situations that can be excluded from the punctuality determination (congestions, force majeures, etc). The share of these late trips is lower than 85%.	€5,- per minute later than 3 minutes minus the minutes the bus departed too late from the previous node or time stop.	- Trip information system - Passengers complaints - Observations by the grantor
Trip departs earlier from the first stop, a node or time stop than the departure time according the timetable.	€10,- per minute early at every first stop, node or time stops.	- Trip information system - Passengers complaints - Observations by the grantor

A3. Requirements R-net

The collaborative authorities made agreements about the characteristics of R-net. The most important aspects are: reliable, recognizable, connected, attractive and convenient (effortless). In Table A.0.2 an overview of the most important requirements for the bus line 400 are presented (R-net, n.d.).

Table A.0.2 R-net requirements

Requirement	2020
Minimal frequency	Working days: - Peak hours: 6 per hour - Off-peak: 4 per hour
Speed	- No requirements in urban areas. - Others: maximum 20 km/h slower than the speed limit. - PT travel time should be maximum 1.5 higher than the time needed when using a car.
Reliability	- No trip cancellations - No early-departures - Guaranteed transfers - Punctual, planned travel time = actual travel time - Up-to-date information

Appendix B. BusMezzo: model implementation

This appendix (p.100-106) is confidential and therefore not visible in this version.

Appendix C. Overview of KPIs

In this appendix an overview of the determined KPI is given. In addition, an short explanation and description of the calculation is included. In C.2 an overview of the definition of the different level of services is given.

C.1. KPI determination

Operator

Holding time per trip [#] and [s]	Number of interventions that a bus is held at a control point per trip and the average holding time per intervention.
Cycle time [s]	80th-percentile of the total trip time; time from depart of the first stop to arrival of the last stop, including the boarding and alighting times.
Variation in cycle time[s]	Variation in the total trip time; difference between the 80th- and 50th-percentile.
Service reliability	Service reliability is expressed in the Coefficient of variation of the headways; the ratio of the standard deviation and the mean. This can be used as indicator of the variability of the data. The higher the CoV, the more variation. In addition, this CoV can subsequently be used in order to determine the level of service (LoS). The LoS indicates the quality of a line, according to TCRP (2013). See also section C.2 of this appendix.
Load factor	Load factor is the occupancy of the bus divided by the capacity.
Crowding variability	The average deviation of the load gives an indication of the level of efficiency of the capacity of the used buses. $$L\_dev_j^t = \frac{\sum_k (L_{j,k}^t - \overline{L_{J)}^t}}{n_{j,k}}$$ Where, ${L_{dev}}_j^t$ = average deviation of the load at stop j $L_{j,k}^t$= observed load at stop j for trip k $\overline{L_j^t}$= average observed load over period t at stop j
Concession requirements	Consisting of denied boarding, probability of finding a seat, trip cancellation, punctuality and regularity. The regularity can be expressed in the PRDM (Van Oort, 2011): $$PRDM_{l,j} = \frac{\sum_k \left\| \frac{H_{j,i}^{sched} - H_{j,i}^{sched}}{H_{j,i}^{sched}} \right\|}{n_{l,j}}$$ Where, $PRDM_{l,j}$ = relative regularity for line l at stop k $H_{j,i}^{sched}$ = relative regularity for line l at stop k $H_{j,i}^{sched}$= relative regularity for line l at stop k $n_{l,j}$ = number of vehicles of line l departing at stop j

Passengers

Perceived in-vehicle time [min]	Perceived average in-vehicle time (PAIVT) is the average in-vehicle time per passengers, multiplied by weighing coefficients, that depends on the occupancy of a vehicle. The higher the occupancy, the higher this weight is. The weights are adapted from
Variation in perceived in-vehicle time [min]	Variation in perceived in-vehicle time is the RBT of the in—vehicle time. The RBT is the reliability buffer time, which can be used as in order to express the variability of the in-vehicle time for passengers. The RBT of the in-vehicle time is the difference between the 95th- and the 50th-percentile of this time component (Van Oort, 2011)
Waiting time [min[	The waiting time is calculated by dividing the actual headway by 2.
Variation in waiting time [min[	The variation of the waiting time can be expressed as excess waiting time; the differences between the average planned waiting time and the actual average waiting time. In addition, another waiting time related component is the RBT of the waiting time. This is the difference between the 95th- and 50th-percentile of the waiting time.
Average standing time [min]	The average time of a trip a passenger have to stand.
Authority	
Probability of finding a seat	This is determined by calculating the average share of passengers that cannot seat during their trip.
Service reliability: punctuality/regularity	Punctuality calculation; share of vehicles that arrive too late, depart too early or depart too late. The exact boundaries depend on the concession requirements. With respect to regularity, in this research the PRDM is chosen as indicator.

In order to be able to compare different strategies from passenger perspective, the average experienced travel time is calculated. This is done by summing up the experienced time components. The average experienced travel time can be used in order to make a final comparison.

$$T_{exp,tt} = T_{PAIVT} + T_{RBT\_PAIVT} + \beta_{waiting}(T_{AWT} + T_{RBT_{AWT}}) \tag{3.1}$$

Where,

$T_{exp,tt}$ = Average experienced travel time per passenger
T_{PAIVT} = Perceived average in-vehicle time
$T_{RBT_{PAIVT}}$ = Reliability Buffer Time due to variability in in-vehicle time
$\beta_{waiting}$ = Weighting waiting time (TCRP, 2013)
T_{AWT} = Average waiting time per passengers
$T_{RBT_{AWT}}$ Reliability Buffer Time due to variability in waiting time

C2. Level of Service

In Table C.0.1 the level of service of transit line are given, based on TCRP, 2013.

Table C.0.1 Level of service based on the CoV of the headways (adapted from (TCRP, 2013)

Level of service (LoS)	CoV[h]	Passengers and operator perspective
A	0.00-0.21	'Service provided like clockwork'
B	0.22-0.30	'Vehicles slightly off headway'
C	0.31-0.39	'Vehicles often off headway'
D	0.40-0.52	'Irregular headways, with some bunching'
E	0.53-0.74	'Frequent bunching'
F	≥0.75	'Most vehicles bunched'

Appendix D. Regularity

D.1. Requirements KPIs

With respect to fornulating KPIs, the following aspects are of importance (Uniman, 2009; Strathman, et al., 1999; Chan, 2007):

- Easy to interpret and to communicate: KPIs represented in time units is most easily interpretable and will therefore be preferential for both the operator and authority.
- Objective and direct comparison should be possible: variations over the day and between routes (low-frequency lines and high-frequency lines) should not have influence on the KPI and comparison should still be possible.
- Orientation to passengers: The KPI should be focus on the perspective and experience of the passengers. As argued by Rietveld (2005) supply-based KPIs overestimate the performance from a passengers perspective. The KPI should therefore represent the perspective of the majority of the passengers.
- Useful for goal settings and assess progress: KPIs should be useful in the context of monitoring and evaluating performance. This means a standard should be formulated and the calculation is accurate and precise by dealing with sampling errors.

D.2. Regularity in practice

In this section an overview is given of bus operators that use regularity indicators, as shown in Table D.0.1. In most cases a threshold value for the headways is used. However, in London the EWT is used as regularity KPI.

Table D.0.1 Different definitions of service regularity

City	definition of regularity	Regularity target	Scheduled headways
Barcelona	h - 1 to h + 3 min		4 – 9min
Brussels	h to h + 2 min		3-11 min
Gothenburg	h - 20%h to h + 20%i	80%	
Lisbon	h - 20%h to h + 20%i	80%	6-10 min
Milan	h – 3 min to h + 3 min		1-8 min
New York	h - 50%h to h + 50%h		2-10 min
Paris	h + 2 min	90%	3-12 min
San Francisco	h - 30%h to h + 30%h	85%	
Singapore	h - 5 min to h + 5min	85%	1-12 min
Vancouver	h – 2 min to h + 4 min, h - 20%h to h + 20%h		1-9 min
London	EWT: 0.5-2.0 min (route dependent)		

* h: the planned headway

Sources: Trompet, Liu, & Graham, 2011 ;Finn, Heddebaut, Kerkhof, Rambaud, Lozano, & Soulas, 2011; Nakasnishi, 1997; LTA, 2017

Appendix E. List of corresponded persons

In this research several persons commented on the research. This appendix provides a list of persons who gave information and commented on the research.

1. Arriva

Arriva employees involved in the planning and operational phase of the transit service were asked about the model and the results by conversational interviews. These interviews were conducted in an informal manner. Arriva employees who commented on the model and the results consist of planners (timetable, fleet, crew), managers, data analysts and drivers. In addition, also other Arriva employees related to the data information provision, gave information and discussed the difficulties in case headway-based control would be implemented.

2. Transport authorities

In addition, the transport authorities Province of Zuid-Holland and Utrecht were consulted in order to give information about the current concession requirements. In addition, aspects that are of importance when implementing regularity control were also discussed. Finally, it was discussed what aspects are important when including regularity in concession requirements.

Province of Zuid-Holland

- Anne Wil Boterman: data-analyst
- Roeland Pieper: concession grantor
- Tom Verhaar: concession grantor

Province of Utrecht

- Jeroen Golstein: senior policy advisor public transport
- Robert van Leusden: senior policy advisor public transport