COMBINATION OF SPEED ADJUSTMENT AND HOLDING CONTROL STRATEGY FOR A REGULARITY-BASED TRANSIT OPERATION

A CASE STUDY OF ALMERE, THE NETHERLANDS

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TUDelft

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Preface

This thesis project marks the end of my journey as a master degree student in Delft. These two years and two months have been a quite challenging experience for me. Especially during the thesis period, which has been demanding me to take a role as a leader and director of my own project. Feeling stressful and down, it would be impossible for me to pass through these conditions alone. Therefore, in this opportunity, I would like to thank all people who have been supporting me until I finally reached this point.

First, I would like to express my greatest gratitude to LPDP, as the one who provided me with this opportunity to continue my master degree in the TU Delft. I hope that this degree could help me to give a great contribution to Indonesia.

I would also like to thank my graduation committee, who have constantly given their feedback and ideas throughout the project. To my daily supervisor, Dr. Niels van Oort and Pieter van der Pot, thank you for your guidance, patience, and helps. As a person who grew up in a developing country without an adequate transit system, I always hope to improve mobility in my country. It was because of these people; I could have the opportunity to work on this project of Keolis, on the topic of the public transport system. To Dr. Oded Cats, thank you for the discussions, and your helps on BusMezzo, for which help me to realize my idea on this project. To Dr. Jan Anne Annema, thank you for your positive words and motivation. To Prof. Serge Hoogendoorn, thank you for your trust in me to carry out this project. Without the supervisions from them, I would not be able to finish this thesis project.

I am also grateful that I have such supportive friends during my study. The TIL friends, Molenstraat sisters, and the fellow Indonesian friends, thank you for the laughs, silliness, stories, and other memorable moments we shared. I rarely felt homesick because of you.

To Ocik, thank you for introducing me to Jordan Peterson, Tom Bilyeu, other inspiring people and reads, through your motivating words every time I felt down.

Lastly, to the ones who will always be there for me, my family. To my parents, who constantly send me their prayers. To my sister and brother, who inspire me to pursue higher education. And, to my little brother, who always reminds me to be a good role model for you to look up to.

Aishah Mahyarni Imran

Delft, 29 October 2018

Executive summary

Introduction

As the population grows, the need for mobility has been growing in recent years. In the case of urban mobility, this trend is subsequently followed by the existence of high-frequency bus transit service since last decades. This service is more prone to the bus-bunching problem since the headway between the consecutive buses can be very short, and the passenger demand is typically higher. It becomes very important to keep the service reliability in an adequate state. Applying a headway-based control strategy is an alternative to obtain an efficient and reliable high-frequency bus operation.

Different issues could be found before applying control strategy in a transit system. In the early stage, selection on which control to apply can be dilemmatic. Among different category of control strategies, holding control is the preferable one to mitigate the irregularity problem. However, there are several contrary arguments on this and stating that speed adjustment as a form of "holding", could obtain a better impact on passengers. Once the strategy is chosen, another issue might appear during the strategy development. To whose perspective the control strategy has to be built. Most attention is usually given to the passenger, while the others are given less attention. Drivers and network impact are the two factors that are often ruled out, even though both are important in determining the performance of control strategy during the implementation. While the attention is all concentrated to yield high serviceability, the practicality is usually forgotten.

Depart from these problems. Thus, the goal of this study is ***to develop a headway control strategy based on a combination of several measures and to evaluate it from a practical point of view.***

Control strategy development for a regularity-based operation

The development of the control strategy starts with identifying the attributes of different strategies. For this study, the focus is put on speed adjustment and holding control. Holding control is beneficial when dwelling time is high. However, it is only applicable when the trips are considered early and sometimes the holding time can be very long and cause higher costs in waiting onboard. In contrast, speed adjustment offers the ability to speeding up for the late trips. The riding time also costs lower than holding time. The proposed control strategy was built based on the combination of these strategies. Different characteristics of both controls enable these strategies to cover each other's limitation.

A set of indicators based on the perspective of the passengers, the operators and the authorities were established to determine the performance of the proposed control strategy. This study provides additional indicators to capture the issues from a driver and network perspective. For the driver, the source of stress such as a high deviation in speed distribution and a high number of control measures taken was considered by understanding its possible effect on incompliance. With respect to network impact, the joint headway distribution between the common lines was investigated.

The proposed control strategy was developed as a rule-based strategy built upon an event-based assumption and was described in a mathematical formulation. By understanding the importance of a real-time manner for a headway-based control strategy, the author chose a simulation method to evaluate the control strategy. The mathematical formulation was included as an addition in an event-based simulation tool, BusMezzo. As additions, several assumptions were considered for the proposed control-strategy, as followed:

1. Real-time communication between the vehicles
2. The system runs in a dedicated lane, thus there is no effect from other road users
3. Ignoring the effect of acceleration and deceleration
4. Arrival time prediction based on the scheduled trip time between stops

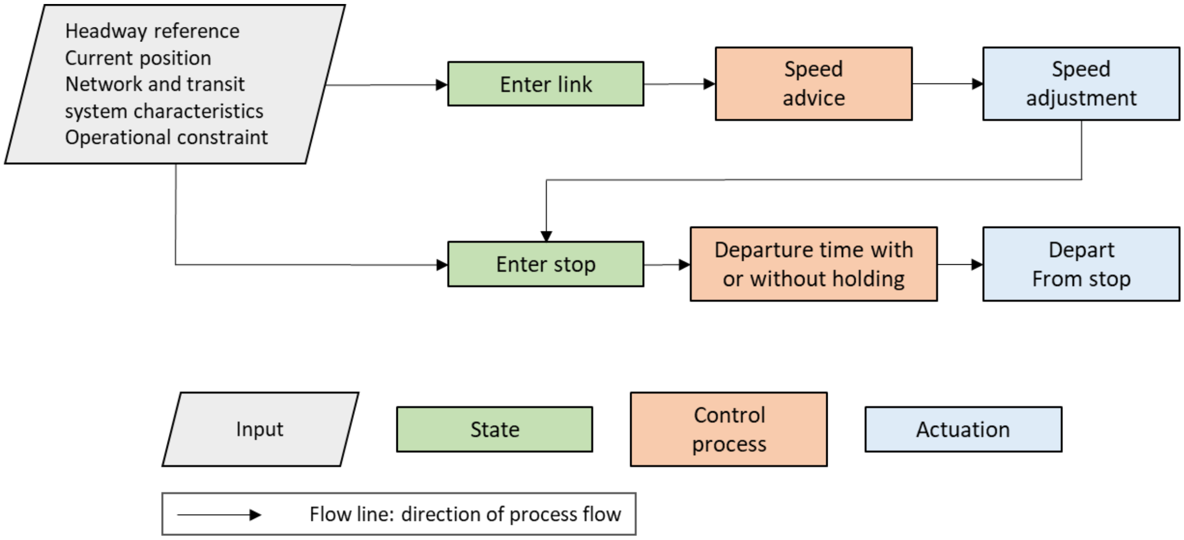

Figure 1 General concept of the controller

Figure 1 depicts the general concept of the proposed control strategy. By applying the event-based concept, there are two locations to take the control decisions: 1) at the link for speed adjustment and, 2) at the stop for holding control. Speed adjustment becomes the main strategy taken in this concept. When slowing down is not possible anymore due to speed boundaries, the controller would suggest to perform holding at a stop. Event-based concept influences the way the vehicles transmit their information to each other. The known state for a vehicle is the time when the vehicle is dwelling, holding, departing and arriving. Thus, the decision on speed adjustment is only possible to take in discrete time, that is when a vehicle leaves a stop before entering a link.

Strategies and scenarios for the evaluation

The assessment of the control strategy was done through a simulation based on a case study of the AllGo bus network, Almere. AllGo is a bus rapid transit system which runs on dedicated lanes. This system is currently controlled under a scheduled-based holding control. For the present study, the operational data of AllGo bus in the period of April-May 2018 was used. There are two lines considered in the assessment, naming Line M5 and Line M7. The system in the AllGo network was modeled in BusMezzo simulation. A validation based on two-sample t-test with a C.I. of 95% on headway result was carried out before simulation.

Three different scenarios were carried out for different strategies in order to assess the performance of the proposed control strategy. Scenario 1 for normal condition, Scenario 2 for a tight schedule, and Scenario 3 for different demand level. The considered strategies in this study are as followed.

SB	: schedule-based holding control, as the reference case for other strategies with several control points. The control points were selected based on the actual control points applied in AllGo network.
EH1	: even headway-based holding control, which applies the same control point as SB does
EHALL	: even headway-based holding control, with control point at all stops
SA	: speed adjustment strategy
SH	: the proposed control strategy, speed adjustment–holding strategy.

In SA and SH, different speed limits were defined based on speed distribution from empirical data as described in table 1 below.

Table 1 Speed range definition

Strategies	Descriptions
SA/SH1.2	SA/SH with a speed limit ranging from 5th to 95th percentile of speed distribution
SA/SH1.3	SA/SH with a speed limit ranging from 25th to 95th percentile of speed distribution
SA/SH2.2	SA/SH with a speed limit ranging from 15th to 75th percentile of speed distribution

Results

Performance of different control strategies

Table 2 summarizes the output of the simulation. Five indicators were chosen to represent a different point of views: regularity, operator, driver, passenger, and authority. Under a certain speed range, SH consistently showed a better regularity, with 11-63% improvement, in comparison to holding control. While the performances between SH and SA were slightly different in general, SH was more capable to maintain the regularity when the demand and headway distribution were more varied.

On the other hand, the system tended to slow down when performing the SH strategy. In general, if the minimum speed was set too low, it caused longer cycle time and consequently requires 8-10% more fleets to operate. SH was also outperformed by holding control when it was assessed from the driver's perspective. While SH was able to reduce the speed variation up to 23%, it required five times more control decisions.

Initially, the development of SH was expected to be ably reducing the holding time, and generalized travel cost subsequently. This study shows that SH consistently resulted in a lower holding time compared to a holding control only.

Nevertheless, as abovementioned, the additional riding time obtained due to slowing down was more dominant than the reduction of holding time. Hence, SH did not give the best value in generalized travel time cost. However, all strategies are considered well performed given the fact that the differences between the strategies were only around one to two minutes, which is argued to be not significant.

Table 2 Summary of simulation results (green = best, red = worst)

Scenarios		Normal condition									Tight schedule									Demand level 1.35								
Strategies		SB	EH1	EHALL	SA1.2	SA1.3	SA2.2	SH1.2	SH1.3	SH2.2	SB	EH1	EHALL	SA1.2	SA1.3	SA2.2	SH1.2	SH1.3	SH2.2	SB	EH1	EHALL	SA1.2	SA1.3	SA2.2	SH1.2	SH1.3	SH2.2
Average CoV headway per line (%)	Line M5, Dir 1	11%	13%	10%	6%	5%	5%	5%	6%	4%	11%	10%	11%	24%	5%	7%	23%	7%	7%	12%	11%	11%	9%	5%	7%	8%	8%	6%
	Line M5, Dir 2	11%	9%	7%	28%	5%	6%	17%	5%	8%	12%	10%	9%	36%	13%	17%	35%	8%	16%	12%	10%	7%	30%	6%	6%	21%	5%	6%
	Line M7, Dir 1	9%	10%	10%	7%	6%	5%	6%	7%	5%	13%	11%	13%	21%	6%	8%	24%	9%	8%	10%	10%	11%	10%	6%	5%	10%	8%	8%
	Line M7, Dir 2	9%	9%	9%	30%	5%	4%	28%	5%	4%	15%	11%	12%	18%	8%	7%	11%	7%	6%	12%	11%	10%	30%	6%	5%	28%	6%	5%
Fleet requirement	Line M5	10	10	10	11	10	10	11	10	11	10	10	10	12	10	10	12	10	10	10	10	10	12	10	11	12	10	11
	Line M7	12	12	12	14	12	12	14	12	13	11	11	11	13	11	12	13	12	12	12	12	12	14	12	13	14	13	13
Nr of control taken	Line M5, Dir 1	1	1	3	15	15	15	17	18	17	1	1	3	15	15	15	17	17	16	1	1	3	15	15	15	17	18	17
	Line M5, Dir 2	1	1	4	15	15	15	17	18	17	0	1	2	15	15	15	17	17	16	1	1	4	15	15	15	17	18	17
	Line M7, Dir 1	2	2	5	16	16	16	19	22	20	0	1	3	16	16	16	18	18	17	2	2	5	16	16	16	19	21	20
	Line M7, Dir 2	1	2	3	16	16	16	18	18	17	1	1	3	16	16	16	18	19	18	1	2	3	16	16	16	18	18	17
Average generalized travel time per passenger (min)		39	40	41	43	40	41	43	41	41	43	43	44	47	43	44	47	44	44	42	43	45	48	43	45	48	44	45
Regular trip (CoV < 0.21) (% trips)	511	98%	93%	94%	99%	100%	100%	99%	100%	100%	88%	88%	91%	51%	100%	100%	52%	100%	100%	86%	87%	92%	97%	100%	100%	98%	100%	100%
	706	100%	99%	99%	91%	98%	99%	91%	98%	99%	92%	93%	94%	90%	100%	100%	90%	100%	100%	94%	96%	96%	100%	100%	100%	96%	100%	100%
	712	100%	97%	94%	98%	99%	100%	97%	95%	100%	87%	89%	84%	67%	100%	100%	63%	99%	100%	80%	89%	89%	93%	100%	100%	95%	97%	90%
	2506	96%	100%	100%	57%	100%	100%	58%	100%	100%	98%	98%	99%	55%	91%	86%	55%	92%	86%	98%	97%	100%	58%	97%	100%	58%	99%	100%
	2706	100%	100%	100%	71%	99%	100%	71%	99%	100%	93%	93%	94%	95%	100%	100%	95%	100%	100%	94%	92%	95%	100%	100%	100%	100%	100%	100%
	2712	93%	99%	96%	33%	100%	100%	35%	100%	100%	81%	88%	82%	57%	89%	96%	86%	93%	99%	91%	88%	97%	36%	91%	100%	38%	100%	100%

Despite the different level of regularity obtained, all strategies gave a high regularity adherence. These results shows the potency of implementing a regularity-based transit operation, despite the limitation in the current concessionaires, which is still referring to a punctuality adherence. However, in relation to this, it should be noted that when selecting the headway-based control strategy, additional costs are likely to occur for migrating the system from punctuality to regularity-based operation. An interview with a staff from Keolis was carried out to explore this cost from the operator's perspective. At a minimum, there are three additional aspects to consider in migrating into a regularity-based control operation. The aspects are regulation, operational planning, and supporting system. In sum, this migration requires a re-organization of every aspect involved in a public transit operation system.

From the performance comparison, one can conclude that the proposed control strategy, SH, is better in providing service regularity while holding control is preferable in term of operational cost and workload to the drivers. Apart from that, selecting a schedule-based control has its own advantage compared to the headway-based control strategy, due to less migration cost it induces. Nonetheless, the best control strategy to apply could not be straightforward to decide from this result. In the end, it depends on the agreement between the involved parties. To what extent they are willing to prioritize or to compromise one aspect to others.

Discussions and Conclusions

Characterizing different control strategies

The performances resulted in the case study were also much affected by certain factors. Schedule-based holding control performs well due to a good quality of schedule. Meanwhile, for the headway-based holding control strategies, scheduling does not give much impact to its performance. Its performance is determined more by the location of the control points. Demand pattern also has an impact in shaping the performance of holding control strategy in general.

Differently for speed adjustment-holding and speed adjustment strategies, there are three aspects that affect its regularity performance, including the arrival time prediction, speed range and demand pattern. Among those aspects, speed adjustment-holding and speed adjustment are most sensitive to the arrival time prediction. When the prediction is less accurate or the actual trip time cannot fulfil the control suggestion perfectly, the effects from the other two factors become more important. Another finding from this study adds more knowledge on the impact of a dominant dwelling time by increasing the demand level. This factor was expected to give a large impact in the performance of speed adjustment-holding and speed adjustment strategy. Meanwhile, the results from this study suggested that dominant dwelling time is only important if the resulted dwelling times between stops become more varied or if the dwelling time cannot be accurately predicted in the arrival time prediction. Moreover, this study also demonstrated that, the proposed control strategy combines both the positive and negative attributes of the speed adjustment and holding control strategy.

Selecting control strategies based on the line characteristics

Figure 2 summarizes the result in a scheme to give an initial knowledge for a preferable control strategy considering different line characteristics. Three conditions are mentioned in the figure, including early trips, high demand variation, and limited arrival time prediction.

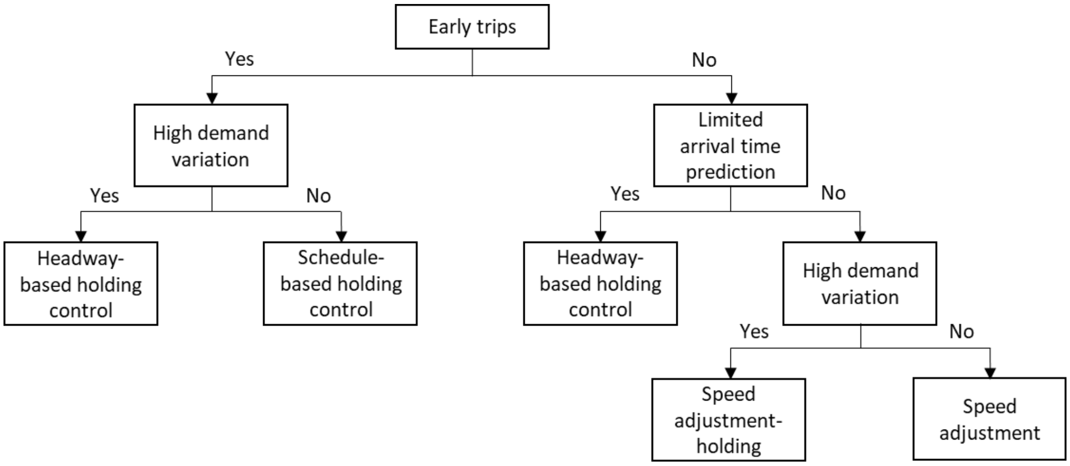

Figure 2 Indication of selecting different control strategies based on the line characteristics

Early trips are defined as a condition where the vehicle is ahead of schedule. High demand variation is described as the condition where dwelling activity is distributed along the route (not concentrated at the early stop(s)) and highly varied between the adjacent stops. Limited arrival time prediction is defined as the condition where the prediction method of arrival time is not robust and less reliable in generating the accurate arrival time prediction. Speed adjustment-holding control strategy requires more conditions to verify before being justified to implement. In contrast, headway-based holding control is sufficient to perform well under different conditions without many requirements, which would make it more favorable to implement.

Network impact

To assess the network impact, the joint headway distribution of a common stop was evaluated in this study. High regularity in a single line does not ensure the same level of performance when being assessed at a network level. There is a potential for uneven passenger load distribution if the network effect is ignored. Nevertheless, the effect would be significant only if the links between the OD of common stops pair have high demand as well as high occupancy rate. Otherwise, the construction of a control strategy with a network assumption is not necessary. In addition, regardless the existence of bunching between the common lines, the passengers, in general, will get a benefit of a waiting time reduction at minimum 57 s in this study case, compared to the planned waiting time for a single line assumption.

Limitations and simplifications

Several limitations and simplifications exist in this study, which imply that the results should be taken with cautiousness. First of all, the simulation does not capture the driver behavior. It cannot capture the lateness due to driver behavior, as well as does not capture how the drivers can drive differently as a reaction to the control given. Second, only a few numbers of interviewees were involved in this study, when discussing the practical aspect of the control strategies.

Lastly, is the simplification and limitation in the proposed control strategy. The strategy works based on an event-based concept. Therefore, the method of arrival time prediction and the control decision are limited, since both could not be executed in a continuous manner. The strategy relies much on driver compliance to be effective, while concurrently, it is also a demanding control, which possibly increases the chance of incompliance of the drivers. Another simplification is the assumption that the system is running in a segregated lane. With this assumption, the system ignores two disturbances. First, the external disturbance from the traffic and other modes to the controlled vehicle. Second, the effect of speed adjustment on other road users. The last simplification is that constructing the control strategy based on a single line assumption.

Recommendations

Scientific recommendations

Departing from the limitations of the present study, several ideas were generated for conducting the future studies.

1. Investigate the perception of the drivers toward the control strategy. The outcome would provide the information to construct a driver-friendly control strategy, to develop an effective driver training method, or to derive design requirements for the user interface of the control guidance.

2. Experiment on the driver behavior during the operation. The result would give additional knowledge or factors that are useful to be incorporated in the simulation model, to imitate the real situation better.
3. Develop a time-based simulation model. It is interesting to see how the effectiveness of combined speed adjustment-holding control strategy differs with this concept, in comparison to the result shown in this study.
4. Develop a robust arrival time prediction method. The objective is then to result in a highly accurate prediction, despite the different uncertain conditions such as in mix-traffic condition or highly varied dwelling time.
5. The inclusion of a network perspective in the modelling stage
   Assume that the assumption on network level is necessary, it is interesting to construct the more appropriate control strategy by taking this factor into account.
6. Involvement of more interviewees
   The interviews could involve more people from different backgrounds, to reduce bias and to understand the problem from different point of views.

Practical recommendations

Implementing regularity-bus operation in AllGo network

AllGo network is a bus transit system, which operates in a dedicated lane. Considering the line characteristics and the cost to migrate into a regularity-based operation, it is better for this network to keep operating based on punctuality. Maintain high punctuality would result in a high regularity as well. Specifically for AllGo network, keeping high punctuality is easier to achieve considering that, the network is less prone to uncertainties. Thus, to remain operating based on punctuality seems to be a better solution than to change the whole system into regularity, while the gain is not significant.

Implementing regularity-based bus operation in general

For other networks in general, if the regularity-based operation is necessary to implement, there are at least three different areas to consider as aforementioned. The further recommendation for these issues is given below.

1. Regulation
   There is a need to have the same understanding on the urgency of applying regularity-based operation. It should be discussed how the regulation can be modified to support the implementation. To what extent the reward and penalty should be applied.
2. Operational planning
   A suggested solution to overcome the scheduling constraint is to apply a peak hour block. The regularity-based operation is justified for a high-frequency system, which is most likely to occur during the peak hour period. This block could be applicable to both the fleets and the crews. In each peak hour block, there are numbers of fleets reserved, which are ready to operate every time it is needed. This fleet is paired with a driver, which is also scheduled for peak hour block. To support this scheme, it is suggested to propose an additional contract for driving in the peak hour block. The drivers might get a higher salary for driving in this block, to compensate for the uncertain working and resting time.

3. Supporting system
   Three supporting systems are distinguished for this recommendation.

<u>ICT system</u>

Regularity-based operation requires a more advanced technology where real-time communication is mandatory. Considering the implementation, not all operators could directly provide this type of communication. Therefore, the author recommends the adaptation of the ICT system as well as the possible control strategy to apply, as listed below.

- Stage 1: vehicle/infrastructure-to-central operator communication
  Possible control: schedule-based holding control
- Stage 2: Stage 1 + vehicle-to-infrastructure (V2I) communication
  Possible control: schedule-based holding control with traffic signal priority
- Stage 3: discrete communication in Stage 1 or 2 + discrete vehicle-to-vehicle (V2V) communication
  Possible control: headway-based holding control with or without traffic signal priority
- Stage 4: Stage 3 with a continuous information exchange
  Possible control: Speed adjustment-holding or speed adjustment, with or without traffic signal priority
- Stage 5: Stage 4 + communication with other road users
  Possible control: C-ITS or possibly, a driverless system

Related to the topic in this study of speed adjustment and holding control, it is advisable to update the ICT system into the Stage 3 (headway-based holding control) or possibly 4 (speed adjustment-holding or speed adjustment).

<u>Passenger-related</u>

In this aspect, the most important thing is to keep the passengers updated with the recent, actual information of the transit operation.

<u>Drivers related</u>

For the drivers, training is a necessity to conduct, so that the drivers could have a deep understanding of the reasoning behind applying headway-based control. Other than that, it is also advisable to have a good design interface for the control guidance system. A suggestion is to adopt the design from an eco-driving guidance system since it has the same variable to control, which is the speed.

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Chapter 1: Introduction and research definition

Service reliability of bus operation has been widely acknowledged as one important determinant that can affect the passenger preference towards this service. Thus, it is obligatory for the bus operators to keep the quality of their service reliability. The purpose is, for instance, to attract more passengers, to satisfy the existing passengers and to achieve an efficient operation (Ding, Mishra, Lin, & Xie, 2015). A concession with authority can also be another reason for this. However, maintaining the service reliability of bus operation is not a straightforward task. Several strategies should be planned and implemented to obtain an efficient and reliable bus operation (Cats, 2014). This chapter introduces the research by explaining the importance of service reliability in bus operation specifically for high-frequent service, along with the latest trend in the operational control strategies.

1.1 Service reliability of high-frequency bus transit system

As the population grows, the need for mobility has also been growing in recent years. In the case of urban mobility, this trend was subsequently followed by the existence of high-frequency bus transit service since the last decades. By having a large capacity to offer, this system is capable of transporting numerous passengers every day. However, when the operation is not well organized, a phenomenon called bus-bunching may occur. Bus-bunching is a problem obtained due to lack of bus service reliability, in term of regularity. It depicts the situation where two consecutive buses, which are supposed to be evenly distributed, arrive at the stop concurrently.

Bus bunching occurs as a result of variability in operation such as in trip times and passenger demand, which further leads to a headway variability (Chapman & Michel, 1978). Figure 1.1 explains this situation. Here, the initial value of headway is notated by *H*. Variability in operation results in additional delay *d*. Thus the headway between two consecutive buses becomes *H+d*. This delay during a trip further affects a number of passengers waiting at the stop. Consequently, it creates another delay due to boarding and alighting activity. Thus, the dwelling time of vehicle 2 at stop 1, *T2,1* becomes larger than dwelling time of vehicle 1 at stop 1 *T1,1*. Consequently, the headway between these vehicles for the next stop also becomes larger.

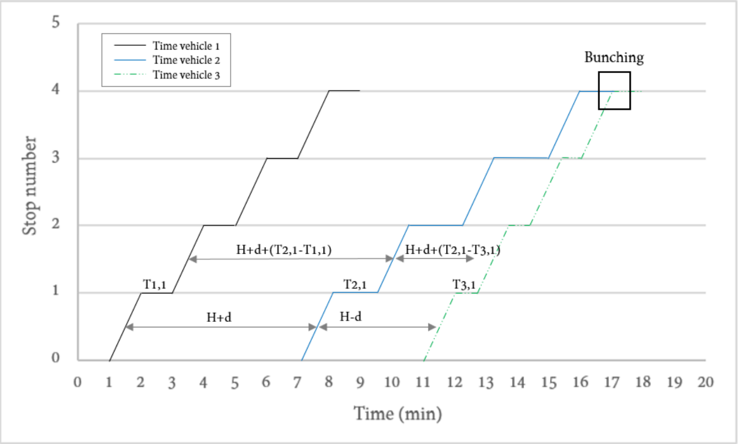

Figure 1. 1 Bunching phenomenon (Chapman & Michel, 1978; van Oort, 2011)

The opposite effect happens for vehicle 3. Its dwelling time $T_{3,1}$ becomes smaller. Thus, its overall trajectory is shifted, and the headway between vehicle 3 and its preceding vehicle becomes smaller than the headway in the previous stop. When there is no control, at some point, there will be a bunching between these two buses, in which the headway then is equal to zero. In figure 1.1, this situation is shown where at the same time (t=17), vehicle 2 and 3 are at the same stop (*stop* 4). This situation is very inefficient from the operational perspective given the fact that one bus can be fully occupied while the others remain empty. Additionally, passengers need to experience a longer waiting time at a stop (P.H.J. & Ceder, 1984).

The high-frequency bus transit service is more prone to the bus-bunching problem since the headway between the consecutive buses can be very short, and the passenger demand is typically higher. Nevertheless, it is very important to keep the service reliability in an adequate state. A common approach to assess the service reliability is by using the time-based indicators: punctuality and regularity indicators. In the punctuality concept, the reliability is assessed by its adherence from the schedule. It is mainly applied for a low-frequency bus. Conversely, the regularity concept is more recommended for high-frequency bus operation. The measurement is observed from its deviation in headway. Given the high frequency, passengers will not plan their trip anymore and thus arrive randomly at the stop. Therefore, they will perceive the reliability from the headway instead of schedule deviation. Regularity is the focus of this study, which will be explained more in Chapter 2.

1.2 Control strategies for regularity problem

A previous study showed that there is 10% of bunching occurrence, which is not preventable. This bunching is purely caused by random variation in link travel time, specifically due to traffic condition. Hence, the needs of having operational control strategy to prevent irregularity in operation are undeniable (West, 2011).

In general, the control strategy can be distinguished into three types: station control strategy, interstation control strategy, and other strategies (Eberlein, Wilson, & Bernstein, 1999). Among these categories, holding control is the preferable strategy to mitigate the irregularity problem (Cats O. , Larijani, Koutsopoulos, & Burghout, 2011). This strategy is a part of a station control strategy. By using this strategy, the vehicle is held at the station until its scheduled departure time or its desirable headway. This strategy can be seen as the most convenient control strategy to implement because it does not stimulate a significant impact on the traffic or passenger (Abkowitz & Lepofsky, 1990; Bartholdi III & Eisenstein, 2012). A cost-benefit study of holding demonstrates the potential benefits of holding in practice which is significant compared to its cost. Besides improving service reliability for passenger, it can increase ridership and add more revenues for the operators (van Oort, 2011). From a scientific point of view, this topic is also favorable to research (see Chapter 2). Several studies formulated the strategy in an optimization problem with a common objective of minimizing total passenger cost (Eberlein, Wilson, & Bernstein , 2001; Hickman, 2001; Sanchez-Martinez, Koutsopoulos, & Wilson, 2016). Meanwhile, other studies focused on finding the most effective rule of holding control by comparing the impacts (Cats O. , Larijani, Koutsopoulos, & Burghout, 2011; Cats O. et al., 2012).

Despite the advantages shown in holding control strategy, other researcher and practitioner argued that holding the bus while the passengers and drivers have been on board is more frustrating

(Chandrasekar, Cheu, ASCE, & Chin, 2002; van der Pot, 2018). Even though the cost of waiting onboard at the station is lower than the cost of waiting for the vehicle to arrive, it is indeed higher than the cost of riding the vehicle (Vansteenwegen & Van Oudheusden, 2007). Thus, one possible solution to this problem is to develop an inter-station control strategy, for example by applying a speed adjustment along the route. In other words, holding on the route by slowing down the vehicle (Chandrasekar, Cheu, ASCE, & Chin, 2002). However, only a few studies can be found on this topic. The majority of the studies on speed adjustment focused on speeding up the vehicle and were combined with holding control to delay the trip and maintain the regularity in a cooperative manner (Pilachowksi, 2009; Daganzo & Pilachowski, 2011). The studies demonstrated promising strategies to relieve bunching phenomenon in high-frequency bus service.

1.3 Problem definition and research gaps, questions, and deliverables

Based on the initial preliminary study, the research gap to be filled from this study are found. In this subsection, the main question and the sub research questions to answer are listed. After that, the deliverables of this research is explained.

1.3.1 Problem definition and research gaps

Control strategies and combined measurement for maintaining regularity

In the vast majority of research, holding control is considered as the most effective strategy for maintaining regularity in transit operation (see Chapter 2). There were several contrary arguments on this and stating that speed adjustment as a form of "holding" when it is needed, would obtain a better impact on passengers and drivers. However, there were only a few studies on this topic. Earlier, Chandrasekar, Cheu, ASCE, & Chin (2002), proposed a speed adjustment strategy by slowing the bus which only referred to forward headway. The strategy was evaluated based on actual bus operation data and showed a good outcome. On the other hand, Pilachowksi (2009) argued that the earlier strategy was not stable and hence proposed a two-way-looking cooperation approach, yet it was found ineffective in the situation in which the dwelling time is dominant. Daganzo C. F. (2009) proposed another forward-looking solution with the adaptive scheme by using a target headway as a form of headway-based holding control which implicitly counting the speed adjustment. The study was later extended in (Daganzo & Pilachowski, 2011) by observing the route as a closed-loop bus line and using a continuum problem. Although it is effective in maintaining the regularity, compared to a discrete problem, it is more prone to bunching situation if no control is taken.

Both holding control and speed adjustment strategy have potential benefit in achieving regular operation with different drawbacks on passengers, operators, and drivers. Implementing holding control may induce annoyance to the passengers. On the other hand, the speed adjustment strategy may be unstable or ineffective in some conditions. It is also difficult to implement because of the variability in trip time (Chen, Adida, & Lin, 2013). Thus, to combine holding control and speed adjustment may generate a more effective headway control strategy in which both controls can complement each other.

In other cases, the combinations between holding control and other measurements show potential benefits. A past study combined holding control with boarding limit by using the optimization model aiming at minimum total travel time for passengers. The results demonstrated that the combination of these strategies outperforms the strategy that only considers holding control, particularly in short headway operation and high passenger demand (Delgado, Munoz, & Giesen, 2012). Nesheli & Ceder (2014) combined holding strategy with stop-skipping and stop-segment strategy aiming at a reduction in passenger travel time and increased number in direct transfers. Both strategies showed satisfying results for the high-frequent system. However, the effect compared to applying only a single strategy was not evaluated.

In this study, one possible strategy to propose is to combine holding and speed adjustment in the form of "holding". Hence, the outcome will be the holding time that needs to be spent at a stop or to be distributed along the route. In past studies, the combination of holding and speed adjustment strategy was implemented differently. Therefore, little is known about the impacts of this combination. From the preceding situations, the first research gap to fill is formulated as follows:

Research gap I: The necessity of insights on a combination of headway control strategies that consider both holding control and speed adjustment.

Evaluation of the practicality aspects of regularity-based control strategies

Evaluation is an important step in developing a control strategy. From the evaluation, one can determine how favorable it is to apply a certain control strategy. However, to the best of the author's knowledge, some simplifications were taken in the past studies in which little-giving attention in practicality, despite the fact that a control strategy is built for being applied in real transit operation.

First, most studies considered only the passengers' and the operators' interest in the assessment of a control strategy (See Chapter 2). The effect on the driver was rarely considered except in (Daganzo & Pilachowski, 2009; Bartholdi III & Eisenstein, 2012; Argote-Carbanero, et al., 2015). This factor is essential by understanding that the driver is the executor of the strategy. If a control strategy induces inconvenience to the drivers, it becomes another cost, which possibly leads to driver non-compliance and ineffectiveness (Phillips, del Rio, Munoz, Delgado, & Giesen, 2015).

Another aspect that was often ruled out is the fact that a transit system is operating in a network. When most control strategies were built with a single line assumption, the researchers did not give the indication of whether the associated control strategy is also applicable in a network context. A study showed how the reliability of a transit system could be different in a single line and network level (Chen, Yu, Zhang, & Guo, 2009). A strategy was successfully distributing the passenger uniformly when being analyzed in a line. However, when different high-frequency lines share several common stops, the passenger distribution was different.

Furthermore, there are other considerations, which are unrelated to the performance of the control strategies. Especially, for regularity-based transit operation. In the literature, the majority of the researchers agree that regularity indicator is more applicable than punctuality indicator for a short headway operation. However, in a practice of high-frequency transit system, punctuality remains the main indicator for performance measurement (TCRP, 2003; van der Pot, 2018). One of the reasons for this situation is due to limited criteria defined in the concessionaire with authority. For instance, by only referring to the on-time performance measurement (Camen, 2010). Another possible reason for not shifting the system into a regularity-based bus operation is a possible conflict with the operational scheduling when the resulted cycle time deviates far from the budgeted crew and vehicle scheduling (Cats O. , 2013). Recently, several operators have been trying to shift their system into a regularity-based operation, including Keolis, which operates the AllGo bus network in Almere. However, the aforementioned factors were part of the problems that impede this migration (van der Pot, 2018). These issues are consequently important to consider when assessing control strategies, as additional considerations in analyzing the cost and benefit of applying the headway-based control strategies.

Following the previous issues, another gap to fill for this study is developed as follows.

Research gap II: Lack of control strategy evaluation, that considers the practicality related to the effect on the drivers, network impact, and general changes in the transit system

Research aim
Several problems are identified in the previous subsections. For the aforementioned problems, the goal of this study is ***to develop a headway control strategy based on a combination of several measures and to evaluate it from a practical point of view.***

1.3.2 Research questions

Further, the identified research gap is formulated into two main research questions, which mainly distinguish the design and evaluation stage of the present study.

RQ I : ***How can holding control and speed-adjustment strategy be combined in order to support an effective regularity-based bus operation?***

The first research question is mainly addressed to generate a control strategy design for regularity-based bus operation. Several sub-research questions are formulated to answer the first main question. First of all, it is important to understand the problem in the past which becomes the reasoning behind the development of the present study. the A process of literature review and interview are carried out focusing on the topic of headway-based control strategies (i.e. holding control and speed adjustment strategy), to achieve this aim both from the theoretical and practical point of view. The output of this process advises the focus of the present study and gives the underlying principle to build the proposed control strategy in the next stage. Three sub-research questions are derived for this aim as follow.

Sub-RQ I.1: **What are the tradeoffs of each control strategy?**
Sub-RQ I.2: **What can be the interest of the drivers in the implementation of the control strategy?**
Sub-RQ I.3: **What can be the potential differences between considering the service reliability of a public transport system in a line level and a network level?**

Secondly, the results from the problem identification are synthesized to develop the proposed control strategy of the present study: the combination of holding control and speed adjustment strategy. This process obtains the conceptual design and evaluation of the proposed control strategy. A sub-research question for this aim is formulated as follows.

Sub-RQ I.4: **How to formulate a model to find a potential combination of strategy?**
By answering the first-four sub-research question, the conceptual design of the combination between holding control and speed adjustment based on the principle of effective regularity-based bus operation is derived, to be the answer of the first main research question.

RQ II: ***What are the benefits and limitations of the combined strategy in a real network implementation?***

The second research question is addressed to evaluate the proposed control strategy thoroughly to show its quality. The second research question will be solved by answering several sub-research questions.

First, it is an idea to compare the performance of the proposed control strategy with the other strategies that are mainly applied in practice or suggested in the literature. This process aims to evaluate the effectiveness and robustness of the proposed control strategy. It also provides the idea of what could be the positive and negative consequences of the proposed control strategy from a practical point of view. A sub-research question for this aim is formulated as follows.

Sub-RQ II.1: How is the performance of the combined strategy when applied in a real network in comparison with other strategies?

A specific focus is put in the control strategy evaluation in a network context to address one of the research gaps concerning the network. A sub-research question for this aim is formulated as follows.

Sub-RQ II.2: How is the performance of the control strategies in a single line and a network differ?

Finally, by answering the second part of the sub-research questions, one can answer the second main research question and achieve the research aim of the present study.

1.4 Research scope

Planning process and control strategies are two of important implements to increase transport system efficiency. The first aspect comprises of three main parts: strategic planning, tactical planning, and operational planning (Ibarra-Rojas, Delgado, Giesen, & Munoz, 2015). The latter is the focus of this study, by considering its potential impact on the strategical planning (Figure 1.2).

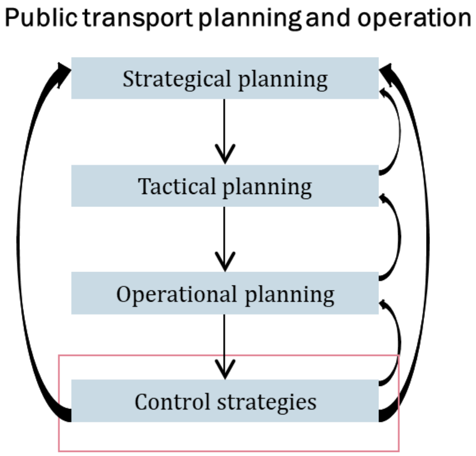

Figure 1. 2 Public transport planning and operation stages

In general, a control strategy needs five steps until it is implemented (Cats O. , n.d.).The first step is the idea generation and problem analysis. Secondly, analyses and lab/desk test. The third is field trial and data collection which is subsequently followed by its analyses on the fourth step. Lastly, is the implementation itself. The scope of this study will be narrowed into the first two steps without testing it in a real experiment due to time limitation.

In addition, the present study will look at the problem from the perspective of the operator. From this point of view, it does not mean that the objective will only focus on reducing the operating cost. Instead, it is more complex as the operator should be able to provide the best service to the passenger under the set of requirements from the authority.

1.5 Research methodology

The approach of the present study is mainly divided into three phases, namely problem identification, design and evaluation concept, and evaluation, or Phase 1, 2, and 3 respectively. The research method used in these phases comprises both the qualitative research method such as literature review and interview, as well as quantitative research method by building a mathematical model of the proposed control strategy and testing it through a simulation based on the data of a chosen case study. The following subsection explains each method in more detail.

Phase 1: Problem identification (Sub-RQ II.1-3)

Phase 1 provides the problem identification of the study. It consists of the first three sub-questions, which explicate the substance of control strategy in transit system operation. In the present study, the exploration of this topic captures both the theoretical and practical point of view. A literature review was conducted for the first aspect, while the latter used an interview approach, as depicted in figure 1.2.

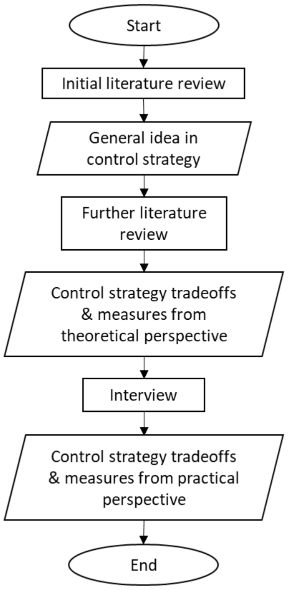

Figure 1. 3 Problem identification approach: literature review and interview

Literature review approach

A literature review was conducted to provide the theoretical basis of the answers, which had been proven in the previous studies. In specific, a literature review was needed to explore the general knowledge of headway-based control strategy in speed adjustment and holding control. In addition, it provided the initial idea for the proposed control strategy and its evaluation based on the perspective of the drivers and network context, which became the reference to answer the remaining sub-questions.

In the literature review, firstly few papers related to the study of control strategy were searched. These papers were analyzed to understand the general idea of the control strategy in the transit system and generate the initial ideas of the study. From here, other interesting papers and authors linked were looked up for a further literature study. Along with this, several keywords were typed in the academic literature search engine such as the Google Scholar and ScienceDirect to discover the other papers related to the present study. Various terms including "holding control" or "headway control" or "control strategy" or "speed control and/or adjustment" along with "network" or "driver" and/or "bus driver" were used in the research. Numerous literature were found. Thus there was a quick scan of the abstract to select the relevant papers. The literature study generated the answers of the related sub-research questions from a theoretical perspective.

Interview approach

Next, an interview was carried out to understand the problem in the current practice of high-frequency bus transit system and verify the findings from the literature. Due to time limitation, the source of the interview was narrowed into the selected case in Almere only. The interviewee selected for the interview were the staff members of the operator, Keolis. The result from the interview completed the research in this phase by adding the concern from the practical point of view. This phase is given in Chapter 2.

Phase 2: Control strategy design and evaluation concept (Sub-RQ I.4)

The first aim of the present study is to develop a combination of speed adjustment and holding control strategy. Sub-RQ I.4, Sub-RQ II.1 and Sub-RQ II.2 were generated to achieve this aim through designing and evaluating the proposed control strategy. In this phase, the design concept was formulated in mathematical terms. In addition, there is a list of performance indicators for evaluation based on the results from the problem identification in Phase 1. This phase is given in Chapter 3.

Phase 3: Control strategy performance evaluation (Sub-RQ II.1 – 2)

For assessment purpose, there was an evaluation phase which is represented by the Sub-RQ II.1-2. In the present study, the evaluation phase was conducted based on a case study strategy of a bus transit operation in Almere. The case study was selected because the evaluation of the control strategy needs a quantitative assessment. This can be done either by using a hypothetical case or an empirical case through a case study. Since practicality is another concern in the present study, the author evaluated the proposed control by referring to an empirical case, which meets the selection criteria. First, it has to be a high-frequency bus transit system, to justify the employment of regularity-based operation. Second, the system should have common lines at some parts of the network, to allow the assessment of the network effect. Third, for practical reason, it is preferable that the system provides a sufficient AVL and APC data. AllGo bus system in Almere has all of this criteria. Thus, it was selected to be the case study. Moreover, AllGo bus system currently runs based on punctuality but manage to work well. It becomes more interesting to see how effective it is to perform a regularity-based operation for high-frequency transit service. Chapter 4.1 provides more details of the case study.

By referring to (Cats, O., n.d.), the evaluation for implementing a control strategy consists of two stages, namely the lab/desktop test and the field trial. As stated in Chapter 1.4, the evaluation in the present study is limited only to a lab/desktop test by a simulation. Due to the time limit, there was no experiment to verify its practicality through a field trial . As a replacement, an indication to the practicality was given through an interview with a practitioner in addition to the quantitative analysis.

Simulation (Sub-RQ II.1 – 2)

The simulation was selected as a method to evaluate the control strategy because it can well reproduce the actual bus operation with a low cost in term of time and money. In the present study, BusMezzo was utilized as the simulation tool to carry this task, with more detail features described in Chapter 3. The output of this method is the effectiveness and robustness measurement of the proposed control strategy relative to the other control strategies. The measurement was done by referring to the performance indicators in Phase 2.

Semi-structured Interview (Sub-RQ II.1)

Along with the result from the simulation, the design concept of the proposed control strategy was discussed with the expert through a semi-structured interview. This method allows the flexibility in the interview to gather as much relevant input as possible. While the simulation was focused more on assessing the effectiveness and robustness, the purpose of the interview was to verify the potential applicability of the proposed concept and the realness of the result from the practical perspective.

The interview was done only with Keolis, due to time limitation. The interview was conducted with a representative from the company to give their assessment in a general way. The interview was conducted in a direct (face-to-face) method. The output of this interview can be the input for the discussion of the proposed concept, to complete the answer of the sub-RQ II.1.

Table 1.1 below gives the summary of the research methodology applied in the present study.

Table 1. 1 Research method

Sub-RQ	Research Method	Phase	Main deliverables
Sub-RQ I.1 **Potential tradeoffs of each control strategy (holding and speed adjustment)**	Literature review Interview	Phase 1	List of tradeoffs of each strategy
Sub-RQ I.2 **The interest of drivers in the implementation of the control strategy**	Literature review Interview		Additional indicator to capture drivers' concern
Sub-RQ I.3 **Potential differences of service reliability**	Literature review Interview		Performance indicator to capture the effectiveness of the control strategy in the network

between line level and network level			
<u>Sub-RQ I.4</u> **The design concept of the proposed control strategy**	Mathematical model	Phase 2	Set of rules for the proposed control strategies
<u>Sub-RQ II.1</u> **Performance of the combined strategy in comparison with other strategies**	Simulation Interview	Phase 3	- Performance measurements based on the predefined performance indicators. - Additional knowledge on the implementation of control strategies from a practical perspective
<u>Sub-RQ II.2</u> **The performance difference between the assessment in a single line and network level**	Simulation		The indications of preferable condition to consider the network impact in designing control strategies

1.6 Report structure

The present study consists of six chapters as depicted in table 1.2 below.

Table 1. 2 Report structure

Chapter	Discussion	Phase (Sub-RQ)
1. Introduction	Background of the study, problem identification, research aim, research questions, methodology, and report structure	-
2. Service reliability and control strategy	Exploration of the concept of service reliability in transit system operation and different control strategies	Phase 1 (Sub-RQ I.1,2,3)
3. Control strategy development	Design and evaluation concept of the proposed control strategy	Phase 2 (Sub-RQ I.4)
4. Assessment of control strategies	Scenario and sensitivity analysis of the proposed control strategy as well as the other strategies	Phase 3 (Sub-RQ II.1-2)
5. Discussion	Discussion on simplification and research limitation in general	-
6. Conclusion and recommendation	Discussion of the findings, conclusion, research contribution, research limitation, recommendation for future studies, critical reflection of the research process	-

Chapter 2: Service Reliability and Control Strategies

This chapter provides the review of the past studies and current practices in transit operation control strategies to answer the sub-research question 1, sub-research question 2, and sub-research question 3 as follow.

Sub-RQ I.1: What are the tradeoffs of each control strategy?
Sub-RQ I.2: What can be the interest of the drivers in the implementation of the control strategy?
Sub-RQ I.3: What can be the potential differences between considering the service reliability of a public transport system in a line level and a network level?

Firstly, there will be a discussion on regularity concept to clear up its differences with punctuality concept as well as its influence on deciding the control strategy for transit operation. A different concept of control strategies will be discussed with a focus on station-based (i.e. holding control) and route-based control (i.e. speed adjustment) strategies as the main topic of the study. The idea is to find out how the effectiveness of these strategies in resolving the regularity problem and the tradeoffs, based on a theoretical and practical point of view.

2.1. Service reliability definition

2.1.1 Service reliability and causes of variability

Service reliability is one important aspect in assessing the level of quality of the transit system. Van Oort (2011) defines service reliability in general as the comparison between the certainty of the service and the planned service as perceived by the users. The similar concept can be applied to the public transport system. In service reliability of public transport system, there is a degree of certainty in the system that may affect its level of reliability perceived by the passenger. In specific, van Oort (2011) explained this certainty degree as four types of service variability that may appear during operation, including variability of departure times, headways, trip times, and arrival times.

In general, the causal factors of this variability can be divided into internal and external causes. The internal causes are the factors generated from the supply side, for instance, the other public transport operations, driver behavior, the quality of scheduling, network, and vehicle design. Meanwhile, external causes are including the weather condition, traffic condition, irregular loads and passenger behavior (Turnquist, 1981; van Oort, 2011). By considering the sources, these factors are more difficult to control by the transit authority.

2.1.2 Service reliability indicator: regularity vs punctuality

In literature, a common approach to measure the reliability is by using a time-based indicator, namely punctuality and regularity. These indicators were also argued as measures to present reliability from the perspective of the transport authorities (van Oort, 2011). The application of this indicator depends on the characteristic of the service operation. In low-frequency service, the passenger arrival will depend on the announced timetable of the service. Thus, the reliability can be determined through the adherence of the service towards the schedule by punctuality indicator (Welding, 1957). In addition, there is also an indicator of additional travel time which represents more the effect of reliability from the passengers perspective (van Oort, 2011). This indicator will be explained more in Section 2.3 about performance measurement.

By contrast, in a high-frequency service, the passengers will not rely on the schedule and arrive randomly at the stop point. A frequent service will make their perception towards the service reliability to be the same even though there is a deviation between the scheduled and actual service. Thus, there is no significant benefit to provide the timetable for the passengers. Passengers will be more concern about the duration of time that they have to spend waiting at the stop. Hence, the operator can strive for the best service reliability by having a regular time headway between service vehicles. An exactly regular service obtains the lowest possible waiting time for passengers, which is equal to the half of the headway (Welding, 1957; van Oort & van Nes, 2009).

From the explanation above, one can see the difference between reliability defined by punctuality and regularity indicator. When a transit service has three minutes delayed from the schedule, the passengers may perceive it as not reliable. Meanwhile for a high-frequency service, with the same amount of delay, it is considered reliable as long as the headway is regular (i.e. other vehicles from the same line may also be delayed to keep the regularity). Service regularity is not only advantageous to maintain the reliability of a transit service but also improve its capacity efficiency by evenly distributing the passengers over vehicles (van Oort & van Nes, 2009). Service regularity is the main indicator to achieve in this study for a short headway bus operation in Almere.

To maintain the regularity is not a straightforward task. Among many causes of variability in operation, Hans et al. (2015) identified in more detail three factors that specifically lead to irregularity. Firstly, is system stability, which can be determined by modelling of the vehicle dynamics. When the system is unstable, the resulted headway may be unstable as well. A regular system will remain regular meanwhile the irregular system will become more irregular. Secondly, the correlation between stochasticity and obtained disturbances. Initial headway variability influences the irregularity more than travel times variability. For this problem, dwelling time is seen as a significant cause. This reasoning aligned with the other studies by (Eberlein et al., 2001; Daganzo, 2009; Ramli et al., 2016). Even if there is no disturbance during the trip, irregularity still occurs when there is a variability in the dwelling time. This factor can highly vary the headway between consecutive buses. Lastly, it was also suggested that a sudden variation in the transit operation results in more irregularity. This is also relevant when the operator wants to decide a strategy.

2.2 Service regularity and control strategy

In the previous subsection, causes of irregularity have been revealed. Variability in operation is indeed one problem that may cause this problem. However, it is also found that even if in an ideal situation, irregularity can occur if there is a difference in the number of boarding and alighting passenger. An act of control is necessary to achieve regularity. This subsection discusses the control strategy to solve the irregularity problem.

2.2.1 Application of control strategy

The control strategy is a solution to achieve efficiency in public transport system operation. It works by reducing the sources of variability in operation. Many researchers have been developing the strategies since decades ago. In general, there are three classifications of a control strategy for transit operation as depicted in figure 2.1, including station control, inter-station control, and other control measures (Eberlein et al., 1999; Ibarra-Rojas, at al., 2015).

Station control strategies take the control decisions at the stops, by using either holding control, stop-skipping, and boarding restriction. Holding control acts by delaying some vehicles to prevent it bunched to each other. On the other hand, stop-skipping and boarding restriction work by speeding up the operation by reducing the main source of variability, the dwelling time. Inter-station control determines the decisions between stops during the trip. The decision includes a speed adjustment strategy where the bus control its speed along the route to reduce headway irregularity. Another approach is by applying a Traffic Signal Priority strategy at the intersection. This strategy controls the circulation at the intersection by giving priority to the vehicles which require it (e.g. give priority for the bus when it is delayed or give it for the car traffic when the bus is found too early). Besides these categories, there are another control strategy measures such as adding or removing vehicle during operation.

In this study, the focus is narrowed into holding as a station-based control and speed adjustment as an inter-station control. Service regularity is the main goal of the proposed strategy. Thus, this study will consider headway-based control by performing holding control and speed adjustment. Later subsections review the earlier studies about these strategies.

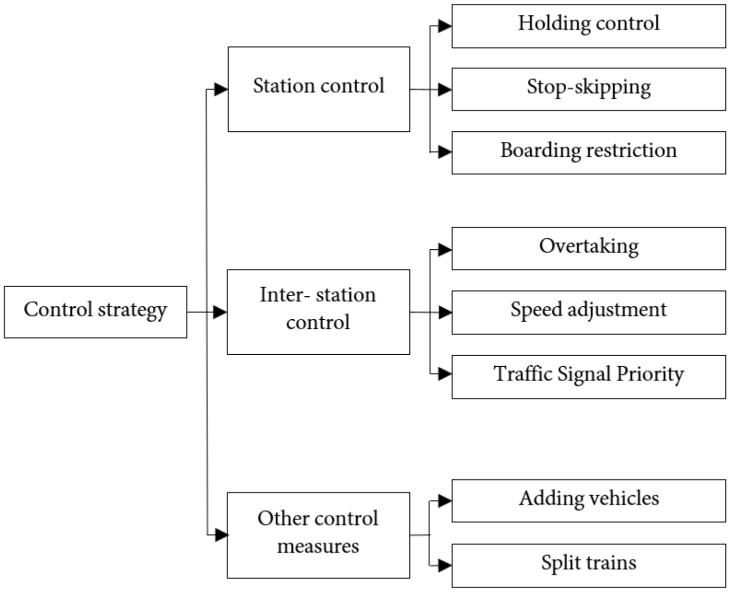

Figure 2. 1 Control strategy classifications (Eberlein et al., 1999; Ibarra-Rojas, Delgado, et al., 2015)

2.2.2 Holding control strategy

Among all existing strategies, holding control is the most popular control to be studied and implemented. This strategy splits up the bunched buses by holding the bus at a control point until its desirable schedule or headway (Turnquist, 1981). In designing holding control, one should concern on two different elements. Firstly, is number and location of time points, which determine the location for holding decision. The second is holding criteria, which decides how holding should be implemented and leads to the holding time decision (Cats O. et al., 2011).

2.2.2.1 Number and location of the control point

The control point is the stop where the control decision is taken. As holding control is decided at the station, the optimality of holding location is highly related to the passenger demand. An early study by Abkowitz & Engelstein (1984) suggested that the optimal control point is the stop that is sensible to the proportion between riding passengers and those waiting at the downstream stop. Particularly, before a series of high demand stops along the route (Furth & Muller, 2009). In specific, it was also preferable to not holding at the stop where the majority of passengers will stay on board (Hickman, 2001). This makes sense because it must be inconvenient for the onboard passengers if they need to wait longer while no one is alighting and let even higher passengers board. The dwelling will be already higher in this setting. Later, van Oort et al. (2012) mentioned that control point at the beginning of a route is beneficial to reduce the additional travel time of passenger. Preventing initial headway variability can give significant impact on avoiding irregularity during the operation.

With respect to the number of control points, several ideas were also stated in the previous studies. The finding from a study of light rail system operation showed that it is sufficient to select only the original terminal as a control point (Eberlein et al. , 2001). However, the majority of the studies concluded that single holding point is not efficient since the holding effect can dissipate quickly at the downstream stops (Barnett, 1974; Abkowitz & Engelstein, 1984; Sun & Hickman, 2008). Multiple control points are better to implement especially for a long route. Yet, the number of control points is not necessarily to be excessive (Furth & Muller, 2007; van Oort et al., 2012). Too much holding will delay the overall travel time of the vehicle. An example demonstrated how assigning all stops as time point stop was not significantly effective compared to applying only three-point stops in a schedule-based holding control (Furth & Muller, 2007). Other researchers stated that two control points could provide enough effectiveness. From a case study in The Hague, locating two holding points at the beginning of the bus line together with a proper timetable could save up to 60% waiting time (van Oort et al., 2012). From the preceding discussion, one can conclude that the number of optimal control points can be different, most probably depends on the characteristics of the route. Furthermore, a study about optimization problem of the number and location of control point aiming at minimum passenger cost suggested that location of control point gives more impact to system performance compared to its number (Cats, Rufi, & Koutsopoulos, 2014).

2.2.2.2 Optimization-based and rule-based holding control

Within these decades, a large amount of research on holding control can be found. In general, holding control is built based on two bases, optimization-based and rule-based holding control.

Optimization-based holding control

In the optimization problem for holding control, minimizing passenger cost is a common objective that can be found. The decision variables can be varied, depend on the proposed concept. Holding control based on the optimization problem is typically very complex. Thus, mainly the problems make the assumptions based on a deterministic approach and ignored time dependency in running time and passenger demand.

Majority of earlier studies in the optimization problem focused only on minimizing passengers waiting time to reflect the reliability of the control. Eberlein et al. (2001) developed a formulation of holding problem, which considered the availability of real-time data based on a rail transit system. The model was based on optimization in a rolling horizon approach, with the objective of minimizing passenger waiting time. It obtained a good result while being tested in a case study of a single bus line in Boston. The model observed the importance of dispatching headway effect while dismissing the effect of demand pattern. The study suggested putting more attention on the terminal schedule constraint. Holding control is consequently causing a delay in a vehicle trip and may trigger another delay for the next trip. Another study by Zolfaghari, Azizi , & Jaber (2004) also focused on applying the holding control at the beginning of the route. It offered an optimization model of holding decision at the first station of vehicles by using binary decision on whether to take the control or not, which also considered the vehicle capacity constraint. This problem also aimed at minimizing waiting time for passengers with additional consideration on the passengers whose got rejected to board.

The objective in the optimization problem of holding control becomes more developed as the study on this topic is updating. Sun & Hickman (2008) considered an additional objective in their formulation: to minimize delayed-onboard experience. The problem was formulated to decide the holding times of multiple vehicles at multiple control points. The result suggested that adding multiple control points offers more possibility to regularize the headway of the vehicle. However, there was no demonstration for the proposed heuristic, since the model was only tested by a hypothetical numerical example.

Holding control in combination with boarding limit was studied in Delgado F. et al. (2009). By aiming at minimum total travel time for passengers, this combination outperforms the strategy that only considers threshold-headway based holding control. However, it did not clearly conclude the favorable condition for the proposed strategy. Delgado et al. (2012) presented an extension of the previous study by developing a more advanced model in a rolling horizon framework. The result from this study demonstrated that the deterministic optimization model tends to overreact the solution. Overall, the result aligned with the previous work, and additionally, it stresses on the significant impact induces by the combination of holding and boarding restriction in short headway operation and high passenger demand in term of waiting time, reliability and comfort.

The aforementioned studies on holding control were all built based on deterministic models. Consequently, the evaluation of the strategy was limited. It could not capture changes happen during the operation. Sanchez-Martinez et al. (2016) included a dynamic condition in their holding model. The optimization problem was integrated with a simulation model. It generated holding times planning, which was derived by explicitly taking into account current and expected state in running time and demand. Running time was modeled as a function of time of day. Demand was modeled using time-varying mean arrival rates at OD-level. Optimization with dynamic inputs gives better performance compared to the model with static inputs in overcrowded condition. However, the strategy was only tested in a hypothetical line.

Rule-based holding control

In a rule-based holding control, there is a holding criterion, which determines how the holding control should be implemented. In general, it can be distinguished into two classifications, scheduled-based and headway-based holding control. The first is aiming at the punctuality adherence of schedule while the latter focuses on reducing the headway variance.

Schedule-based holding control is built based on a concept of holding the departure of the early buses at a predefined control point until its scheduled time. Conceptually, it works by preventing early departure from the schedule. The concept is built on punctuality. Hence it is mainly suggested for a service with low-frequency. As has been mentioned previously, scheduling quality is one determinant of operational variability. Thus, the efficiency of this control is mainly determined by the timetable and slack time design. In the literature, the common problems that can be found are optimization of schedule including trip time, slack time, layover time as well as transfer possibility, to minimize passenger cost.

Furth & Muller (2007) determined the amount of slack to be inserted in the schedule, both on the route and at the terminal. A model was built based on optimization of running time and cycle time that considered passenger and operating cost. By assuming a single hypothetical bus line, it was found that in the optimal schedule, the waiting cost was reduced due to running time supplement and improvement in arrival time variability.

Another study of schedule-based holding with a goal in increasing service reliability was presented by van Oort et al. (2012). The approach taken here was by adding adjustment in timetable through trip time and holding control decision. When being tested in a case study of single bus and tram lines in The Hague, it was found that taking the 35-percentile value to design the trip time, could lead to improvements of passenger reliability in travel time. When it was combined with holding control, the result was even more satisfactory.

Headway-based holding control focuses on reducing the headway variance (Abkowitz & Lepofsky, 1990; Cats O. et al., 2011; Cats O. et al., 2012). This criterion is preferable in a short headway operation where the passengers arrive randomly at the stop and ignore the schedule.

One of the earliest studies by Abkowitz & Lepofsky (1990) presented a holding strategy, which held the vehicle until it achieves targeted minimum headway, based on a forward-looking headway. It minimized total waiting time for a passenger on board and at the stop by determining the control stop and threshold level of the headway for each route. The evaluation of the strategy was done by experimental design of different lines in Massachusetts. The strategy successfully reduced the expected waiting time. Moreover, the strategy showed a potential saving in the operational expenses if the route is operating under capacity by reducing the number of fleets needed.

At a prior time, headway-based holding control was hard to implement due to the limitations of technology. As the development of real-time information equipment grows, the research on headway-based control has been developing as well. Daganzo C. F. (2009) proposed an adaptive control scheme, which dynamically generated the holding times at each control point based on real-time headway information and commercial speed. It implicitly counted speed adjustment in the rule to maintain the commercial speed as close as the planned speed. The control was only applied for the following bus of a pair, thus referred to forward headway. The result showed that the proposed strategy is more effective than applying scheduled-based. Furthermore, it demonstrated that frequent control through having a shorter segment is beneficial to allow quick mitigation of the problem in the system.

Daganzo & Pilachowski (2009) studied about adaptive control strategy that adjusted bus speed in a real-time manner based on its spacing with the preceding and the following buses, through coordination between buses. The goal of this study was to achieve regular headways while maintaining a high possible commercial speed. The study considered a closed loop route for the buses and assumed that they were connected by springs. The headway control was applied continuously and led to better performance compared to the discrete forward-looking strategy by

(Daganzo C. F., 2009). However, it was harder to implement. Additionally, the continuum problem was more prone to bunching phenomenon if there was no control applied. In the discrete problem, the system will have a less standard deviation of the bus spacing and headway; hence, the buses will stay longer near equilibrium state.

Xuan, Argote, & Daganzo (2011) developed a dynamic holding strategy called a simple control, which not only maintaining regular headway but also increasing schedule adherence by introducing a virtual schedule at the control points. Hence, this strategy can be applied in both short-headway and long-headway transit operation. The problem was solved by choosing the control efficient to express the holding time of the model, that minimize the slack time and standard deviation from the schedule. From the evaluation using a hypothetical line, the strategy successfully reduced 40% slack time compared to schedule-based, and similar to headway-based holding strategy (i.e. forward, backward, and both headway looking control).

Another study on bus dynamic headway-based holding strategy done by Bartholdi III & Eisenstein (2012). Conceptually, this strategy is similar to Daganzo C. F. (2009). However, it argued that bus coordination based on target headways might incorrectly estimate the actual headways since it is not static. As a proposed strategy, they introduced a self-coordinating strategy, which neglected the schedule and any predefined target headway but estimated the backward headway. The study focused on the coordinated adjustment of commercial speed in real time and derived the target bus velocity from estimated passenger demand. The study expected time dependency in the speed by considering the variability in traffic and ridership. Due to coordination, the headway could be readjusted from any condition, including disruption occurrence. Validation of this strategy was conducted in an experimental set up of a single bus line. Recently, Zhang & Lo (2018) developed a holding control strategy based on the work of Bartholdi III & Eisenstein (2012). While the previous study only considered backward headway, this study looked both at the headway between the preceding and following of the controlled bus. This strategy successfully improves the headway regularity in uneven headway cases, and in a case, that has sudden headway variance due to addition and removal of the bus during the operation. In overall, it performs better than of Bartholdi III & Eisenstein (2012) by considering that it is able to improve the headway variance in a faster manner. However, the evaluation was only done by an analytical study.

2.2.2.3 Summary on holding control

A brief summary can be concluded from holding control strategy. Multiple studies have shown the effectiveness of holding strategy to maintain service reliability, both punctuality and regularity. Not all of the past studies discussed the comparison between one to another strategy. Nevertheless, there are some of the references discussed the conditions that make each control preferable to use (Furth & Muller, 2007; van Oort, et al., 2010; van der Werff, 2017; Bartholdi III & Eisenstein, 2012; Daganzo, 2009; Sanchez-Martinez, et al., 2016; Xuan, et al., 2011). Table 2.1 below summarizes the comparison between each control.

Table 2. 1 Comparison of the effectiveness of each holding control strategy

Conditions	**SB**	**HB**				**OPT**	
		FH	**BH**	**EH**	**SC**	**OS**	**OD**
Low frequent service	2*	1	1	1	1	1	1

High frequent service with the following conditions:							
1. No maximum holding time	2	1	1	3	none	none	none
2. The transition between high-frequent and low-frequent service	2	1	1	1	none	none	none
3. Low demand rate	1	2	2	2	none	none	none
5. High demand rate (overcrowded condition)	1	3	2	4	4	4	5
6. High demand rate and needs for schedule adherence	1	1	1	3	4	none	none
7. Many disruptions	1	3	3	4	4	4	4
8. Not arriving early, but not enough turnaround time	1	4	4	4	none	none	none
9. Not arriving early, enough turnaround time with high demand at terminal	2	1	1	1	none	none	none
10. Higher service frequency	1	2	2	3	3	3	4
Note:							
SB	= Schedule-based holding control						
HB	= Headway-based holding control						
FH	= Forward headway (Daganzo, 2009, Abkowitz & Lepofsky, 1990)						
BH	= Backward headway (Bartholdi III et al., 2012)						
EH	= Even headway (Daganzo & Pilachowski, 2009; Pilachowski, 2009; Cats, O., et al., 2012; van der Werff, 2017; Zhang & Lo, 2018)						
SC	= Simple control (Xuan et al., 2011)						
OS	= Optimal holding control based on static input (Sanchez-Martinez et al., 2016)						
OD	= Optimal holding control based on dynamic input (Sanchez-Martinez et al., 2016)						
OPT	= Optimization based holding control						
*) the numbers represent the relative score of the associated control strategy in comparison to other strategies compared. (e.g. 1 = less preferable, 5 = most preferable)							

Besides the specific conditions mentioned above, there are general aspects, which can affect the effectiveness of holding control, as listed below.

i) Dispatching headway plays an important role in regularity. This headway determines the propagation of headway deviation along the route (Eberlein, 2001).

ii) Location of control points. By looking at the first aspect, it is recommended to have a control point at the beginning of the route. The additional control points are not strictly required but depends on the characteristic of the route and the demand. In fact, the location of the control point is essential than its number (Abkowitz & Engelstein, 1984; Eberlein et al., 2001; Hickman, 2009; Furth & Muller, 2009; van Oort et al., 2012; Cats, O. et al., 2014)

iii) Particularly for schedule-based holding control, its effectiveness is mainly driven by the quality of schedule, including determination of trip time distribution, slack time, layover time(Furth & Muller, 2007; van Oort et al., 2012)
iv) Particularly for headway-based holding control, the reference of headway considered affect the effectiveness of the control (Abkowitz & Lepofsky, 1990; Daganzo, 2009; Daganzo & Pilachowski, 2009; Pilachowski, 2009; Cats, O., et al., 2012; Bartholdi III, et al., 2012; van der Werff, 2017; Zhang & Lo, 2018)

The passenger is the main stakeholder of service reliability of public transport system. Thus, the implementation of holding control is advantageous by considering its minimum negative impact on passengers. In opposite to other station control strategy, it only generates longer waiting time on board but not rejecting the passengers except in overcrowded condition. From the operator perspective, schedule-based holding control is very practical. Meanwhile, headway-based holding control needs a more advanced operation but can be more flexible. It allows the possibility of addition or removal of the fleet, depends on the real-time situation of the demand. It has potential savings in operating cost.

On the other hand, when the holding control is not optimal, it may negatively impact the passengers as well as the drivers. Too much holding time will longer the total cycle time. If the operation planning is still run based on schedule, it may ruin the vehicle and crew scheduling. This situation is undesirable during the operation. Furthermore, too much waiting on board will cause inconvenience for the passengers. It adds the overall travel time for passengers. Moreover, even though the cost of waiting onboard at the station is lower than the cost of waiting for the vehicle to arrive, it is indeed higher than the cost of riding the vehicle (Vansteenwegen & Van Oudheusden, 2007). When several studies included this aspect as the objective of the optimization problem, one can conclude that this is clearly a problem to consider in holding control.

2.2.3 Speed adjustment strategy

In contrast to holding strategy, the study about speed adjustment for the transit system is not as extensive as a study on holding control. Many studies were found in the area of car traffic. From the literature, the research on speed adjustment differs in four main topics. The first topic is aiming at comfort and safety as found in (Wu, 2009; Pauw et al., 2014) and the second is focusing on homogenization to improve the traffic flow (Soriguera et al., 2017; Han, Chen, & Ahn, 2017). These topics were mainly found in the study of car traffic. Thus, will be excluded from the review.

The third topic is speed adjustment to improve the operational service reliability for the transit system, either to reduce headway deviation, to improve punctuality or to support transfer synchronization. Many studies on speed adjustment are developed based on control theory. Pilachowski (2009), proposed a concept of two-way cooperation by arguing that speed adjustment of a bus will affect the spacing of at least three buses. The control rule was formulated as a continuum approximation model. At the controlled equilibrium speed, the bus tends to locate itself between its preceding and following buses with equal spacing. The control was evaluated by using a microscopic simulation tool, applied in a single bus line. The proposed control strategy was successful in preventing the bus bunching phenomenon. However, the author noted that as this was a route-based control, it would not be effective for the route, which have a dominant dwelling time.

Ampountolas & Kring (2015) adapted the car-following model by deriving a bus-following model into bus-to-bus collaborative control strategies to mitigate bunching. In the study, it was assumed that bus-to-bus cooperation and real-time response of the drivers allowed the continuous-time bus-following models to model bunching phenomenon and remote feedback control. The state information of the leading bus was used as an input to control the state in the following bus. The control was implemented in the form of speed adjustment. There was a feedback loop to provide the actual state after control is taken. The strategy was modeled based on two control laws, deterministic linear (Linear Quadratic - LQR) and nonlinear (Lambda). The results showed that both controllers mainly slow down the buses to avoid bunching, yet it is effective to reduce the headway adherence and the waiting times for the passengers.

Sirmatel & Geroliminis (2017) developed a predictive controller based on mixed logical dynamical (MLD) model, which considered the dynamic of passenger demands and maximum bus speeds. The controller objective was to regularize the headway as well as improving the travel time. The study compared three different control. The first one was a PD-like Bus Speed Controller (PD-BSC), which controlled the bus by optimizing the error in the position and speed of the bus to achieve an ideal headway. The second was a linear model predictive control (LMPC), which predicted the state of the bus along the prediction horizon and estimated the information regarding the traffic conditions, dwell times and arrival time at the upcoming stops as a result of previous speed and a number of passengers. The third was the proposed control, hybrid model predictive control (HMPC), which approximated the arrival time and dwell time by using a prediction model. The estimations are made based on the control input from the current event. In the evaluation, HMPC performs better than LMPC and PD-BSC. PD-BSC has the worst performance, which appeared due to a lack of coordination between the buses involved.

Other studies based on control theory, (Daganzo, 2009; Daganzo & Pilachowski, 2009; Bartholdi III & Eisenstein, 2012; Zhang & Lo, 2018), have been reviewed in the previous section. The common outcome considered in these studies is to hold the bus when it is too early, with a maximum possible commercial speed. This concept was developed based on the problem that there is a significant reduction in the value of commercial speed when holding control is too long.

Speed adjustment in combination with the traffic signal priority is also used to avoid irregularity problem. Earlier, Chandrasekar (2002) proposed a route-based control strategy, which delayed the buses by reducing its speed instead of holding them at the station. Headway to the preceding bus became the indicator for control, and when the value is too large, the bus will speed up with the support of signal priority in the intersection. It was found that the strategy worked well to reduce the headway coefficient of variation and excess waiting time. Teng & Jin (2015) proposed a combination of three different strategies including signal control, speed adjustment, and holding control with the help of bus-to-bus communication. Speed adjustment was the main control to revise the headway deviation. The other strategies were taken only at the intersection when necessary. The proposed strategy was evaluated based on actual data of a single bus line in Shanghai by using simulation. It successfully improved the headway variance of the system, as well as the efficiency of the bus fleet and cost travel for passengers.

Punctuality also becomes an objective to apply a speed adjustment control. Wu, Tan, Shen, & Wang (2016) earlier developed a model to improve bus punctuality as well as general traffic at the intersection. In this study, speed guidance was the main control to achieve punctuality, which was also supported by signal priority control with an optimal green light scheme. The model worked by benefiting from the characteristic of the connected vehicle, which allowed real-time information exchange between buses and the control system. Based on the observed state, the controller estimated the arrival time of the bus at the downstream stop as a basis of control decision. The controller also performed holding when there is a potential of early departure. The control successfully achieved the objective during the evaluation in the simulated single bus line with an intersection.

Recently, Liang & Wei (2017) developed a speed control model with an objective of improving punctuality and maximizing passenger revenue through the reduction of the average delay. It was assumed that the bus line shares the same traffic as the car. Thus the control relied highly on the optimal signal priority. The study also developed an arrival-time window prediction to determine the optimal time at the intersection. Through simulation of a hypothetical case, the proposed control showed a promising result by giving a significant improvement in the average passenger delay-time for different traffic conditions.

Different objectives were found in Liu & Ceder (2016), which combined speed adjustment with other strategies (e.g. holding, stop-skipping,) under a communication-based cooperative control strategy to increase transfer synchronization. It demonstrated how the strategy performance differs due to the influence of cooperativeness. By including cooperative manner, drivers did not only adjust the speed but also distribute the information to other vehicles and gives a better outcome.

The fourth topic on speed adjustment is a controlled development to optimize fuel consumption. This topic is mostly found in rail mode transport such as metro or heavy rail. Different speed profile can significantly result in different energy consumption for this mode. There is a little amount of research studying on this topic for buses. Ma, Xie, & Han (2012) combined holding control, speed adjustment and signal priority strategy to minimize energy consumption and emission as well as to increase service reliability of the transit system. Conceptually, the strategy optimized the bus speed and bus holding time to determine its arrival time at a stop line of an intersection and decision to stop or pass. It assumed a real-time communication between buses and traffic controller technologies. The framework of the system optimized the speed upstream and downstream of the bus stop, and also the holding time at the control point. Another study optimized the speed profile of the bus by using dynamic programming and considering the energy consumed during bus operation (e.g. accelerating and decelerating). The outcome was an advised speed profile to be informed to the drivers (Nouveliere et al., 2008).

2.2.3.1 Summary on speed adjustment strategy

Speed adjustment strategy is not only applicable for the transit system, but also for car traffic. It can resolve different objective problems due to its possibility to be combined with other strategies. Figure 2.2 summarizes several purposes of applying speed adjustment strategy in the majority of previous studies.

The focus of this study is to maintain regularity in operation. Thus deeper attention will be given here for the study purposing on reducing headway deviation.

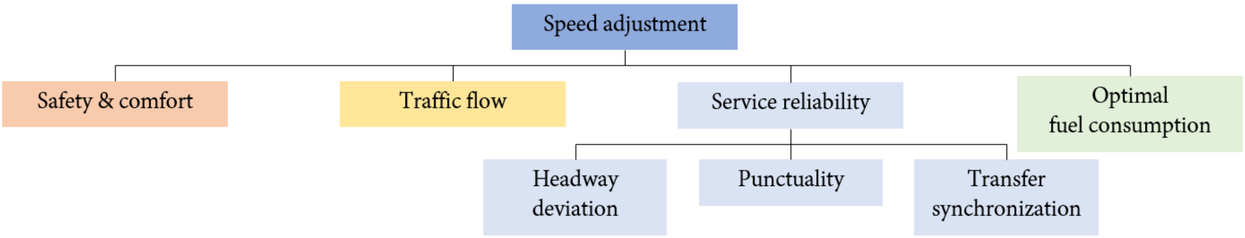

Figure 2. 2 Purposes of speed adjustment strategy

Several aspects can be concluded from the previous studies to mitigate irregularity problem:

i) Headway reference. Chandrasekar (2002) translated holding time based on forward headway into speed reduction along the route. However, Pilachowski (2009) argued that this control is not effective to mitigate large disruptions. It is more efficient to refer to both the preceding and the following headway.

ii) Control point. Daganzo (2009); Bartholdi III & Eisenstein (2012); Teng & Jin (2015) showed that controlling the speed in a continuous manner obtain a better system performance. However, this situation may lead to a worse situation (bunching) if it is not sufficiently controlled (Bartholdi III & Eisenstein, 2012).

iii) Issues during the implementation.
   - Applying continuous speed control requires advanced technology. Nevertheless, the recent development of technology has allowed the possibility to go into this direction for example by having AVL installed on board.
   - Speed adjustment is difficult to implement due to variability in trip time (Chen, Adida, & Lin, 2013). However, the previous study demonstrated that it is still possible to apply this strategy in mix traffic condition but then the estimation of arrival time should be done in a more robust manner. As an alternative, the combination with other strategies is also helpful to generate the overall optimality of the control.

iv) As an interstation control, speed adjustment may not be effective for the route with a dominant dwelling time at stops Pilachowski (2009). This becomes another reason to combine speed adjustment with other strategies.

2.3 Assessment of the effectiveness of the control strategy

The effectiveness of a control strategy can be assessed from the way it resolves the problems during operation or from the level of reliability it obtains. For this purpose, several indicators can be classified based on the control objective. Majority of previous studies took the indicators on the basis of the passenger and operator perspectives. Meanwhile, a few studies also included the perspective of the authority with concern on practicality (Cats, 2014; van der Werff, 2017).

A. Passenger perspective

The passenger is the main object in a public transport system especially when assessing service reliability. One characteristic of transit service that can attract passenger is a trip time. It includes access/egress time, waiting time, and in-vehicle time. The first aspect is excluded in this study because it cannot be affected during the real-time operation. Most of the research in Section 2.2 take into account waiting time and total travel time as the evaluation indicators. To capture the reliability from passenger's point of view, Furth & Muller (2007) and van Oort (2011) described extra indicators: reliability buffer time (RBT) and additional travel time. In the holding control study, sometimes waiting time on board is also considered in the control objective (Sun & Hickman, 2008). Too much holding at high-frequency transit system is not acceptable by the passengers. Furthermore, the perceived weight during this period is larger than those during the riding time (Vansteenwegen & Van Oudheusden, 2007). When there is a capacity constraint, the waiting time for passengers who are rejected is also calculated (Delgado, 2012). Besides the time-based reliability indicators, van Oort (2011) adding that comfort also contributes in overall attractiveness of the transit system. Thus, there is another indicator, average standing time (AST), which is essential in an overcrowded condition (van der Werff, 2017).

B. Operator perspective

Service reliability and costs are the focus of the operator. Punctuality and regularity are common indicators of reliability from the perspective of the operator (van Oort, 2011). There exist different indicators to assess regularity, for instance, the standard deviation of the headway difference (CoV headway), relative regularity (PDRM), and excess waiting time (EWT) (TCRP, 2003; Hakkesteegt & Muller, 1981). This study will take CoV headway as the indicator for evaluating the performance of the strategy. However, one should concern that this indicator is only looking at the perspective of the supply side of the transit system. It does not capture the effect of unreliability from the passengers' perspective. The next point discusses this issue in more detail.

For holding control strategy, holding time also becomes a concern for the operator. Its value contributes to the total travel time or total cycle time in the perspective of the operator. This indicator is crucial because, at the higher level, there is a constraint in the operational planning (i.e. vehicle and crew scheduling). Cats O. et al., (2012) added schedule adherence at relief point to represent this condition. The fleet requirement is also a relevant indicator for a headway-based control because the number of fleets can change during the operation (Cats O. , et al., 2012). Other than that, is passenger load, to show the effectiveness of the control to distribute the load per vehicle (Sanchez-Martinez et al., 2016).

C. Authority perspective

Service reliability is certainly a focus of the authority. However, the indicator can be different depends on the concession agreement. A study by van Oort (2014) analyzed performance indicators that are set by different public transport authorities in several cities. From the data collected, it is known that in general, the authorities only consider the operational level to improve service reliability of the system. Additionally, the majority of them only assess the reliability from the supply side. Punctuality indicator is the most common indicator found. Problematically, the analysis shows that different authorities translate the indicator differently. In most cities, the punctuality assessment refers to the deviation between the schedule and actual departure time at a stop, within a certain bandwidth. Each city defines a different range of bandwidth value, which biases the comparison of performance between different operations. As a solution, the study suggested using an additional travel time instead (van Oort, 2011). This indicator can capture the unreliability effect on the passenger. Moreover, it is comparable to the travel time, and it has only one definition, which prevents bias in the assessment. Another study by van der Werff (2017) set a different indicator. Instead of only focusing on a time-based indicator, it assessed the level of comfort that can be provided by a transit system by counting the probability of finding a seat. This is a relevant indicator for a case where the system is constantly crowded. Specific for the present study, the performance indicator from the authority perspective will be taken from the ones that are considered in the case of AllGo operation, which will be explained in Section 3.2.

Considering that the direction of this study is on regularity-based transit operation, additional indicators are given. The first indicator is headway adherence, which calculates the percentage of trips that have acceptable regularity level (CoV 0.21 based on TCRP, 2013). The second indicator is the ratio between the actual and desired planning. These indicators refer to a study by Cats, O. (2014) in regularity-based operation. The indicators were defined in a stepwise function explained in the paper, to allow reward and penalty calculation for the operation.

2.3.1 Effectiveness of control strategy under different behavior of drivers

The previous section mentions three important stakeholders, which are relevant for the design of operational control strategy. The indicator assesses the control strategy by estimating how the system performs when the control is implemented. However, the control itself may be implemented differently compared to the suggestion. One possible reason for this is the driver behavior (van Oort, 2011; Cats O. , 2014; Argote-Cabanero et al., 2015; Phillips et al., 2015; van der Werff, 2017). The factor of the driver is rarely included in the literature on control strategies.

van der Werff (2017) tested the even-headway strategy and concluded that the effect of driver compliance is not significant to the performance of the strategy. However, for the cases where the control strategy is sensitive to driver compliance, the reasoning behind the compliance itself is not clearly described in the study. In general, study about driver compliance on control strategy is rarely conducted.

In this study, driver behavior towards the control strategy is defined as driver acceptance. To assess driver acceptance, one can assess it through a data collection of driver thoughts or observe it directly by having a field-experimental study. The first approach can be answered for instance by using a theory of planned behavior. This concept predicts individual action by observing behavioral, normative, and control beliefs of a condition. As far as acknowledged by the author, this approach has never been conducted for bus driver case. To have at least the same setting of being controlled, a study explored beliefs, which affect driver compliance in speed limit control for a highway as described in table 2.2.

From the definition given in Table 2.2, Elliott, Christopher, and Christopher (2005) showed that driver compliance could be affected by different factors. To comply or not comply with a certain control, the drivers might think of the possible consequence they get when applying the control. This is more like an internal factor from the drivers themselves. Their decision could also be affected by the external situation. This situation could occur from the behavior of other drivers or road users, thus, more on the social point of view. Besides, it could also occur from the situation in general such as the condition of the road, or the characteristics of the control applied.

Table 2. 2 Beliefs to comply with speed limits (Elliott, Christopher, & Christopher, 2005)

Beliefs	Definition
Behavioral beliefs	Advantages and disadvantages to comply
Normative beliefs	Social referents to comply
Control beliefs	Factors that may inhibit or facilitate compliance

Related to the third factor, the control beliefs, past studies on headway-based holding control suggested making the control implementation as simple as possible to understand. Thus, it does not burden the drivers (Daganzo & Pilachowski, 2009; Bartholdi III & Eisenstein, 2012). Aside from the interface given to the passengers, the characteristics of control given also affect the drivers. An experimental study of a headway-based holding control in Spain found that the compliance of drivers became lower as more variability is given in the recommendations (Argote-Cabanero et al.,2015). According to this, the simplicity can be defined as less variability in control. A similar suggestion was given in a study of the speed limit in the roadway, which introduced several approaches to set speed limits. One of the approaches is to set the limits in the way that it does not deviate much from the driving speed to ensure its reasonability from the driver point of view (Elvik, 2002).

In this study, there are two types of control considered. Both holding control and speed adjustment strategy have a potentially negative effect on drivers. Holding the bus too long at the station or setting a specific speed during the journey is disturbing for drivers (van Oort et al., 2010; Tarko, 2009; van der Pot, 2018). The effect should be taken into account to predict the acceptance of the control.

2.3.2 Effectiveness of control strategy in a network context

In the majority of studies, the control effect of the service reliability was only assessed based on a single line. Few attentions were given in the reliability of a whole network. In the network, there are two possible interactions between lines, which involve the passenger's activity. The first interaction is a connection, where passengers can transfer to other services. However, for a network that operates a high-frequency service, this interaction is less important. There are several studies in Section 2.2 aiming at transfer synchronization in which mostly done for a long-headway operation.

The second interaction is a multiline corridor where several lines share common stops along the corridor segment. In this segment, the regularity can differ with one of a single line (Chen, Yu, Zhang, & Guo, 2009). A strategy may successfully distribute the passenger uniformly when being analyzed in a line. However, when different high-frequency lines share several similar stops, passenger distribution may be different. In term of headway, it is not suitable anymore to assume an independent line headway distributions. There is a difference in the interaction between successive vehicles which may lead to pairing and is needed to be considered in the timetable coordination (Bellei & Gkoumas, 2010).

There is a need for cooperation between the lines to achieve regularity in the network (van Oort & van Nes, 2005; Bellei & Gkoumas, 2010; Hernandez et al., 2015). van Oort & van Nes (2005) considered the coordination at the strategic level by scheduling. The study analyzed regularity of different implementations of interacted lines based on the schedule of a tram line in The Hague. The first possibility was to have an uncoordinated schedule between two lines. The second possibility was to have a coordinated schedule where both lines have the same average headway. For the first case, the regularity was low when the punctuality of each case is high. The second case obviously gave a much better performance in regularity when the service is punctual.

Differently, Argote-Cabanero et al. (2015) and Hernandez, et al., (2015) analyzed the effect of common lines at the real-time operational level. The first study built a dynamic holding control based on control theory. Here, the effect of multiline was modeled in a function describing the physical sense of the lines connected to the common stops. However, the control was purposed for a punctuality-based operation. In a different manner, Hernandez et al. (2015) conducted an optimization problem of holding control strategy by considering the network effect. The study concluded that when there are multiple lines in the same corridor, the best decision control can be made by utilizing centralized control, thus by coordination between lines. In the optimization problem, the coordination effect was represented by incorporating the effect of different passenger types from each line.

Schmocker et al. (2016) also considered different types of passenger to analyze bunching effect in a network context. It discovered that common stops could improve the regularity significantly specifically for an operation that allows overtaking between bus lines, with the tradeoff of spreading delay to more reliable lines. The result was contradicted with Bellei & Gkoumas (2010). Yet, it should be emphasized that "bunching" of different lines can be justified if the passengers involved are unconcerned of the differences (Argote-Cabanero et al., 2015; Hernandez et al., 2015; Schmocker et al., 2016). Thus, even if the vehicle is paired at the common stops, the passengers who have chosen one line to reach their destination may not be affected by the bunching effect. The passenger's load can still be evenly distributed for this type of passenger. By contrast, when the passengers are unconcerned, there is a possibility of regularity improvement from vehicle overtaking by seeing the different lines as an additional service for a particular trip of the passengers as in (Schmocker et al., 2016). Otherwise, bunching can be verified because the vehicles are assembled at the same stop simultaneously. Moreover, this situation would worsen the reliability of the later vehicle(s).

From the past literature, several conclusions can be made about control strategy in a network level. Evidently, there is a need to analyze the transit system performance at the network level, equally when a control strategy is implemented. It is also important to look at a smaller scale by taking into account different types of passengers involved in the interacted lines.

Network effect in control strategy can be analyzed either by including it during the development of the control or by assessing the impact during performance evaluation of the control. Different passenger types in the interacted lines yield a possibility that a single-line-based control strategy can still perform well in a network setting. Hence, this study will incorporate the network effect in the evaluation part to get the insight on how far the performance differs.

2.4 Headway-based control strategy in practice: a case study of AllGo bus operation, Almere

Apart from the theory, headway-based control has not been fully implemented in practice. Thus, a further data collection is needed to verify the issues mentioned above. In this study, the problems in the implementation were analyzed based on the case of AllGo bus in Almere. Several interviews with the staffs of AllGo bus Almere were conducted, including the concession manager, network scheduler and fleet manager.

2.4.1 Result

AllGo bus is a bus service, which adopts a concept of bus rapid transit and hence aims at high capacity and high-frequency service. Despite its high-frequent concept, AllGo bus still operates based on punctuality indicator. The concession is one reason behind this. On-time performance is the main indicator among the listed indicator in the concession. Another important indicator is whether the trip scheduled is successfully run or not. One can observe how these two indicators can conflict with the headway-based control.

In the previous subsection, it has been explained how the headway-based works so that it ignores the concept of scheduling. This becomes the problem when Keolis should comply with punctuality concept. Additionally, by understanding that the operation of the headway-based concept is not restricted to the schedule, the implementation is flexible to some extent. If a disruption occurs, the bus can adjust its headway so that it remains to provide regular service. On the other hand, the concession defines an indicator concerning the completion of the trips. If the trip is run based on schedule, one could assess clearly, whether a trip is completed or not. By contrast, the flexibility of headway-based control may blur the assessment on this aspect. Looking further at the network effect, currently, Keolis also does not really pay attention to how a network effect in operation is. Since the current operation is strictly referring to the schedule, they only measure the performance at the stop level.

Furthermore, it is believed that it may obtain confusion on the passengers in the first period of implementation if the schedule is completely discarded. As applied in every new system, it may need months until the passengers fully adapt to this concept. To support the adaptation, it seems necessary to have stages of implementation instead of completely transforming into the headway-based concept.

Another problem regarding the dismissal of the timetable is a potential conflict with the fleet and crew scheduling. Currently, these operational aspects are derived from the design timetable. Interlinings is common to use for the current fleet management to make fleet utilization becomes efficient. In headway-based control, this system may potentially obtain a problem if there is a delay occurs in one line because it will subsequently affect a delay in another line. On the other hand, given the fact that the headway-based control will be only applied during the peak hour, the effects may be minimized.

Headway-based control is also potential to cause problems in the driver scheduling, although it may be not as problematic as in the fleet scheduling. A reason for this is due to the fact that most drivers will have a break after a maximum three hours driving. Thus, if there is a delay in one line, it will not ruin the next shift of the drivers because they will have a break first. However, the delay should be kept low to assure that the drivers have their rights to have enough break. There is also a case where the drivers should switch their shift. In this situation, the problem will be similar to those in the fleet scheduling. To sum up, the flexibility of headway control should be limited to some extent which assures that the headway control does not ruin the operational scheduling.

With respect to the operational control, AllGo bus currently operates under a schedule-based holding control since it runs based on a fixed timetable. While theoretically it is argued that headway-based control would work better, according to the staffs, schedule-based holding control runs effectively during the five months of AllGo bus operation. The fact that the bus runs in a separated lane is one significant influencer on this. There are still some minor problems with reliability, which are mainly caused by external factors and technical problem. Currently, AllGo bus also does not have a problem concerning the driver behavior. The drivers generally comply with the schedule-based control strategy, which can be indicated from the current performance of AllGo with 90% punctuality. While holding is arguably not convenient for the drivers when it is too long (van der Pot, 2018), the drivers in AllGo bus operation do not seem to have a problem with it. The drivers never complained about the concept of holding, but more on the occurrence of technical problems. Keolis is aware that applying too much holding will burden the drivers. Hence, in its implementation, holding is only necessary at several major stops (e.g. where there is a connection with the rail system). On the other hand, as has been mentioned in 2.3, a potential problem may occur when the control concept is changed into headway-based holding or speed control since more variations will be suggested to the drivers during the operation.

2.4.2 Summary on headway-based control strategy in practice

To summarize, there is four addition of potential issues in the implementation of headway-based operation from the practical perspective by referring to the AllGo bus operation, as followed.

1. Concession. It is difficult if the operation still refers to punctuality and trip completion while it does not refer to a timetable anymore. Based on the reasoning that the service is provided for passengers, it is then advisable to focus on the indicator that clearly captures the quality of service from the perspective of the passengers. For instance, to use the additional travel time indicator instead of referring to punctuality. van Oort (2014) suggested using this indicator since it represents the reliability effect on passengers better. Another suggestion is to use headway adherence, as mentioned in Section 2.3. With a similar concept to punctuality adherence, this indicator shows the percentage of trips with an acceptable level of regularity.
2. Passenger adaptation. Passengers always have to adapt everytime a new system is introduced. The operator cannot prevent this issue but can minimize the negative impact by planning the implementation in stages.
3. Conflict with the operational scheduling. Punctuality indicator can be used at this level as suggested by Cats O. et al., (2012). Thus at the relief point, there is a certain bandwidth to assess whether a trip cycle of a fleet can cause delay to its following schedule.
4. Potential burden on the drivers if another control is introduced. To cope with this problem, first, an indication of the burden should be given through a new indicator concerning on the drivers, as aforementioned in the previous subsection. Later on, more tactical steps can be derived to help minimize the complexity in the implementation and prevent burden for the drives.

2.5 Conclusions

This chapter explores two focus aspects of the study: i) headway control strategy (i.e. holding control and speed adjustment), ii) perspective of the drivers, network and practicality. Through this exploration, this chapter provides the answers to Sub-RQ I.1, Sub-RQ I.2, and Sub-RQ I.3. In this section, the first part gives the answer to each sub-question. The second part follows to give the synthesis of the literature review.

Sub-RQ I.1: What are the tradeoffs of each control strategy?

The previous sections show different control strategies developed in past studies. Each strategy has its own characteristics, which affect its effectiveness. In the present study, the focus is limited to speed adjustment and holding control as a headway-based control strategy. Both strategies are found to be effective in solving service reliability problem. These controls have different basic characteristics, since holding control works at the station, while speed adjustment is implemented along the route. Refer to this condition; each strategy has different strengths and weaknesses in the implementation of public transit services. Table 2.3 has summarized the tradeoffs between the strategies.

Table 2. 3 Tradeoffs in holding control and speed adjustment strategy

Holding control		**Speed adjustment**	
(+)	(-)	(+)	(-)
• Flexible • Minimum effect on passengers (in term of boarding failure) • Works well for high demand rate	• Applicable only when the trips are considered arriving early, thus, in general, it lengthens the total cycle time • Conflicted with the operational scheduling • Cost of waiting onboard at station > cost of riding • Need more advanced technology	• Flexible • Riding time costs less • Minimum effect on passengers (in term of boarding failure) • Applicable for late and early arrival condition	• Need more advanced technology • Highly depend on trip time variability • Not effective for a route with a dominant dwelling time • Acceleration and deceleration affect comfort
Notes:			
Black text: common strengths			
Blue text: Tradeoffs that can complement each other			
Red text: weaknesses that need further consideration (not analyzed in this study)			

There are three characteristics to distinguish, which are indicated by different text colors. The black texts indicate the common strengths of speed adjustment and holding control. When look at these strategies as headway-based control, both strategies provide the flexibility since it is not necessary to comply with a timetable. Furthermore, it produces the minimum effect on passengers in term of boarding failure, if the system is not overload. Other strategies such as boarding limit and stop skipping have potential in this failure even in an underload condition.

The blue texts indicate the attributes that become weaknesses in one strategy but can be complemented by the other through its strengths. For instance, while holding control is not applicable for a delay situation, speed adjustment can cover this weakness if both controls are combined. On the other hand, while speed adjustment may be not effective in a situation with dominant dwelling time, holding control compensates it. Furthermore, implementing slowing down on the route instead of holding at stop could be beneficial since waiting time onboard costs 1.5 higher than riding time.

These characteristics are the reasons behind combining speed adjustment and holding control in one strategy, as will be given in Chapter 3. Yet, further evaluation is required to provide an objective assessment of this hypothesis. The evaluation will be given in Chapter 4.

Lastly, the red texts represent the weaknesses of both controls, which remain problems regardless of the combination. Potential conflict with the operational scheduling is unpreventable for a headway-based control strategy. Except, at the operational level, it is also set to be schedule-free.

This also applies for speed adjustment strategy even though it may minimize the effect because it is able to react to a delay situation by speeding up.

Headway-based control strategy also relies on a more advanced technology since it requires real-time information. Speed adjustment seems more dependent to this because the control is taken more continuously compared to holding strategy. Another specific problem in speed adjustment is its dependency of effectiveness on a trip time variability. Furthermore, speed affects passenger comfort and hence should have a certain boundary to keep it convenient. The listed characteristics in the red text need further attention to resolve.

Besides the problems mentioned above, implementing a headway-based control strategy will induce other potential problems from the practical perspective. Several additional problems are listed from an interview with staff in the Keolis, as followed.

1. Concessionaire
2. Passenger adaptation
3. Potential burden on the drivers if another control is introduced

Sub-RQ I.2: What can be the interest of the drivers in the implementation of the control strategy?
This chapter also identifies several interests of the drivers to answer the second sub research question.
In an implementation of the control strategy, driver acceptance is important as it determines the effectiveness of control strategy implementation. Theoretically, factors influencing driver acceptance could be revealed through a behavioral research method, yet this approach has not been carried out in the past studies for bus drivers. However, several indications were given from the experimental studies in the past. The first factor is **the extent that the control strategy can burden the drivers**. The second is **the variability of the control strategy**. The third, related only to the speed control, is **the deviation of the speed limit from the regular driving speed of the drivers**. These factors are taken as evaluation indicators, which will be elaborated in Chapter 3. A further assessment of the control strategies will be given in Chapter 4.

Sub-RQ I.3: What can be the potential differences between considering the service reliability of a public transport system in a line level and a network level?
Literature review in this chapter tries to answer the third sub research question. The network defined in this study is the situation where there is an interaction between lines, in the form of a multiline corridor, in which both lines share common stops. **A potential difference when this situation is considered, is the assumption of the headway distribution**. When the passengers involved in these lines are unconcerned of the differences between lines, it is not relevant to assume headway distribution based on a single line. Instead, the combined headway has to be calculated. Thus, it is possible that bunching was happening when a system observed as a network, while its regularity is perfect at a line level. This factor is also taken as an evaluation indicator, to be given in Chapter 3, and be assessed in Chapter 4.

2.5.1 Synthesis

Literature review on headway control strategies leads to the conclusion that early studies mainly focused on holding control strategy. Different approaches have been taken for the studies. Earlier studies focus more on the optimization problem. In this approach, the control objective is also developing from only passengers waiting time until considering the effect of rejected passengers. While mostly the model is built based on a deterministic approach, recent studies start to develop the optimization with stochasticity effect. As technology develops, research on real-time adaptive headway control is also growing. It becomes possible to look at continuous speed control to maintain service regularity.

Fundamentally, passengers are the main objective of implementing control strategy with the ultimate goal on service reliability. Researchers also take into account the operators in the evaluation part to see the effect in the supply side. This assessment can indicate the feasibility of the control for implementation. By understanding the urgency of this aspect, several newer studies include the drivers in the evaluation part in term of their acceptance.

Table 2.4 summarizes these aspects from the past studies. The first column defines the sources of the reviewed studies. The second column describes the headway control strategies considered. Some of the studies combined several measures for the proposed strategy. The information inside the brackets indicates the specific approach that was taken. "forward hw", "backward hw", and "even hw" indicate the headway reference to decide the control. The third column defines the solution method of the control and the objective. "Opt." stands for optimization problem which majority is aiming to minimize passenger cost. Among all the reviewed studies, only one study optimized the problem based on fuel consumption (Ma, Xie & Han, 2012). The last two columns define how the control being evaluated. "Perspective" defines the different point of view which determine the selected performance indicators. "Scope" shows the scale of the control evaluation. The majority of the studies ignored drivers in the evaluation part. It also simplified the actual condition by neglecting network effect in operation.

The present study develops a headway control strategy based on the combination of holding control and speed adjustment for an effective regularity-based operation. The proposed strategy is a rule-based strategy which is built upon the idea that waiting time on board has a higher weight than riding time. Thus, the control aims to have a minimum holding possible and hence being actuated by speed adjustment at most. In addition, the study takes into account more implementation parts by including the driver's acceptance and network effect in the evaluation. Additional indicators are introduced in this study for this reason. Speed distribution is taken to estimate driver's acceptance since speed adjustment is the main control in this study. Additionally, different passenger types will be defined to estimate the effect of the multiline corridor in the control implementation. The choice taken in the present study is mainly driven by a time limitation. The idea still can be expanded for instance by using optimization to develop the control and to consider the driver and network effect not only in the evaluation part but also in the design part.

Table 2. 4 Reviewed studies

Author (Year)	**Strategy***	**Solution method (Control objective)**	**Evaluation**	
			Perspective	**Scope**
Abkowitz & Lepofsky (1990)	HC (forward hw)	Rule-based (Regularity)	Passenger and operator	Single line
Eberlein, Wilson & Bernstein (2001)	HC	Opt.	Passenger and operator	Single line
Chandrasekar (2002)	SA (forward hw) + TSP	Rule-based (Regularity)	Passenger and operator	Single line
Zolfaghari, Azizi , & Jaber (2004)	HC	Opt.	Passenger	Single line
Furth & Muller (2007)	HC	Opt.	Passenger and operator	Single line
Nouveliere, et al. (2008)	SA	Opt (Fuel consumption)	Operator	Single line
Sun & Hickman (2008)	HC	Opt.	Passenger and operator	Single line
Daganzo C.F. (2009)	HC (forward hw) + SA	Rule-based (Regularity)	Passenger and operator	Single line
Daganzo & Pilachowski (2009)	HC (even hw) + SA + SS	Rule-based (Regularity)	Passenger, operator and driver	Single line
Delgado F., et al. (2009)	HC + BL	Opt.	Passenger	Single line
Pilachowski (2009)	SA (even hw)	Rule-based (Regularity)	Passenger and operator	Single line
van Oort, Wilson & van Nes (2010)	HC	Rule-based (Regularity)	Passenger	Single line
Xuan, Argote & Daganzo (2011)	HC (forward hw with virtual schedule)	Rule-based (Regularity + Punctuality)	Passenger and operator	Single line
Batholdi III & Eisenstein (2012)	HC (backward hw) + SA + SS	Rule-based (Regularity)	Passenger, operator and driver	Single line
Cats, et al. (2011, 2012)	HC (target & even hw)	Rule-based (Regularity)	Passenger and operator	Single line
Delgado F., et al. (2012)	HC + BL	Opt.	Passenger and operator	Single line
Ma, Xie & Han (2012)	HC + SA + TSP	Opt (Fuel consumption)	Passenger and operator	Two lines
van Oort, Boterman & van Nes (2012)	HC	Rule-based (Punctuality)	Passenger	Single line
Ampountolas & Kring (2015)	SA (forward hw)	Rule-based (Regularity)	Passenger and operator	Single line
Argote-Carbanero, et al. (2015)	HC (forward hw with virtual schedule)	Rule-based (Punctuality)	Passenger, operator and driver	Two lines
Hernandez, et al. (2015)	HC	Opt	Passenger and operator	Two lines
Teng & Jin (2015)	HC + SA + TSP	Opt	Passenger and operator	Single line
Liu & Ceder (2016)	HC + SA + SS	Opt	Passenger and operator	Two lines
Sanchez-Martinez et al. (2016)	HC	Opt.	Passenger and operator	Single line
Wu, Tan, Shen, & Wang (2016)	SA + TSP + HC	Rule-based (Punctuality)	Passenger, operator, road user	Single line
Liang & Wei (2017)	SA + TSP	Rule-based (Punctuality)	Passenger, operator, road user	Single line
Sirmatel & Geroliminis (2017)	SA (even hw)	Rule-based (Regularity)	Passenger and operator	Single line
Zhang & Lo (2018)	SA (even hw)	Rule-based (Regularity)	Passenger and operator	Single line
Present study	**HC + SA**	**Rule-based (Regularity)**	**Passenger, operator and driver**	**Two lines**

***) Note:**

HC = Holding control
SA = Speed adjustment
SS = Stop-skipping
CV = connected vehicle
TSP = Transit Signal Priority
BL = Boarding limit
VSL = Variable Speed Limit

Chapter 3: Control strategy development

This chapter explains the model development of the proposed control strategy in the present study. There are two parts of model development in this research. The first part is a design stage, which derives the framework to combine speed adjustment and holding control in a mathematical model formulation. Prior to this, several assumptions are derived from the literature review. The second part is the evaluation stage, which explains the evaluation concept of the strategy, such as the tool, performance indicators, as well as the scenarios to run. This chapter presents the answer for sub-RQ I.4, *"How to formulate a model to find a potential combination of strategy?"*.

3.1 Design stage: Rule-based speed and holding control concept

This chapter explains the concept of the proposed control strategy in the present study. The main attribute of the proposed concept is a combination of speed adjustment and holding control strategy to maintain regularity in operation. In the previous chapter, potential characteristics in combining these strategies were identified. These characteristics are:

- Viability in a situation with dominant dwelling time.
- Possibility to generate lower generalized travel time, due to the lower cost obtained by riding time.
- Applicability in early and late conditions.

To achieve the characteristics above, a general concept is formulated as followed. Speed adjustment allows the vehicles to maintain their headways along the link for which reduces the necessity of holding at the control point. However, further corrective action can be taken through holding strategy at the predefined control points if the headway remains irregular. Both speed adjustment and holding control in this combination consider the headway between the observed vehicle and its preceding as well as its following vehicle. Thus, the strategy requires coordination between three consecutive vehicles at each vehicle observation through real-time communication.

The following are the assumptions taken in the developed strategy for this study.

1. Real-time communication.
   To support the coordination, there exists a real-time communication either between buses or through a central operator, which provides the controlled vehicle with the information of its state as well as its leading and following vehicles in an event-based (i.e. arriving or departing).
2. Dedicated lane.
   The system runs in a dedicated lane. Thus, the effect of the traffic of other modes is not considered.
3. Ignoring the effect of acceleration and deceleration.
   The effect of acceleration and deceleration in speed adjustment will not be defined in detail. However, it will be included implicitly in a parameter while determining the suggested speed, along with the possible delay of driver reaction time towards the control.
4. Arrival time prediction based on scheduled trip time.
   The prediction of arrival time refers to a scheduled trip time between stops defined in the timetable. With this assumption, the prediction is still derived in a real-time manner as a further result from assumption 1. However, since there is no information transmitted when

the vehicle is on the route, the time duration between arrival time at one stop to its next stop is taken from the scheduled trip time.

As the proposed control strategy performs both the speed adjustment and holding control, the control decision can be taken either at the link or at the stop. For every time a vehicle is being controlled, the definition of the associated stop and link is given as follows.

1) The stop associated with the controlled vehicle is the nearest stop to be approached by the controlled vehicle. As a control decision point, it is possible to apply holding control once the vehicle arrives at this stop if only the stop is a part of the designed control points. The suggested decision will be in the form of departure time.
2) The link associated with the controlled vehicle is the upstream link of the approached stop. At this location, the controlled vehicle is suggested to adjust the speed based on the observed headways as soon as it enters the link. At each link, the speed advice is given once at the very beginning of the link, as illustrated in figure 3.1 below. Thus, there is no revision regarding the speed actuation between the stops nor new information on other vehicles.

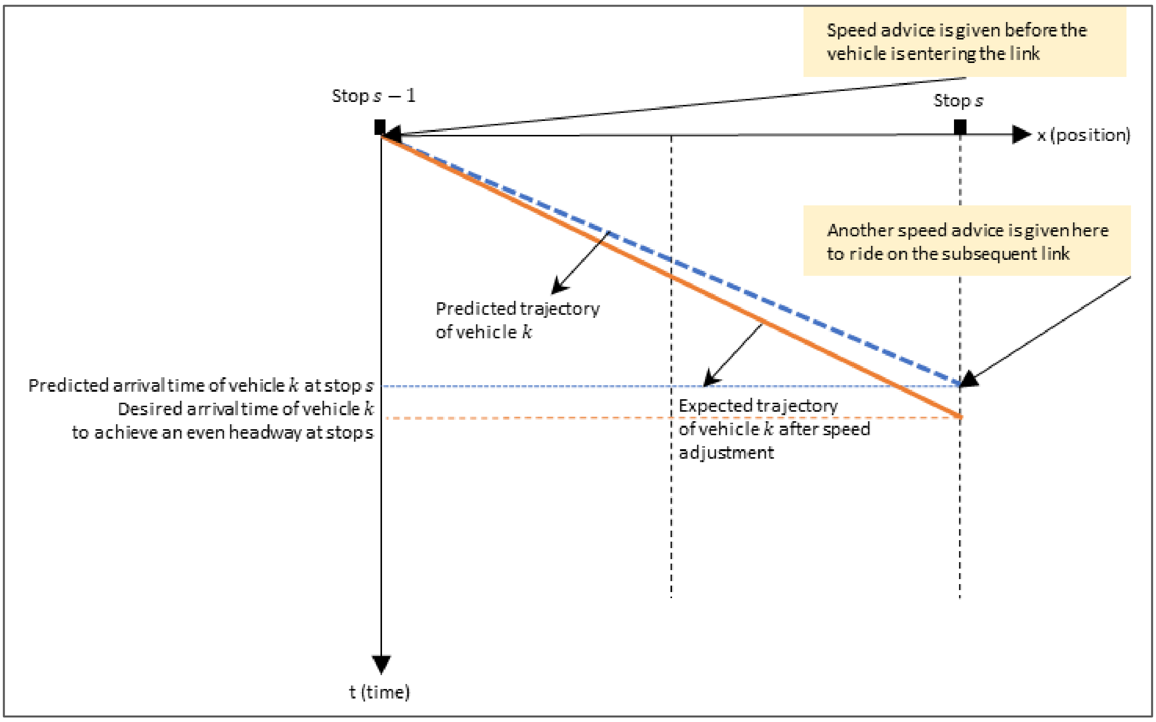

Figure 3. 1 Illustration of speed advice

Figure 3.2 depicts the general concept of the proposed control for each pair of stop and link. The control starts when the vehicle starts entering the upstream link of the approached stop.

Prior to this, there is a generation of the input data. Four types of input are distinguished. The first input is goal related. Here, the aim of the control is a regularity, thus referring to headway. As aforementioned in Chapter 2, different headway references can be considered. For this controller, the controller refers to an even headway, which takes into account both the preceding and the following of the observed vehicle. Different reference may generate different control decision suggested in the next step. The second input is the current state of the system at the observation time. In the proposed concept, the considered state is the position of the vehicle, whether it is at a stop or a link. The third input is network related such as length of the link, scheduled trip time at one link, the position of the stop and other network characteristics.

Lastly, is operational constraints, which give boundary in the control decision suggested such as the speed limit for speed adjustment, or maximum and minimum holding time for holding control.

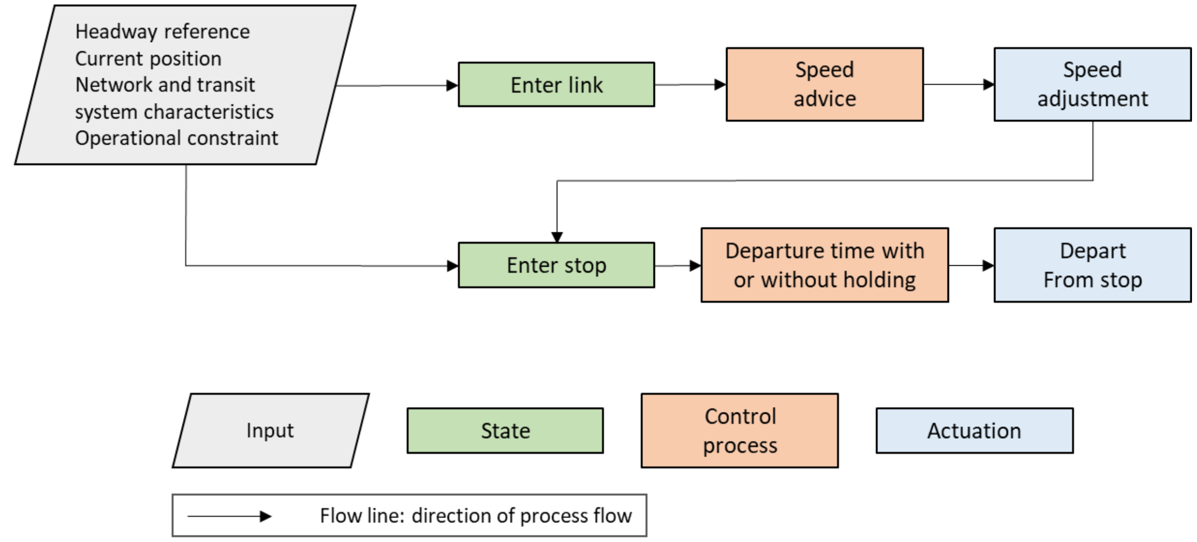

Figure 3. 2 General concepts of the controller

The inputs provide information for the controller to determine the control decision. As mentioned previously, the control decision is given either as a speed adjustment or holding, depends on the position of the vehicle when being controlled. When the vehicle is located at a link, the controller gives speed advice to perform a speed adjustment. On the other hand, when the vehicle is stopping, the controller gives the advice in the form of departure time of the associated vehicle from the stop. It is important to be noted that if the observation shows that the vehicle is too early at a stop, the controller will consider additional holding time when determining the departure time, as long as it stops at a predefined control point. A more detail description of this approach is given in the next section.

3.1.1 Mathematical formulation

In this section, the framework of the proposed concept is formulated in a mathematical term. The purpose is to allow the framework being modeled in a simulation tool and evaluated quantitatively. The mathematical formulation in general consists of two parts, following the two different locations aforementioned. Before explaining the formulation, first, the notations used in the mathematical model are described as followed.

Notation

J : a set of lines observed
K : a set of vehicles controlled
L : a set of links upstream the stops observed
S : a set of stops observed
ε : additional time (delay in headway calculation, the reaction time of driver, acceleration and deceleration effect)
v^{max} : maximum speed allowed in the system
v^{min} : minimum speed allowed in the system
$D_{j,s}$: location of line j stop s, measured from the first stop ($D_{j,1} = 0$)
$x_{j,k}$: observed position of line j vehicle k, measured from the first stop ($D_{j,1} = 0$)
$I_{j,l}$: length of line j link l, measured from the distance of its upstream and downstream stop

$d_{j,k,s}$: departure time of line j vehicle k from stop s
$w_{j,k,s}$: dwelling time of line j vehicle k at stop s
$a_{j,k,s}$: estimated arrival time of line j vehicle k at stop s
$a^{p}_{j,k,s}$: predicted arrival time of line j vehicle k at stop s
$a^{a}_{j,k,s}$: actual arrival time of line j vehicle k at stop s
t : the time when the observation is made
$t^{p}_{j,l}$: scheduled trip time at line j link l
$t^{s}_{j,k,l}$: suggested trip time of line j vehicle k on the upstream link l
$h^{f}_{j,k,k-1}$: headway at line j between the controlled vehicle k and its preceding vehicle $k-1$
$h^{b}_{j,k,k+1}$: headway at line j between the controlled vehicle k and its following vehicle $k+1$
$h^{e}_{j,k}$: even headway between vehicle k and its preceding and following
TPS : time point stop/control points for holding control, ($TPS \subseteq$ S)
h : suggested holding time
h^{max} : maximum holding time
h^{min} : minimum holding time to consider at TPS

3.1.1.1 Control at link section

Each control process begins at this location, indicated by an entrance of the observed vehicle to the first link. The controller outcome at this location is speed advice to be followed by the vehicle. Figure 3.3 describes the detailed framework of the speed advised derivation process for speed adjustment.

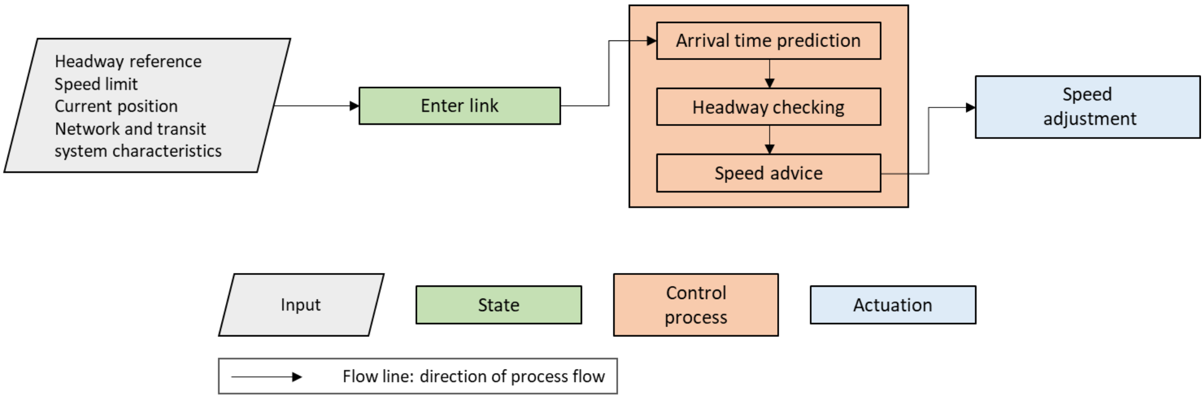

Figure 3. 3 Control process at link section

Input
Headway reference : even headway, $h^{e}_{j,k}$
Speed limit : v^{min}, v^{max}
Current position : $x_{j,k-1}$, $x_{j,k}$, $x_{j,k+1}$
Network and transit system characteristics : $D_{j,s}$, $I_{j,l}$, $t^{p}_{j,l}$

Control process
In this section, the input data is processed to generate the desirable headway. As aforementioned, the headway is calculated by considering the preceding and the following vehicle. This headway is notated by $h^{e}_{j,k}$. Prior to this calculation, the input data $x_{j,k-1}$, $x_{j,k}$, $x_{j,k+1}$ in term of the position of the preceding, observed, and following vehicles respectively are

translated into the predicted arrival times. Different predictions are generated for different vehicles as $a_{j,k-1,s}$, $a_{j,k,s}$, and $a_{j,k+1,s}$ for the preceding, controlled, and following controlled.

Arrival time prediction

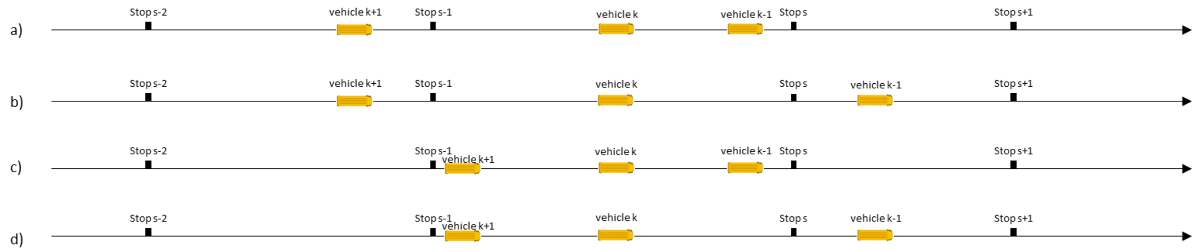

Figure 3. 4 Possibility of different positions during the observation time

In equation (1), one can see that there are two options to calculate the arrival time,$a_{j,k-1,s}$, of the preceding vehicle at the particular stop. The arrival time can be the actual time,$a^{a}_{j,k-1,s}$, if the preceding vehicle $k-1$, has arrived at stop s. However, at some conditions, such as when the consecutive stops are distant, or the preceding vehicle experiences a severe delay, it is possible that vehicle $k-1$ has not reached the stop s at the time the controlled vehicle k, is observed. In this situation, arrival time should be estimated as $a^{p}_{j,k-1,s}$. The first condition is depicted in figure 3.4 (b) and (d) while the latter is shown in figure 3.4 (a) and (c). The further the headway distance between vehicles, the more possibilities of different positions occur (e.g. separated by more than one stop). Nevertheless, during the simulation, this prediction will keep referring to the most updated information of each vehicle.

For vehicle $k-1$,

- $a_{j,k-1,s} = a^{a}_{j,k-1,s}, \qquad if\ x_{j,k} > D_{j,s}, \qquad (1)$
- $a_{j,k-1,s} = a^{p}_{j,k-1,s} = a^{a}_{j,k-1,s-1} + t^{p}_{j,l}, \qquad otherwise$

Equation (2) depicts the condition for the controlled vehicle k. In this case, the arrival time $a_{j,k,s}$ should always be estimated, because the observation always happen when the vehicle is approaching stop s.

For vehicle k,

$$a_{j,k,s} = a^{p}_{j,k,s} = a^{a}_{j,k,s-1} + t^{p}_{j,l} \qquad (2)$$

Equation (3) describes the condition for the following vehicle $k+1$. Similar to the equation (1), the arrival time of vehicle $k+1$ also has several options depending on its location when the observation happens. If during the observation time it has not passed stop $s-1$, the estimated arrival time $a_{j,k+1,s-1}$ refers to the prediction based on its current position to stop $s-1$ and the scheduled trip time from stop $s-1$ to stop s (figure 3.4 (a) and (b)). On the other hand, if the following vehicle has passed stop $s-1$ at the observation time, then the derivation of the estimated arrival time is similar to the equation (2) as seen in figure 3.4 (c) and (d).

For vehicle $k+1$,

$$a_{j,k+1,s} = a^{p}_{j,k+1,s-1} + t^{p}_{j,l}, \qquad if\ D_{j,s-2} < x_{j,k+1} < D_{j,s-1} \quad (3)$$

Where,

$$a^{p}_{j,k+1,s-1} = a^{a}_{j,k+1,s-2} + t^{p}_{j,l-1}$$

$$a_{j,k+1,s} = a^{p}_{j,k+1,s} = a^{a}_{j,k+1,s-1} + t^{p}_{j,l}, \qquad if\ x_{j,k+1} > D_{j,s-1},$$

Headway checking

After estimating the arrival time, one can predict the time headway value between the vehicles. The result from preceding vehicle $k-1$ generates the forward headway $h^{f}_{j,k}$ while the calculation for following vehicle $k+1$ obtains the backward headway $h^{b}_{j,k}$. To capture both values in the desirable headway, even headway $h^{e}_{j,k}$, is calculated based on the objective that the controlled vehicle is located approximately in the middle of the vehicles in front of and behind it. Refer to this objective, one can see from the formula that the desirable headway for the controlled vehicle is the half of headway difference between its preceding and following vehicle, as formulated in equation (4).

$$h^{f}_{j,k,k-1} = a_{j,k,s} - a_{j,k-1,s}$$

$$h^{b}_{j,k,k+1} = a_{j,k+1,s} - a_{j,k,s}$$

$$h^{e}_{j,k} = \frac{h^{f}_{j,k,k-1} + h^{b}_{j,k,k+1}}{2} = \frac{(a_{j,k,s} - a_{j,k-1,s}) + (a_{j,k+1,s} - a_{j,k,s})}{2} = \frac{a_{j,k+1,s} - a_{j,k-1,s}}{2} \qquad (4)$$

The value of even headway becomes the reference of the desired arrival time of vehicle k at stop s and subsequently the advised trajectory, as depicted in the following figure.

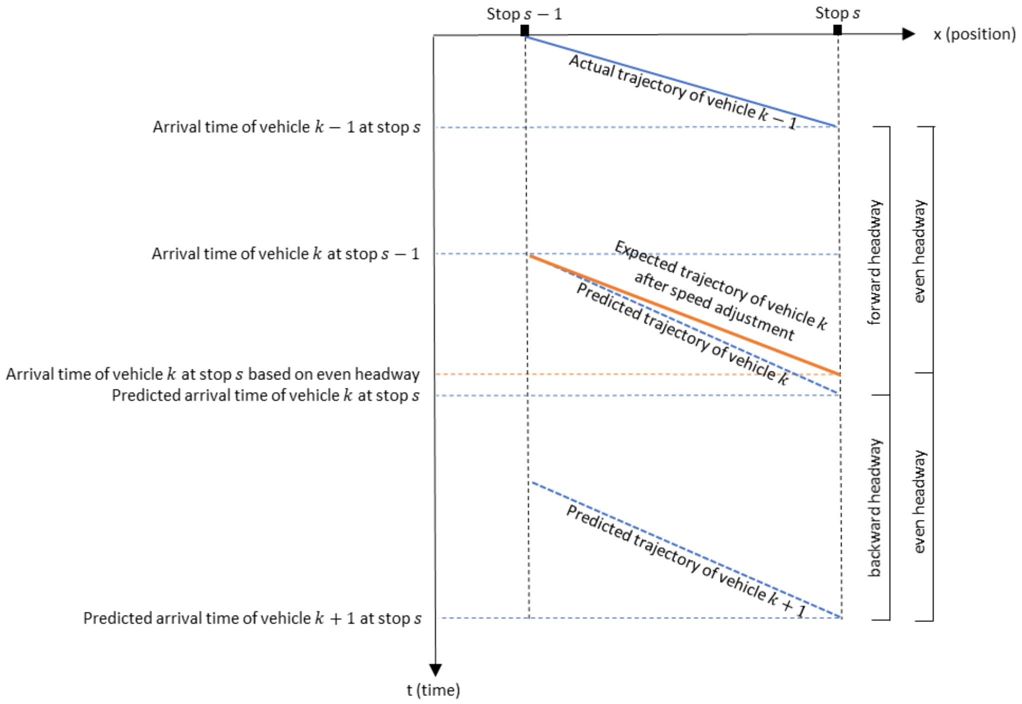

Figure 3. 5 Deriving even headway into the desired arrival time

Speed advice

After knowing the planned trajectory of vehicle k as seen in figure 3.5, the system will suggest a value of trip time to the controlled vehicle, notated by $t^{s}_{j,k,l}$, so that it can satisfy the planned trajectory on link l. Besides, there is parameter ε to capture the additional time that may occur due to delay from driver reaction and small effect from accelerating and decelerating the vehicle. When adjusting the speed or trip time in this case, there is another constraint for which the suggested speed should always be in the range of minimum, v^{min} , and maximum value, v^{max}. This constraint defines $t_{j,k,l}$ the allowable trip time to take while riding on link l formulated in the equation (5).

$$
\begin{aligned}
t^{s}_{j,k,l} &= a_{j,k-1,s} + h^{e}_{j,k} - d_{j,k,s-1} + \varepsilon \\
t_{j,k,l} &= \frac{D_{j,s} - D_{j,s-1}}{\max\left[min\left(\frac{D_{j,s} - D_{j,s-1}}{t^{s}_{j,k,l}}, v^{max}\right), v^{min}\right]}
\end{aligned}
\qquad (5)
$$

Actuation

The speed suggestion obtained in the control process is actuated by performing a speed adjustment. In reality, the driver performs the actuation. In this study, a simulation tool, BusMezzo, performs the speed adjustment in term of trip time. The more detail description of this tool is given in Chapter 3.3. Due to disturbance, such as driver compliance or traffic condition, the actuation may not give a perfect result as expected in the prediction phase. However, there is no feedback for the speed actuation along the route. The control decision is only given once at the beginning of the link. There is only a measurement once the vehicle enters the next control decision point (i.e. stop) to update the information of the vehicle position.

3.1.1.2 Control at the stop point

If the vehicle has reached the stop s, the control process will obtain different outcomes, i.e. departure times. Figure 3.5 describes the control process at the stop point.

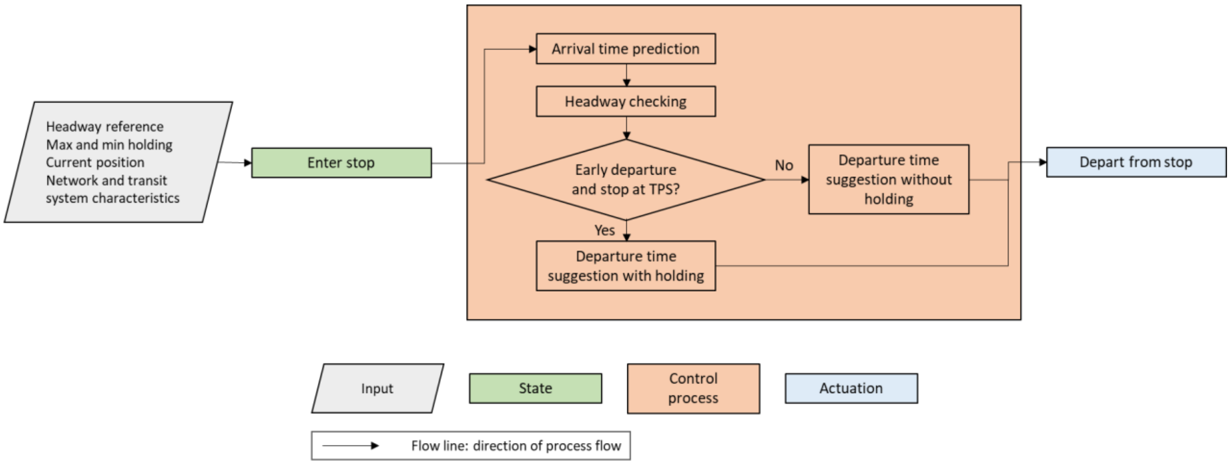

Figure 3. 6 Control process at the stop point

Input

Headway reference : even headway, $h^{e}_{j,k}$

Holding limit : h^{min}, h^{max}

Current position : $x_{j,k-1}$, $x_{j,k}$, $x_{j,k+1}$

Network and transit system characteristics : $D_{j,s}$, $I_{j,l}$, $t^{p}_{j,l}$

Control process

Arrival time prediction

After the arrival of vehicle k at stop s, the arrival time data $a_{j,k-1,s}$ and $a_{j,k,s}$ will be updated based on the actual condition. Nevertheless, a prediction $a_{j,k+1,s}$ is still necessary for vehicle $k+1$. Similar to the first condition, the arrival time value is then used to determine the even headway $h^{e}_{j,k}$. This value is considered once the vehicle k finishes boarding and alighting activity at the stop s and ready to depart.

For vehicle $k-1$,

$$a_{j,k-1,s} = a^{a}_{j,k-1,s} \tag{6}$$

For vehicle k,

$$a_{j,k,s} = a^{a}_{j,k,s} \tag{7}$$

For vehicle $k+1$,

$$a_{j,k+1,s} = a^{p}_{j,k+1,s-1} + t^{p}_{j,l}, \qquad if\ D_{j,s-2} < x_{j,k+1} < D_{j,s-1} \tag{8}$$

Where,

$$a^{p}_{j,k+1,s-1} = a^{a}_{j,k+1,s-2} + t^{p}_{j,l-1}$$

$$a_{j,k+1,s} = a^{p}_{j,k+1,s} = a^{a}_{j,k+1,s-1} + t^{p}_{j,l}, \qquad if\ x_{j,k+1} > D_{j,s-1},$$

Headway and early departure check

At stop s, the headway control is applied to the vehicle by holding control. The control can be distinguished based on its lateness, whether it is potential to be an early or late departure when the holding time is zero. Since the arrival time of the preceding vehicle is fixed, the indicator to determine the lateness only depends on the comparison between $h^{e}_{j,k}$ and the forward headway, $h^{f}_{j,k,k-1}$.

For late departure ($h^{f}_{j,k,k-1} > h^{e}_{j,k}$), it is not possible to implement holding control regardless of the type of the bus stop. The departure time $d_{j,k,s}$ will only depend on the arrival time $a_{j,k,s}$ and dwelling time $w_{j,k,s}$ at that stop as formulated in the equation (9).

$$d_{j,k,s} = a_{j,k,s} + w_{j,k,s}, \qquad h^{f}_{j,k,k-1} > h^{e}_{j,k} \tag{9}$$

For early departure ($h^{f}_{j,k,k-1} < h^{e}_{j,k}$), holding control can be an option to control the headway. The selection can be determined based on the type of stop where the vehicle is observed. If the vehicle stops at a control point belonged to a subset of TPS, the departure time of vehicle k from that stop will also consider the possible holding time to apply in the limit of minimum headway as in (Cats et al., 2011). In this framework, if the resulted holding time h is larger than h^{min}, it will be treated by holding control. Thus, for holding, the decision is only on departure time $d_{j,k,s}$ (equation 10). However, the holding time is limited to the predefined maximum holding time, h^{max}. Holding too long at the stop induces a negative impact for the passengers (van Oort, et al., 2012). Hence, the vehicle should depart from the stop once it reach the maximum holding time, regardless the $h^{e}_{j,k}$.

$$d_{j,k,s} = min\left(a_{j,k-1,s} + h^{e}_{j,k}, a_{j,k,s} - w_{j,k,s} + h^{max}\right), \qquad \forall s \in TPS\ and\ h > h^{min} \quad (10)$$

Where,

$$h = min\left(a_{j,k-1,s} + h^{e}_{j,k}, a_{j,k,s} - w_{j,k,s} + h^{max}\right) - \left(a_{j,k,s} + w_{j,k,s}\right)$$

On the other hand, if there is a potential of the early departure meanwhile the observed stop is not a control point ($s \notin TPS$) or the suggested holding time is smaller than or equal to the minimum holding time to consider ($h < h^{min}$), the departure time $d_{j,k,s}$ is similar to the equation 9 and can be rewritten as followed.

$$d_{j,k,s} = a_{j,k,s} + w_{j,k,s}, \qquad \forall s \notin TPS\ or\ h \le h^{min}\ or\ h^{f}_{j,k,k-1} > h^{e}_{j,k} \quad (11)$$

Actuation

The control advice given from the control process is the departure time suggestion. The actuation of this advice is the time when the vehicle departs from the observed stop. After this process, the vehicle k enters the next link and treated again with the control process at the link, with different reference of stop s and link l.

The concept of combined control strategy given in this chapter is only the design-stage to describe how the proposed control will work. There is an evaluation stage concept given in the next section, to assess the effectiveness of the concept objectively,

3.2 Evaluation stage: Indicator of effectiveness

The purpose of the evaluation stage is to assess the performance or effectiveness of the proposed control strategy quantitatively. This section provides the evaluation concept for the present study. The first part explains the indicators taken to assess the control strategy. The second part describes several alternatives of the control strategies to allow performance comparison. The last part describes the scenario planning to test the robustness of the proposed concept.

3.2.1 Performance indicators

The indicators for performance evaluation have been described in Section 2.3. To evaluate the control strategies, the indicators are selected by taking into account the perspective of passengers, operators, authorities, as well as drivers. As has been mentioned, in this study, there are new indicators to capture the need of the drivers and to understand the network effect in the transit system. This subsection describes both new indicators.

3.2.1.1 Indicators for the drivers

The basic idea to include the driver's perspective in the evaluation is to predict their compliance towards the control. The literature shows that the implementation of the control should be as simple as possible so that it does not burden or add more stress to the drivers. From the psychological perspective, one can also see burden as the things that stress the drivers (Johansson, Evans, Rydstedt, & Carrere, 1998; Rodrigues, Kaiseler, Aguiar, Cunha, & Barros, 2015).

Driving a bus as its basic form is already mentally demanding and offers lack of decision freedom for the drivers (Tse, Flin, & Mearns, 2006). In general, there are two common sources of the stressors for bus drivers, namely the external environment (e.g. congestion, interaction with other road users, unexpected effect, and comfort of the cabin) and job design (e.g. time pressure, resting time, shift pattern, and social isolation). (Johansson, Evans, Rydstedt, & Carrere, 1998;

Rodrigues, Kaiseler, Aguiar, Cunha, & Barros, 2015; Hlotova, Cats, & Meijer, 2014; Tse, Flin, & Mearns, 2006). Among these stressors, (Rodrigues, Kaiseler, Aguiar, Cunha, & Barros, 2015) concluded that the main source of stress is other drivers and pedestrians behaviors, followed by the difficulty of driving due route geometric and time schedule restriction. The first two are external causes, which also happen for the car drivers and is uncontrollable. Meanwhile, the latter is coming from job design, which can be varied for different operations. Timetable limits the flexibility of the drivers and leads to pressure for them. When it is already stressful for the drivers to have a regular operation, adding control strategies may make it worse since the drivers will be more controlled. A different situation may occur for the regularity-based operation by the removal of schedule. The drivers may not completely be free from control because it has additional control to keep its regularity. However, compared to an operation involving a schedule-based control, an even-headway control strategy is significantly effective to lessen the stress levels of the bus driver due to the flexibility it offers.

When the stressful condition occurs, bus drivers can give different responses to cope with it. They may show positive response such as becoming more focus or realizing the mistakes they did. On the other hand, the may also obtain negative response to cope with the situation, for instance by emotionally reacting (emotional coping), confrontation (confrontation coping), or ignorance (ignorance coping) and reduce attention to the driving task (Dorn, Stephen, af Wahlberg, & Gandolfi, 2010). Although there is no study that explicitly correlates the aggrieved feeling of the driver with the negative response that they may show when feeling stress, we believe that those negative feelings may lead to incompliance as a part of ignorance coping. The proofing of the relation is out of the scope of this study. However, for the current study, we assume that stressful condition is a burden that that could induce the ignorance of the driver or incompliance.

For this study, different types of burden can be identified for holding and speed control strategies. The focus is on job design, specifically on the way of control that can limit the flexibility of the drivers.

i) Schedule-based holding control:
This control requires the drivers to stick with the schedule given. Holding strategy adds another control since it prevents the driver to leave early. A study has proven that the stress level of the drivers increase when schedule adherence is required.

ii) Headway-based holding control
The drivers are still under control when holding is applied. However, they can ignore the schedule in this situation and relieve their stress. For the strategy referring to an even headway, it also allows the drivers to cooperate with each other in maintaining a regular operation together. This scheme helps them to understand the chain effect of lateness occurrence instead of blaming themselves for it and getting more stressed (Hlotova, Cats, & Meijer, 2014).

iii) Speed control
When the strategy is applied based on an even headway, it will give the same effect by providing greater flexibility in term of schedule and allowing coordination between the drivers. However, this strategy controls the driver by giving the speed advice and limiting the freedom to decide the cruising speed.

It is difficult to assess driver behavior under the control strategies from simulation only. The stress level resulted from the controlled feeling is also hard to evaluate without an experiment. However, one can predict how stressful the drivers are by observing the speed. The previous study observed that accelerating and braking increase the perceived tension of the driver (Hlotova, Cats, & Meijer, 2014; Magana, Organero, Fisteus, & Fernandez, 2016). When the two acts are taken more frequently, the stress level of the driver will be higher. This also implies how the aggressiveness of the driving or nervous feeling of the drivers will be. (Watson & Milkins, 1986; Barlow, Latham, McCrae, & Boulter, 2009) proposed positive kinetic energy (PKE) statistic to describe this situation as in the following equation.

$$PKE = \frac{\sum(v_f^2 - v_i^2)}{x}\ for\ v_f > v_i \qquad (12)$$

Where

PKE = positive kinetic energy (kmph²/km)

v_i = initial speed (kmph)

v_i = final speed (kmph)

x = distance (km)

PKE is actually the sum of positive differences in kinetic energy. In the equation above, the distance is put as a denominator to normalize the value so that it is comparable in different condition. The higher PKE value implies a more aggressive driving and more nervous feeling on the driver. This indicator can be used to describe how the speed control in the present study can burden the drivers because of the speed advice given along the route. By changing the notation, the equation for this study is redefined as followed.

$$PKE = \frac{\sum(v{\prime}_n^2 - v_n^2)}{x}\ for\ v'_n > v_n \qquad (13)$$

Where,

PKE : positive kinetic energy (kph²/km)

v_n : speed of vehicle n at the time observed (kph)
v'_n : suggested speed of vehicle n at the time observed, at the upstream of the observed stop or
(kph)
x : distance (km)

In this study, it is not possible to assess PKE for other strategies by BusMezzo, since it is not giving the speed profile resulted from the simulation. For the speed adjustment itself, since the speed has been determine before the vehicle enters the link, PKE is not calculated to compare the different strategies. To compare the different strategies, we will use the coefficient of variation of the resulted speed.

$$CoV_s = \frac{\sigma_s}{\mu_s} \qquad (14)$$

Where,

CoV_s : coefficient of variation of the speed

σ_s : standard deviation of the speed

μ_s : mean of the speed

CoV_S describes the relative variability of the vehicle speed during the simulated operation. The higher the value implies how the drivers should adjust their speed to maintain the preferable operation. Different strategies may give different trends of the CoV_S value. For the schedule-based holding, this value can be high because, at some points, the drivers should adjust their speed to adhere with the schedule. In headway-based holding, the variability may be lower because the driver can drive more freely. However, it cannot be fully guaranteed because there are many sources of randomness, which exist and affect the variability. Lastly, for the speed control, the value may be also high because the speed is frequently controlled during the operation. On the other hand, it is also possible to have low variability by changing the minimum and maximum speed limit.

Another alternative to indicate the burden on the drivers is by measuring how many control advices given to the drivers. Adding more controls is potential to increase the stress level of the drivers (Rodrigues, Kaiseler, Aguiar, Cunha, & Barros, 2015). Moreover, less variability in control leads to higher compliance of the drivers (Argote-Cabanero et al.,2015). Thus, this can be an indication of how the proposed control strategy can affect the stress level of the drivers as well as its potential to be followed or be ignored. This indicator is formulated in the equation (15).

$$n_c = \sum c \tag{15}$$

Where,

c : counting of the control advices given during a vehicle trip from the start to the end point

n_c : sum of the control advices given during a vehicle trip from the start to the end point

3.2.1.2 Indicator for the network effect

One possible situation in a transit network is the existence of multiple lines in the same corridor, as aforementioned in Section 2.3. This condition is beneficial if the multiple lines can support each other to obtain more efficient operation. However, if there is no coordination between the lines, it may obtain a bunching effect between lines. To assess this effect, there is a need to first distinguish the type of passengers involved in the situation. Bunching of different lines can be justified if the passengers involved are unconcerned of the differences (Argote-Cabanero, Daganzo, & Lynn, 2015; Hernandez, Munoz, & Delgado, 2015; Schmocker, Sun, Fonzone, & Liu, 2016).

For this purpose, the passengers will be divided into two groups.

i) The passengers whose the OD-pair points are served by the lines considered.
This is a group for the passengers that will get affected by the multiline operation. If the join operation of the multiline is regular, these passengers will get the benefit such as the waiting time saving. Improvement in trip time cannot be justified because it is possible that the served stops between the OD points are different for each line. On the other hand, if the operation between the different lines is not regular, it will be a disadvantage for the passengers as well as the operator. If the percentage of this passenger is high in the served line, the multiline irregularity may result in the capacity inefficiency or non-uniform passenger load between the considered OD-pair point.

ii) Other passengers

The passengers in this group are those who select a certain line to reach their destination. In the other word, only a specific line serves their OD-pair points. Thus, one can treat the evaluation as a single line operation.

To assess the multiline regularity, the CoV of headway will be calculated from the joint headway distribution of the involved common stops. Therefore, for this value, the headway will be derived from the arrival time difference of the vehicle from the involved common lines. This headway value can be formulated as followed.

$$H_m = a^a_{m,n-1,o} - a^a_{m,n,o} \tag{16}$$

Where,

H_m : joint headway between the vehicles coming from multiple lines m

$a^a_{m,n,o}$: actual arrival time of multiple lines m, in which vehicle n operating on, at common stop o

From the value of H_m, the CoV of headway is then formulated as seen in the equation (17).

$$CoV_m = \frac{stdev_{H_m}}{\overline{H_m}} \tag{17}$$

Where,

CoV_m : CoV of joint headway H_m

$stdev_{H_m}$: standard deviation of distribution of H_m

$\overline{H_m}$: mean of distribution of H_m

3.2.1.3 Summary of performance indicators

Besides the indicators in 3.2.1.1 and 3.2.1.2, there are other measures to take into account in order to evaluate the performance of the strategy. The measurement is referring to the point of view of the operator. Nevertheless, it considers not only the operation and practicality of the proposed control strategy but also the effect on demand part (passengers) and its suitability with the regulation (authority). Chapter 2.3 has mentioned some of the indicators used in the past literature, which are relevant to the present study and summarized in Table 3.1.

Table 3. 1 Performance indicators

Stakeholder	Performance indicators
Operators	- CoV headway - Cycle time and its variation (85th – 50th) - Fleet requirement
Drivers	- CoV speed - Number of control advices given
Passengers	- Average waiting time at a stop and its variation (95th – 50th) - EWT - Holding time and variation (95th – 50th) - Average trip time between stops and variation (95th – 50th) - Total weighted in-vehicle time and its variation (95th-50th) - Generalized travel time
Authorities	- Punctuality at main stops - Headway adherence at main stops (Cats, 2014) - The ratio between actual and desired headway at main stops (Cats, 2014)

3.2.2 Performance comparison

Besides the performance evaluation of the proposed strategy, other strategies are also considered to allow the performance comparison through different alternatives. The first scenario taken is capturing the current practice, which applies the schedule-based holding control. This is the reference case to observe how effective the control can be in comparison to the current practice. Furthermore, since the focus of the study is the combination of headway-based holding and speed control, there are also cases that consider only single strategy, thus only holding and only speed control.

i) Base case: schedule-based holding

By applying this strategy at the predefined control points, the vehicle is held until its scheduled departure time. Thus, for this case,

$$d_{j,k,s} = max\ (min\left(d^{p}_{j,k,s}, a_{j,k,s} - w_{j,k,s} + h^{\max}\right), a_{j,k,s} + w_{j,k,s}), \qquad \forall s \in TPS \quad (18)$$

$$d_{j,k,s} = a_{j,k,s} + w_{j,k,s}, \qquad \forall s \notin TPS$$

Where,

$d^{p}_{j,k,s}$: schedule departure time of line j vehicle k from stop s
$a_{j,k,s}$: arrival time of line j vehicle k at stop s
$w_{j,k,s}$: dwelling time of line j vehicle k at stop s
$h^{\max}$: maximum holding time
TPS : time point stop for holding control

For this case, the TPS will follow the existing TPS in the case study.

ii) Headway-based holding only

This alternative performs the headway-based with even headway, similar to the one described in the Subsection 2.2.2.2. Thus, in this case,

$$d_{j,k,s} = \max\left(min\left(a_{j,k-1,s} + h^{e}_{j,k}, a_{j,k,s} - w_{j,k,s} + h^{\max}\right), a_{j,k,s} + w_{j,k,s}\right), \qquad \forall s \in TPS \quad (19)$$

$$d_{j,k,s} = a_{j,k,s} + w_{j,k,s}, \qquad \forall s \notin TPS$$

Where,

$a_{j,k-1,s}$: arrival time of line j vehicle $k-1$ at stop s
$h^{e}_{j,k}$: even headway between vehicle k at its preceding and following
$a_{j,k,s}$: arrival time of line j vehicle k at stop s
$w_{j,k,s}$: dwelling time of line j vehicle k at stop s
$h^{\max}$: maximum holding time
TPS : time point stop for holding control

This strategy is further divided into two, which are different in term of the location of the control point. First, it only considers limited numbers of TPS. The locations are similar to the control point selected for the schedule-based holding control in the current practice. Second, is to design all stops as the TPS. The total cycle time may be longer. However, it offers a higher service regularity (Daganzo and Pilachowski, 2009; Cats et al., 2010). For this strategy, the holding time is limited to predefined maximum holding time of 60 s.

iii) Speed control only

In this control, the algorithm for speed control is similar to the one described in Section 3.1. The difference is that there is no option to hold the vehicle at the stop if the vehicle is too early. Instead, the holding will be applied by slowing down the vehicle. This strategy is similar to the proposed strategy, but then there is no TPS defined along the route.

3.2.3 Scenarios

After performance comparison, the proposed control strategy is further tested under different scenarios. The purpose of this step is to assess the robustness of the strategy under different conditions of operation. With respect to this, three scenarios are defined as followed.

Scenario 1: Normal condition

Scenario 1 is the base scenario where all conditions are set similarly to the average condition in the chosen case study.

Scenario 2: Tight schedule

Although speed adjustment-holding control developed in this study is a headway-based model, the arrival time prediction relies on the scheduled trip time between stops. Hence, the intention of this scenario is to understand how sensitive the strategy is towards different trip time prediction. Simultaneously, this scenario also allows the evaluation of the effectiveness of schedule-based control. It is known that scheduling is the main determinant of the performance of schedule-based holding control (Furth & Muller, 2007; van Oort et al., 2012). Therefore, it is interesting to see how the performance of the reference strategy changes under different scheduling, and compare it to the other strategies.

Scenario 3: Different demand level

As an interstation control strategy, speed control is expected to be less effective when the dwelling time is dominant. However, the performance difference has not been tested for the case where speed adjustment and holding control is combined. In this scenario, the strategies will be tested under two other demand levels.

The more detail description of each scenario is given in Chapter 4.

3.3 Simulation model

The previous sections have provided the conceptual design and evaluation stage of the proposed control. After developing the concept, the next stage is to do performance analysis. In the present study, this stage is done through a simulation model. This method provides a description of the activity of the vehicles and passengers during time simulated, which gives an insight of the system performance.

In the present study, BusMezzo is selected as the tool for the evaluation. BusMezzo is an event-based simulator which is built within a mesoscopic traffic-simulation model, Mezzo. Thus, it is suitable for the evaluation stage as it allows the modeling of dynamic transit operation in a large network, which also considers the movement of vehicles involved without requiring excessive computational effort. BusMezzo works based on the event, for which refers to the order of event's list to run from one to another event. Another advantage of BusMezzo is its stochasticity, which is able to model uncertainty in operation and to simulate it in a real-time manner (Cats, Burghout, Toledo, & Koutsopoulos, 2010).

BusMezzo uses the characteristics of the transit system as the input for the simulation, including the transit route, transit network, transit fleet, and transit demand. One stochasticity in the simulation is derived from the node server definition in the network. The node server describes the riding time of a link. One can also define the traffic condition that may affect the duration of the riding time within the particular links by using a speed density function. In term of transit operation, these links will be the lines that are served by the transit system.

When defining the transit network, BusMezzo is not only able to model the physical characteristics of the transit system. It can also define the disruptions that may happen during the operation of the system by defining traffic incidents and its time or modifying the derived trip time distribution. This feature is useful to model different scenarios of the operation related to service disruption.

BusMezzo has several functions of the dwelling time model. The first is the simplest one by describing dwelling time as a linear relationship between the boarding and alighting process. The other function models the dwelling time as the maximum time of both processes. This function is more reasonable to capture the real situation in which boarding usually happen simultaneously with alighting. In both functions, BusMezzo gives an option to consider the overcrowding effect for the overall dwelling time. Lastly, BusMezzo can model the dwelling time based on the TCRP function. In addition, when modeling the dwelling time, BusMezzo considers the effect of the characteristics of the operating vehicle and the stop in all conditions.

In the demand modelling, there are several forms of input for BusMezzo. Demand rates can be defined as boarding and alighting rates at the stops or from the OD-matrix at the line level or stop level. The simulation generates the passengers randomly based on Poisson-distribution defined. By having the OD-pairs, the simulation can first generate the initial choice set of path for trip pairs in the network. As an agent-based model, BusMezzo allows the behavioral modelling of the passengers based on a random utility discrete choice model. Thus, as the simulation runs, it is possible if the passengers adapt their trip choice and consider new paths based on the current situation in the network. As supports, one can determine the level of real-time information that is given to the passengers. The more detail description of BusMezzo features can be found in a study by Cats, Burghout, Toledo, & Koutsopoulos (2010).

Specifically for this study, the most important feature of BusMezzo is that it models the control strategies during the operation. In prior to the simulation, the scheduled trip time between stops is defined. This allows the detection of the earliness of lateness in operation. Based on this information, the model can decide if it should take a control decision or not. Currently, BusMezzo provides the model for holding control strategies, both the schedule-based holding and the headway-based holding. For the latter one, it is also possible to determine the headway reference to derive the holding time. One can choose the reference from only the preceding vehicle, following vehicle or from the mean headway of both. The definition of holding strategy is defined along with its control point. The existing BusMezzo does not have a feature for modeling the speed control. Thus, additional code will be added to the BusMezzo.

Due to the stochastic effect in BusMezzo, multiple runs of simulations are required to achieve a statistically significant result. The number of observations to include in the model is determined by equation (20). Prior to the calculation of N, an initial replication of n is first executed to find the value of mean and standard deviation.

$$N \geq \left(\frac{t_{\frac{\alpha}{2}} * S_n}{E} \right)^2 \tag{20}$$

N : number of required sample

$t_{\frac{\alpha}{2}}$: student t-value for confidence level α

S_n : standard deviation of the measured variable based on the initial sample

E : margin of error, the maximum error allowed between the sample mean and the population mean

3.4 Conclusions

There are two parts in this chapter, which explain the development of the proposed control strategy. The first part provides the design stage of the proposed control strategy. The second part explains the evaluation stage taken to assess the performance of the developed strategy. These parts give the answer to the fourth sub-research question, "*How to formulate a model to find a potential combination of strategy?*".

The proposed control measure is developed as a rule-based strategy, which runs in a real-time manner where there is a communication between vehicles. This control is built upon an event-based concept. Thus, the information transmitted is about the time it has completed an event (e.g. arriving, dwelling, holding, departing, and riding). All information is given at the station. Thus it ignores the effect of accelerating and decelerating along the route. In addition, the method of arrival time prediction is relying only on the scheduled trip time. The developed control is assumed to run in a dedicated lane only.

An initial idea of this control is to reduce the holding time. Therefore, the main strategy in the proposed control is speed adjustment. The system suggests a speed value to take before the vehicle enters the link. Holding control becomes an additional strategy, which will be taken when the system is still considered early (e.g. when the system has reached the minimum speed limit). This concept is described in a mathematical formulation and is put in BusMezzo, a simulation tool, as an additional feature.

To verify the potential of the proposed control strategy, several performance indicators are selected based on different perspectives, including the perspective of the operators, drivers, passengers, and authorities. To capture the driver's perspective, this study includes two additional indicators such as CoV speed and number of control taken. To assess the control strategy in a network level, another indicator naming CoV of joint headway is chosen. The evaluation of the proposed control strategy is done through simulation and is given in Chapter 4. The additional indicators are provided to complete the answers of Sub-RQ I.2 and Sub-RQ I.3.

Chapter 4: Assessment of the control strategies

This chapter explains the assessment of the control strategies given in Chapter 3 to answer the Sub-RQ II.1 and Sub-RQ II.2 as follow.

Sub-RQ II.1: How is the performance of the combined strategy when applied in a real network in comparison with other strategies?

Sub-RQ II.2: How is the performance of the control strategies in a single line and a network be different?

The control strategies were tested using a case study, which is explained in the first section of this chapter, Section 4.1. In this study, BusMezzo was performed as a tool to simulate the case study. Section 4.2 provides the validation of the simulation by comparing the result with the observed data. Section 4.3 gives the scenario analysis of the proposed control strategy by comparing its performance with the other control strategies to answer Sub-RQ II.1 and Sub-RQ II.2. Section 4.4 gives the overall conclusion of this chapter.

4.1 Case Study: Almere

To assess the control strategies, this research used a case study by referring to the operation of AllGo by Keolis. AllGo is a bus rapid transit system which runs on dedicated lanes. This transit system has just been operated in Almere since December 2017. This system is currently controlled under a scheduled-based holding control. The network consists of seven lines with several transfer points with the rail transit, as seen in figure 4.1.

Figure 4. 1 AllGo Bus Network, Almere

All lines are served by a bus with the seating capacity of 35 passengers and a standing capacity of 103 passengers. In the analysis, only line M5 and M7 will be considered (figure 4.2).

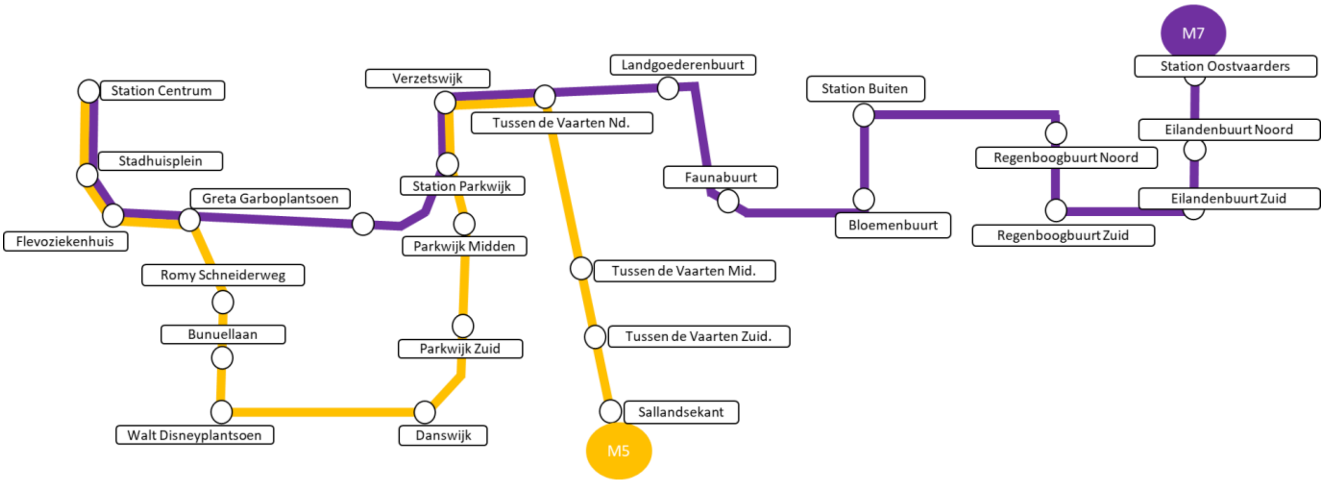

Figure 4. 2 Line M5 and M7

The background criteria behind the selection of these lines are:

1. The two lines operate with short headway (5 minutes)
2. These lines have the most common stops compared to the other line pairs
3. The length of the lines was considerably long among the network, which allows a higher possibility of irregularity during the operation (see figure 4.1).

Table 4.1 and 4.2 present the characteristics of both lines. The hatched cells represent the common stops of both lines. Line M5 has 16 stops with the average line length of 9.1 km. Meanwhile, line M7 operates on 17 stops with the average length of 10.8 km. In this study, the stop index of each line was redefined to clear the difference between lines. For line M5, all stop index starts with "50" for direction 1 and "250" for direction 2. This also applies for line M7. All stop index starts with "70" for direction 1 and "270" for direction 2.

Table 4. 1 Line M5

Nr Stop	M5 (Direction 1)	Distance between stops (m)	Nr Stop	M5 (Direction 2)	Distance between stops (m)
501	Station Centrum	0	2501	Sallandsekant	
502	Stadhuisplein	423	2502	Tussen de Vaarten Zuid	599
503	Flevoziekenhuis	275	2503	Tussen de Vaarten Midden	562
504	Greta Garboplantsoen	662	2504	Tussen de Vaarten Noord	1029
505	Romy Schneiderweg	701	2505	Verzetswijk	855
506	Bunuellaan	502	2506	Station Parkwijk	385
507	Walt Disneyplantsoen	431	2507	Parkwijk Midden	503
508	Danswijk	917	2508	Parkwijk Zuid	633
509	Parkwijk Zuid	590	2509	Danswijk	610
510	Parkwijk Midden	668	2510	Walt Disneyplantsoen	955
511	Station Parkwijk	538	2511	Bunuellaan	391
512	Verzetswijk	348	2512	Romy Schneiderweg	500
513	Tussen de Vaarten Noord	865	2513	Greta Garboplantsoen	754
514	Tussen de Vaarten Midden	990	2514	Flevoziekenhuis	566
515	Tussen de Vaarten Zuid	568	2515	Stadhuisplein	265
516	Sallandsekant	754	2516	Station Centrum	428
	Total length	9232		Total length	9035

Table 4. 2 Line M7

Nr Stop	M7 (Direction 1)	Distance between stops (m)	Nr Stop	M7 (Direction 2)	Distance between stops (m)
701	Station Centrum		2701	Station Oostvaarders	
702	Stadhuisplein	447	2702	Eilandenbuurt Noord	426
703	Flevoziekenhuis	275	2703	Eilandenbuurt Zuid	429
704	Greta Garboplantsoen	646	2704	Regenboogbuurt Zuid	785
705	Parkwijk West	720	2705	Regenboogbuurt Noord	539
706	Station Parkwijk	693	2706	Station Buiten	1455
707	Verzetswijk	348	2707	Bloemenbuurt	723
708	Tussen de Vaarten Noord	859	2708	Faunabuurt	843
709	Landgoederenbuurt	914	2709	Landgoederenbuurt	680
710	Faunabuurt	700	2710	Tussen de Vaarten Noord	968
711	Bloemenbuurt	860	2711	Verzetswijk	855
712	Station Buiten	648	2712	Station Parkwijk	382
713	Regenboogbuurt Noord	1507	2713	Parkwijk West	628
714	Regenboogbuurt Zuid	545	2714	Greta Garboplantsoen	766
715	Eilandenbuurt Zuid	794	2715	Flevoziekenhuis	566
716	Eilandenbuurt Noord	417	2716	Stadhuisplein	265
717	Station Oostvaarders	523	2717	Station Centrum	428
	Total length	10896		Total length	10738

For the present study, the operational data of AllGo bus in the period of April-May 2018 was used. Prior to the system simulation, a preliminary analysis based on the operation in these months was conducted and given in the Appendix A. The results from the preliminary analysis became the input for the simulation tool, BusMezzo. Based on the given data, BusMezzo reproduced the operational condition in the case study to allow the assessment in a lab test for the next step. Validation of the results from BusMezzo was conducted prior to the assessment as given in the following subsection.

4.2 Case study: input and validation

4.2.1 Input

Prior to the simulation of the case study in BusMezzo, several inputs were needed so that the simulation tool can model the actual operation perfectly. One important input to determine was the link travel time in the transit system. This parameter was modeled based on the empirical data in the form of lognormal distribution as explained in Appendix A.

The second input was the dwelling time function. Based on the empirical data of boarding and alighting activity, this function was derived by using a multiple linear regression. Hence, it was assumed that the dwelling time was the result of the required time for boarding and alighting. The outcome of the regression was formulated as below, with the R-square value of 0.398.

$$w_s = 10.006 + 1.726b_s + 1.443a_s \tag{21}$$

Where,

w_s : dwelling time at stop s

b_s : number of boarding passengers at stop s

a_s : number of alighting passengers at stop s

By mean of addition, there was a consideration of the crowding effect in the dwelling function, as the capacity of the vehicle might also affect the boarding and alighting activity. In the present study, this effect was modeled based on a non-linear crowding effect as defined by Weidmann (Oded 2010), as below.

$$w_s = 10.006 + (1.726 b_s + 1.443 a_s) * \left[1 + \frac{3}{4}\left(\max\left\{0, \frac{l^n - seats^n}{cap^n - seats^n}\right\}\right)^2\right] \quad (22)$$

Where,

l^n : passenger load in vehicle n

$seats^n$: number of seats of vehicle n

cap^n : maximum capacity of vehicle n

Although the dwelling time function was derived from the observed data, there was a drawback of using the function in the simulation. The constant in the dwelling time function gave additional time for dwelling, even if there was no boarding or alighting activity. On the other hand, in the actual operation, this value will be zero. When there were many trips without boarding or alighting activity, this addition will reduce the earliness during the operation, and hence might underestimate the effect of holding control applied.

The third input was the passenger demand, which was derived based on two data sources. The first data was the number of boarding and alighting passenger for each bus. This information was useful to determine the parameter in dwelling function. The second data source was the smart card data, which provided the OD matrix of passenger trip. This data allowed the assessment of the system in a network context since it gave an insight into how a passenger can have two options of line to reach their destination.

The last input was the transit system characteristics, such as the line length, stop location, timetable, and vehicle scheduling. Currently, the AllGo bus operation has been operating the schedule-based holding strategy (Appendix A). This strategy was also modeled in the simulation. The simulation modeled the AllGo operation during the weekdays for the 2.5 hours morning peak period from around 06:30 AM to 09:00 AM.

4.2.2 Validation

Validation was the next step after determining the parameter of the simulation. The outputs of headway distributions from the actual and simulated operation were compared. In the simulation, this aspect was obtained from the interaction between travel time between stops and dwelling time for passenger activities, in which defined as the inputs. A two-sample t-test was performed to check the obtained headway distribution. In this test, the null hypothesis was that the two sets of data come from independent random samples of normal distributions with equal means and variance. Table 4.3 summarizes the result of the two-sample t-test.

Table 4. 3 Two-sample t-test result for headway distribution

Nr Stop	p-value	Nr Stop	p-value	Nr Stop	p-value	Nr Stop	p-value
501	0.619	**701**	0.798	**2501**	0.683	**2701**	0.679
502	0.364	**702**	0.591	**2502**	0.674	**2702**	0.488
503	0.148	**703**	0.223	**2503**	0.528	**2703**	0.259
504	0.264	**704**	0.153	**2504**	0.275	**2704**	0.173
505	0.410	**705**	0.203	**2505**	0.290	**2705**	0.270
506	0.273	**706**	0.187	**2506**	0.931	**2706**	0.226

507	0.247	**707**	0.053	**2507**	0.779	**2707**	0.218
508	0.211	**708**	0.117	**2508**	0.868	**2708**	0.290
509	0.104	**709**	0.077	**2509**	0.838	**2709**	0.354
510	0.173	**710**	0.077	**2510**	0.811	**2710**	0.548
511	0.170	**711**	0.153	**2511**	0.865	**2711**	0.698
512	0.095	**712**	0.200	**2512**	0.951	**2712**	0.636
513	0.087	**713**	0.800	**2513**	0.949	**2713**	0.612
514	0.103	**714**	0.711	**2514**	0.987	**2714**	0.496
515	0.080	**715**	0.781	**2515**	0.749	**2715**	0.428
516	0.032	**716**	0.872	**2516**	0.399	**2716**	0.225
		717	0.967			**2717**	0.054

With a 95% confidence interval, the output from the simulation matches well the observed data. Stop 516 resulted in a lower p-value, but it was still acceptable with a 98% confidence interval.

4.3 Scenario analysis

4.3.1 Sample size

All the input was modeled in BusMezzo. Since BusMezzo runs based on stochasticity, the simulation requires a number of samples to give a reliable result. Accuracy in term of headway distribution determined the number of runs in the present study. For initial run n = 28 and confidence interval of 95%, the student-t value was 2.048. The desired accuracy was 5% and the required number of sample was determined based on equation 20. This resulted in a number of sample n to be at least 91.72. Thus, for the present study, 100 simulation runs were carried out for each scenario to achieve a sufficient level of accuracy.

4.3.2 Additional parameter

There were other parameters defined related to the control strategy tested. The first parameter was the weight of time given for each passenger activity, including waiting at the stop, dwelling, waiting on board, and riding with a ratio of 2: 1.5: 1.5: 1 respectively (Vansteenwegen & Van Oudheusden, 2007).

In addition to that, there was a parameter of minimum and maximum trip time allowed during speed adjustment strategy. In this study, the minimum trip time was limited by the maximum speed allowed in the AllGo network. Meanwhile, the maximum trip time was tested by different cases. Lastly, was the driver response parameter, which was assumed to be 1 s (Ning, Xun, Gao, Zhang, 2015).

4.3.3 Strategy design

In this evaluation, the performance of the combined strategy was compared to other existing strategies. In total, there were five different strategies tested as listed below.

1. SB: schedule-based holding control with control points at 511, 706, 712, 2506, 2706, 2712. In the actual operation of the AllGo network, these stops were taken as the control points because they were located in the station. Thus, punctuality was required to support passenger transfer activity between bus and train. Furthermore, high activity of passenger boarding and alighting in these stops were also high which make these stops become more favorable to be control points.
2. EH1: headway-based holding control with the same control point as above, with a maximum holding time of 60 s.

3. EHALL: headway-based holding control at all stops, with a maximum holding time of 60 s at each stop.
4. SA: speed adjustment at every link of the line.
5. SH: speed adjustment + EHALL

For SA and SH strategy, different speed ranges were defined based on the empirical data of speed distribution in Appendix A. The defined speed ranges were detailed as below.

Table 4. 4 Speed range description for SA and SH

Name	Detail
SA1.2	Speed adjustment with a wide range of speed (5th - 95th percentile)
SA1.3	Speed adjustment with a narrower range of speed by increasing the minimum speed (25th – 95th percentile)
SA2.2	Speed adjustment with a narrower range of speed by decreasing the maximum speed (15th – 75th percentile)
SH1.2	SA1.2 + EHALL
SH1.3	SA1.3 + EHALL
SH2.2	SA2.2 + EHALL

4.3.4 Scenario design

In this study, different scenarios were applied to obtain insight into the performance of the proposed strategy, as well as its relative performance to other strategies. These scenarios were listed as followed.

Scenario 1: Normal condition

A base condition, which referred to a normal operation in AllGo network, Almere.

Scenario 2: Tight schedule

In this scenario, the trip time schedule used for the assessment was reduced into the 85th percentile of actual trip time distribution in the data. This value referred to the percentile taken for planning the timetable in the AllGo operation. It was possible to take a lower reference from the distribution. However, it would be unreasonable to test a schedule-based holding control with an extremely tight scheduled.

Scenario 3: Different demand level

This scenario assessed the strategy based on a lower and higher demand condition (0.65 and 1.35 normal demand condition).

In each scenario, the performance indicators listed in Chapter 3 were used. Hence, each strategy was assessed based on the perspective of the operator, driver, passenger, and authority. Afterwards, additional assessment looking at the network impact on the different strategy was given.

4.3.5 Results: Scenario 1 - Normal Condition

Operator perspective

From the perspective of the operator, there were two main factors to consider. The first was coefficient of variation of headway to assess the regularity of the strategies. Secondly was the total trip time at 85th percentile and its variation, to assess its suitability for the vehicle scheduling.

CoV headway

The coefficient of variation (CoV) headway was calculated from the headway distribution obtained at each stop from the simulation. Figure 4.3 shows the comparison of CoV headway between different strategies for Line M5 Direction 1 and 2. The result from Line M7 was not shown here since the outcome was quite similar to Line M5 (Appendix C).

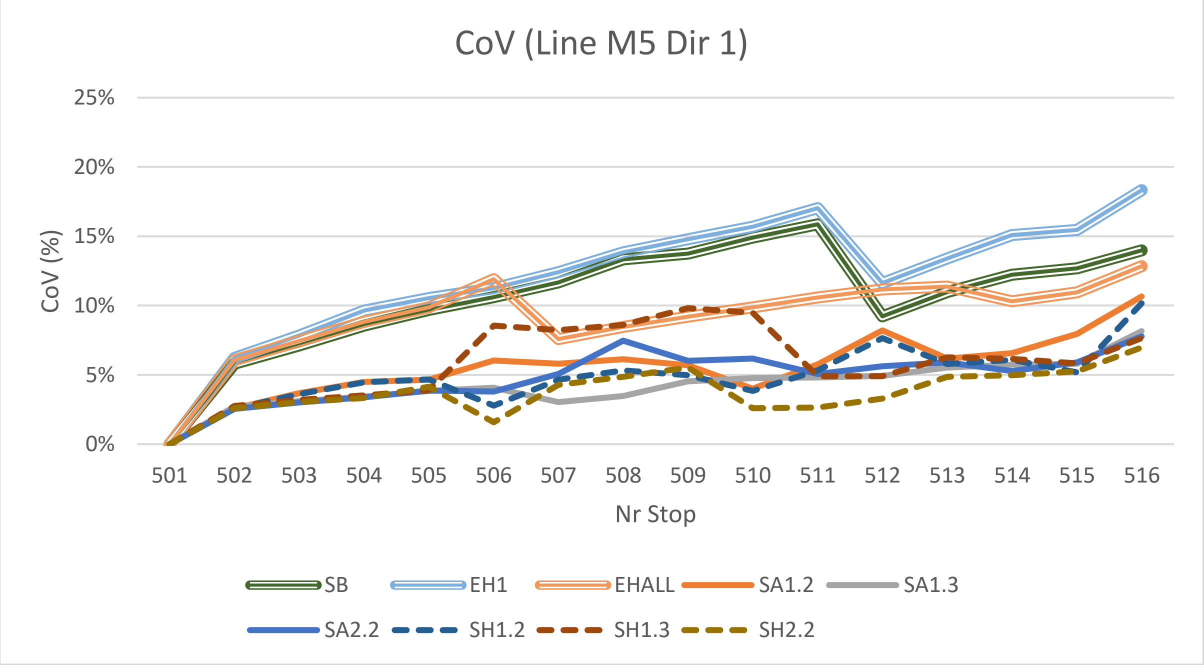

Figure 4. 3 CoV headway comparison for Line M5 Direction 1

In Line M5 Direction 1, it can be seen clearly how the performance between SB, EH1, and EHALL differed. For SB and EH1, as expected, these strategies successfully reduced the variability after the control point at Stop 511. In this picture, one can observe that SB gave a larger reduction compared to EH1. One reasoning behind this was that, in the simulation, the holding time for EH1 was limited to 60s. Meanwhile, SB was allowed to hold until it reaches the desirable schedule. From the preliminary analysis in Appendix A, the actual trip time distribution between stops was in general lower than the scheduled trip time. The schedule itself gave the possibility of early trips in the system. Thus, SB was very effective to apply. However, a great reduction in headway variability implied an excessive holding time taken at the control point.

EHALL, as expected gave the best performance compared to SB and EH1. At 506, there was a small increase in CoV headway of this strategy. Apparently, the demand at 505 was very low, which makes unvarying dwelling time at this stop. Consequently, in SB and EH1, additional headway variability came from trip time only. In EHALL, the system added holding time at Stop 505 since the following vehicle had just entered the route. Due to the scheduling, the trips were considered early compared to the schedule of the following vehicle. However, this holding added more variability for time stop at 505 and subsequently increased the headway variability at 506.

SA and SH, in general, outperformed SB, EH1 and EHALL in Line M5 Direction 1. The obvious increase in CoV headway was shown SH1.3. This strategy allowed a higher speed limit with a range of 25th-95th respectively. Three factors behind this result were the scheduling, speed range, and holding activity. The schedule for the first five stops was much above the actual trip time. Thus, the first trip ($k = 1$) was much earlier than the schedule, and the following trips tended to be faster as well at the early stop (i.e. 502). The earliness grew as the speed range restricted the trip time of vehicle k from 502 to 503, while it was supposed to ride slower. From Stop 503, vehicle k was able to take a slower speed and also apply holding at a stop. When vehicle k was at 505, the following vehicle $k + 1$ had entered the route and even arrived at 502. Recall that the trip to 502 was always faster. This state created a new arrival time prediction of vehicle $k + 1$, which triggered vehicle k to speed up to Stop 506. For SH1.3, higher limit of minimum and maximum trip time led to greater earliness, which required these strategies to keep taking the maximum trip time possible. When the arrival time prediction of the following vehicle was updated, the riding time to 506 for these strategies were fluctuating and consequently increased the headway variability at Stop 506. This condition continued to the following stops for SH1.3, thus the CoV was growing until getting stabilized after reaching Stop 509. At this state, vehicle $k + 2$ had also entered the link, affected the headway prediction for vehicle $k + 1$ and subsequently vehicle k. This interaction reduced the headway variability at Stop 510 and 511 for two strategies.

With the same range of speed, SA1.3 turned out to perform better than SH1.3. Without any ability to hold, this strategy could only stick to the maximum trip time allowed when slowing down was required. Since the time spent without holding in SA was lower than in SH, the information of the new arrival time prediction came earlier than in the case where holding existed, and this condition affected the speed decision.

In this network, dwelling time did not significantly affect the regularity performance. High demand occurred at the first and second stop, thus for SA and SH, in general, only the variability at the early stops disturbed by dwelling time. Secondly, the excessive scheduled trip time had accommodated the dwelling time as well. Thus there was a little chance of bunching due to late trips from the preceding vehicle. The same reason generated a low headway variability for SA case.

Different from the previous example, in Line M5 Direction 2, SB strategy seemed ineffective to apply. In this line, the control point was located at 2506. Looking at the planning, the main reason behind this was due to limited planning on trip time. The scheduled trip time from 2501 to 2504 was sufficient compared to the actual trip time only, but not if the dwelling time was included. Thus, the trips at the early stops tended to late and did not give the SB the chance to hold. Oppositely, regardless of the schedule design, EH1 and EHALL effectively reduced the variability in this network.

In addition, in this case, SA and SH with a wide speed range could not perform effectively compared to SB, EH1, and EHALL. The first trip $k = 1$ tended to late compared to the schedule, and hence dragged the following trips $k > 1$ to ride slower. The succeeding vehicle $k + 1$ entered the route and gave the updated state to vehicle k at Stop 504. Therefore, the headway variability suddenly changed at Stop 505. At this part, the strategies had a tendency to take the trip time boundaries value to match the arrival time prediction. Thus, the wider the range, the worse the variability obtained and the longer it took to stabilize.

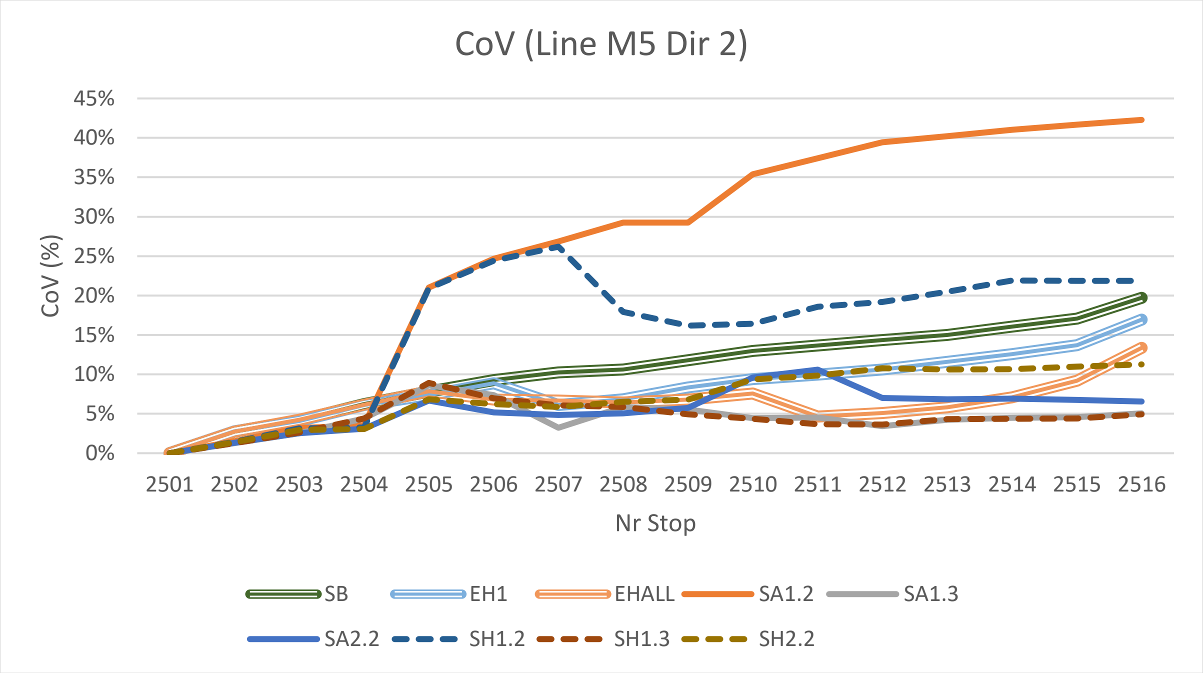

Figure 4. 4 CoV headway for Line M5 Direction 2

Moreover, the demand at Stop 2506 was quite high and added more variability. In SH strategy, holding supported the system to stabilize more quickly. Specifically for SA1.2, before it was stabilized, high demand activity started to occur from Stop 2509. Hence, in this strategy, the headway was getting higher.

In the second case, speed range with a higher minimum and maximum trip time was advantageous due to its ability to ride faster to stabilize the headway, after demand activity or limited trip time. This situation was the opposite of the first case, where SH1.2 at the first case performed better than SH1.3 since it allowed a slower trip time to stabilize the headway more quickly after being too early at the beginning.

Other indicators :Cycle time (85th) and variation in cycle time (85th – 50th), fleet requirement

Table 4.5 shows the summary of performance for different strategies. Different colors indicate the performance quality of one strategy relative to the other strategies.

Table 4. 5 Performance summary from an operator perspective (green = best, red = worst)

Strategy		SB	EH1	EHALL	SA1.2	SA1.3	SA2.2	SH1.2	SH1.3	SH2.2
Cycle time at 85th percentile (s)	**Line M5**	2724	2731	2832	3281	2875	2961	3211	2926	3005
	Line M7	3340	3374	3489	3998	3465	3576	4011	3533	3606
Cycle time variation (s)	**Line M5**	77	78	84	201	94	83	174	104	86
	Line M7	67	80	105	209	97	49	208	110	56
Fleet requirement (fleet)	**Line M5**	10	10	10	11	10	10	11	10	11
	Line M7	12	12	12	14	12	12	14	12	13

Cycle time is an indication to determine the vehicle scheduling during the operation. This indicator consists of a total trip time of each line direction and layover time at each line. In AllGo network, total trip time scheduled for Line M5 Direction 1, 2, Line M7 Direction 1, 2 are 1200 s, 1320 s, 1560 s and 1560 s respectively, which was designed with an assumption of the 85th percentile of trip time distribution. Meanwhile, for each line, the layovers for Direction 1 and 2 were 60 s and 120 s.

With better performance in regularity, EH1 did not require much addition to the cycle time. SA and SH, in general, obtained a worse result for this indicator. In general, the vehicle tended to slow down as found in the study by Ampountolas & Kring (2015). Due to slowing down, the speed range then somewhat defined the resulted cycle time for SA and SH. With an ability to ride at a very low speed, SA1.2 and SH1.2 obtained an excessive cycle time, which was undesirable from the perspective of the operator. By contrast, SA1.3 and SH1.3 gave preferable results by allowing higher speed. When comparing SA and SH only, for the same speed range, SH obtained in higher cycle time due to the ability of holding at stops.

Variation of the cycle time was defined as the difference between the 85th and 50th percentile value of the distribution. Speed range also defined this value for SA and SH. The lowest variation was shown from SA2.2 and SH2.2 by having a limited speed range. However, holding control gave a better variability in general.

From the value of cycle time, the fleet requirement per line was derived for each strategy. As a consequence of higher cycle time for SA and SH, the current fleet planning (refer to SB) could only fulfil the requirement for SA1.3, SH1.3, and SA2.2. The additional fleet was required to operate the other strategies, which led to additional operational cost for the operator.

Driver perspective
Besides looking at the operator's perspective in general, a specific focus was given in this study to assess the control strategy from the driver's perspective. Two indicators defined in Chapter 3 were used for the assessment as seen in table 4.6.

Table 4. 6 Performance summary from a driver perspective (green = best, red = worst)

Strategy		**SB**	**EH1**	**EHALL**	**SA1.2**	**SA1.3**	**SA2.2**	**SH1.2**	**SH1.3**	**SH2.2**
Nr of control taken	**Line M5, Dir 1**	1	1	3	15	15	15	17	18	17
	Line M5, Dir 2	1	1	4	15	15	15	17	18	17
	Line M7, Dir 1	2	2	5	16	16	16	19	22	20
	Line M7, Dir 2	1	2	3	16	16	16	18	18	17
CoV Speed per line (%)	**Line M5, Dir 1**	22%	22%	22%	33%	22%	18%	33%	22%	18%
	Line M5, Dir 2	24%	24%	24%	27%	20%	19%	27%	20%	19%
	Line M7, Dir 1	22%	22%	22%	32%	20%	16%	32%	22%	16%
	Line M7, Dir 2	26%	26%	26%	30%	23%	20%	30%	23%	20%

The first indicator was the number of control taken per line. As expected, the first three strategies were preferable since they only required few controls per trip. On the other hand, SA and SH gave more loads to the drivers since these strategies required the drivers to be controlled continuously until the end stop. In SH, the result was worse because besides adjusting the speed, the driver should also apply holding when it was needed. From all strategies, SH1.3 was the worst. This strategy allowed a higher speed thus in some conditions; it required more holding at the stop to regularize the headway.

The second indicator was the coefficient of variation (CoV) speed to indicate the aggressiveness of the driver due to changing speed. For SB, EH1, and EHALL the values were all referring to the empirical data of AllGo network. The preliminary analysis in Appendix A showed a pattern where the speed obtained was influenced by the location of the control point (e.g. slower while approaching the control point). Thus, this CoV was actually only relevant for SB and EH1 as both have the same control point locations.

Applying speed adjustment and its combination with holding control, in this case, did not automatically improve the variation in speed. It depended on the speed range applied in the strategy. Having speed adjustment only without holding control sometimes was better to keep a lower variation in speed. In general, the COV speed variation could be improved by speed adjustment, if the allowable speed was also limited as seen in SH2.2 and SA2.2

Passenger perspective
From the perspective of a passenger, the strategies were assessed based on different time components, which was summarized in Table 4.7. Generally, this time component can be distinguished into waiting time, holding time, the trip time between stops, in-vehicle time, and generalized travel time. For waiting time, the first indicator was the average waiting time. In the current operation, the planned headway between trips was 300 s with a desired average waiting time of 150 s. This indicator compared how long on average, the passengers should wait at the stop to ride the bus. For this aspect, EHALL obtained the best performance compared to others with the lowest waiting time value, while SB was the worst strategy. However, the performance difference between one and another strategy was not significant with a maximum difference of 7.0 s (i.e. with SA1.2 and SH1.2). This time component was related to excess waiting time (EWT), which determines the additional waiting time required compared to the planned waiting time.

While EWT compared only the average condition, there was reliability buffer time (RBT) of waiting time, which was defined as the difference between the 95th and 50th waiting time distribution (van Oort, 2011). It describes the variation of the resulted waiting time. An example can be seen from EHALL and SH2.2. EHALL was considered the best in average waiting time and EWT as it provided the lowest number for these indicators. However, from RBT waiting time, it was known that the variation was quite high. In some situations, there were possibilities that the passengers have to wait longer.

SH2.2 on the other hand, gave a slightly higher number for the first two indicators, with the difference of only 2.0 s. However, from the RBT waiting time, the variation was shown to be low, implying that this strategy consistently gave the same value for waiting time because of good regularity. When looking only at the average condition, EHALL was the best strategy. However, if we looked at it as a whole condition, SA2.2 and SH2.2 were the best. On the other hand, SB was the worst strategies.

The other indicators were total holding time and average trip time between stops. These indicators capture the different tradeoff from holding control and speed adjustment. When comparing EHALL and SH, we could observe that SH required lower holding time with the consequence of higher trip time. The lower the minimum speed limit defined in SH, the lower holding time was required because the strategy adjusted the speed first before applying the holding control. Hence, EHALL obtained the highest average total holding time while SH1.2 gave the longest average trip time between stops.

For the in-vehicle time, a comparison was made based on the weighted time component for the related passenger activity (dwelling, holding, trip time). SB, EH1, EHALL obtained a lower value in total in-vehicle time compared to SA and SH. Although SA and SH reduced the holding time, which had a higher weight compared to trip time, this result implied that the additional trip time resulted was more significant than the reduction. SA and SH tended to slow down along the route as seen in the previous indicator. It was even worse for SH since it allowed the vehicle to hold at all stops. Consequently, SH1.2 turned out to be the worst strategy due to slowing down and holding.

Table 4. 7 Performance summary from a passenger perspective (green = best, red = worst)

Strategy		SB	EH1	EHALL	SA1.2	SA1.3	SA2.2	SH1.2	SH1.3	SH2.2
Average Waiting Time (s)	**Line M5, Dir 1**	149	149	147	148	149	148	148	148	148
	Line M5, Dir 2	151	150	150	157	151	151	157	152	152
	Line M7, Dir 1	150	149	147	148	149	149	148	149	149
	Line M7, Dir 2	150	149	148	145	149	150	145	149	150
RBT Waiting Time (s)	**Line M5, Dir 1**	24	26	21	13	9	11	13	19	9
	Line M5, Dir 2	26	20	14	74	11	13	74	11	19
	Line M7, Dir 1	20	21	20	17	15	12	17	15	13
	Line M7, Dir 2	21	20	20	52	12	9	52	12	9
EWT (s)	**Line M5, Dir 1**	-1	-1	-3	-2	-1	-2	-2	-2	-2
	Line M5, Dir 2	1	0	0	7	1	1	7	2	2
	Line M7, Dir 1	0	-1	-3	-2	-1	-1	-2	-1	-1
	Line M7, Dir 2	-0.32	-1	-2	-5	-1	-0.27	-5	-1	-0.29
Average Total Holding Time (s)	**Line M5, Dir 1**	12.28	10.21	78.12	0.00	0.00	0.00	11.71	41.77	33.26
	Line M5, Dir 2	0.00	10.52	47.53	0.00	0.00	0.00	28.61	29.12	20.30
	Line M7, Dir 1	119.75	51.90	126.66	0.00	0.00	0.00	47.09	98.30	33.57
	Line M7, Dir 2	44.74	46.43	64.17	0.00	0.00	0.00	26.90	14.02	1.52
RBT Total Holding Time (s)	**Line M5, Dir 1**	24.80	24.45	134.32	0.00	0.00	0.00	27.67	73.77	33.48
	Line M5, Dir 2	0.00	20.01	84.64	0.00	0.00	0.00	55.00	40.13	28.18
	Line M7, Dir 1	66.15	67.81	168.83	0.00	0.00	0.00	58.98	87.60	48.10
	Line M7, Dir 2	36.11	67.06	89.16	0.00	0.00	0.00	70.95	27.11	6.29
Average Trip Time between Stops (s)	**Line M5, Dir 1**	65.91	65.95	65.89	72.46	68.51	71.73	72.26	67.33	70.76
	Line M5, Dir 2	65.92	65.94	65.99	88.94	72.24	76.32	83.96	71.66	76.44
	Line M7, Dir 1	73.44	73.45	73.43	84.53	78.67	84.34	82.55	75.70	83.93
	Line M7, Dir 2	75.10	75.07	75.11	99.24	79.28	76.74	97.94	78.79	76.38
RBT Trip Time (s)	**Line M5, Dir 1**	29.48	29.50	29.46	56.32	43.38	45.26	56.02	42.85	45.84
	Line M5, Dir 2	29.38	29.41	29.42	57.03	39.67	47.85	56.60	39.19	46.88
	Line M7, Dir 1	46.93	47.06	47.10	56.84	46.06	50.02	56.64	49.48	50.93
	Line M7, Dir 2	46.14	46.08	46.14	83.75	62.88	43.12	83.61	63.07	42.53
Total weighted In-Vehicle Time (passenger.s)	**Line M5, Dir 1**	2.E+05	2.E+05	2.E+05	2.E+05	2.E+05	2.E+05	2.E+05	2.E+05	2.E+05
	Line M5, Dir 2	4.E+05	4.E+05	4.E+05	5.E+05	4.E+05	4.E+05	5.E+05	4.E+05	4.E+05
	Line M7, Dir 1	5.E+05	5.E+05	5.E+05	5.E+05	5.E+05	5.E+05	5.E+05	5.E+05	5.E+05
	Line M7, Dir 2	9.E+05	9.E+05	9.E+05	1.E+06	9.E+05	1.E+06	1.E+06	9.E+05	1.E+06
RBT In-Vehicle Time (passenger.s)	**Line M5, Dir 1**	1.E+04	2.E+04	2.E+04	1.E+04	2.E+04	2.E+04	2.E+04	2.E+04	1.E+04
	Line M5, Dir 2	2.E+04	2.E+04	2.E+04	2.E+04	2.E+04	2.E+04	2.E+04	2.E+04	2.E+04
	Line M7, Dir 1	3.E+04	4.E+04	4.E+04	4.E+04	3.E+04	4.E+04	4.E+04	4.E+04	3.E+04
	Line M7, Dir 2	3.E+04	4.E+04	4.E+04	5.E+04	4.E+04	4.E+04	5.E+04	4.E+04	4.E+04
Average generalized travel time per passenger (min)		39	40	41	43	40	41	43	41	41

The last indicator was the generalized travel time, which included the waiting time as well. SB turned out to be the best strategy compared to others. This strategy was better in term of in-vehicle time component, which dominated the total travel cost. With the same reasoning, again, SA1.2 and SH1.2 were the worst strategies.

Authority perspective

One concern of the authority for Almere case was punctuality at main stops (i.e. stations). In current operation, these stops were designed as the control point locations. Table 4.8 summarizes the punctuality at the main points.

In the concessionaires, punctuality was defined as a range between 0 to 120 s from the scheduled departure. Based on this definition, SB was the best strategy among the others. Most trips were early; hence, there was a high possibility of holding at the control point. If the compliance rate was 100%, no early trips would occur for this strategy. EH1, on the other hand, obtained a high number of early trips. Note that for EH1, the holding time was limited to 60 s. Thus, when the scheduling was quite loose, EH1 might leave the stop once it has reached 60 s of holding, which was considered early according to the schedule. SA and SH, in general, were giving less early trips, except SA1.3, but resulting in more delays. In term of punctuality, SH1.3 obtained the best outcome, which was comparable with EHALL as another headway-based control strategy.

Table 4. 8 Performance summary from an authority perspective (green = best, red = worst)

Strategy	Nr Stop	SB	EH1	EHALL	SA1.2	SA1.3	SA2.2	SH1.2	SH1.3	SH2.2
Early (% trips)	511/706	0%	23%	3%	0%	30%	0%	0%	12%	0%
	712	0%	86%	6%	0%	46%	0%	0%	0%	0%
	2506	0%	1%	1%	1%	1%	1%	1%	1%	1%
	2706	0%	3%	2%	0%	0%	0%	0%	0%	0%
	2712	0%	0%	0%	0%	0%	0%	0%	0%	0%
On-time (% trips)	511/706	96%	74%	92%	90%	65%	93%	89%	83%	92%
	712	96%	10%	85%	83%	50%	89%	80%	92%	87%
	2506	100%	99%	98%	11%	91%	72%	10%	90%	68%
	2706	100%	97%	98%	11%	100%	32%	10%	100%	33%
	2712	96%	85%	70%	0%	81%	0%	0%	66%	0%
Delay>120 s (% trips)	511/706	4%	4%	5%	10%	5%	7%	11%	5%	8%
	712	4%	4%	9%	17%	4%	11%	20%	8%	13%
	2506	0%	0%	1%	88%	8%	28%	90%	9%	32%
	2706	0%	0%	0%	89%	0%	68%	89%	0%	67%
	2712	4%	15%	29%	100%	19%	100%	100%	34%	100%
Regular trip (CoV < 0.21) (% trips)	511	98%	93%	94%	99%	100%	100%	99%	100%	100%
	706	100%	99%	99%	91%	98%	99%	91%	98%	99%
	712	100%	97%	94%	98%	99%	100%	97%	95%	100%
	2506	96%	100%	100%	57%	100%	100%	58%	100%	100%
	2706	100%	100%	100%	71%	99%	100%	71%	99%	100%
	2712	93%	99%	96%	33%	100%	100%	35%	100%	100%
Average ratio of actual/desired headway	511	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.99
	706	0.99	0.99	0.99	0.99	1.00	1.00	0.99	1.00	1.00
	712	1.01	0.99	0.96	0.98	0.99	0.99	0.98	0.99	0.99
	2506	1.00	1.01	1.00	1.04	1.01	1.01	1.04	1.01	1.01
	2706	0.99	0.99	0.99	1.01	1.00	1.00	1.01	1.00	1.00
	2712	1.00	0.99	0.97	1.02	0.98	0.99	1.02	0.98	0.99

One idea behind having punctuality at the main stops is to assure that the bus service supports the passengers' need well to transport to/from the stations. Considering that AllGo service was a high-frequent system, it was not a problem if the schedule was ignored and just focus to the regularity. Concerning this idea, the percentage of regular trips obtained for the associated stops were also analyzed. The regular trips were defined as the trips that have a level of service A with a CoV of 0.21 or less (TCRP, 2013). In general, all strategies showed great performance in obtaining regular trips at the main stops. There were slight differences between in regularity percentages, however, still considered well based on the classification of headway adherence in the indicator. Thus, SB was still the best strategy assessed from the perspective of authority. For the headway-based control strategy, SH1.3 could be another choice, if preventing the early trips was really a concern.

Conclusion on Scenario 1
The assessment on the strategy performance based on the operator perspective was done for different indicators. Based on the assessment of CoV headway, several conclusions can be drawn. First, regarding the current strategy SB, it performed effectively to maintain regularity when much buffer was available in the schedule. This finding aligns with the result of past studies (Furth & Muller, 2007; van Oort et al., 2012). However, the concern should be put on the length of holding time. By contrast, when the schedule was tighter, SB could not perform well anymore. Different performances were shown by EH1 and EHALL. These strategies were effective regardless of the quality of scheduling and demand pattern if the control point was located correctly. EHALL, for example, was not beneficial for a stop with a low demand activity. This result corroborated the findings from the past studies (Abkowitz & Engelstein, 1984; Eberlein et al., 2001; Hickman, 2009; Furth & Muller, 2009; van Oort et al., 2012; Cats, O. et al., 2014).

For SA and SH, the results suggest that the quality of scheduling, speed range, holding, and demand activity affects the performance of the strategy in a different manner for different conditions. SA outperformed SH when the demand is low and concentrated at the early stops, and the trips tend to be early. However, SH was more capable of reducing the headway variability compared to SA, after a disturbance such as high demand activity. Even though the SA and SH worked based on headway, specifically for this study, the quality of scheduling becomes important as it provides the arrival time prediction for the control to take a decision in speed. For speed range, a wide speed range could be very (dis)advantageous depending on the scheduling and demand pattern. The safe option is to pick a narrower range. Thus it does not react too sensitively to the new information.

A good performance in regularity by SA and SH, in general, came with a cost of excessive and high varying total trip time, as well as fleet requirement. Although these strategies have the ability to speed up, most of the time vehicle was slowing down, aligned with the result in Ampountolas & Kring (2015). SA and SH could perform better if the speed limit was set in a higher value, as seen in SA1.3 and SH1.3.

From a driver perspective, SA2.2 and SH2.2 with a narrow speed range outperformed the other strategies in term of keeping a low variation in speed. However, the characteristics of speed adjustment itself, force the driver to be controlled every time along the route. Station control strategy was definitely better in term of this indicator.

Based on the perspective of the passengers, different travel time components were analyzed to assess different strategies. From the average generalized travel cost, it turned out that SB was the best strategy from the perspective of the passenger. The main reason behind this was that because this strategy required a shorter travel time. For this case, different performance quality in waiting time did not significantly impact the overall travel cost because the differences between one and other strategies were very small. Although SB seemed to perform worse compared to others, in general, it still gave waiting time value around the desired one (i.e. 150 s), and the variation was less than 30 s. In contrast, SA and SH gave a worse outcome. The main reason behind this was mainly because of the way the system works. SA and SH required a lot of slowing down along the route, which consequently increased the total travel time.

Lastly, from the perspective of the authority, the overall performance of SB could not be exceeded. However, this condition was mainly supported by a good quality of schedule. SH1.3 could be another option if punctuality was kept as an indicator to assess the performance. Yet, by definition, it was not relevant anymore to measure a headway-based control strategy using the punctuality indicator.

4.3.6 Results: Scenario 2 - Tight schedule (based on 85th percentile of actual trip time distribution)

The second scenario was to change the schedule by applying a tighter schedule. The schedule was designed based on 85th percentile of the actual trip time distribution. This number was chosen to keep the scenario make sense because, from the literature, it was expected that it would be unbeneficial for SB if a much tighter schedule was chosen.

Operator perspective

Coefficient of headway

Figure 4.5 shows the CoV headway comparison for Line M5 Direction 1 for a tight schedule.The performances of SA1.2 and SH1.2 were getting worse because the schedule was tighter than the one applied in scenario 1. Hence the trips tended to be late. After the following vehicle entered the route, the vehicle tended to drive faster. However, since at the beginning SA/SH1.2 was overly slowing down, the headway became not stable after the new information regarding the following vehicle was updated. The same thing happened with SA1.2 and SH1.2 in scenario 1 Line M5 Dir 2. With additional holding, it was difficult for SH1.2 to improve the performance since the trips tended to be late instead of early.

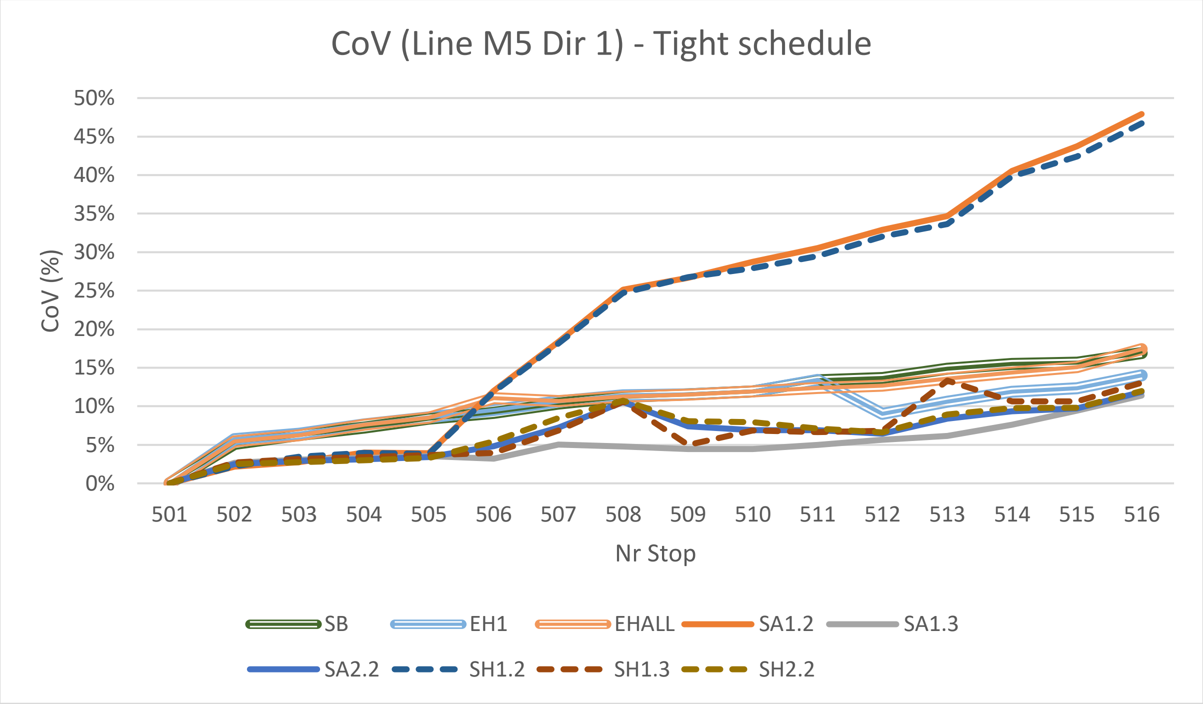

Figure 4. 5 CoV headway comparison for Line M5 Direction 1 (85th percentile schedule)

Unexpectedly, for EHALL, the variability also became higher. Most likely, this situation occurred because the demand was high at the early stop, which subsequently led to late trips. EHALL kept performing holding control. However, the possibility of being early was less likely to occur or only a few seconds of holding required. EHALL kept taking this chance to hold, but as the demand was mostly low, holding at the earlier stops only reducing the earliness at the last part(s) of the line. No chance to hold anymore, thus, the variability was also rising. Differently, for EH1, it stored the earliness due to variability until reaching Stop 511. Thus, it had a chance to take holding and performed effectively compared to SB.

SA1.3 became the best strategy mainly because of its higher capability to speed up and lower capability of slowing down. The first trip k always considered late due to a tight schedule. Thus, the second trip tended to go slower. In SA1.3, its limited ability to slow down forced the vehicle to always take the maximum trip time it was allowed. Due to this condition, there was actually a possibility for bunching, especially between the first and second trip, if the dwelling time was dominant. However, for the rest of the trips, the headway tended to be consistent and gave an overall lower value of headway variability.

On the other hand, SH1.3 could not give the same performance because besides slowing down, it also applied holding control and made the headway become more varied compared to SA1.3, which kept the same value of trip time on every ride. Since the demand was not high in the rest of the route, adding holding control for SH1.3 was not beneficial.

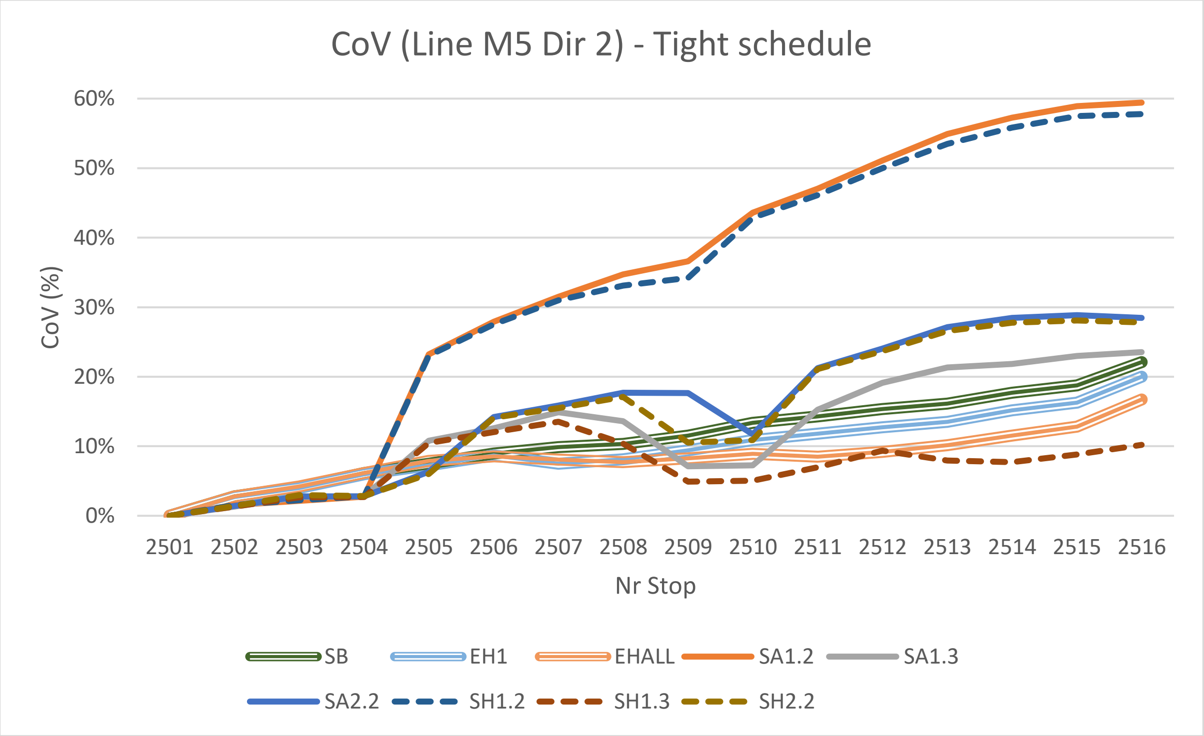

Figure 4. 6 CoV headway comparison for Line M5 Direction 2 (85th percentile schedule)

Figure 4.6 depicts the CoV headway comparison for a tight schedule in Line M5 Direction 2. SB still showed a bad performance as seen in the first scenario. Meanwhile, EHALL, different from Direction 1, performed effectively. The main reason behind this was due to the demand pattern of this direction. While in Direction 1 the demand was concentrated at the early stop(s), the demand pattern in Direction 2 was high from the middle to the end of the route. Thus, holding activity was more beneficial to perform in this direction.

SA and SH on the other way, showing much worse performance compared to the first scenario. In the first scenario, SA1.2 and SH1.2 had already shown a bad performance due to the following reasons. First, was due to the limited trip time planning at the early stops. The system had a tendency to go slower, up to its allowable maximum trip time. The maximum trip time itself, in general, was much longer than the trip time prediction. Once the following vehicle entered the system at around the fifth stop, the system predicted that the following vehicle would come early (due to limited trip time planning), while the existing vehicle has been driving too slowly. Thus, the system became unstable because it failed to speed up to meet the even headway after slowing too much. The larger the difference between the trip time planning and the maximum trip time allowed was, the worse the stability was. By changing the schedule into a tighter one, the gap became larger. This did not only apply for SA1.2 and SH1.2 but also to SA1.3, SH1.3, SA2.2 and SH2.2. Thus, the performance of these strategies all deteriorated. Holding on SH did not give significant impact since the trips tended to be late compared to the prediction. The variability worsened due to higher demand along the route.

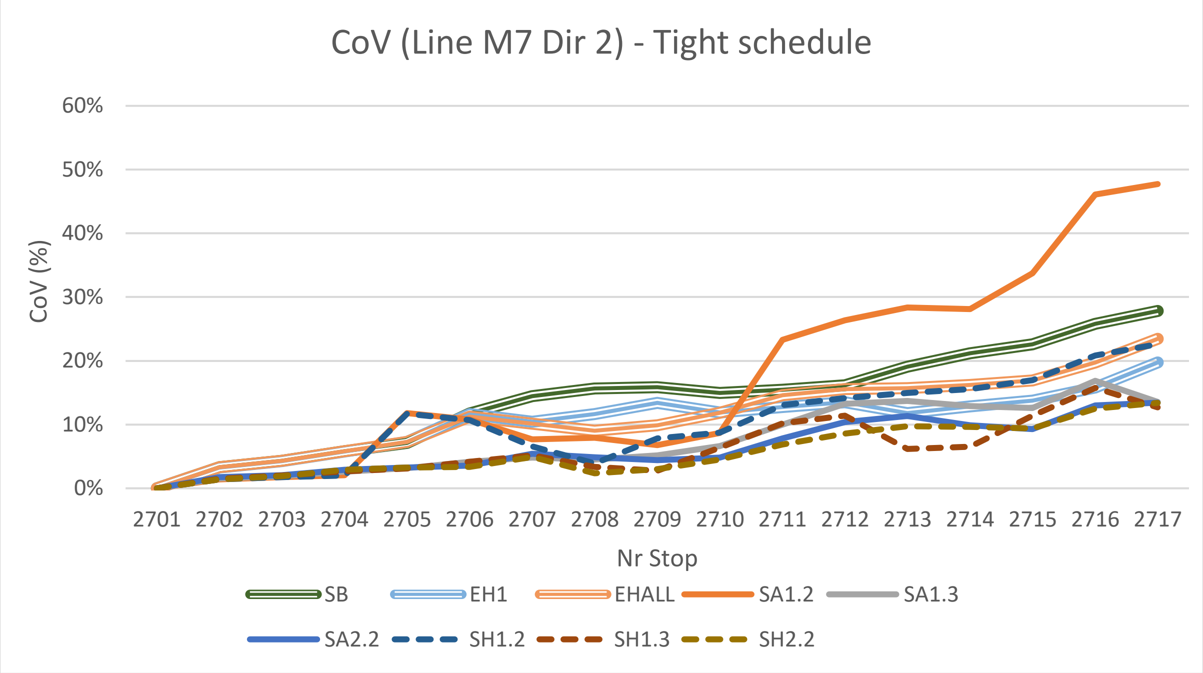

Figure 4. 7 CoV headway comparison for Line M7 Direction 2 (85th percentile schedule)

Another interesting observation can be observed in Line M7 Direction 2. In the first case, the performance of SA and SH (Appendix C) was worse than what was shown in Line M5 Direction 2. However, by applying a tighter schedule, the headway variability on this line was much improved. In the first case, the scheduled trip time to 2706 was much higher than the actual trip time distribution. Due to this prediction, the system perceived that the trip was always earlier than it should be. Hence, the system tended to ride slower up to the maximum trip time. When the following vehicle entered the route, the system became unstable because of the large state gap between too much slowing down and speeding up. When changing the schedule, the trip time prediction to 2706 was just in the right amount. Thus, it was not ruined by the prediction of the arrival time of the following vehicle. In this case, the effect of holding in SH in comparison to SA was also clearer (e.g. look at 2710). These results imply how a good prediction of arrival time could result in a better regularity level.

Other indicators : Cycle time (85th) and variation in cycle time (85th – 50th), fleet requirement

Table 4. 9 Performance summary from operator perspective – Scenario 2 (green = best, red = worst)

Strategy		SB	EH1	EHALL	SA1.2	SA1.3	SA2.2	SH1.2	SH1.3	SH2.2
Cycle time at 85th percentile (s)	**Line M5**	2730	2738	2755	3505	2863	2939	3484	2850	2935
	Line M7	3225	3225	3239	3860	3206	3329	3855	3317	3337
Cycle time variation (s)	**Line M5**	102	92	92	342	170	148	335	216	158
	Line M7	71	61	56	184	66	57	202	57	61
Fleet requirement (fleet)	**Line M5**	10	10	10	12	10	10	12	10	10
	Line M7	11	11	11	13	11	12	13	12	12

In cycle time, the performances of all strategies were in general similar to the performance in the first scenario.

When comparing the cycle time obtained between SB and EHALL, the difference was surprisingly much smaller (i.e. a maximum of 25 s) compared to the first scenario (i.e. up to 100 s), with much different performance in regularity. However, for SA and SH, the obtained cycle time became much higher as well as its variation, except for SA1.3. Hence, for the fleet requirement, it was preferable to pick between the first three strategies or SA1.3. In overall, based on these three indicators, EHALL was the best strategy.

Driver perspective

Table 4.10 summarizes the performance of all strategies from a driver perspective. There was no significant difference in performance assessed from a driver perspective. SA2.2 and SH2.2 remained the best as it restricted the speed limit. Meanwhile, SB and EH1 were the best if considering all aspects for the drivers. However, it was worth to note that, in this scenario, the CoV speed of SB, EH1, and EHALL in the simulation was not affected by changing the schedule since it was the input for the simulation. An interesting finding was found in the number of control taken. Compressing the trip time schedule reduced the holding decision for all strategies, implying more late trips occurrence.

Table 4. 10 Performance summary from a driver perspective (green = best, red = worst)

Strategy		SB	EH1	EHALL	SA1.2	SA1.3	SA2.2	SH1.2	SH1.3	SH2.2
Nr of control taken	**Line M5, Dir 1**	1	1	3	15	15	15	17	17	16
	Line M5, Dir 2	0	1	2	15	15	15	17	17	16
	Line M7, Dir 1	0	1	3	16	16	16	18	18	17
	Line M7, Dir 2	1	1	3	16	16	16	18	19	18
CoV Speed per line (%)	**Line M5, Dir 1**	22%	22%	22%	28%	23%	18%	29%	22%	17%
	Line M5, Dir 2	24%	24%	24%	27%	25%	20%	29%	25%	20%
	Line M7, Dir 1	22%	22%	22%	31%	23%	18%	30%	23%	18%
	Line M7, Dir 2	26%	26%	26%	37%	26%	21%	36%	26%	20%

Passenger perspective

From table 4.11, no significant difference can be found for the performance based on passenger perspective. However, in term of average waiting time, SA1.2 and SH1.2 were now worse than SB. However, looking at the difference in generalized travel time per passenger between the strategies, SB turned out to be one of the most affected strategies due to different scheduling, along with SA2.2. Meanwhile, EHALL and SH1.3 were less affected due to different scheduling. However, SB remained the best strategy based on passenger perspective by considering only on generalized travel time per passenger indicator.

Table 4. 11 Performance summary from a passenger perspective (green = best, red = worst)

Strategy		SB	EH1	EHALL	SA1.2	SA1.3	SA2.2	SH1.2	SH1.3	SH2.2
Average Waiting Time (s)	**Line M5, Dir 1**	150	149	147	152	149	148	152	149	148
	Line M5, Dir 2	150	150	150	157	151	152	157	150	152
	Line M7, Dir 1	150	149	148	151	149	148	155	148	148
	Line M7, Dir 2	150	149	148	148	148	149	147	149	149
RBT Waiting Time (s)	**Line M5, Dir 1**	26	24	24	59	9	12	58	10	13
	Line M5, Dir 2	26	22	19	92	30	41	89	19	38
	Line M7, Dir 1	27	24	23	59	10	16	71	12	16
	Line M7, Dir 2	31	25	24	36	13	12	24	11	10
EWT (s)	**Line M5, Dir 1**	0	-1	-3	2	-1	-2	2	-1	-2
	Line M5, Dir 2	0	0	0	7	1	2	7	0	2
	Line M7, Dir 1	0	-1	-2	1	-1	-2	5	-2	-2
	Line M7, Dir 2	0	-1	-2	-2	-2	-1	-3	-1	-1
Average Total Holding Time (s)	**Line M5, Dir 1**	0.00	12.30	29.28	0.00	0.00	0.00	7.97	4.94	2.81
	Line M5, Dir 2	0.00	4.22	12.09	0.00	0.00	0.00	9.45	11.31	1.94
	Line M7, Dir 1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Line M7, Dir 2	0.00	17.12	30.10	0.00	0.00	0.00	34.56	33.00	14.84
RBT Total Holding Time (s)	**Line M5, Dir 2**	0.00	25.06	78.83	0.00	0.00	0.00	22.93	9.71	5.59
	Line M7, Dir 1	0.00	12.74	37.90	0.00	0.00	0.00	25.92	22.59	7.04
	Line M7, Dir 2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Line M5, Dir 1	0.00	41.78	80.28	0.00	0.00	0.00	43.76	37.74	15.26
Average Trip Time between Stops (s)	**Line M5, Dir 1**	65.85	65.91	65.91	79.31	64.30	68.45	78.35	64.49	68.12
	Line M7, Dir 1	73.54	73.50	73.49	84.98	72.60	77.39	85.03	72.99	76.74
	Line M5, Dir 2	65.96	66.02	65.94	89.54	68.83	74.59	87.91	66.99	73.95
	Line M7, Dir 2	75.08	75.11	75.11	85.55	74.33	80.71	80.61	74.28	79.59
RBT Trip Time (s)	**Line M5, Dir 2**	29.29	29.41	29.42	53.58	37.84	38.90	53.44	36.17	38.24
	Line M7, Dir 1	47.18	47.05	47.20	63.85	57.34	55.44	65.71	58.94	55.08
	Line M7, Dir 2	29.47	29.42	29.34	59.69	47.76	49.10	60.22	46.17	48.60
	Line M5, Dir 1	46.39	46.02	46.19	58.86	47.69	51.86	55.10	47.17	51.19
Total weighted In-Vehicle Time (passenger.s)	**Line M5, Dir 1**	2.E+05	2.E+05	2.E+05	3.E+05	2.E+05	2.E+05	3.E+05	2.E+05	2.E+05
	Line M5, Dir 2	4.E+05	4.E+05	4.E+05	5.E+05	4.E+05	5.E+05	5.E+05	4.E+05	5.E+05
	Line M7, Dir 1	5.E+05	5.E+05	5.E+05	5.E+05	5.E+05	5.E+05	6.E+05	5.E+05	5.E+05
	Line M7, Dir 2	9.E+05	9.E+05	9.E+05	1.E+06	9.E+05	1.E+06	1.E+06	9.E+05	1.E+06
RBT In-Vehicle Time (passenger.s)	**Line M5, Dir 1**	2.E+04	2.E+04	2.E+04	2.E+04	2.E+04	2.E+04	2.E+04	2.E+04	2.E+04
	Line M5, Dir 2	3.E+04	3.E+04	2.E+04	3.E+04	3.E+04	2.E+04	3.E+04	3.E+04	2.E+04
	Line M7, Dir 1	4.E+04	4.E+04	5.E+04	5.E+04	4.E+04	4.E+04	5.E+04	4.E+04	5.E+04
	Line M7, Dir 2	5.E+04	4.E+04	4.E+04	6.E+04	5.E+04	6.E+04	6.E+04	4.E+04	5.E+04
Average generalized travel time per passenger		43	43	44	47	43	44	47	44	44
Increase in average generalized travel time per		9%	8%	7%	8%	8%	9%	8%	7%	7%

Authority perspective

Table 4. 12 Performance summary from an authority perspective (green = best, red = worst)

Strategy	Nr Stop	SB	EH1	EHALL	SA1.2	SA1.3	SA2.2	SH1.2	SH1.3	SH2.2
Early (% trips)	511/706	0%	0%	0%	0%	0%	0%	0%	0%	0%
	712	0%	0%	0%	0%	0%	0%	0%	0%	0%
	2506	0%	0%	0%	0%	0%	0%	0%	0%	0%
	2706	0%	0%	0%	0%	0%	0%	0%	0%	0%
	2712	0%	0%	0%	0%	0%	0%	0%	0%	0%
On-time (% trips)	511/706	92%	91%	87%	44%	90%	84%	42%	87%	84%
	712	60%	53%	47%	9%	81%	43%	5%	78%	39%
	2506	100%	100%	99%	5%	84%	5%	5%	81%	6%
	2706	96%	96%	95%	82%	90%	88%	82%	90%	88%
	2712	46%	37%	28%	3%	75%	0%	0%	64%	0%
Delay>120 s (% trips)	511/706	8%	9%	13%	56%	10%	16%	58%	13%	16%
	712	40%	47%	53%	91%	19%	57%	95%	22%	61%
	2506	0%	0%	1%	95%	16%	95%	95%	19%	94%
	2706	4%	4%	5%	18%	10%	12%	18%	10%	12%
	2712	54%	63%	72%	97%	25%	100%	100%	36%	100%
Regular trip (CoV < 0.21) (% trips)	511	88%	88%	91%	51%	100%	100%	52%	100%	100%
	706	92%	93%	94%	90%	100%	100%	90%	100%	100%
	712	87%	89%	84%	67%	100%	100%	63%	99%	100%
	2506	98%	98%	99%	55%	91%	86%	55%	92%	86%
	2706	93%	93%	94%	95%	100%	100%	95%	100%	100%
	2712	81%	88%	82%	57%	89%	96%	86%	93%	99%
Average ratio of actual/desired headway	511	1.00	1.00	0.97	1.02	0.98	0.97	1.01	0.97	0.97
	706	0.99	0.99	0.99	1.00	0.99	1.00	1.00	0.99	0.99
	712	1.00	1.00	0.97	1.04	0.98	0.99	1.05	0.98	0.99
	2506	1.00	1.00	1.00	1.04	1.02	1.02	1.04	1.02	1.02
	2706	0.99	0.99	0.99	0.99	0.99	1.00	0.99	0.99	1.00
	2712	1.00	1.00	0.96	0.97	0.96	0.97	0.94	0.96	0.97

In term of punctuality, as aforementioned, more late trips occurred. A system with SB, EH1, and EHALL generated more delay trips in average, compared to SA1.3 and SH1.3. From the assessment of the overall performance, these two strategies also came out to be the best strategies among the others by offering the best regularity at the main stops.

Conclusion on Scenario 2

From Scenario 2, several conclusions can be drawn. Headway variability in SB strategy was found to be sensitive towards the trip time schedule. The main reason was due to ability in having the early trips, which gave a chance to execute holding. A tight schedule did not give the possibility for this in SB. Thus, SB was not an effective anymore as it was in the first case.

EH1 and EHALL, on the other hand, still performed well under this change. Particularly for EHALL, this effectiveness was happening under one condition, in which related to the demand pattern in the route. When the demand was only high at the early stops, EHALL might not be as effective as EH1 nor SB.

Although SA and SH worked based on headway references, these strategies were also much affected by the change in schedule trip time. This finding was much related to the way the control works. The SA and SH control in this study took the scheduled trip time as the reference for predicting the arrival time. Thus, the way the control predicts the arrival time was very much sensitive to the performance of SA and SH strategy. In this case, the prediction of arrival time was even more influential in determining the performance of SA and SH than demand pattern at stops. Overall, EHALL gave the best performance. Its performance was also comparable with SH1.3 and SA1.3.

4.3.7 Results: Scenario 3 - Different demand level

As discussed in Chapter 2, speed adjustment is not advisable to apply when the dwelling time dominates the system. From scenario 1 and 2, the effects of different demand patterns have been analyzed. In this scenario, the assessment on the strategy is given by changing the demand condition uniformly by modifying the demand level into 0.65 and 1.35 times of the average condition.

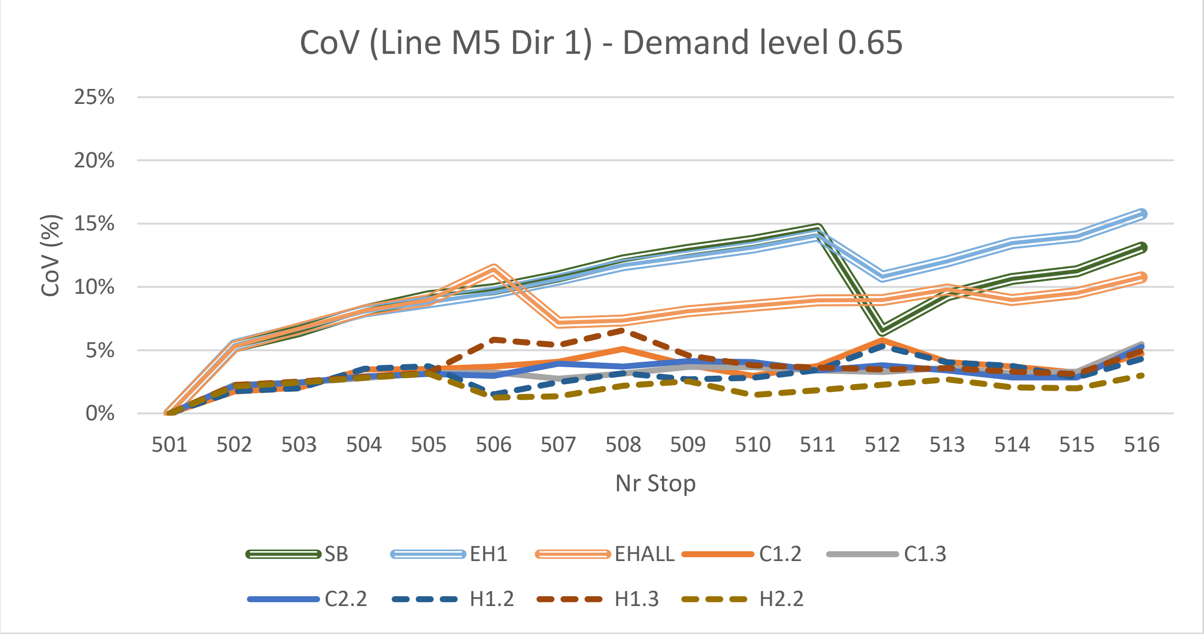

Figure 4. 8 CoV headway of scenario 3 – Demand 0.65 times (example from Line M5 Dir 1)

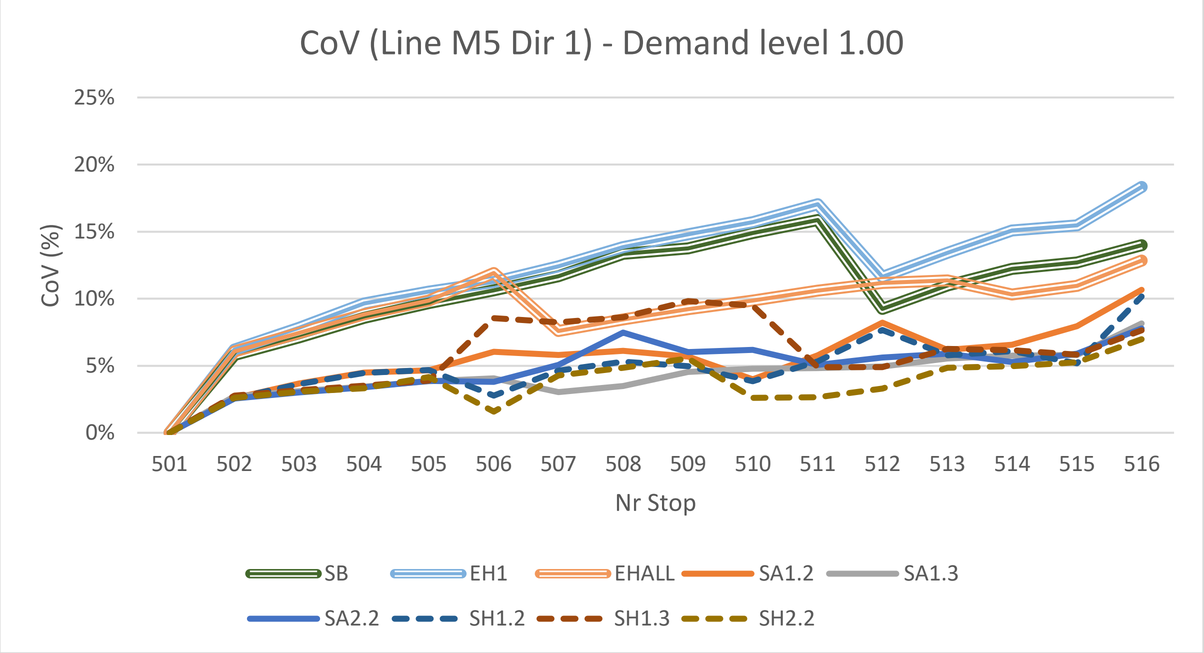

Figure 4. 9 CoV headway of scenario 3 – Demand 1.00 times (example from Line M5 Dir 1)

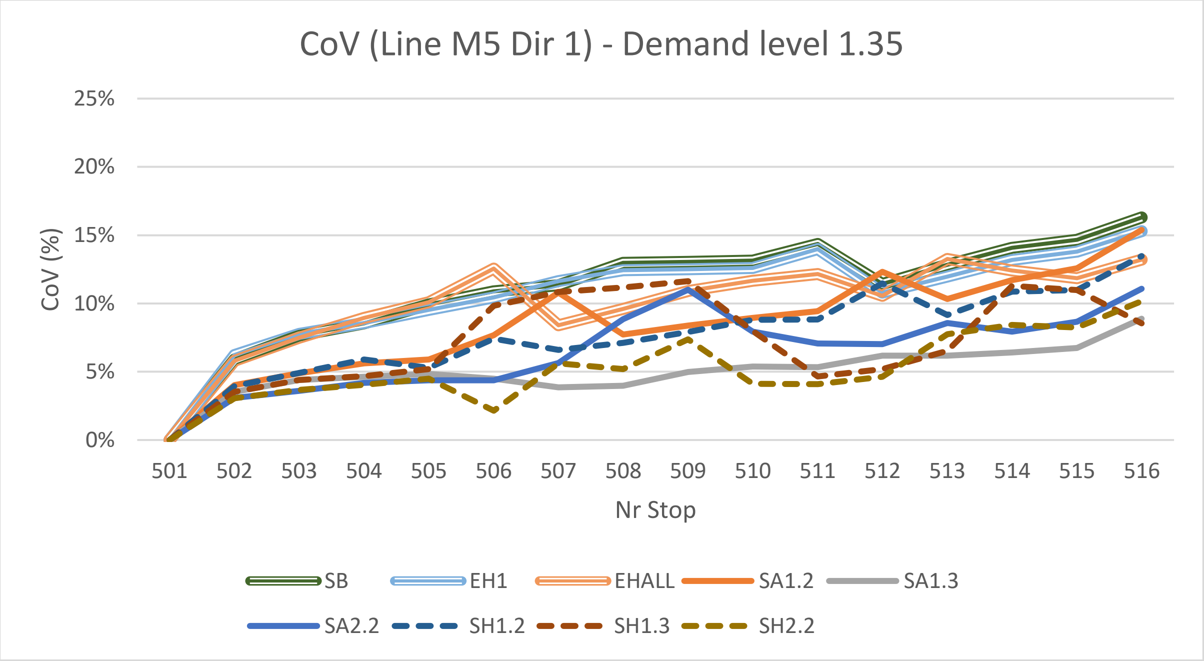

Figure 4. 10 CoV headway of scenario 3 – Demand 1.35 times (example from Line M5 Dir 1)

Figure 4.8, 4.9 and 4.10 showed an example of the comparison between different strategies under demand level 0.65, 1.00, and 1.35 times higher for Line M5 Direction 1. In overall, SA and SH strategies still performed well under this condition. Increasing demand level did not significantly affect SA and SH strategies unless a demand at one stop was significantly different with its surroundings (e.g. Stop 505 to 506, and Stop 510 to 511). For this situation, the CoV suddenly increased when the speed could not be forced to go faster (e.g. for SA 1.2 and SH1.2). Another line directions had the same outcomes when a higher demand rate was applied (Appendix D). In addition, compared to SH, SA also reacted more sensitively to a condition where a significant passenger activity occurred (Appendix D). Meanwhile, different demand levels only gave a small effect to SB, EH1, and EHALL in term of regularity. Besides regularity, the performances in the other aspects were also the same when being compared relatively to other strategies.

Conclusion on Scenario 3
By increasing the demand level uniformly, the performance of SA and SH was deteriorating, but the difference was not as significant as if the demand pattern or arrival time prediction was changed, especially for SH strategy. For SA, this condition affected its performance more, especially for the case where there was a significant difference of demand in one stop compared to its surrounding. Oppositely, SB, EH1, and EHALL were not much affected by this change.

4.3.8 Results: Assessing the control strategies from a practical point of view

Apart from the evaluation of the control strategies through a simulation, additional evaluation was done through an interview with an expert from Keolis (Appendix E). This part of evaluation aims for assessing the control strategies from the practical perspective. Particularly in Keolis, the operation still refers to punctuality, despite the high-frequency service it offers during the peak hour period. Meanwhile, the other strategies assessed in this section were working based on headway. Therefore, from the interview, the control strategies was distinguished into two based on its working system (i.e. punctuality and regularity based) regardless of the different types of headway control strategies we have in this chapter.

From the interview, the punctuality-based control strategy was considered preferable in this case study, compared to the headway-based control strategies in a way that it does not require any changes to operate. The operation on the basis of regularity, requires several changes, not only at the operational level but also at the strategic level. In more details, the changes can be categorized into three as follows.

1. Regulation
   The first thing related to the regulation is the concessionaires. As aforementioned in Section 2.4, the majority of the concessionaires are still selecting punctuality as the indicator to assess the reliability of the transit system. This concept does not match with the way the headway-based control could be assessed. However, in the previous section, the headway-based control strategies were shown to be able to provide high regularity adherence as a replacement for punctuality adherence. This might provide the basic idea for the authority to consider regularity-based operation in the concessionaires.
   A potential problem on a contractual agreement with the driver's organization is considered more crucial, as the regulation was usually stricter. Several things that have to take into account are the problem related to break-time and workload per day.
2. Operational planning
   This problem consists of the planning of fleet and driver scheduling. The first scheduling should be considered as it is related to the operational cost, while the latter is highly related to the first aspect, contractual agreement with the driver's organization.
3. Supporting system
   This aspect includes the additional internal things that need to be modified to migrate into regularity-based operation, including the ICT system, passenger information, and driver-control interface.

Conclusion on the assessment based on the practical point of view
By looking at the aspects above, a migration from punctuality- to regularity-based system operation requires significant changes in the re-organization of the public transport system. The passenger will be the one who is least affected by the changes. The other parties, including the drivers, the operators, the authorities, and the others involved in the public transport system, might get more impacts from this migration. Therefore, all actors should understand the urgency behind this migration very well to prevent conflict when moving into a regularity-based operation (Appendix E).

4.3.9 Results: Assessing the network impact in the strategies

As an additional assessment, an observation was made to understand the impact of having an interaction between lines at the common stops. Line M5 and Line M7 have at least six common stops in each direction. For the assessment, an example was taken by looking at Stop 2513 and 2714 from Line M5 and Line M7 respectively. Several reasons behind this selection are:

1. The schedule between these stops were closed (headway = 120 s and 180 s).
2. A high number of passengers originating from these stops to other common stops (29 passengers per hour).
3. The stops were located almost at the end of the line. Thus both lines do not start from a perfectly regular headway or punctual schedule. This condition allows the regularity assessment at this stop.

The assessment in this part will only look at one indicator, the combined headway between the two lines. First of all, table 4.13 below shows the summary of headway comparison between a single line when the interaction between lines was taken into account.

Table 4. 13 Headway comparison: Single line vs interacting line (green = best, red = worst)

Strategies		**SB**	**EH1**	**EHALL**	**SA1.2**	**SA1.3**	**SA2.2**	**SH1.2**	**SH1.3**	**SH2.2**
Single line	**CoV at 2513**	15%	12%	6%	40%	4%	7%	20%	4%	11%
	CoV at 2714	12%	9%	12%	50%	4%	5%	46%	6%	5%
Interacting lines	**CoV at 2513/2714**	28%	42%	28%	56%	28%	24%	57%	40%	33%
% passenger board to Line M5 Dir 2		49%	36%	44%	71%	55%	49%	67%	63%	60%
% passenger board to Line M7 Dir 2		51%	64%	56%	29%	45%	51%	33%	37%	40%

From the table, we can observe how different it was when the interaction between lines was considered. The regularity, obviously, will be higher than the ones shown at stops in a single line assumption. Given the fact that in the scheduling, the headways between these lines were 120 s and 180 s, if the desired mean was 150 s, thus, at a minimum, the standard deviation will be 30 s with a CoV_m headway of 20% in case all trips were punctual.

Mathematically, the relationship between the CoVs of different strategies for the Almere case could be formulated in a linear equation as shown below,

$$CoV_m = CoV_{2513} * 0.269 + CoV_{2714} * 0.605$$

Where,

CoV_m : combined CoV for the common stops

CoV_{2513} : CoV at Stop 2513

CoV_{2714} : CoV at Stop 2714

This relationship has an R^2 of 0.6 with a p-value of 0.005, thus, there was a significant linear regression relationship exist between the CoV at Stop 2513, Stop 2714 and the combined CoV at the significance level of 0.05. However, it seemed that there was still many unexplained things by using this equation, giving the moderate value of the R^2. Also, the residual obtained was quite high with -0.76.

With a low regularity in a single line assumption at Stop 2513 and 2714, SA1.3 and SA2.2 also gave better performance when an interaction between lines was considered. By contrast, when the regularity was bad at both stops with strategy SA1.2, the resulted combined headway was also performing badly. However, this does not always mean that the regularity of the common stops can be reflected directly from the regularity of each associated stop. An example can be seen in SH1.3 and SB strategies. In the first case, the regularity per single line was very high. However, when it was seen from a network perspective, the regularity was considerably worse. Meanwhile, SB showed a sufficient regularity at both stops but then resulted in a good regularity in the combined headway in comparison to the other strategies. The dynamic of the system seems to be the source of this situation.

After understanding the regularity state of the AllGo network based on a network perspective, it was also important to understand why this regularity matters. Different outcome of passengers ratio for each line in all strategies can be seen in table 4.13. The higher the value of combined CoV_m, the higher the inequality of the load for the two lines. In SA2.2, when the combined CoV_m was low, the passenger load from this stop was equally distributed for Line M5 and M7 (49% and 51%). The worst situation can be seen in SA1.2, where Line M5 Direction 2 should carry almost 2.5 times more passengers than Line M7 did. This will not be a problem if the demand level is low so that inequality will not give a significant impact. However, when the demand rate for the OD demand for the common stop is high, one should give concern to this when designing the control strategy, so that the interaction between lines can be optimized, and does not burden one line only.

Table 4. 14 PDRM and resulted additional travel time: interacting line (green = best, red = worst)

Strategies	SB	EH1	EHALL	SA1.2	SA1.3	SA2.2	SH1.2	SH1.3	SH2.2
PDRM	0.229	0.350	0.235	0.476	0.236	0.196	0.494	0.338	0.269
Average additional TT (s)	4	9	4	17	4	3	18	9	5
Average reduction in waiting time compared to single line assumption (s)	71	66	71	58	71	72	57	66	70

Table 4.14 describes the PDRM and additional travel time of Stop 2513/2714 when two lines were interacting. From this number, one can derive the reduction of waiting time that can be reached by considering the interacting lines, compared to a single line only. At a minimum, there was a reduction of waiting time of 57 s on average by having the common lines.

When looking from a network perspective, SA2.2 and SB gave the best performances. For SB, scheduling became the reason. As aforementioned, if the trips were punctual, the headway will be at least 120 s and 180 s. Thus, when there was an irregularity for each line, it was possible to have a headway closer to 150 s. Meanwhile, for SA2.2, since the control strategy itself was not designed based on network perspective, the outcome might be coincidental and only applied for this particular case.

Conclusion on network assessment

Regardless of the regularity level of the common stops, passengers, in general, will get the benefit from this interaction due to waiting time reduction. However, for the operator, it is better to optimize the combined regularity so that the passenger loads can be distributed equally to the related line. This consequently affects the comfort level of the passengers as well.

4.4 Conclusions

This chapter assesses the developed control strategy based on different indicators and its comparison with the other strategies by using a simulation tool. The result given in this chapter provides the answers to the Sub-RQ II.1 and Sub-RQ II.2

Sub-RQ II.1: How was the performance of the combined strategy when applied in a real network in comparison with other strategies?

In this chapter, the performance of the proposed strategy, SH, were assessed and compared to other strategies including SB (schedule-based holding control, the current strategy in AllGo network), EH (headway-based holding control), and SA (speed adjustment only). For holding strategy, the control points were defined based on the actual control points in the AllGo network. Meanwhile, for SA and SH, different speed ranges were determined based on the actual speed distribution from the AllGo network. All strategies were assessed based on four different perspectives under three different scenarios. Table 4.15 summarizes the result from the simulation. Five indicators were chosen to represent different perspectives. Average CoV headway per line indicates the regularity of each strategy as it was the main objective of this study.

Table 4. 15 Summary of performance comparison between the best strategies (green = best, red = worst)

Scenarios		Normal condition									Tight schedule									Demand level 1.35								
Strategies		SB	EH1	EHALL	SA1.2	SA1.3	SA2.2	SH1.2	SH1.3	SH2.2	SB	EH1	EHALL	SA1.2	SA1.3	SA2.2	SH1.2	SH1.3	SH2.2	SB	EH1	EHALL	SA1.2	SA1.3	SA2.2	SH1.2	SH1.3	SH2.2
Average CoV headway per line (%)	Line M5, Dir 1	11%	13%	10%	6%	5%	5%	5%	6%	4%	11%	10%	11%	24%	5%	7%	23%	7%	7%	12%	11%	11%	9%	5%	7%	8%	8%	6%
	Line M5, Dir 2	11%	9%	7%	28%	5%	6%	17%	5%	8%	12%	10%	9%	36%	13%	17%	35%	8%	16%	12%	10%	7%	30%	6%	6%	21%	5%	6%
	Line M7, Dir 1	9%	10%	10%	7%	6%	5%	6%	7%	5%	13%	11%	13%	21%	6%	8%	24%	9%	8%	10%	10%	11%	10%	6%	5%	10%	8%	8%
	Line M7, Dir 2	9%	9%	9%	30%	5%	4%	28%	5%	4%	15%	11%	12%	18%	8%	7%	11%	7%	6%	12%	11%	10%	30%	6%	5%	28%	6%	5%
Fleet requirement	Line M5	10	10	10	11	10	10	11	10	11	10	10	10	12	10	10	12	10	10	10	10	10	12	10	11	12	10	11
	Line M7	12	12	12	14	12	12	14	12	13	11	11	11	13	11	12	13	12	12	12	12	12	14	12	13	14	13	13
Nr of control taken	Line M5, Dir 1	1	1	3	15	15	15	17	18	17	1	1	3	15	15	15	17	17	16	1	1	3	15	15	15	17	18	17
	Line M5, Dir 2	1	1	4	15	15	15	17	18	17	0	1	2	15	15	15	17	17	16	1	1	4	15	15	15	17	18	17
	Line M7, Dir 1	2	2	5	16	16	16	19	22	20	0	1	3	16	16	16	18	18	17	2	2	5	16	16	16	19	21	20
	Line M7, Dir 2	1	2	3	16	16	16	18	18	17	1	1	3	16	16	16	18	19	18	1	2	3	16	16	16	18	18	17
Average generalized travel time per passenger (min)		39	40	41	43	40	41	43	41	41	43	43	44	47	43	44	47	44	44	42	43	45	48	43	45	48	44	45
Regular trip (CoV < 0.21) (% trips)	511	98%	93%	94%	99%	100%	100%	99%	100%	100%	88%	88%	91%	51%	100%	100%	52%	100%	100%	86%	87%	92%	97%	100%	100%	98%	100%	100%
	706	100%	99%	99%	91%	98%	99%	91%	98%	99%	92%	93%	94%	90%	100%	100%	90%	100%	100%	94%	96%	96%	100%	100%	100%	96%	100%	100%
	712	100%	97%	94%	98%	99%	100%	97%	95%	100%	87%	89%	84%	67%	100%	100%	63%	99%	100%	80%	89%	89%	93%	100%	100%	95%	97%	90%
	2506	96%	100%	100%	57%	100%	100%	58%	100%	100%	98%	98%	99%	55%	91%	86%	55%	92%	86%	98%	97%	100%	58%	97%	100%	58%	99%	100%
	2706	100%	100%	100%	71%	99%	100%	71%	99%	100%	93%	93%	94%	95%	100%	100%	95%	100%	100%	94%	92%	95%	100%	100%	100%	100%	100%	100%
	2712	93%	99%	96%	33%	100%	100%	35%	100%	100%	81%	88%	82%	57%	89%	96%	86%	93%	99%	91%	88%	97%	36%	91%	100%	38%	100%	100%

The fleet requirement was selected as it is better in capturing the operational cost compared to cycle time. The number of control taken was chosen to represent the driver perspective instead of CoV speed because of the significant performance differences were shown in this factor. Average generalized travel time per passenger concludes the travel time components of the passenger. From the authority perspective, the percentage of the regular trip is shown.

In term of average regularity per line, SH consistently gave better performance in comparison to holding control under a correct speed range. On the other hand, there was only a slight difference between the average regularity obtained from SH and SA. In general, SA obtained a better regularity when the demand was high at the early stops (e.g. Direction 1). These controls also reacted differently to demand condition, when both were having high headway variation. High demand condition in combination with high demand variation magnified the headway variability for SA, while for SH it became an advantage to improve the regularity. It also provided a better regularity compared to SA when a dwelling time at a stop was highly different in comparison to its adjacent stops. Nevertheless, while SH performed relatively better compared to other strategies, all the assessed strategies also had a good regularity performance considering that the resulted CoV headway was lower than 0.21 or equal to LoS A in term of service reliability (TCRP, 2013).

While SH provided a higher regularity, it required more fleet to operate due to obtaining longer cycle time. SH, as well as SA, tended to slow down instead of speeding up as shown in a study by Ampountolas & Kring (2015). The lower the minimum speed limit defined, the longer the cycle time obtained. While holding control and SA have the potential to lengthen the trip time by holding and slowing down, SH combined these characteristics and hence turned out to be the worst strategy in term of fleet requirements.

The similar condition applies to the number of control taken. SA itself was already demanding in term of load given to the drivers. SH added more loads by suggesting the drivers to also hold at the stops**. In this study, SH was able to reduce the speed variation up to 23% by limiting the speed** (Table 4.6, Table 4.10). However, the benefits were not significant as the cost of having at minimum five times more control decisions. Thus, based on the indicators of fleet requirement and number of control taken, holding controls (SB, EH1, EHALL) were better than SH.

In term of generalized travel time, SH obtained a higher value compared to other strategies. SB, in contrast, gave the best value of travel time. The best strategy of SH, SH1.3, obtained up to two minutes of additional perceived travel time compared to SB. The effect of in-vehicle time obtained by SH was larger than the waiting time and holding time reduction it could give.

Good regularity obtained by all strategies was further justified by looking at the regularity adherence from the authority perspective. Based on the stepwise function defined in (Cats, 2014), SB demonstrated that although its regularity was relatively lower compared to other strategies, the resulted headway adherence was still acceptable.

From running the simulation under different scenarios, the characteristics of SH could be further observed. For speed adjustment and SH, in particular, having a tighter schedule gave more impact in regularity compared to increasing demand level. Scheduled trip time affected the arrival time prediction for SH. Performance of SB in regularity also decreased in a tighter schedule, since it lowered the occurrence of early trips and chance to hold. EH1 and EHALL were effective regardless of the quality of scheduling and demand if the control point was located correctly.

Setting the demand level up to 1.35 times reduced the performance of SH in term of increasing cycle time and passenger travel time. In this scenario, holding activity was still high since the actual trip time was much lower than the scheduled trip time. In addition, higher demand added more dwelling time. These added to longer travel time as well as total trip time.

From a practical point of view, SB is considered better in term of not requiring any changes to implement. However, the performance offered by SH and the other headway control strategies need to be considered as well, to decide its worthiness to implement. Furthermore, all parties involved in the public transport operation have to agree on this migration, if the regularity-based operation is required.

Sub-RQ II.2: How was the performance of the control strategies in a single line and a network differ?

An assessment of the network effect in regularity was also conducted in this chapter. One stop at direction 2 was observed due to the following reasons: the scheduled arrival time of the common lines at this stop was close, a high number of passengers originating from this stop, and the common lines do not start from a perfectly regular headway or punctual schedule. The assessment was made based on the CoV headway by considering the arrival of the bus from both lines serving the common stop.

For the strategies tested, low regularity in single line does not ensure the regularity in network perspective. In SH1.3 for example, it showed a great regularity as a single line, while actually, a bunching was happening at the common stop when looking at it based on a network perspective. Therefore, there was an uneven passenger load distribution between the observed common lines, which was not considered when the control strategy was evaluated based on a single line assumption. For the AllGo case, this uneven load did not give a significant impact because the resulted occupancy rate due to this additional load was much lower than the capacity of the operating bus. Otherwise, this effect should be taken into account while designing the control strategies.

From the assessment, it was found that the proposed control strategy could not provide regularity in a network level while the others did. Nonetheless, this result is considered as a coincidence due to differences in the dynamics obtained by each control, considering that none of the control strategies was designed with a network level assumption. Furthermore, regardless the regularity level of the common stops, passengers, in general, will get the benefit from this interaction due to the waiting time reduction at minimum 57 s from the initial planned waiting time in a single line (150 s).

Chapter 5: Discussions

In this chapter, discussions regarding the limitation and result of the study are given. In the first section, there is a discussion on findings of the proposed control strategy. The second and third section contain the discussions of the simulation model utilized in the study and the proposed model.

5.1 Combination of speed-adjustment and holding control strategy

A closer look is given to observe the performance of the combination of speed-adjustment and holding control strategy developed in this study. Table 6.1 captures the findings on speed-adjustment and headway-based holding control strategy in the present and the past studies, to compare with the combined control strategy resulted in this study.

Table 5. 1 Findings comparison

Strategies	Past literature	Present study		
		Speed adjustment – holding control	**Speed adjustment**	**Holding control**
Speed adjustment	The performance depends on the robustness of arrival time prediction (Chen, Adida, & Lin, 2013)	Arrival time prediction is the main determinant of the performance, followed by speed range and demand pattern. Related to the demand pattern, the location of control point affects the effectiveness of this control.	Arrival time prediction is the main determinant of the performance, followed by speed range and demand pattern.	Not relevant.
Holding control	Control point location (Abkowitz & Engelstein, 1984; Eberlein et al., 2001; Hickman, 2009; Furth & Muller, 2009; van Oort, et al., 2012; Cats, O., et al., 2014)		Without holding, speed adjustment sometimes works better than speed adjustment-holding control (i.e. related to demand pattern).	The location of control point affects the effectiveness of this control.
Speed adjustment	Sensitive to a dominant dwelling time (Pilachowski, 2009)	Ability to hold helps to resolve the problem related to a dominant dwelling time. Constantly obtains good regularity and waiting time reduction.	Sensitive if dwelling time at one stop is much different with the dwelling time at its adjacent stops (i.e. related to demand pattern).	Not sensitive
Speed adjustment	With a speed adjustment, the vehicle does not need to hold (Chandrasekar, 2002), but, in general, then it tends to slow down (Ampountolas & Kring, 2015)	The system tends to slow down, and requires a less holding time. However, these add up to a longer total trip time.	The vehicle tends to slow down.	No speed adjustment
Holding control	Holding control lengthens the total trip time but still in a reasonable window (Cats, O., 2011; van der Werff, 2017)		No holding	It lengthens the total trip time in a reasonable manner (less than one minute).

First, the discussion on the factors that affect the regularity performance of each control strategy is given. Chen, Adida, & Lin (2013), in their study suggested that the robustness of the arrival time prediction determines the performance of speed adjustment strategy. High uncertainty during the operation will not influence the performance obtained, as long as the prediction is robust. The same argument is provided in this study.

Arrival time prediction is the input to determine the headway of a vehicle and its following. In speed adjustment, this prediction becomes the indication of whether a vehicle is considered early or not. It is derived into a suggested speed to approach a specific stop. When this prediction is much higher than the actual trip time including the dwelling time, the system will always assume that a vehicle is too early, and hence keep a slow riding time. This also applies to the other way around. For a case where the vehicle always keeps a slow riding time, this can be a disadvantage in using the speed adjustment strategy. Other than having a better total trip time by allowing speeding up, the trip will be lengthened instead. Inaccurate arrival time prediction also affects the regularity built along the route. When the prediction is too high, and a vehicle keeps slowing down, it would suddenly have to speed up until its maximum speed limit, when its following vehicle enters the route as seen in Chapter 4 for SA1.2 and SH1.2. This phenomenon can lead to uneven headway for a certain stop. By contrast, when the prediction matches the actual trip time, the regularity level will remain high. For the developed control, the arrival time prediction is made based on the scheduled trip time. Thus, the quality of scheduling indirectly affects the regularity performance of speed adjustment.

In regards to arrival, time prediction, this study also suggests that speed range is another determinant on the performance of speed adjustment. Speed range becomes a problem when the arrival time prediction is less accurate. Different speed range allows the vehicle to take a speed value, which can be lower or higher than its trip time prediction. This causes irregularity at a stop when the value taken has a large deviation to the trip time prediction.

Related to passenger demand, different findings are captured from the past studies between speed adjustment and holding control. In the studies of holding control, it was argued that the location of control point determines the strategy performance, in which also related to the demand pattern of the passengers (Abkowitz & Engelstein, 1984; Eberlein et al., 2001; Hickman, 2009; Furth & Muller, 2009; van Oort, et al., 2012; Cats, O., et al., 2014). The results of this study on this study agrees with this statement. Instead of creating a better regularity, holding at a stop with low passenger activity worsens the regularity level because it adds variability to the stop.

Meanwhile for speed adjustment, Pilachowski (2009) stated that this strategy is sensitive to an operation with a dominant dwelling time. This study shows that when demand is less varied or only high at the early stops, speed adjustment is indeed capable of providing regularity. The control will simply react similarly to its preceding trips. The demand between stops is not varied. Thus, it is sufficient by controlling only the trip time. In opposite, speed adjustment cannot perform well when the demand varies, for example, when there is a significant difference of dwelling time between one stop and its adjacent stops. Demand level turns out to have a small role in affecting the regularity performance of speed adjustment. Except if, the increase causes a large difference of dwelling time between stops, this factor gives a little effect even for speed adjustment.

In speed adjustment-holding strategy, both demand pattern and the control points give effects to the performance of this strategy. In a condition with a low-varied demand, the holding performed by this strategy adds more variability, which then leads to less regularity. It is possible that in this condition, speed adjustment outperforms the proposed control strategy. Oppositely, when the demand is highly varied, holding supports the speed adjustment-holding strategy to work better and even reduces the headway variability.

Among arrival time prediction, speed range and demand pattern, this study argues that the first is the most important factor in determining the performance of speed adjustment-holding as well as speed adjustment. When the prediction is not robust, then the effects from the latter factors become more significant.

Speed adjustment was expected to give the ability of speeding up when the vehicles are late. It is also potential to reduce the holding time at the station, which possibly increases annoyance to the passengers (Chandrasekar, 2002). However, Ampountolas & Kring (2015) showed in their study that the speed adjustment tends to slow down the vehicle to reach a regularity performance. This outcome is also shown in this study. Most of the time, the vehicles was slowing down when speed adjustment and speed adjustment-holding was applied. Thus, in overall, these strategies resulted in a longer total trip time. By combining the strategies, speed adjustment-holding strategy shows how it could significantly reduce the holding time by replacing it with slowing down on the route. However, when the vehicles perceive that it is still too early, the vehicle will perform both slowing down and holding, which leads to even longer total trip time compared to other strategies.

The combination of speed adjustment and holding control strategy in the present study was derived from the idea that with this combination, both controls will cover the flaws of each other. The findings and discussions from this study, nevertheless, demonstrate that by combining these controls, not only the strengths are combined, but also the weaknesses. Speed adjustment-holding control is indeed capable to cope with demand variability that becomes a problem to speed adjustment. While at the same time, the location of controls for this strategy should be selected with cautions.

5.2 Simplifications and model limitations

5.2.1 Simplifications in simulation

This study relies on simulation for the assessment phase. While simulation is used to reproduce the actual operation, there are several simplifications and limitations taken, which might reduce the realness of the result.

1. Driver behavior

   In the simulation, the driver behavior is not captured. When this aspect is ignored, the factors below may be less accurate.

   Riding time between stops

   The simulation determines the riding time between stops based on a predefined trip time distribution. In reality, the trip time distribution is affected by the characteristics of the operations, either the timetable or the control strategy applied. An example is seen in this study from the AllGo network case, which applies a schedule-based holding. The speed distribution derived from the empirical data shows a slowing down pattern every time a bus is approaching a control point stop. This distribution indicates that bus drivers behave based on the control strategy applied, knowing that they are professional and trained drivers. The riding time pattern between stops should be different when different control is applied.

   Dispatch from the stop

   In a schedule-based practice, an operator usually defines a punctuality window to classify earliness and lateness. As for the lateness, the boundaries applied could be minutes after the scheduled departure time. In the actual operation, the drivers might delay the trip departure for a few minutes, due to a coffee break or changing shift. It is allowable in the

AllGo network since delay up to 120 s is still considered as on-time by definition. This usually happens in the first stop or stop that allows driver change. This kind of delay is not captured in the simulation.

By contrast, in practice, the bus driver would skip the stop directly when there is no passenger to board or alight at a stop. The simulation models the dwelling time based on a linear equation. Thus, there is a constant in the function, which forces the bus to have a minimum dwelling time at all stops, regardless of the number of passengers to board or alight. In the situation where the demand is low, but the schedule is tight, this simplification may underestimate the performance of holding control because the earliness has been filled by the minimum dwelling time.

2. Regular dispatch from the terminal

   This simplification is related to the first aspect discussed in driver behavior. Other than the driver, it is also possible that the fleet is coming late to the terminal due to vehicle chaining. However, in this study, a simplification was made by assigning different fleet for a different trip. Thus, the result from simulation will overestimate the regularity at the terminal, which is always punctual based on the scheduled arrival time. This simplification is done for all strategies. Thus, the source of irregularity at the first stop is only from the variation of dwelling time.

5.2.2 Limitations in the approach

5.2.2.1 Limited number of interviewees

The interview is one of the approaches taken in this study, to give the additional point of view in the strategy. However, the interview itself was only conducted with few numbers of people from the operators, which might induce bias in the result. The time limitation is also a reason behind this limitation because the interview is not the main approach taken for this study.

5.3 Limitations in the proposed control strategy

Besides simplification in the simulation, the proposed control strategy also has its limitation. This part describes the limitation of the proposed control strategy and its effect on strategy performance.

5.3.1 Event-based concept

In general, the limitation of the proposed control strategy is due to its event-based concept. With this concept, there is a real-time information exchange between the vehicles; however, the information will be transmitted, only after a certain event happens. This procedure affects several aspects in the way the speed adjustment works in this study.

1. Limited arrival time prediction based on the scheduled trip time between stops
   In the developed control strategy, the arrival time is derived based on a scheduled trip time between stops. With an event-based concept, it is only possible to know the vehicle state in term of its arrival and departure time at a certain stop. Consequently, it becomes difficult to predict the arrival time of a vehicle at a stop. The only way to predict it is by referring to the historical data or in this case the scheduled trip time between stops. This prediction combined with the updated information on the actual arrival time of vehicle; produce the arrival time prediction to be considered in determining the headway status. This assumption is less accurate since the trip time of each vehicle can be much different as the control strategy modifies it to fulfil the even headway requirement. A misjudgment of the

headway status subsequently affects the control decision and the dynamic of the following trips in general.

2. Discrete control decision

   Control decision is much related to the information of arrival time prediction. Since the strategy works in event-based (i.e. departing and arriving), it is not possible to change the control decision on speed adjustment between these two states. If the arrival time prediction is roughly the same with the actual arrival time, there is no problem in applying discrete control decision. When it is not, the resulted headway will be, on the other hand, becomes uneven.

   An illustration on this situation is as followed. When a vehicle k decides its speed to ride from Stop 2 to Stop 3, it recognizes that vehicle $k + 1$ is far behind it. Therefore, vehicle k decides to slow down so that the headway to vehicle $k - 1$ and $k + 1$ becomes more even. During the ride of vehicle k from Stop 2 to Stop 3, it is possible that vehicle $k + 1$ is speeding up to catch vehicle k, because from the perspective of vehicle $k + 1$, it is much late compared to vehicle k. Both vehicles are not aware of each other "speed status" during the drive. As a result, the headway between vehicle k and vehicle $k + 1$ becomes small, while the headway between vehicle $k - 1$ and k , as well as $k + 1$ and $k + 2$, becomes larger.

   If it is possible to exchange the information and revise the decision during the ride, both vehicles would know that instead of getting the desired headway, their headways are getting closer. As a result, they can revise their decision so that they would still have an even headway when arriving at the stops.

Instead of event-based concept, the time-based concept seems more suitable to allow a more robust arrival time prediction. This concept allows us to know what is happening at each time step. Additional information such as vehicle position and speed can be given. It enables the system to be aware of changes happening on the other vehicles as the result of the control applied. The same information can be processed to be a more accurate arrival time prediction.

5.3.2 Reliance on driver compliance

The results in Chapter 4 show how good the speed adjustment-holding strategy is to give a regularity performance. Applying speed adjustment means reducing the possibility of uncertainty during operation, particularly, in trip time variation. Thus, it is reasonable that the regularity becomes low. However, this result also comes with the assumption that the drivers fully comply to the control suggestion. In practice, it is not possible to have this condition. Moreover, knowing that in speed adjustment, the driver is given control decision frequently to achieve the desired headway. Thus, there is a higher chance of incompliance when applying the proposed control strategy. There are two possibilities of incompliance of driver in the proposed strategy. The first is when the driver completely ignores the control suggestion. Secondly is when the driver cannot follow the suggestion perfectly.

However, for an event-based concept utilized by the proposed strategy in this study, the effect on driver incompliance might be low. When a vehicle disregards the control given, its headway target will fail to achieve. However, this will not affect the arrival time prediction made by its preceding and succeeding vehicle. Remember that the prediction is made based on scheduled trip time and will be adjusted once there is an update of an arrival and departure state of another vehicle. Thus, other vehicles can compensate this incompliance.

Still, in this study, the issue on incompliance was not investigated. Although it seems possible to rely on other vehicles' compliance to get a low regularity, it is unknown to what extent this incompliance can be handled.

5.3.3 The system runs in a segregated lane

Another assumption taken in this study is that the system is running in a separated lane. By having this assumption, two factors are ignored. First, is the disturbance from the traffic and other modes to the controlled bus. Second, the effect of speed adjustment on the traffic and other modes.

There are at least two benefits occur by ignoring the first factor. Dedicated lane removes the uncertainties from the traffic and hence allows the system to have a more accurate arrival time prediction. In addition, it allows the vehicle to follow the suggestion perfectly if the driver fully complies. When the system runs on a mixed traffic condition, the system would not have these advantages anymore. However, it could not be verified how much the effect would be since this study did not test this condition. Several possibilities to occur are discussed as follows.

Disturbances from the traffic and other modes add trip time uncertainties. For arrival time prediction, the accuracy is highly determined by the robustness of the prediction method. The prediction method used in this study might be less reliable for this condition. However, by using a frequently updated prediction method, it seems possible to get high accuracy in arrival time prediction regardless of the traffic condition. Still, it would be difficult for the drivers to follow perfectly the speed suggestion given. As a headway-based control, this problem might be resolved by relying on the perfectness of the control measures of other vehicles. Another possibility is to perform more controls at the station. Thus, the combined control might act more like a holding control-only strategy.

Assume that the first factor is not a problem anymore, another problem occurs as this strategy might affect its surrounding traffic. When a bus is frequently adjusting its speed, this might induce annoyance for the closest vehicles since these vehicles might need to adjust their speed as well. Like a domino effect, these vehicles would then affect other vehicles nearby. From a wider view, the accumulation of speed changing effect would disrupt the traffic flow and lead to a more congested situation. Due to this problem, it seems better to keep the proposed control strategy or speed adjustment strategy in general for a system with a dedicated lane only.

5.3.4 Built upon a single line assumption

Development of the control strategy based on a single line assumption is a choice taken at the beginning due to time restriction. The strategy was developed based on a single line assumption; however, the network perspective was given for the evaluation part. As the results, even though the combination of speed adjustment and holding control gives a low regularity for certain stops, it performs badly when network perspective is taken into consideration. Holding control and speed adjustment, on the other hand, gives a good result in this indicator. Regardless of this outcome, it may be coincidental and only applied for this particular case since the control strategy itself was not designed based on network perspective

The question is then, whether it is necessary to take network assumption in the control strategy development. From Chapter 4, it is known that irregularity in common stops leads to unbalance passenger load to the associated common lines. Thus, the answer is, it depends on how high the demand rate is to make the passenger load ratio becomes significant.

In the AllGo network, there are seven common stops exist between the two lines. From all OD pairs in common stops, only one OD has a quite high number of passenger demand (29 passengers per hour). OD passenger in other common stops are either very low or is concentrated to one line only, for example, due to shorter travel time. For passengers, the significant effect from the irregularity is more on comfort level. Having two lines serve their destination is an advantage already regardless the amount of waiting time reduction it could give. However, if the effect is more on comfort, this might not be the case for AllGo, which has a high capacity bus.

Other considerations are the location of the common stop and the corresponding occupancy pattern. The common stop example in this study is the fourth last stop for both lines. On one side, it becomes interesting to observe, knowing that the irregularity must have been developed at this stop. On the other side, the impact on passenger becomes less. In the AllGo network, after the example common stop, the occupancy of the bus starts decreasing significantly as most passengers alighting (Appendix A). The impact on comfort level becomes less relevant than if an overcrowding situation occurs.

From this discussion, the author agrees that the network perspective is necessary to take into account after considering several conditions including high demand level and high occupancy between OD common stops pair.

Nevertheless, in this study, the interaction between lines to take into account is only limited to the common lines interaction. The interaction between lines can be found in a different form such as intersection at stop or junction. For this condition, considering the network perspective might be required to improve the operation. When there is an intersection at a stop, it would be beneficial to consider this interaction so that the transferability between the intersect lines could be optimized. The same condition applied for the intersection at the junction. Considering this interaction would enable the optimization of the signal given in the traffic signal priority system if this type of control is applied in the corresponding network.

Chapter 6: Conclusions and Recommendations

From past studies concerning on headway-based control strategy, different characteristics shown by each strategy makes it becomes interesting to see how the performance will be upgraded when different measures are combined. Furthermore, many operators still operate a high-frequency transit system based on punctuality, despite the fact that theoretically, regularity is a more suitable indicator to apply. With respect to the practical perspective, the past studies on headway-based control strategy also often ignored the interest of driver and effect of the network, in assessing the performance.

The author conducted this study to answer the questions arisen from these problems by using a case study of AllGo network in Almere, the Netherlands. This chapter sums up the study by providing the conclusions in Section 6.1, the recommendations in Section 6.2 and followed by the reflections in Section 6.3.

6.1 Conclusions

This study constructs a combination of different control strategies in a rule-based approach to achieve the objective, "***to develop a headway control strategy based on a combination of several measures and to evaluate it from a practical point of view***". The scope of the study is limited to a high-frequency transit system only. When the majority of past studies concerned more on the reliability aspect of the control strategy, this study provides an additional point of view in practicality.

A combination of speed adjustment and holding control strategy was built by first understanding the attributes of each strategy. The author conducted a literature review to gain knowledge of the control strategies from a theoretical point of view. Subsequently, the author conducted several interviews with staffs from a bus operator, Keolis, to complete the knowledge from the practical perspective. The findings from past studies showed that headway-based control strategy is a suitable control for a high-frequency transit system. Yet, practically, several challenges occur to implement this concept in real operation. Therefore, different perspectives were selected as the basis for evaluating the proposed control strategy in the context of service reliability as well as practicality. The interest of the operator, the driver, the passenger, and the authority were considered along with the network effect. Additionally, the author selected three other control strategies to allow the performance comparison with proposed strategies. The selected control strategies are schedule-based holding control, headway-based holding control, and speed adjustment.

In this study, the author describes the conceptual framework of speed adjustment-holding control strategy in an event-based concept. Speed adjustment becomes the main control decision, aiming at a reduction in the holding time. Holding control is available to take if the system still needs to slow down. The evaluation was carried out in a mesoscopic simulation model, BusMezzo, to allow the model runs with a vehicle level of detail, in a real-time manner without costing large simulation time. The AllGo network in Almere was taken as the study case for the assessment.

6.1.1 Characterizing different control strategies

The findings from the study show that each control strategy has a certain aspect that highly influences the resulted regularity. Quality of scheduling is a main determinant of the schedule-based holding control performance. When the schedule is tighter, this control does not work effectively anymore. This result validates the findings from the past literature. The headway-based holding control, as expected is not sensitive to the schedule, as it is working based on headway. However, the performance is less effective when the control point is not located correctly. In some cases, when the demand is low and uniform, headway-based holding worsens the regularity. Meanwhile, this characteristic of demand is beneficial for a schedule-based holding strategy to be applied. This result also gives evidence for the findings in the past literature.

With respect to speed adjustment-holding control strategy as well as speed adjustment, there are three different aspects, which affect its regularity performance. These aspects are **the arrival time prediction, speed range and demand pattern.** From three factors above, speed adjustment-holding and speed adjustment strategies are most sensitive to the arrival time prediction. When the prediction is less accurate or the actual trip time cannot fulfil the suggestion perfectly, the effect from the other two factors become more important. Looking closer to the combination of speed adjustment and holding control strategy, the findings also suggest that combining these strategies means combining both the strengths and the drawbacks of each control.

6.1.2 Implementation of different control strategies: selecting control strategies based on the tradeoffs

The result from this study shows that **speed adjustment-holding strategy gives 11-63% improvement in regularity performance** compared to holding control strategies. However, it requires **8 – 10% more fleet** to operate if the speed limit is defined in a lower range. Speed adjustment-holding strategy is more problematic for the drivers. **Speed adjustment-holding strategy is able to reduce the speed variation up to 23%** but is very demanding as it requires **a minimum five times more control decisions**, in which implying much higher workload for the drivers and gives a possibly higher chance of the drivers to ignore it. This problem is also applied for speed adjustment. With speed adjustment-holding and speed adjustment, the system tends to slow down. Speed adjustment-holding obtains a **higher generalized travel time by adding a minimum 1-2 minutes**, due to much longer riding times obtained. Speed adjustment-holding strategy is better in providing regularity but is outperformed in the other aspects.

If the driver's comfort is the main concern, holding control is better, by requiring 67% fewer control measures. In addition, if operational cost is the focus, **holding control** will be the best strategy by **improving the number of fleet requirement** around 8-9% compared to speed adjustment, and speed adjustment-holding strategy, except the speed range in the latter strategies, is set in a higher value.

Other than concerning only at the operators and the drivers, one might argue that it is better to focus on the efficiency given by the service by also considering the benefit of providing a better service. Thus, related to the regularity or passenger perspective. The study shows that schedule-based holding control strategy obtains the lowest generalized travel time although the difference is only around 1–4%, or within one to two minutes. The practitioner argues that passengers may not be aware of this slight difference, and hence it can be ignored. Thus, **all strategies are acceptable from the perspective of the passengers.** For an authority, concessionaires seem to be a potential constraint in implementing the regularity-based operation. With a regularity-based indicator used in this study, speed adjustment-holding, speed adjustment as well as the holding strategies shown to be able in offering high regularity adherence and potential in the implementation of the regularity-based transit operation.

To sum up, **in this study case, speed adjustment-holding strategy is better in providing service regularity, while holding control is preferable in term of operational cost and workload to the drivers**. In the end, the decision on which control strategy to apply depends on the agreement between the involved stakeholders, which aspect should be prioritized and which aspect can be compromised.

6.1.3 Implementation of different control strategies: Selecting control strategies based on the line characteristics

Line characteristic is the main reasoning behind the different performance of the strategies shown in this study. Figure 6.1 summarizes these characteristics in a scheme to give an initial knowledge on when a control strategy is preferable to implement by considering its line characteristics. In the figure, three conditions are mentioned including early trips, high demand variation, and limited arrival time prediction.

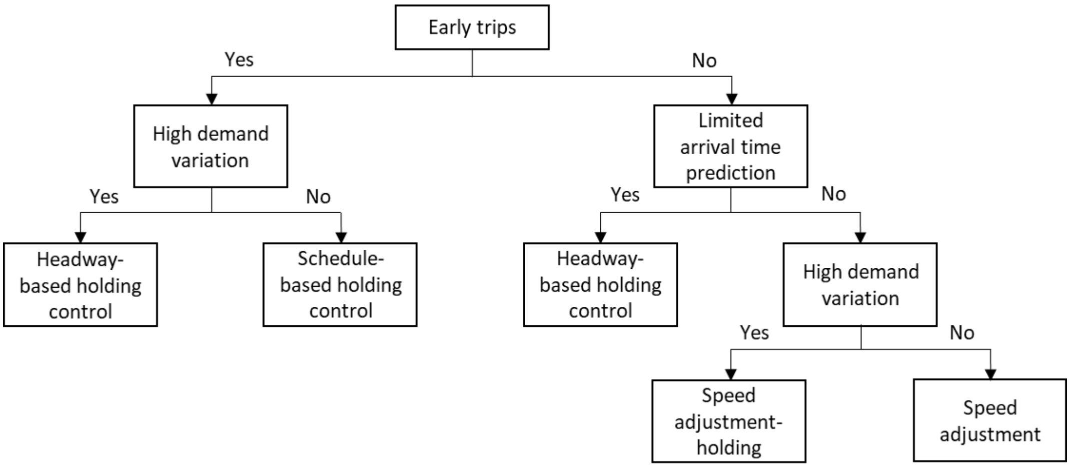

Figure 6. 1 Indication of selecting different control strategies based on the line characteristics

Early trip is defined as a condition where the vehicle is ahead of schedule. By having this condition, it is possible to only modify the timetable instead of applying control strategy. However, the two solutions are on a different level. The first is on a tactical level and static, while the second is on an operational level and dynamic. As a tactical level solution, modifying timetable would involve more stakeholders. Furthermore, it requires changes on a broader level (e.g. timetable planning, timetable information). In addition, the timetable cannot cope with the dynamic happening during the operation (e.g. higher demand level). This solution is applicable but is not relevant for a longer-term period. By applying a control strategy, the changes are made at a local level, only when it is needed. In addition, it is also able to react dynamically based on the situation during the operation. Thus, applying control strategies as a solution to the early trips problem is selected for this scheme.

High demand variation is described as the condition where dwelling activity is distributed along the route (not concentrated at the early stop(s)) and highly varied between the adjacent stops.

Limited arrival time prediction is defined as the condition where the prediction method of arrival time is not robust and less reliable in generating the accurate arrival time prediction. In this study, the prediction method is referring to the scheduled trip time between stops, thus, can be considered as limited. In some conditions, it obtains a good regularity because the allocated trip time is somehow matched with the actual trip time. However, when it is not matched, the performance could deteriorate significantly. Moreover, in the study, there is no assessment of performance in term of trip time variation. Thus, the author argues that the respective situation can be considered as limited arrival time prediction as well, knowing that it would be difficult to have a robust prediction.

Based on line characteristics, **speed adjustment-holding control strategy requires more conditions to verify before being justified to implement.** In contrast, headway-based holding control is sufficient to perform well under different conditions without many requirements, which would make it more favorable to implement.

6.1.4 Performance of control strategies in a network level

This study also considered the network impact on the tested control strategies. There are several corridors with common lines found, which allowed the assessment for this aspect. The results showed that there is a potential for the uneven loading occurs when the strategy is not built upon a network perspective. This condition can lead to overloading situation for one line. However, the effect is significant only if the demand level and occupancy rate of the vehicle are high between the OD of the common stops pair. These characteristics of line justify whether network level assumption is necessary to consider during the construction of control strategy.

The speed-adjustment holding strategy developed in this study performed worse in a network context in term of regularity, while the other strategies still gave high regularity level. These results nevertheless might be coincidence, since all control strategies were designed with a single line assumption. Regardless of the regularity level, in general, the interaction between common lines is beneficial as it reduces the waiting time at stop compared to the single line condition.

6.2 Recommendations

6.2.1 Recommendation for further research

The present study has managed to achieve its objective and answer its main research question, although some limitations still exist. These limitations can be developed into directions for future research as followed.

1. Investigate the perception of the driver toward the control strategy.
   This study gives a prediction of preferable strategies for the drivers, which is derived from the indicator given in the past studies. However, this prediction is not verified by a further evaluation from the drivers itself. For the further research, the insight on this topic research will be very valuable for several reasons. First, it provides the information to develop a driver-friendly control strategy or to develop the right method for driver training in practice. The insight would also be useful to derive design requirement for the user interface in delivering the control advice. A revealed or stated choice experiment are the possible approaches to conduct this topic recommendation.
2. Experiment on driver behavior during operation
   While the previous recommendation is on the preference of the drivers, this suggestion is more on exploring the driver behavior during the operation to capture the pattern and uncertainty occurred from their behavior. This study showed that in the empirical data analysis, a certain pattern shown in speed profile with respect to the implemented control strategy. This kind of behavior is interesting to study in future research to derive a variable

of driver behavior. This variable can be incorporated into the simulation model, to better model the reality and do not misestimate the performance of the control strategy.

3. Develop a time-based simulation model

   As discussed in this study, the potential of the proposed strategy seems limited in an event-based simulation model. Thus, it is recommended to develop a further study by building the model on a timely basis. With this model, all information can be collected in a more continuous manner. Therefore, the control decision can be taken and revised more frequently. It is interesting to see how the effectiveness of combined speed adjustment-holding control strategy differs with this concept, in comparison to the result shown in this study.
4. Develop a robust arrival time prediction method

   This study shows the effectiveness of suitability between the predicted and actual arrival time in influencing the performance of the proposed strategy. Therefore, it is important to develop a robust arrival time prediction method, which considers the dynamic changes during the operation. This method is then assessed by its accuracy to predict the actual arrival time under different uncertain conditions including, high variability in the dwelling time and mix-traffic condition. It is also interesting to consider the strategies in the perspective of driverless operations.
5. The inclusion of a network perspective in the modelling stage

   The study concludes that the network perspective is not necessary to consider in developing a control strategy for common lines interaction. An exception is made if the demand between common stops OD pair is high and has the potency to cause an overload condition. For this situation, the author suggests to develop a further study by taking into account network perspective in designing a control strategy. One main aspect to include in the study is the joint headway of the common lines. Moreover, it is also important to think of a good transition from the non-common lines section to the common lines section, and vice versa.
6. Involve more interviewees

   In the future study, it is recommended to involve more interviewees to reduce bias in the evaluation part of the strategy. The interviews could involve different people from different backgrounds, for example, the passengers, the drivers, people from the authorities, and people from the operators.

6.2.2 Practical recommendations

To implement the regularity-based bus operation, additional tasks including regulation, operational planning and the supporting system should be considered as extra costs to take into account before implementing the strategy (Appendix E). This “migration cost” was not considered nor assessed in this study. Thus, this part gives the practical recommendation in implementing speed adjustment-control strategy or regularity-based bus operation in general. This section is divided into two parts. The first part of this section provides a practical recommendation specifically for Keolis, as the operator behind the AllGo network. The second part of this section gives a practical recommendation of the implementation from a general perspective.

6.2.2.1 Implementing regularity-based bus operation in the AllGo network

As a system operated with a dedicated lane, speed adjustment and the proposed control were expected to be working well in this network. However, the result from this study shows that the schedule-based holding strategy outperforms the two aforementioned strategies in more aspects. The same condition applied for headway-based holding control. This actually can be predicted already, considering the high punctuality that the system currently has. AllGo network in particular also has the characteristics that support the performance of schedule-based holding control (e.g. good quality of scheduling).

To change a system into regularity-based operation, the problem is not only related to the control strategy itself but also related to the strategic planning and requires changes in every aspect of the public transport system. Hence, for a dedicated lane bus operation such as Almere, it is better to keep the punctuality high so that the regularity can be achieved, rather than changing the whole system into regularity, while the gain is insignificant.

Apart from the case study that was evaluated in this study, it is worth to note that the current evaluation only considered two out of seven lines in AllGo network. It is recommended to also investigate the performance of the control strategies in the other lines, or perhaps in the other concessionaire of Keolis, which may result in different results compared to one obtained from the present study.

6.2.2.1 Implementing regularity-based bus operation in general

Before implementing a headway-based control strategy, the author suggests to follow the steps given in (Cats O., n.d.) as mentioned in Chapter 1. First of all, idea generation and lab/desk test as having been conducted in this study, are required as the first and the second step for the implementation. These steps give the initial idea of the urgency for implementing the regularity-based operation. With the scheme given in this study, the operator can first determine whether the regularity-based operation is necessary. Then, a field trial and data collection are needed, along with the analyses. Hence, in the end, the headway-based control strategy could be implemented in the system.

From step one, two, three and four, the operator should consider several steps if it is found that a headway-based control strategy is really necessary. At least, there are three different areas to focus on, as listed below based on its priority.

1. Regulation

Regulation is the first thing to consider, concerning its legality and possibility to give constraint in the implementation. Before moving into a regularity-based operation, the actors involved in the regulation of the public transport system should agree on the urgency of applying this concept. Afterwards, it should be discussed how the regulation can be modified to support the implementation.
With respect to the authority, the indicators applied in this study can be used as a reference to develop the new measurement for the concessionaire. The additional thing to consider is to what extent the reward and penalty should be applied. Meanwhile, the regulation related to the driver employment should be discussed based on the proposed change in operational planning in the next point.

2. Operational planning

Operational planning is the second thing to consider, understanding that the dynamic system of headway-based concept will give a significant impact on this area. The existence of the schedule can be a constraint to a regularity-based operation. A suggestion for this problem is to apply a peak hour block since the possible time to have a regularity-based operation is during the peak hour. For fleet allocation, there is a number of fleets reserved in each peak hour block, which are ready to operate every time it is needed. This fleet is paired with a driver, which is also scheduled for peak hour block.

It seems better to have these pairs centralized at one location, to ease the procedure. The number of fleet and driver required for each block is derived based on the desired headway and period of peak hour. During the peak hour block, the fleet and driver will be dynamically dispatched based on the needs for the operation and their availability. This concept is similar to what exists in on-demand transport service.

Having this block can also be a solution to the problem with the driver's requirement for scheduling. Based on the regulation of driver organization, the problem that might occur in the implementation of regularity-based transit operation is related to the maximum continuous working hours and break time. In regularity-based operation, having a certain amount of break or working time is difficult to determine in the beginning since the operation will be more dynamic. Thus, it is better to propose an additional contract for driving in the peak hour block. The drivers might get a higher salary for driving in this block, to compensate the uncertain rest time during the regularity-based operation. When a driver is having a peak hour block and followed by regular scheduling afterwards, it is better to give a gap for several hours between the two schedules, knowing that the end of peak hour block could vary. Moreover, the operators should re-discuss the result from this planning with the driver organization to assure that it satisfies the existing regulation.

3. Supporting system

Supporting system is the least complex thing to think of, considering that it only involves the internal organization of the operator. This consists of the ICT system, passenger and drivers related.

ICT system

Real-time information is crucial for regularity-based transit operation. On the other hand, not every operator could easily provide an advanced ICT system at once. Thus, the ICT system could be adopted in stages. However, the operator should understand to what limit the features of each stage could be utilized in term of the control strategies. The author recommends the adaptation of the ICT system as followed.

- Stage 1: vehicle/infrastructure-to-central operator communication
  No need vehicle-to-vehicle (V2V) nor vehicle-to-infrastructure (V2I) information exchange, but communication between the vehicle and the central operator is required. Control is decentralized on each vehicle, by fully relying on the timetable. The central operator regularly monitors the operation, to check the adherence of the schedule, and possibly process and provide the updated schedule due to changes during the operation. It also controls the infrastructure. Thus, the communication from the infrastructure to the vehicle is one-way communication only.
  Considering that the central operator has all the information about the vehicles, it is actually possible to already apply a headway-based control strategy as a centralized control. However, the workload will be much heavier considering the number of vehicles involved. It is also more prone to a system breakdown, once there is an error in the central operator's system.
  Possible control: schedule-based holding control

- Stage 2: Stage 1 + V2I communication
  This stage enables the information exchange between the vehicle and the traffic signal. Thus, the infrastructure can prioritize or hold the vehicle on the route, depends on the vehicle state.
  Possible control: schedule-based holding control with traffic signal priority

- Stage 3: discrete communication in Stage 1 or 2 + discrete V2V communication
  This stage allows the communication between vehicles in a discrete manner (e.g. only information at the stops, not continuous). V2V communication enables the vehicle to determine the headway value, which is valuable in deriving the suggestion for a headway-based control strategy in a decentralized manner. Thus, it does not burden the central system. The central operator would in charge only as a monitoring system. However, as found in this study, discrete V2V communication cannot always support a robust arrival time prediction. Thus, speed adjustment is only justified to apply when the operator sure that they have a robust prediction.
  Possible control: headway-based holding control with or without traffic signal priority

- Stage 4: Stage 3 with a continuous information exchange
  The similar stage to Stage 3, with the difference that now the information is transmitted in a smaller time steps or continuously. This condition allows a more robust arrival time prediction.
  Possible control: speed adjustment-holding or speed adjustment, with or without traffic signal priority

- Stage 5: Stage 4 + communication with other road users
  For a transit system that operates in a mixed-traffic condition, Stage 4 is sufficient to support speed adjustment-holding or speed adjustment strategy as long as it has a robust arrival time prediction. However, in the future, it is also possible to have communication between the buses and other road users. This interaction could enhance the effectiveness of the control strategy as well as the performance level of the traffic in general. This integration is known as C-ITS when all road users are interacting with each other and cooperating to reach the optimal condition.
  Possible control: C-ITS or possibly, a driverless system

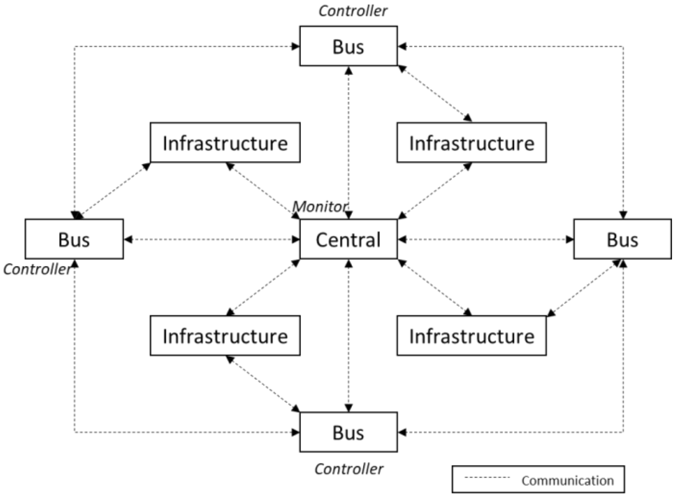

Figure 6. 2 Example of interaction between different actors

Related to the topic in this study of speed adjustment and holding control, it is advisable to update the ICT system into the Stage 3 or possibly 4. For these stages, an illustration of the interaction can be depicted in figure 6.2.

Passenger-related

The most important thing in passenger adaptation is providing information. With a regularity-based operation, the operator should update the information regarding the service frequently, as a substitution of certainty given by a schedule. At the bus stop, the information will always be in term of minute, counting down to the closest vehicle to arrive. A frequent update is also given in the bus, showing the predicted travel time to arrive at each destination stop. This does not require many changes as this is already being applied in public transport operation in general.

Drivers related

First of all, it is important to assure that the drivers have a deep understanding of why they should follow this control strategy.

In the AllGo network, the drivers already work based on a schedule-based holding control. Thus, the adjustment for them might be less difficult considering that, the drivers have been used to work under control strategy. However, training for the driver is still necessary. In this training, it is important to mention the urgency in applying the regularity-based operation concept, the benefits and consequences of performing this control, along with the rules applied in the associated control strategy. A driving simulator as a part of training is also recommended to increase the understanding level of the drivers.

Secondly, to design the user interface of the control with the least possible impact to the driver in term of annoyance.

For the AllGo network, there is already equipment to help the drivers control their operation to comply with the schedule in each bus. This equipment gives a countdown to the departure time from the control point. If the current system is changed into a headway-based holding control, there should not be many changes in the way they drive. It is the counting down system, which will be adjusted into a departure time based on headway. In addition, the drivers do not have to be aware with the schedule, which is also an advantage to relieve their burden. This type of interface is working well in the AllGo network, as indicated from the high level of punctuality in this system. Thus, it is advisable to adopt this kind of interface for the other operations.

Speed adjustment, on the other hand, requires a different treatment. Remember that, the concept of speed adjustment itself restricts the drivers in term of high number of control taken. Thus, great design of user interface in the system is necessary for several reasons: to prevent an annoying feeling on the drivers, to lessen the cognitive workload to the drivers, and to optimize the compliance of the drivers.

A suggestion is to adapt the design interface for the eco-driving guidance system. This system also controls the vehicle speed, but with a different goal of reducing the energy consumption. One suggestion from an interface design on eco-driving guidance suggests to include real-time feedback information to improve the compliance of the drivers towards the guidance system (Beloufa et al., 2017). For speed adjustment strategy, this feedback could be displayed as headway status resulted from the current speed, to indicate whether the vehicle is too early or late. In addition, other than fully relying on the visual or auditory system for design interface, a haptic pedal system could become another option. This system has less potential dangers given the fact that the visual display draws more attention of the drivers away from the road (Jamson , Hibberd, & Merat, 2015).

Another suggestion is to alter the system applied in a car GPS system to warn the drivers when they are exceeding the speed limit in a highway. With this concept, it is possible to let the drivers drive as they wish, but there is an additional warning using a red color indicator or a sound when they deviate from the suggested speed boundary.

Besides designing a preferable guidance interface, reducing the workload during the speed adjustment could also be done by applying the control at few sections only. Thus, the feeling of being over-controlled could be prevented. The speed adjustment could be applied only when the distance from one to another stop is considerably far.

6.3 Reflections

In this section, the author shares the reflection on the research process, which is not directly related to the main research question only. There are two sections of reflection given. The first is a reflection concerning the scope and methodological selection in this study. The second is a reflection, which is related to the execution of the research.

6.3.1 Reflections on the methodological choice of the study

Regarding selection in the methodology, I personally think that simulation is a good method to evaluate the control strategy because it can capture the reality better compared to a deterministic model. To achieve the goal of the study, an addition was included to BusMezzo as the simulation tool of this study. When tried the new simulation for the first time, I was a doubt that it generates the correct output. However, after did several trial and error with different input and tried to derive the process analytically, I finally could be assured that the model works.

6.3.2 Reflections on the execution of the research

A great amount of time during this study was spent to analyze the preliminary data, to model it in the simulation and to do the trial error of the implementation of the proposed control strategy in the simulation. This process has given me the experience to do the same challenge I would face in the future. However, if I were able to start it over again, I would like to focus more on assessing more scenarios and if to capture the difference between strategies based on its efficiency such as a cost-benefit comparison, rather than individual performance indicator only.

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Appendix A: Preliminary Data Analysis

This section analyzed the actual operation of AllGo bus network Almere. The analysis was done per aspects including trip time, demand, and speed for each line direction. As aforementioned, the present study only look at two lines, the Line M5 and M7. The current control strategy applied at this network is the schedule-based holding control at several stops as summarized in table A.1 below.

Table A. 1 Control points of the current AllGo bus network operation

Line	Direction	Number of control point	Nr of stop
M5	1	1	511
M5	2	1	2506
M7	1	2	706 and 712
M7	2	2	2706 and 2712

Trip time

The observed trip time data is fitted into a lognormal distribution with a 95% confidence interval. Most of the actual trip time between stops showed a shorter duration than the scheduled trip time as it was planned based on the 85th percentile as seen in table A.2.

Table A. 2 Actual versus scheduled trip time between stops

Nr Stop	85th Actual TT	Planned TT	Nr Stop	85th Actual TT	Planned TT	Nr Stop	85th Actual TT	Planned TT	Nr Stop	85th Actual TT	Planned TT
501	0	0	**2501**	0	0	**701**	0	0	**2701**	0	0
502	74	109	**2502**	66	66	**702**	74	111	**2702**	65	62
503	52	71	**2503**	61	61	**703**	52	69	**2703**	54	63
504	76	60	**2504**	106	113	**704**	71	60	**2704**	80	115
505	73	103	**2505**	87	124	**705**	75	92	**2705**	60	65
506	56	74	**2506**	74	56	**706**	90	88	**2706**	180	175
507	59	63	**2507**	69	69	**707**	48	49	**2707**	112	77
508	101	60	**2508**	66	87	**708**	84	122	**2708**	85	90
509	64	79	**2509**	76	84	**709**	90	129	**2709**	77	73
510	74	89	**2510**	100	120	**710**	78	95	**2710**	90	132
511	75	72	**2511**	45	57	**711**	92	117	**2711**	84	116
512	46	52	**2512**	56	73	**712**	98	148	**2712**	75	52
513	91	128	**2513**	84	110	**713**	176	176	**2713**	76	81
514	97	103	**2514**	66	120	**714**	58	64	**2714**	78	99
515	60	59	**2515**	50	53	**715**	82	110	**2715**	66	120
516	103	78	**2516**	96	127	**716**	49	58	**2716**	50	54
						717	81	72	**2717**	96	126

However, dwelling time is not designed in the schedule. Thus, by considering the additional time from the dwelling time, the designed trip time is considerably not excessive. Table A.3 demonstrates the actual total trip time distribution per line direction. In the observed data, the total trip time is calculated from the time when the fleet departs from the first stop and ends when the fleet arrives at the last stop. Thus, the total trip time does not include the dwelling time at the first and the last stop.

By looking at table A.2, an observation can be made to the direction 2 of each line. This direction gives a higher total trip time compared to direction 1. A possible reason behind this is due to different location of the control point stops.

Table A.3 Total trip time distribution

Line	Direction	Excluding dwelling time			Including dwelling time		
		Mean	Planned 85th perc.	Actual 85th perc.	Mean	Planned 85th perc.	Actual 85th perc.
M5	1	988	1200	1069	1185	1200	1261
M5	2	981	1200	1040	1231	1200	1326
M7	1	1175	1500	1256	1522	1560	1585
M7	2	1184	1500	1252	1539	1560	1634

In Line M5 direction 1, the control point stops is located further from the first stop (i.e. Stop 511, while it is at 2506 at M5 direction 2). Thus, in this direction, it allows the bus to run earlier when triping to 11 stops before being adjusted to the schedule at the control point if it is still too early. Meanwhile for Line M5 direction 2, the operation will be already adjusted to the schedule at the sixth stop. Hence, its possibility to have early total trip time becomes lower. The same reason applied for Line M7. Although the location of control point in is the same for the two directions, one should consider that in 712 and 2706 (i.e. Station Buiten stop), there is additional time to dwell to allow fleet exchange. It gives an additional holding time, which lower the possibility of direction 2 to have excessive earlier trips after stop 2706. As the result, the overall total trip time in direction 2 is higher than it is in direction 1.

Headway

Figure A.1 below demonstrates the regularity performance of the AllGo bus network. Coefficient of variation (CoV) of the headway distribution is used as the indicator to assess this aspect.

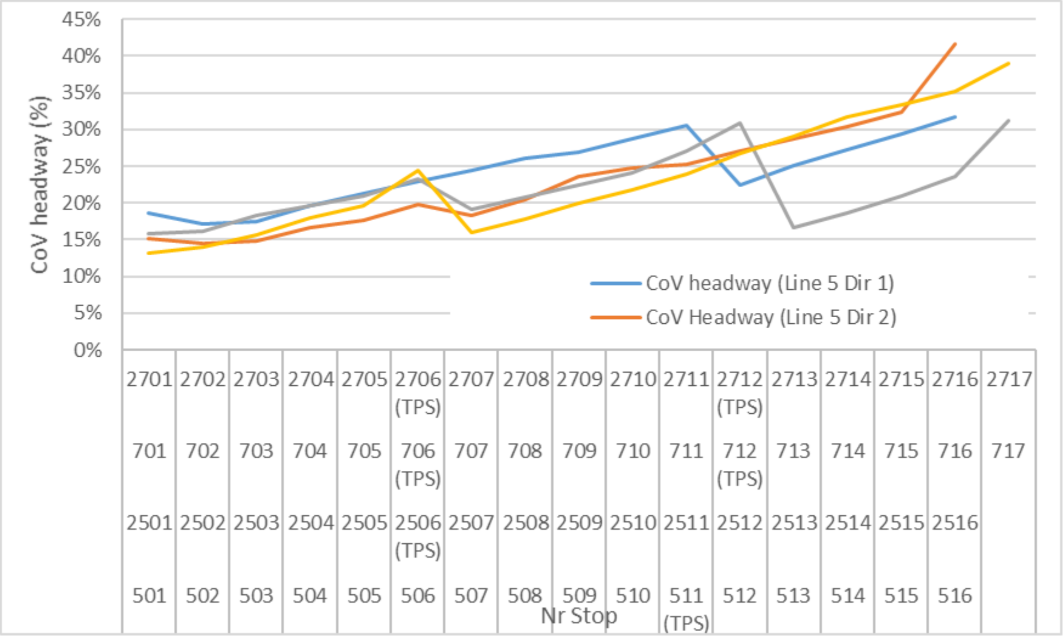


Figure A. 1 CoV headway AllGo network

Punctuality

One of the indicator stated in the concession of Almere is the punctuality at the important transfer points, which subsequently designed as the control points for schedule-based holding control. Figure A.1 depicts the percentage of punctuality at the control points. In Almere operation, a trip is considered early if it departs before the schedule and is considered late if it departs more than 120 seconds from the schedule. Based on this definition, the performance of AllGo network in term of punctuality is considerably high as seen in figure A.1. At maximum, around 13.71 % of the trips stopping at 511 were early, which might be resulted from the incompliance from the drivers.

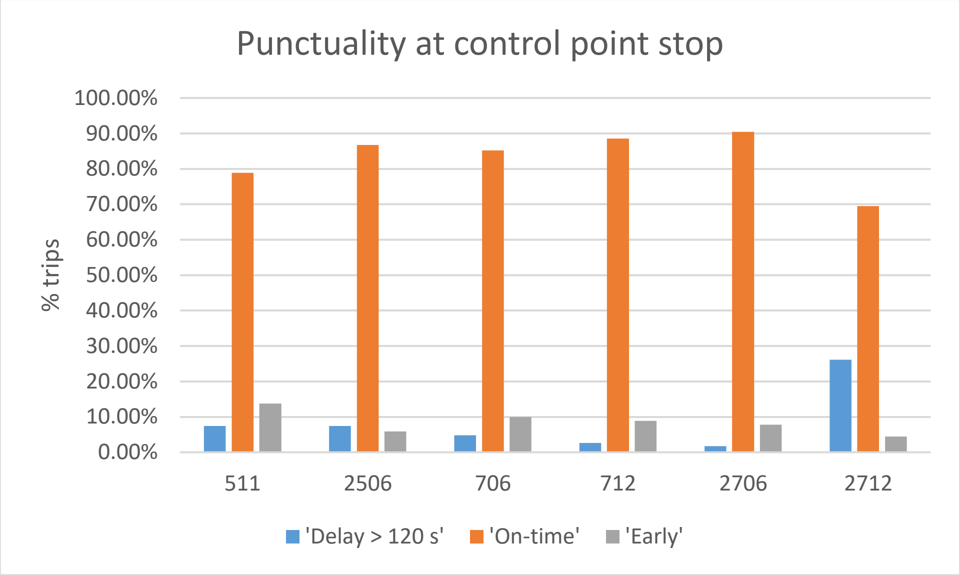


Figure A. 2 Percentage of punctual trips

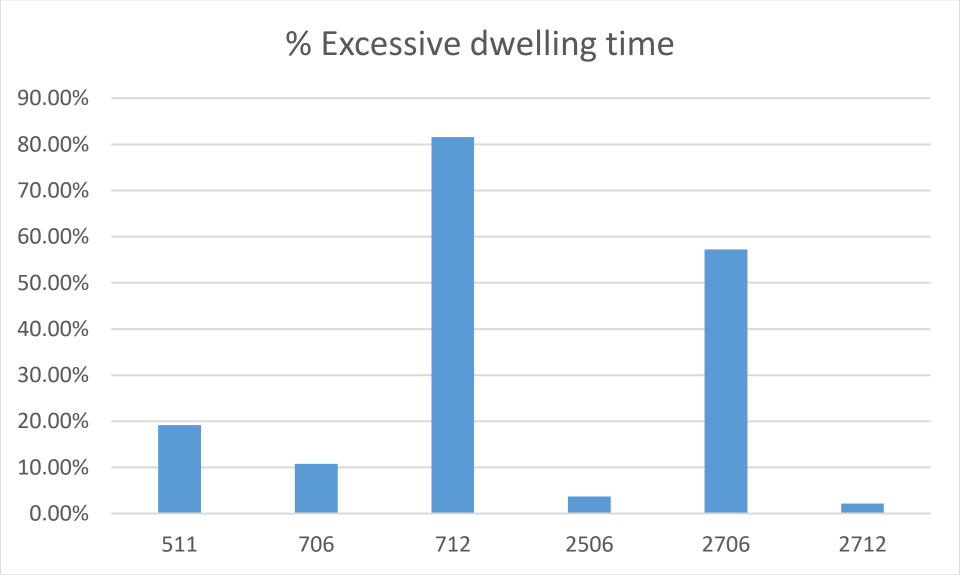


Figure A. 3 Dwelling time at the control points

However, this punctuality has the consequence of excessive dwelling time at the control points. Figure A.2 depicts the percentage of trips at the control points with a dwelling time more than 60 seconds. Most of the trips stopping at 712 and 2706 has a long dwelling time. In default, there is an additional 60 seconds to dwell at these stops. As the result, up to 53% and 12% of the trips had dwelling time even more than 120 seconds as seen in figure A.3. For the passengers, it must be inconvenience to wait this long at the stops.

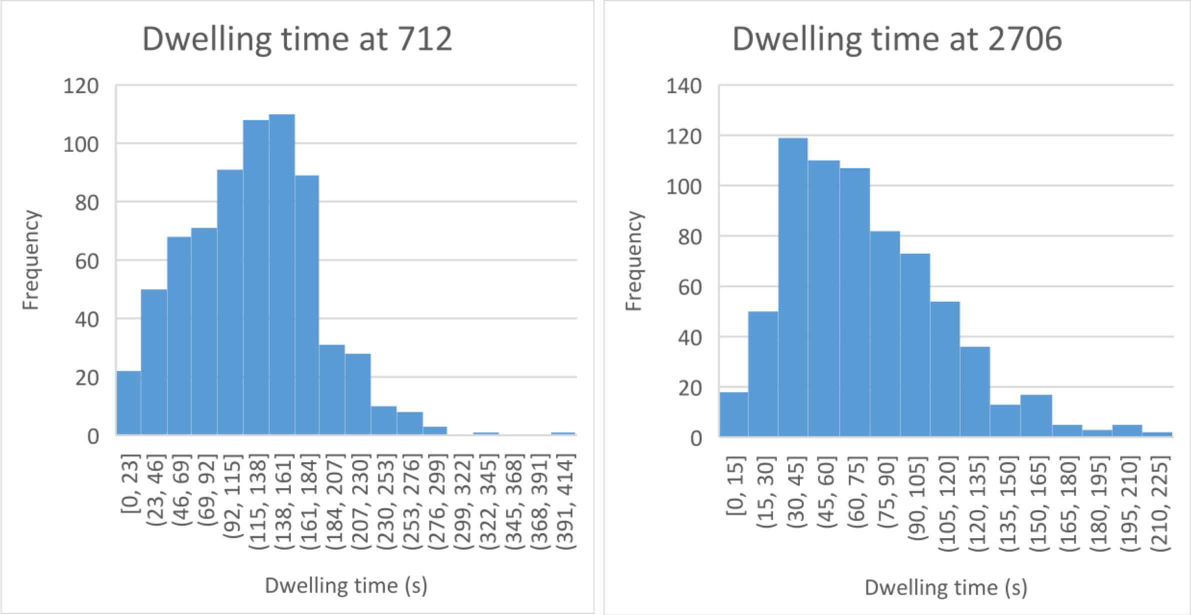
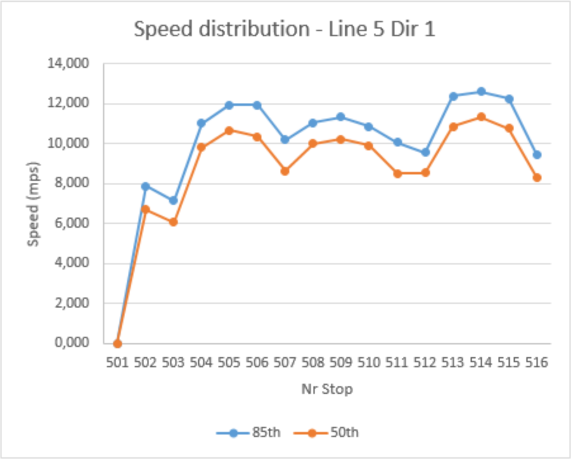


Figure A. 4 Dwelling time distribution at stop 712 and 2706

Speed

From the observed vehicle data, it is also possible to look at the speed taken during the operation. The average speed taken for each line was ranging from 9.08 to 9.44 mps. For a more detail observation, Figure A.4 describes the value of the 50th and 85th percentile of speed distribution taken for each trip from stop to stop. The speed was fluctuated along the route. One interesting thing to see is that the speed tend to get slower each time the vehicle approaching the control point stops (i.e. 511, 2506, 706, 712, 2706, and 2712). Knowing that holding control is applied at these stops, the drivers seemed to take a preventive act already by slowing down the vehicle. Without given any suggestion, the drivers already applied speed adjustment during the operation. The same behavior could be observed when the vehicle the end stop. Nonetheless, to get a more clear idea of this behavior one should do a preference survey on the drivers, which is out of the scope of this study.



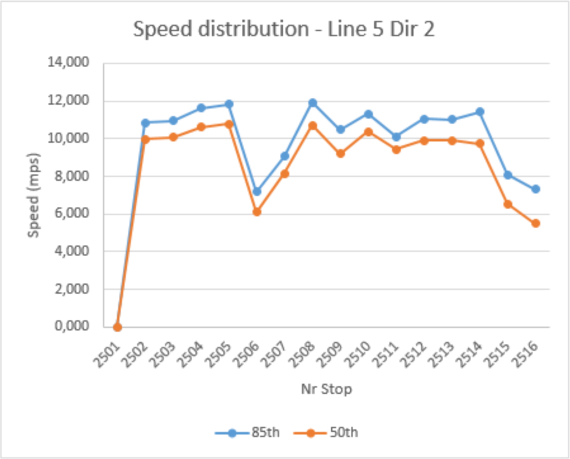


Figure A. 5 Speed distribution of AllGo network

Demand

The demand analysis is derived based on the boarding alighting number at each bus. Currently, Keolis records the data by using fare in/out data, infrared installation at buses, and APC data. The first one provides the most complete data of the operation in April and May 2018. However, the comparison with the infrared counting shows noticeable differences due to fare evasion. Thus, for the analysis, the value is taken from the infrared counter to provide a more accurate number. The analysis was conducted per line and direction.

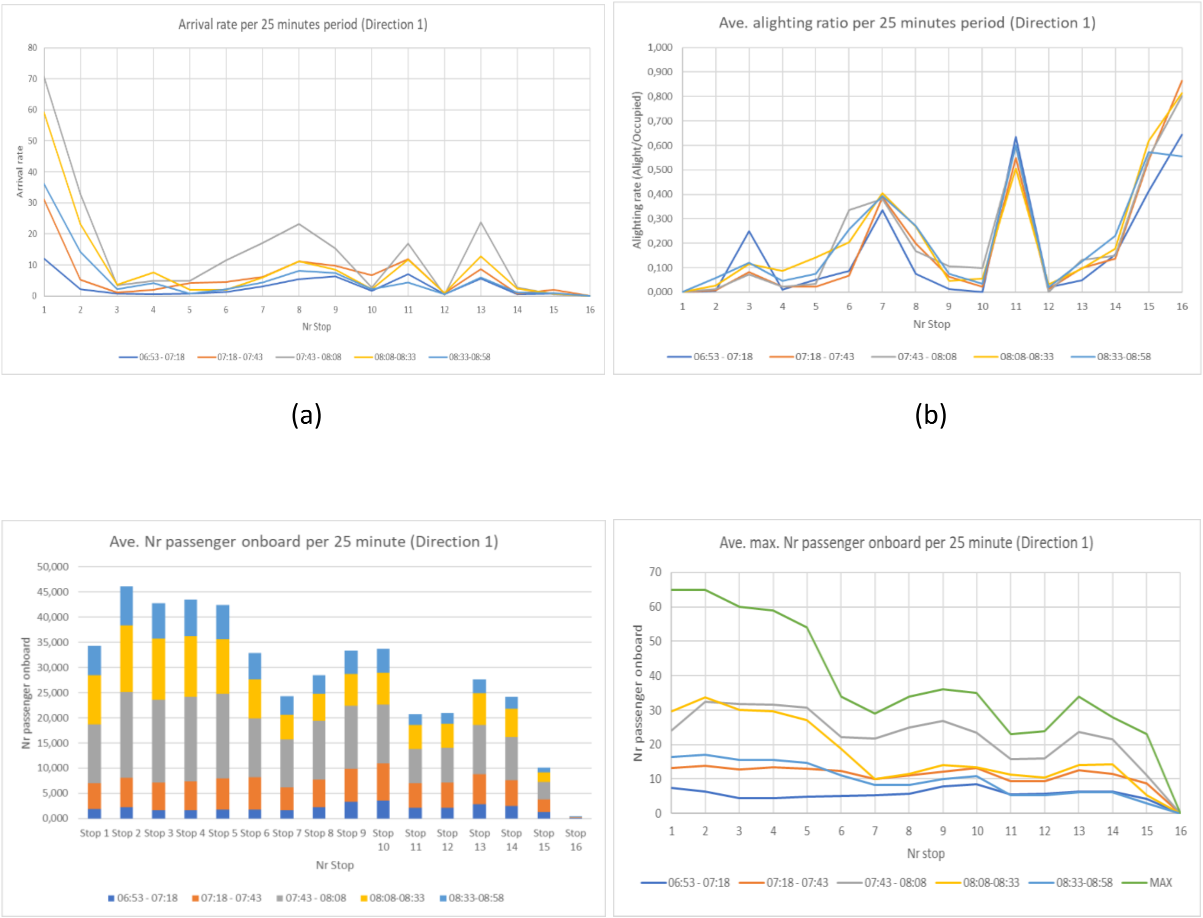
Line M5

Direction 1

Figure A.5 depict the arrival rate, alighting ratio, and number of passengers onboard of line M5 direction 1 at each stop. The peak period is within 07:43-08:08. The highest number of boarding passengers shown in Stop 1 and Stop 2, at Station Centrum and Stadhuisplein. By observing the significant numbers at these stops, one concluded that the trip in direction 1 is for the commuters that are attracted from the other cities and trip also by the train. The number of passenger remained high until Stop 5. There is a noticeable alighting ratio at Stop 3, Flevoziekenhuis, however it was not significant enough to reduce the number of passengers onboard.

Thus, the number of onboard passengers is still high until a significant alighting at Stop 6 and Stop 7, Waltdisneyplantsoen and Danswijk. Specifically for Stop 7, the high rate of alighting caused around 10% trips had dwelling time more than one minute. From Stop 8 to Stop 10, the number of passenger onboard increases and then again significant alighting occurred at Stop 11, Station Parkwijk. At this stop, the dwelling time is also high. However, since this stop is also a holding point, one could not concluded boarding alighting activity as the cause of the long dwelling time. Stop 13, Tussen de Vaarten Noord, seems also important by looking at the number of passenger boarding at this point.

The number shown in Figure A.5(c) does not demonstrate a problem in capacity. It is worth to note that this number is based on average condition. Figure A.5(d) depicts the onboard condition based on the average maximum number, compared with the maximum number occurred at each stop during April 2018. Still, compared to the total capacity of 138 per bus, it seems that there is no capacity issue in the of line M5 direction 1.



(a) (b)

(c) (d)

Figure A. 6 M5 Direction 1: (a) Demand rate; (b) Alighting ratio; (c) Ave. nr passenger onboard; (d) Ave. max nr passenger onboard

Besides capacity, it is interesting to see the occupancy pattern of demand in this direction. This pattern determine how regularity should be better prioritize. Van Oort (2011) defines three common occupancy pattern on transit lines (figure A.6). The first pattern describes the situation where the demand is high at the first stop, but remains the same until the end stop. In this situation, the irregularity does not give a significant impact when it happen along the route. On the other, it is important to keep the regularity at the first stop. The second pattern shows the situation where the occupancy keep increasing until the half part of the line and then decrease. For this situation, regularity becomes important at the first half of the line. The last pattern shows similar pattern as in the second one, but with significant demand increases at a stop in the middle of the line. The regularity is important at the first half of the line, particularly at this stop.

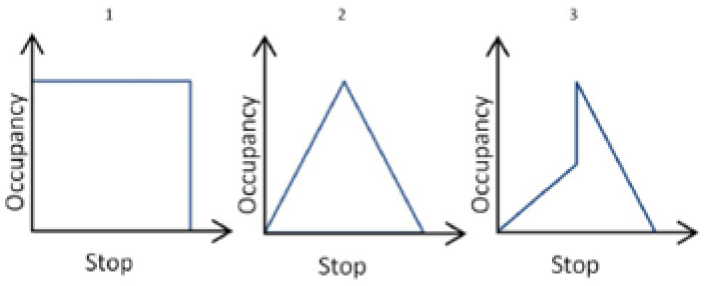
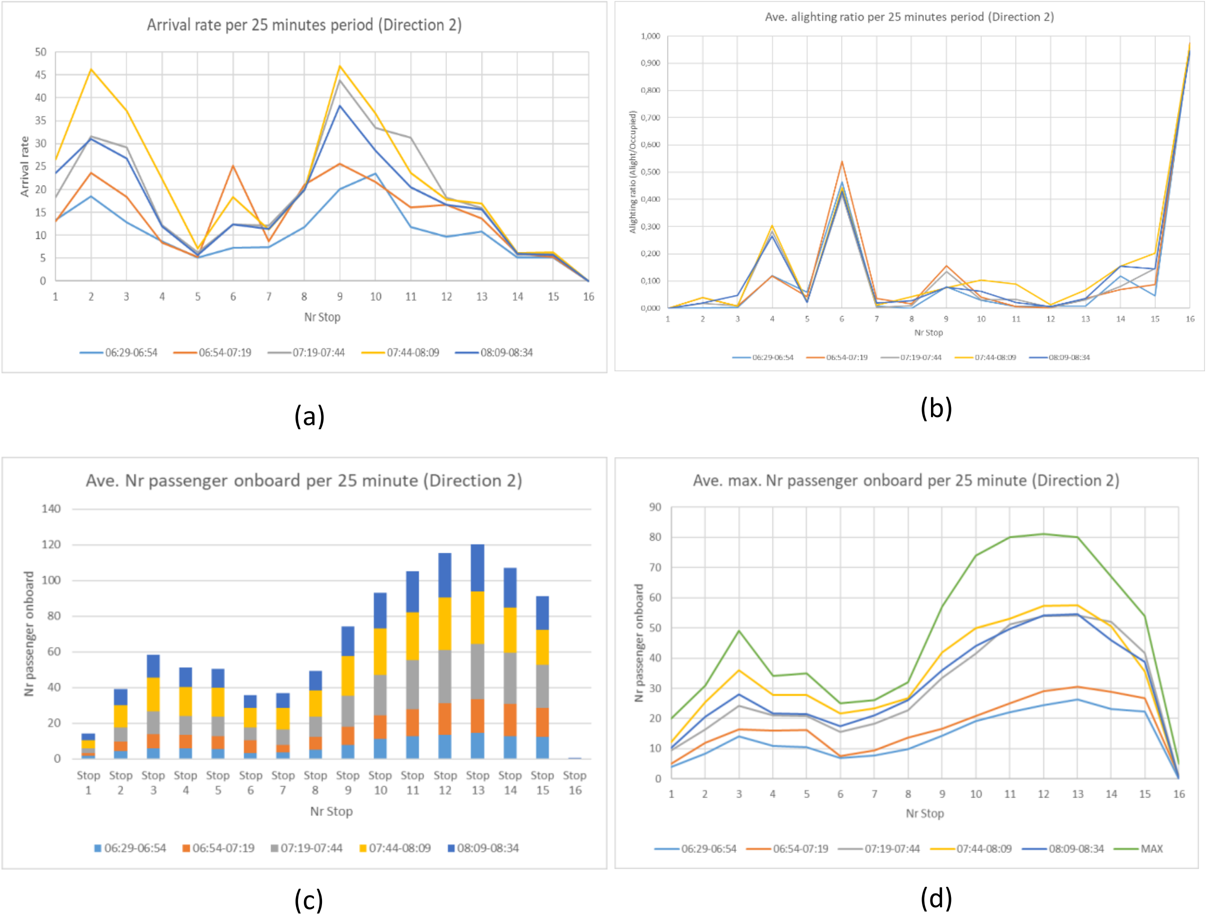


Figure A. 7 Occupancy pattern on transit line (van Oort, 2011)

When observing figure A.5 (c), one can see that, the highest occupancy occurs at the first stops. Although it keeps changing along the route, generally, the demand decreases as it goes further from the first stop. For this line, it seems important to maintain the regularity at stop 1 and stop 2.

Direction 2

Figure A.7 shows the data from line M5 direction 2. In contrast to the direction 1 where the demand is concentrated in the upstream of the line, in direction 2, the demand rates are more distributed at the several stops. Stop 1 and Stop 6 are stations, which give noted demand rate capturing the passengers from other cities triping by train. Besides it, other stops also contributed in the high number of demand that occur from the residential area in the city.



(a)

(b)

(c)

(d)

Figure A. 8 M5 Direction 2: (a) Demand rate; (b) Alighting ratio; (c) Ave. nr passenger onboard; (d) Ave. max nr passenger onboard

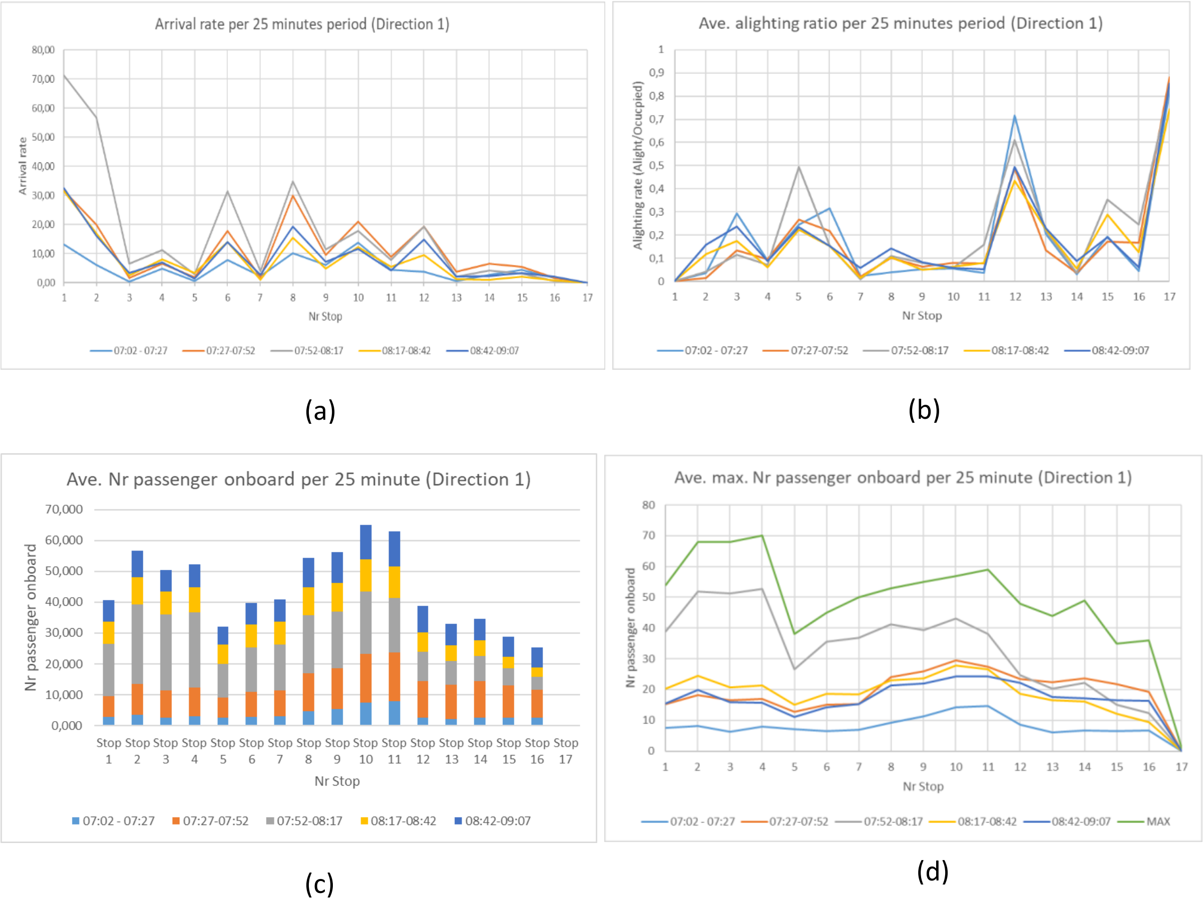
The peak period for direction 2 is around 07:44-08:09. The highest demand rate at a stop in the direction 2 is lower than those in the direction 1. Nonetheless, since the high rate occurs in several stops, this direction has higher total demand. Figure A.7 (c) demonstrates the average occupancy of this line direction. Direction 2 captures different pattern compared to direction 1. In this direction, the highest occupancy of the bus capacity occurs at the downstream of the line. The boarding activity at Stop 9, Danswijk, gives a significant effect for the demand rate at the downstream of the line. The alighting rate is also low, which keeps the number high. From the pattern, a conclusion is that many of the passengers in this direction have the Stop 16, Station Centrum, as their end destination. However, similar to the direction 1, here, capacity is also not a problem when looking at figure A.7 (c) and (d).

The occupancy pattern shown indicates that, regularity is important in most part of the line, particularly between stop 1 and stop 3, as well as the part between stop 7 and stop 13. Special attention should be given to stop 2 and stop 9, where the boarding activity is significantly high while the alighting rate is low.

Line M7

Direction 1

In direction 1, the peak period occurred between 07:52-08:17 at Stop 1 and 2. The trend is similar with line M5. The highest bus occupancy is seen at the upstream of the line. However, in another time range, for instance between 07:27-07:52, the link between Stop 8 and Stop 11 had higher occupancy. Stop 8, Tussen de Vaarten Noord, gave the greatest contribution in these links.



(a)

(b)

(c)

(d)

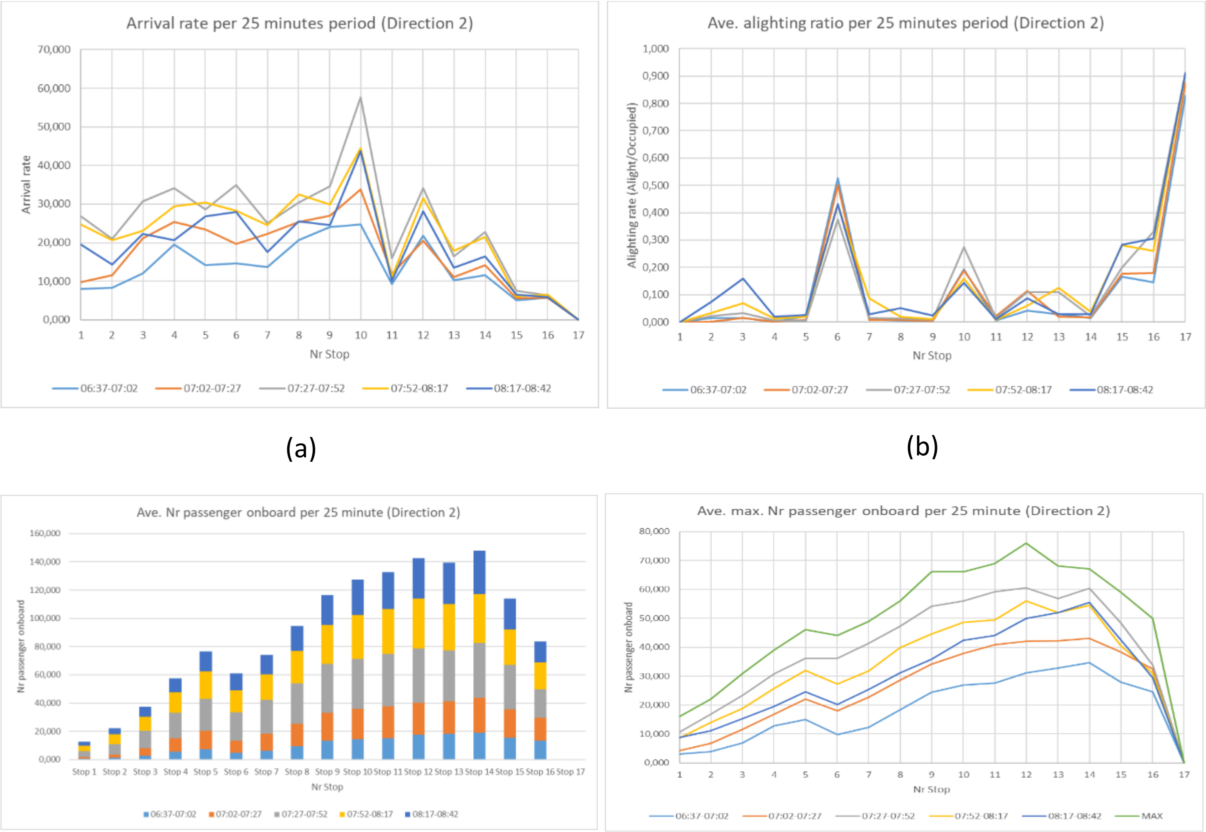
Figure A. 9 M7 Direction 1: (a) Demand rate; (b) Alighting ratio; (c) Ave. nr passenger onboard; (d) Ave. max nr passenger onboard

At the stations, Stop 6 Station Parkwijk and Stop 12 Station Buiten, noticeable boarding and alighting activity occurred simultaneously. Yet, the dwelling time function would not clearly capture these activities due holding decision at these stops. Some of the main destination stops in this direction are Stop 5, Parkwijk West, and Stop 12, Station Buiten. The high ratio of alighting at these stops captured this information. In this direction, again, there is no capacity problem during peak hour. The maximum number occurred was still below the capacity limit of the bus.

From the occupancy pattern, no general pattern can be observed. The boarding pattern is high at several non-consecutive stops. If referring only to the boarding and occupancy pattern, we found that the regularity is important to be maintained at stop 1, 2, 8 and 10.

Direction 2

Direction 2 shows a shifted peak period to the earlier time between 07:27 – 07:52. Demand at each stop increased gradually, except at the Stop 6, Station Buiten where in average almost half of the passengers alighted. At Stop 10, Tussen de Vaarten Noord, a high demand is identified. However, there was a quite significant alighting process at the same time so that the bus occupancy did not much different. The demand then kept increasing again it reached Stop 15, 16, 17 which are most likely the main end point of many of the passengers in this line. Due to this pattern, it is better to keep the regularity along the route up to stop 14. In addition, figure A.9 (c) shows that this direction also does not have capacity problem during the operation.



(a) (b)

(c) (d)

Figure A. 10 M7 Direction 2: (a) Demand rate; (b) Alighting ratio; (c) Ave. nr passenger onboard; (d) Ave. max nr passenger onboard

Conclusion on Appendix A

Several conclusions for the preliminary data analysis are as followed.

i) The fit of trip time distribution is found to be a lognormal distribution with 95% confidence interval. Generally, the actual trip time between stops were lower than the planning. Hence, the schedule-based holding control could significantly improve the overall performance of the system in term of punctuality and regularity.

ii) While the punctuality at the control point stops of AllGo bus network was high, the dwelling time at some stops, specifically at the holding points, were found to be too long (i.e. greater than 60 seconds). In different directions, at the same holding points, the length of the holding time can be significantly different. An analysis on this is due to the distance between the holding point and the starting stop. The further the distance, the greater unreliability that needs to be controlled. However, still, by looking at the resulted holding time, there is a need to limit the maximum holding so that it does not bother the passengers onboard.

iii) The speed distribution of all line directions had the same pattern. The speed was slower during the trips to the control points, which indicates the awareness of the drivers to not having an early trips from the control point stops. Nevertheless, a preference survey is needed if one intends to get the clear idea behind this behavior, which is out of scope of this study.

iv) Among all the common stops between two lines, four stops are seen to be more important at each lines, which may also useful to be analyzed in the next step. These stops are, Station Centrum, Stadshuisplein, Station Parkwijk, and Tussen de Vaarten Noord.

v) When divided the trip into one period of 25 minutes, the peak period is found to be between around ±15 minutes from 08:00. Although the demand is high, it is found that in this period, the bus capacity is still able to accommodate the demand well.

vi) The occupancy pattern is different for each line. Thus, for the scenario analysis, it seems more interesting to see different level of demand.

Appendix B: Experiment on a simple network

A simulation based on a simple network was conducted to understand the characteristics of the speed adjustment as well as its combination with headway-based holding control. The characteristics of the simple network was described as followed. A bus line consists of 16 stops with the same distance between stops. As each link has the same distance, the trip time distribution for each link was assumed to be the same (Table B. 1).

Table B. 1 Characteristics of the simple case

Number of stops	16
Number of links	15
Distance between stops	430 m
Trip time distribution	Lognormal distribution with mean of 64.80 and standard deviation of 9.15
Headway between trips	300 s

Three different cases were conducted to see the regularity performance of the strategy, including,

- Case I: No demand
- Case II: Modifying the maximum trip time
- Case III: Adding demand

Case I: No-demand

For an even headway-based control strategy, arrival time prediction becomes an important thing that can affect the performance. Hence, to see only the impact of this factor, the first setting is to remove all demand from the network. In the control design, the arrival time is derived from the trip time planned in the schedule. Two different conditions were tested. The first condition is when the trip time is over-designed (OS) thus, much higher than the actual trip time distribution (e.g. planned trip time = 100 s). The second condition is when the trip time is under-designed (US), by taking the mean of the trip time distribution as the scheduled trip time. The designed trip time was also set to be the maximum limit for the trip time for speed adjustment.

SA – US	Speed adjustment (SA) with limited buffer in trip time (US)
SA – OS	Speed adjustment (SA) with excessive buffer in trip time (OS)
SH – US	SA – US with possibility to hold at all stops
SH – OS	SA – OS with possibility to hold at all stops

Figure B.1 shows the comparison of coefficient of variation (CoV) of the headway along the route between the four conditions. From the figure, it can be seen that the headway variability keeps increasing at every certain number of stops. Note that the arrival time prediction in this study is derived from trip time planning to further determine the even headway. When controlling a vehicle, the following vehicle may have not entered the route. Thus, for this situation, the prediction for the following vehicle relies on the schedule. This makes the headway variability lower at the early stops of the route. When the following vehicle starts entering the route, the prediction is adjusted by also considering the real time information of it. The adjustment process adds variability to the system. Thus, when the headway between trips is changed or if the trip time planning is modified, the increased in variability may shift as well.

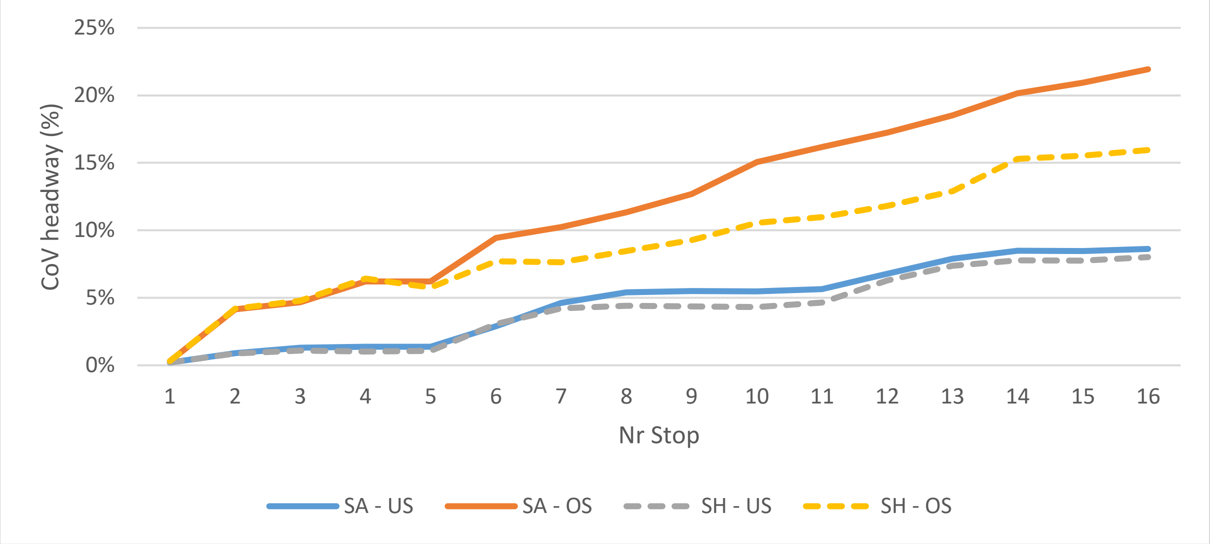


Figure B. 1 CoV headway comparison from different assumptions of arrival time prediction

With respect to trip time planning, figure B.2 shows that deriving the arrival time prediction based on the under-designed trip time (US) always give a better performance.

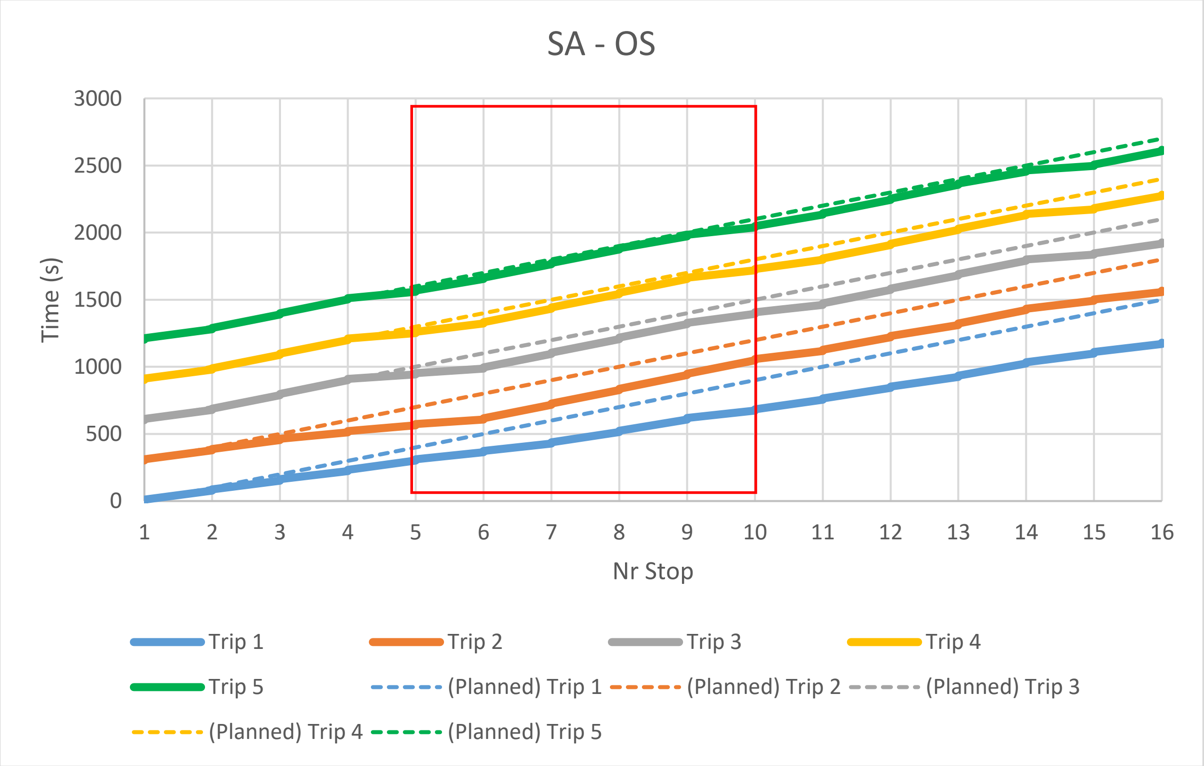


Figure B. 2 Vehicle trajectory SA – OS

With an over-designed (OS) trip time planning, the actual trip time in the first trip will be always lower than the planning. Hence, the consecutive trip will tend to speed up as well to catch its preceding. However, at some point it may leave the following vehicle further. The excessive planned trip time amplifies the earliness effect, so that the trip will start slowing down when considering the arrival time prediction from the following vehicle. However, due to excessive speeding up at the beginning, the vehicle needs to slowing down to reach the even headway. In the SA case, slowing down is limited to the maximum trip time while the vehicle might need to be slower than it is allowed. On the other hand, SH can better fulfil the even headway by allowing holding at stops. This state can be seen in the figure B.3 between Stop 5 and Stop 10.

Different outcome is shown in the US case. The excessive speeding up at the beginning does not occur in the US case because the actual trip time match well with the planning. Therefore, it does not have to significantly slowing down to keep an even headway with the following vehicle. Thus, the resulted headway is less varied and there is no significant effect between applying SA and SH in this case. However, one should consider that this kind of planning is sensitive to the late trips. If the variability is high, prediction based limited planning on trip time may cause bunching when the preceding trips are much late.

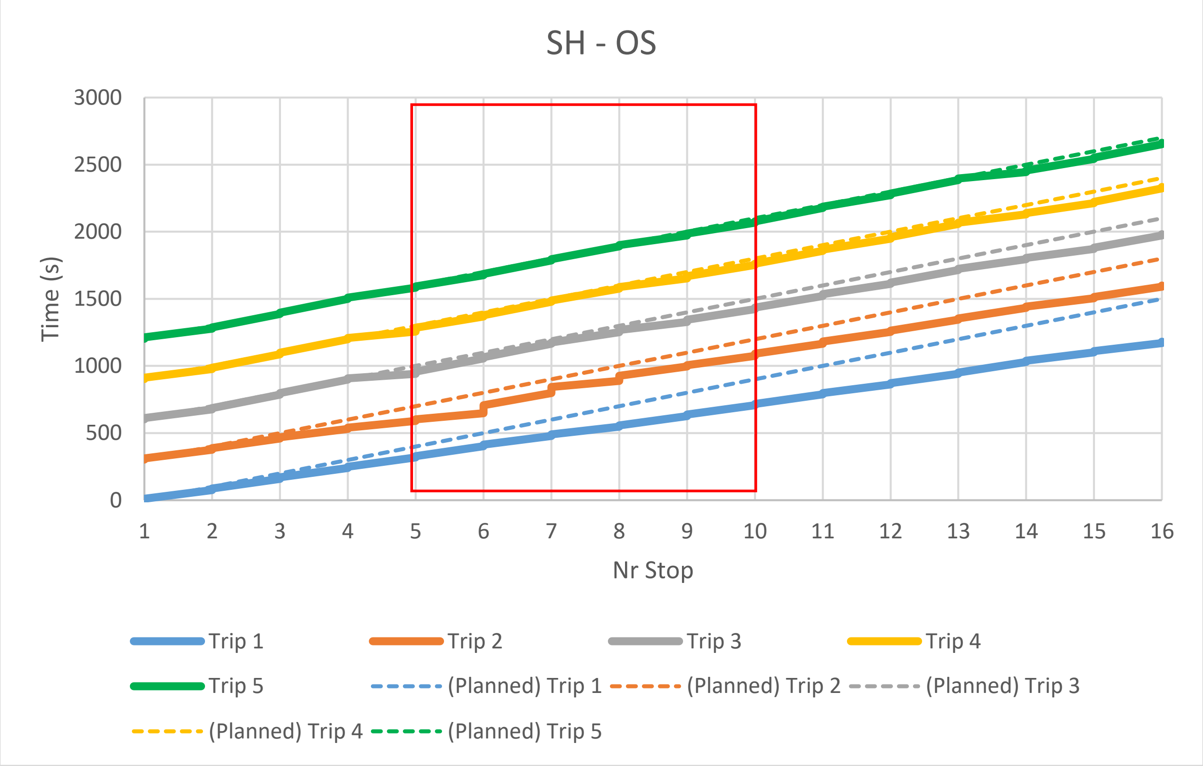


Figure B. 3 Vehicle trajectory SH - OS

Case II: Modifying maximum trip time

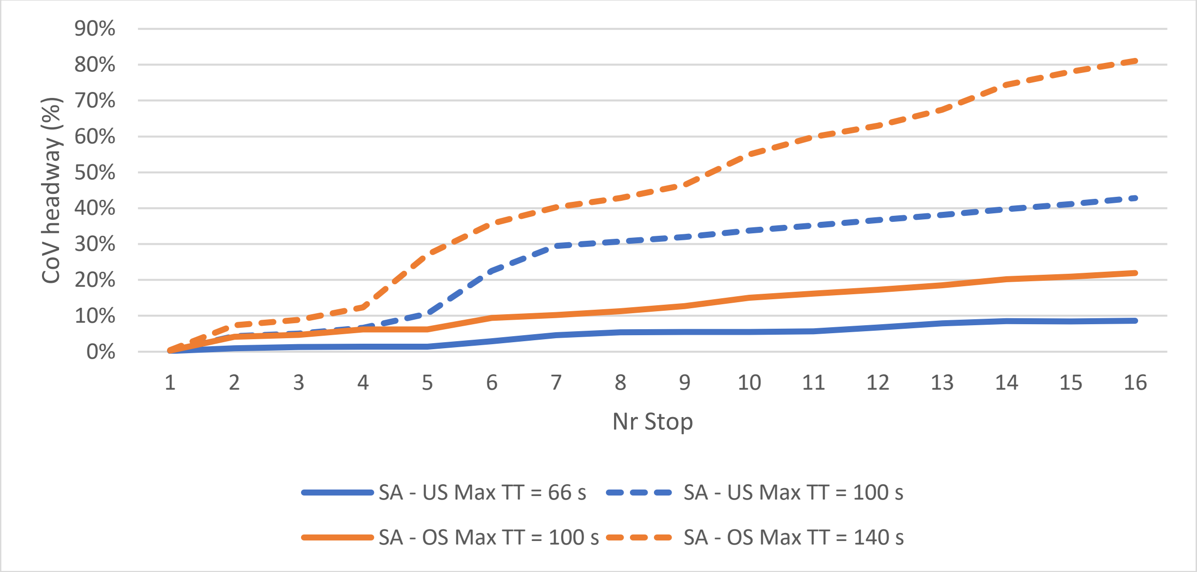


Figure B. 4 CoV headway comparison from different assumptions of maximum trip time OS-SA case

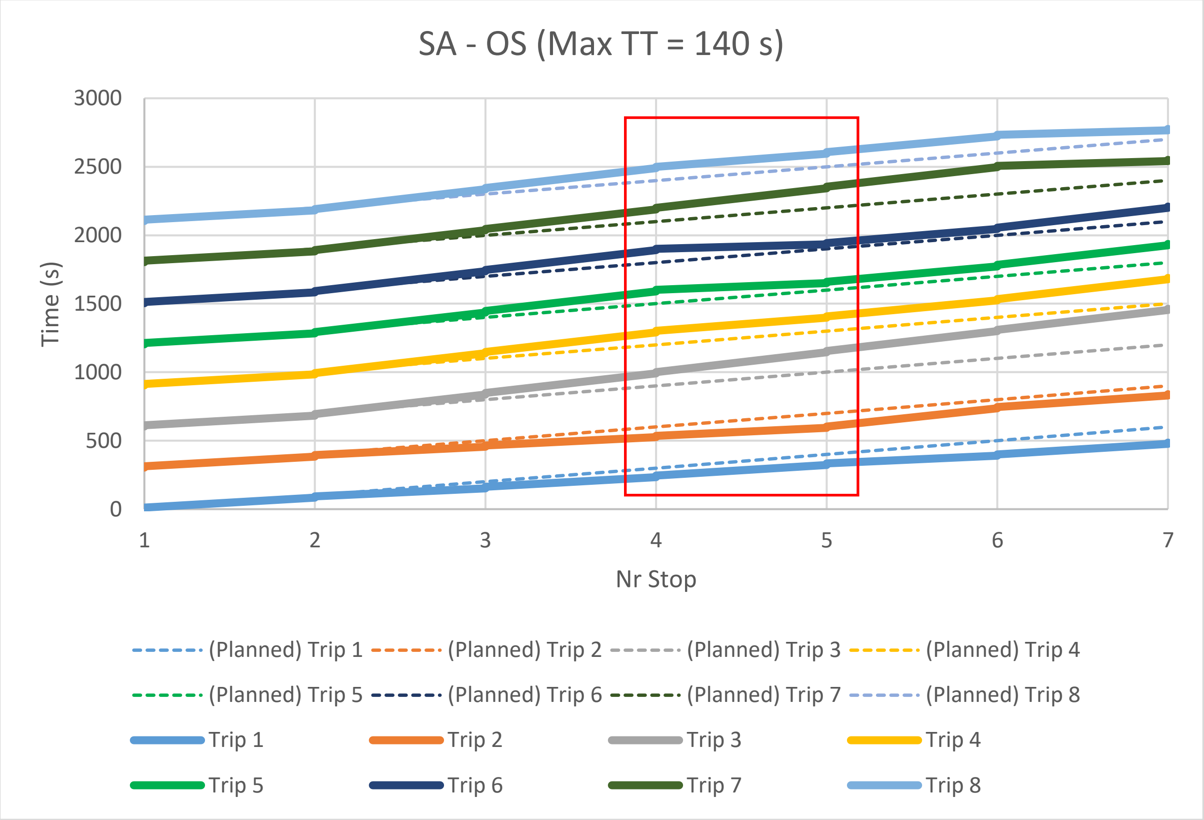
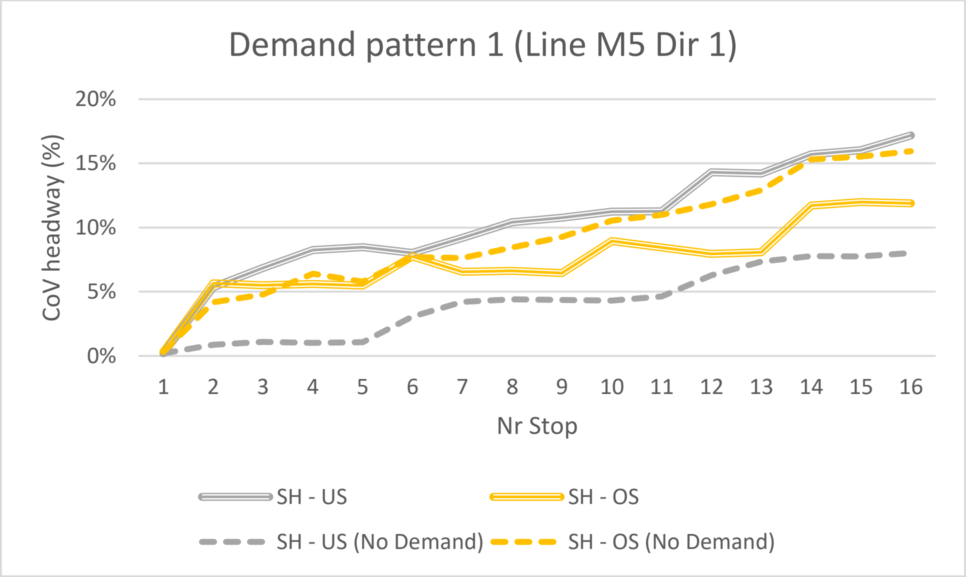


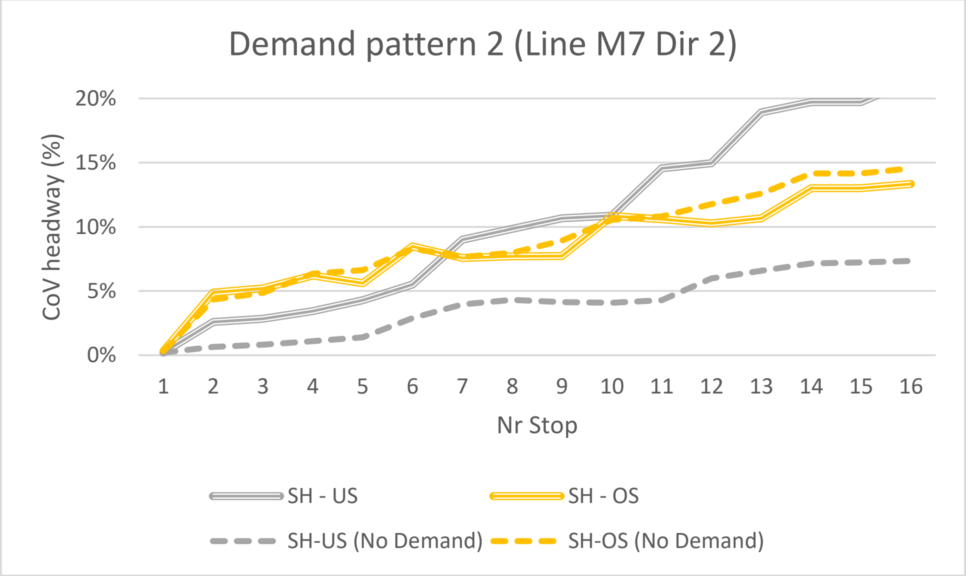
Figure B. 5 Vehicle trajectory for OS-SA Max TT = 140 s

In the first case, applying SA with OS turned out to be ineffective since the maximum trip time limiting the ability of the system to reach the even headway. The same condition applied for SA – US if many late trips occur. Thus, in this case, a higher maximum trip time was tested to see the impact on the system. In this case, the maximum trip time for US case and OS case was set to be 100 s and 140 s. Figure B.4 shows that increasing the maximum trip time worsen the headway variability in the system. Higher maximum trip time let the trips to be slower when reacting to the late trips. At first, the headway variability will be low when the prediction of the following trips is referring to the schedule only. However, after the following vehicle enters the system (i.e. when the preceding vehicle is at stop for 4 and 5 for OS and US respectively), real-time event determined the arrival time prediction. The "slow" trips suddenly have to speed up because its following vehicle is predicted to still be on-time, as seen in the figure B.5 for SA-OS case.

Case III: Adding demand to the network



(a)



(b)

Figure B. 6 CoV headway comparison for SH case for different demand condition

Another factor that seems to be affecting the performance of interstation control strategy, is demand at stop. In this case, the characteristics of SA and SH will be analyzed by adding demand to the network. Two different demand patterns were used for this analysis based on the empirical data of AllGo network Line M5 direction 1 and M7 direction 2 (Appendix A). The first one has a very high passenger activity at the early stops. Meanwhile, the second one has few passengers at the early stops, which keep increasing along the route.

Different demand pattern resulted in different outcome as seen in figures above. Regardless the demand condition, under-design (US) always obtain a higher CoV headway when demand is introduced. Since the trip time planning is limited, there is a high chance that the actual trip time exceeds the trip time budget and potentially result in a bunching situation since the maximum trip time set is also limited. However, it is interesting to see how the headway variability development in this case. For the first demand pattern (Figure B.6 (a)), the headway variability increases significantly from the beginning. For SH-US, this situation occurs due to high passenger activity at Stop 1, which subsequently increases the arrival time variability of the second stop. Meanwhile, for SH-OS, even when there is no demand, the variability at the beginning is already high because trip time variability. Passenger activity only adds small effect to this.

For SH-US, the headway variability increases uniformly along the route. Interestingly for SH-OS, the obtained CoV headway is better than when there is no demand. Passenger activity gives additional time to fill the time budget for trip time. Hence, there is no excessive speeding up or slowing down anymore.

Figure B.6 (b) depicts the headway variability development for the second demand pattern. In the early part of the route, SH-US outperforms the SH-OS since the demand is low. Thus, SH-US is still capable to regularize the headway. However, once the demand is high (i.e. from Stop 6), the headway variability starts to grow. On the other hand, low demand give a disadvantage for SH-OS as it potentially creates the situation where the vehicle is excessively speeding up or slowing. For a low demand condition at the beginning, it gives the same effect as if there is no demand (Case I). The variability at this part is higher, but then it performs better when the demand increases.

Conclusions on Appendix B

This experiment tested the control strategy in a simple setting to understand the way the control strategy works. Three different conditions were tested, including no demand condition, modifying the maximum trip time, and with demand condition. Regularity is the factor to assess in this experiment.

From three different cases, several factors were found to be important in affecting the performance of the combined control strategy. These factors are,

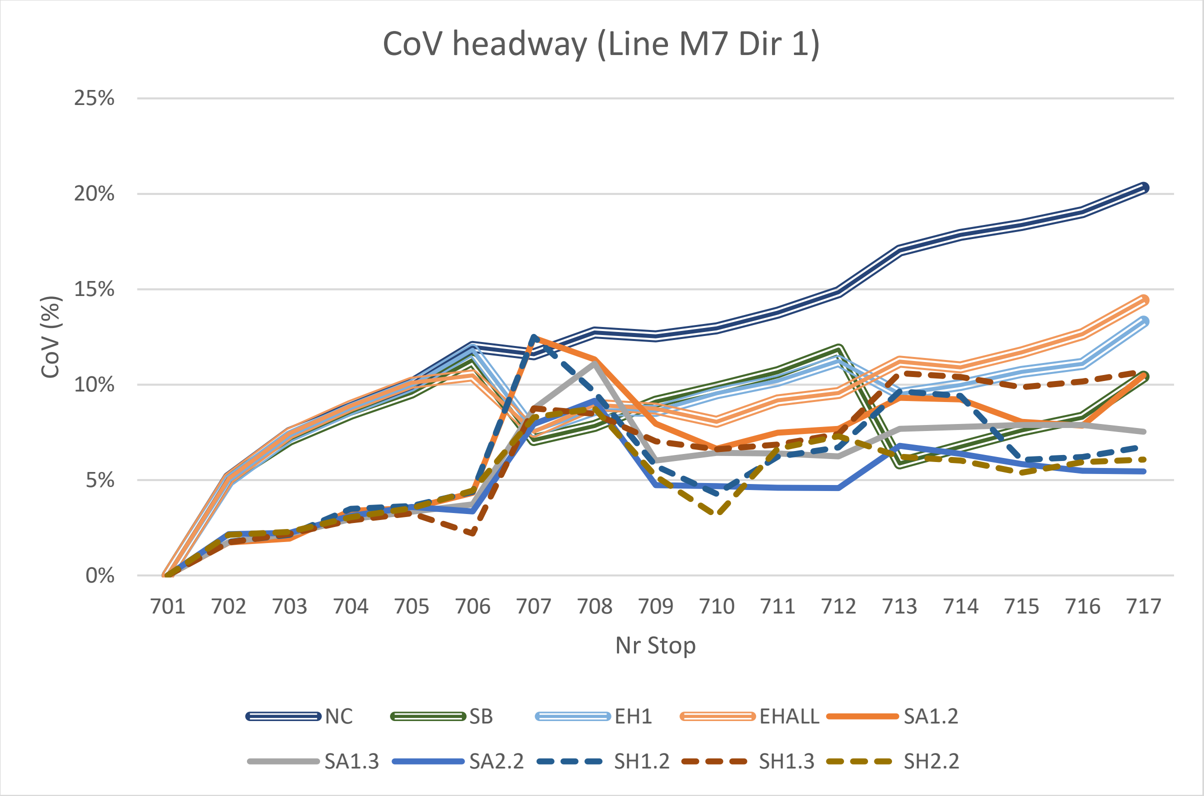
1. Arrival time prediction
2. Speed range
3. Demand pattern

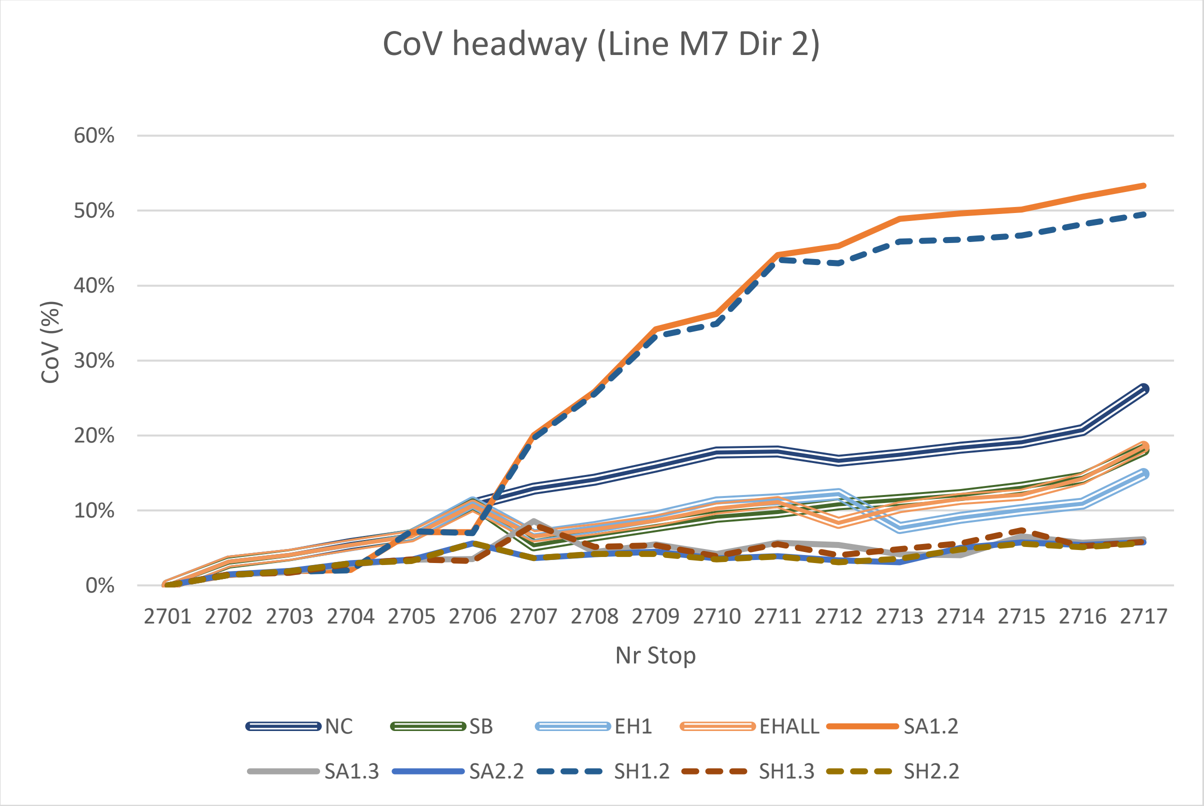
The first conclusion is related to the combined strategy in respect to speed adjustment strategy only. Adding holding to speed adjustment appears to be helpful to regularize the headway. The control ability of speed adjustment is limited to the trip time boundaries while adding holding gives additional capability to maintain the headway. The speed range given in the control defines this boundary. However, in relation to this, set a higher value for maximum trip time does not positively influence the performance of speed adjustment strategy. It is still better to add holding at stop to reach regularity.

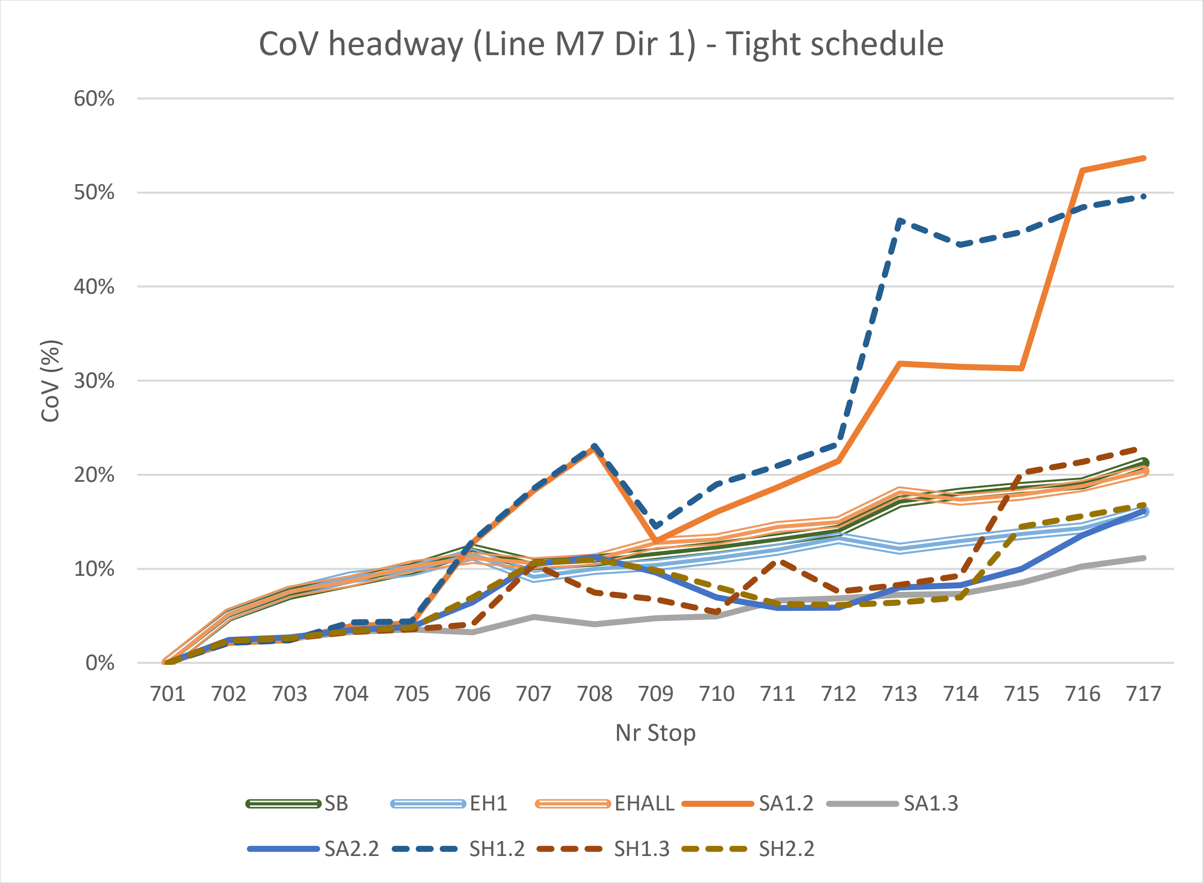
Secondly, the outcome of Case I and Case III, leads to the conclusion that the trip time design can well support the performance of speed adjustment-holding strategy. It is inadvisable to excessively or limitedly design the trip time. One should design the trip time in a right amount by considering the riding time along the route as well as passenger activity at stop. Although in past studies, demand was considered as a factor that can worsen the performance of the strategy, it is still manageable by having a right prediction of trip time. Note that, in this experiment, trip time is important, as it becomes the reference for arrival time prediction. Furthermore, it is also worth to note that demand pattern can add (dis)advantage for the system. Considering that, the system itself naturally adds variability along the route, having higher demand in the middle to the rest of the route may double the source of variability as seen in Case III.

Apart from the outcome of this experiment, it is important to note that the result in this part was generated from a simple scenario. Hence, there was a further test of the strategy through a case study to evaluate the performance of the strategy in a more complex setting.

Appendix C: Scenario 1 & Scenario 2

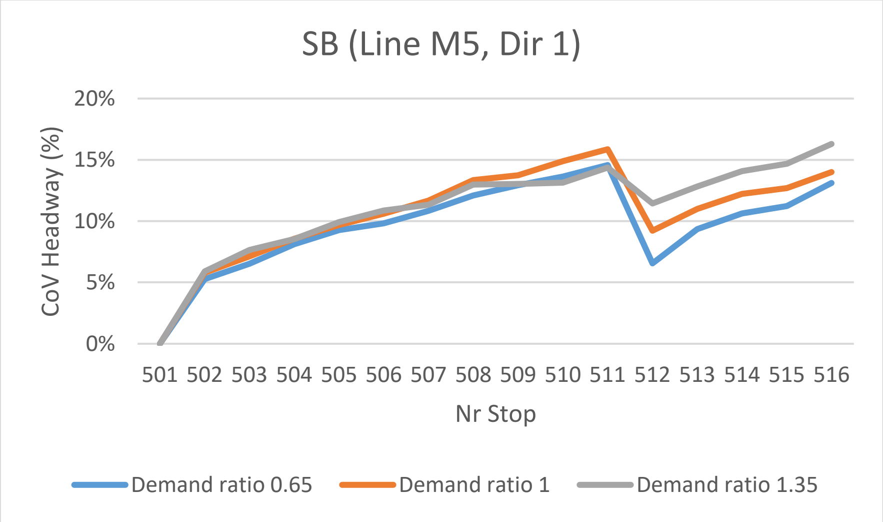


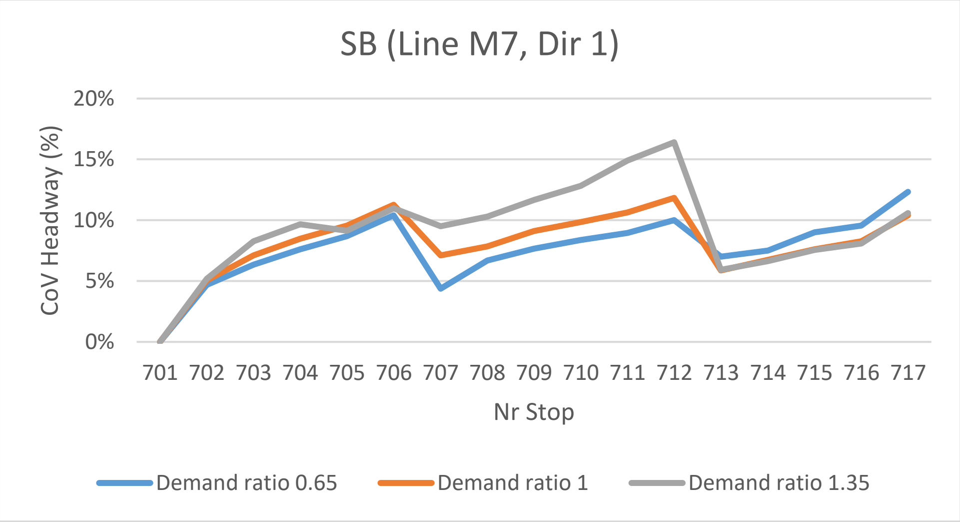


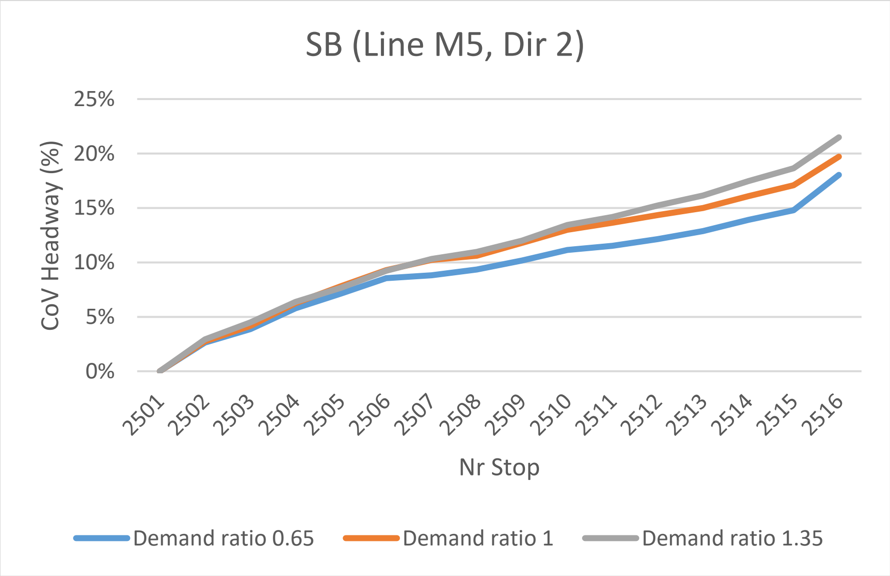

CoV headway (Line M7 Dir 1) - Tight schedule
60%
50%
40%
30%
20%
10%
0%
CoV (%)
701
702
703
704
705
706
707
708
709
710
711
712
713
714
715
716
717
Nr Stop
SB
EH1
EHALL
SA1.2
SA1.3
SA2.2
SH1.2
SH1.3
SH2.2

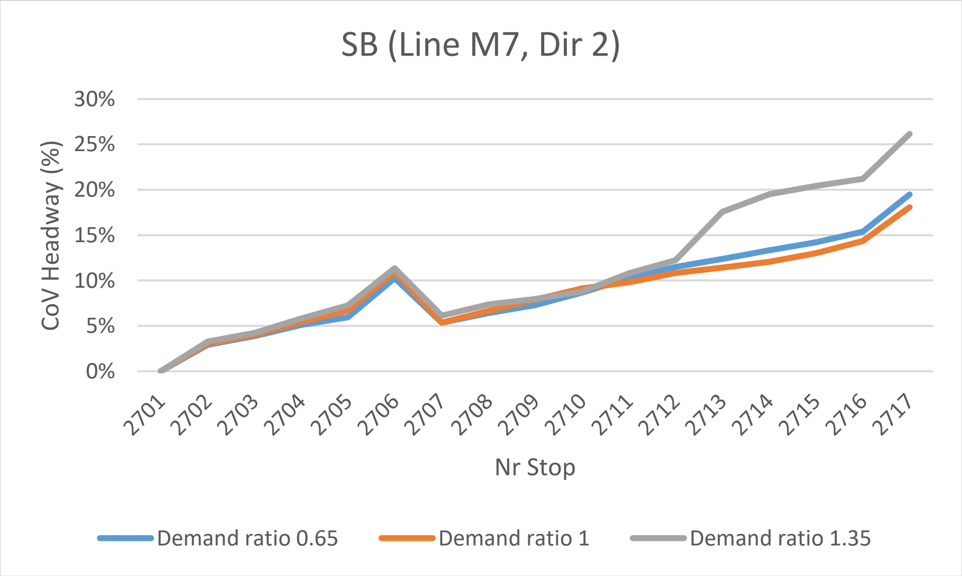
S

Appendix D: Scenario 3

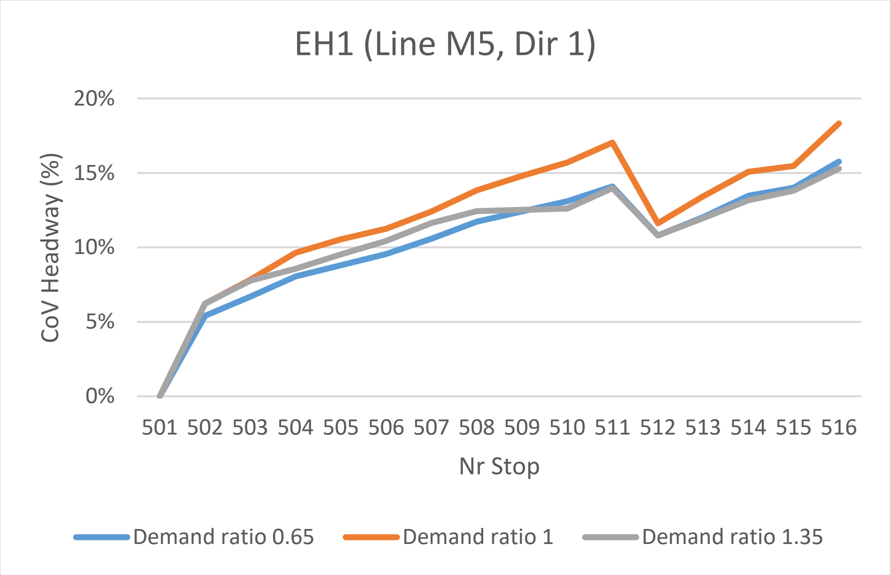


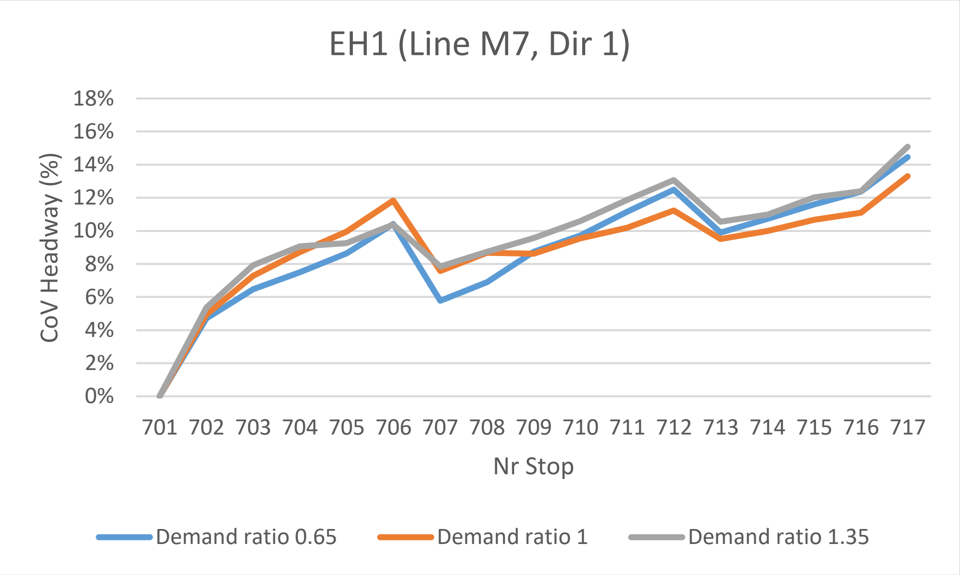


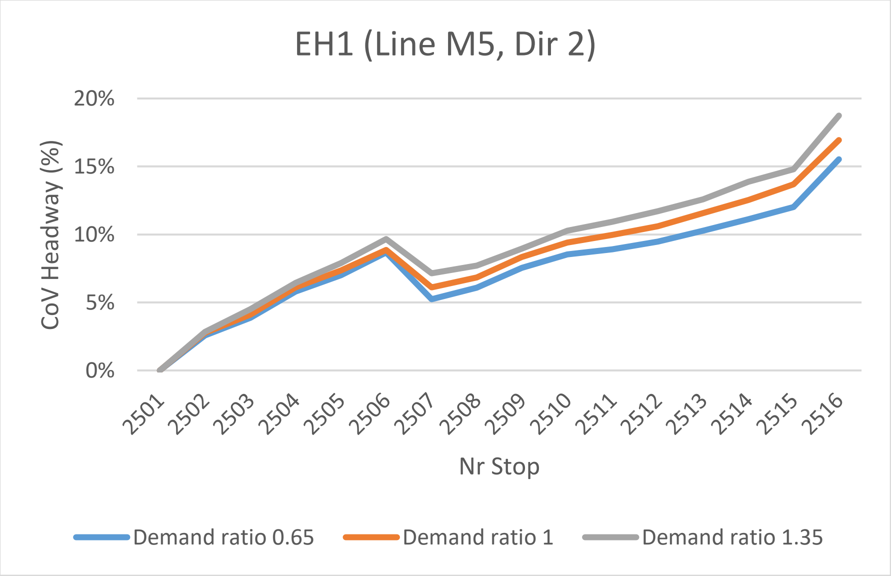


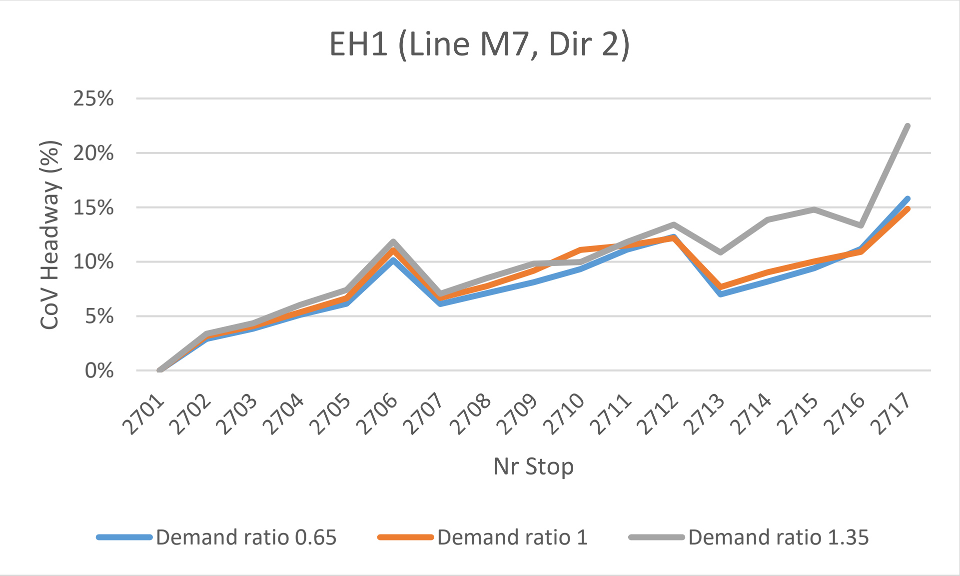


T

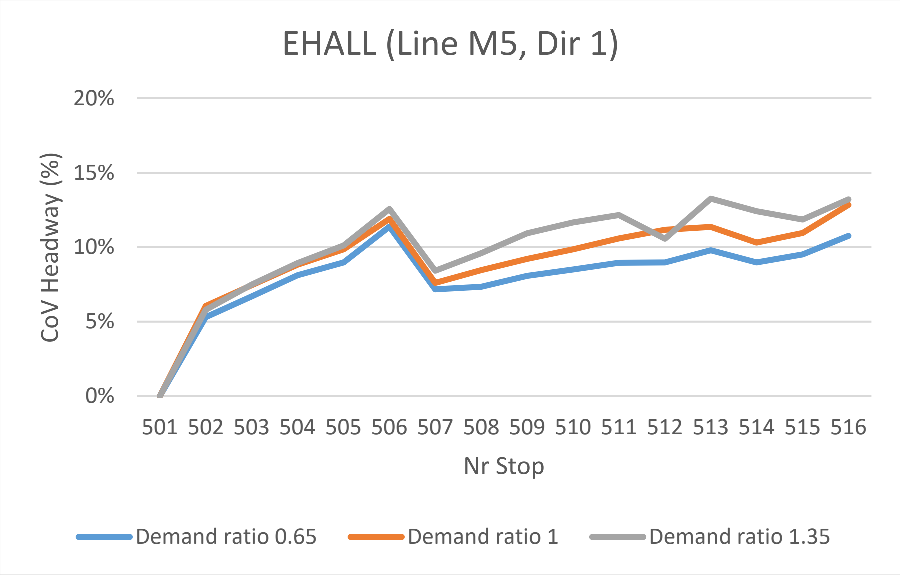

EH1 (Line M5, Dir 1)
CoV Headway (%)
20%
15%
10%
5%
0%
501 502 503 504 505 506 507 508 509 510 511 512 513 514 515 516
Nr Stop
Demand ratio 0.65
Demand ratio 1
Demand ratio 1.35

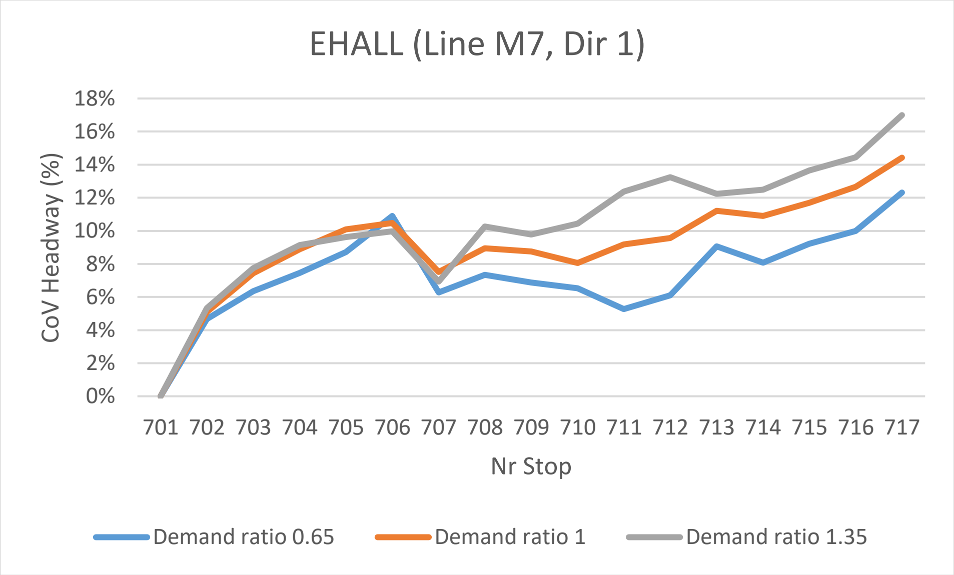

EH1 (Line M7, Dir 1)
CoV Headway (%)
18%
16%
14%
12%
10%
8%
6%
4%
2%
0%
701 702 703 704 705 706 707 708 709 710 711 712 713 714 715 716 717
Nr Stop
Demand ratio 0.65
Demand ratio 1
Demand ratio 1.35

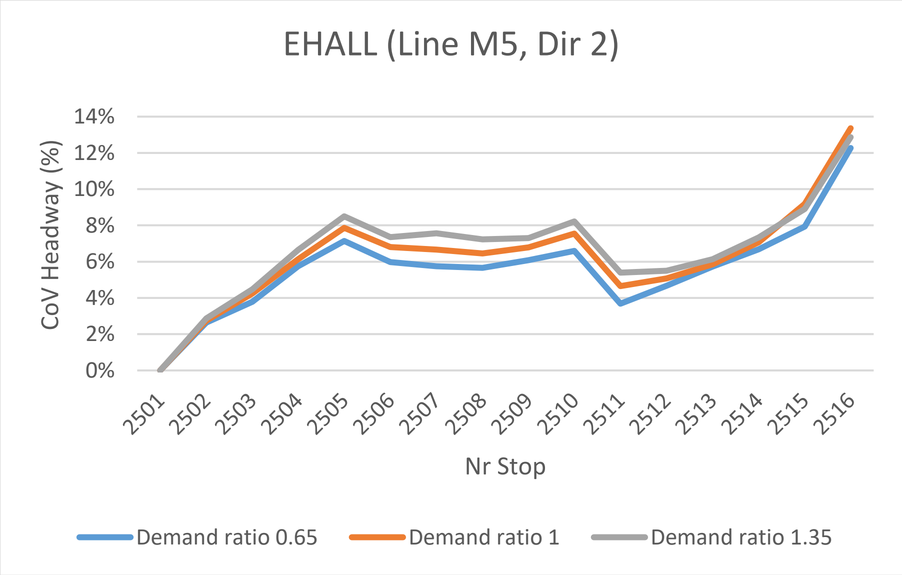

EH1 (Line M5, Dir 2)
CoV Headway (%)
20%
15%
10%
5%
0%
2501 2502 2503 2504 2505 2506 2507 2508 2509 2510 2511 2512 2513 2514 2515 2516
Nr Stop
Demand ratio 0.65
Demand ratio 1
Demand ratio 1.35

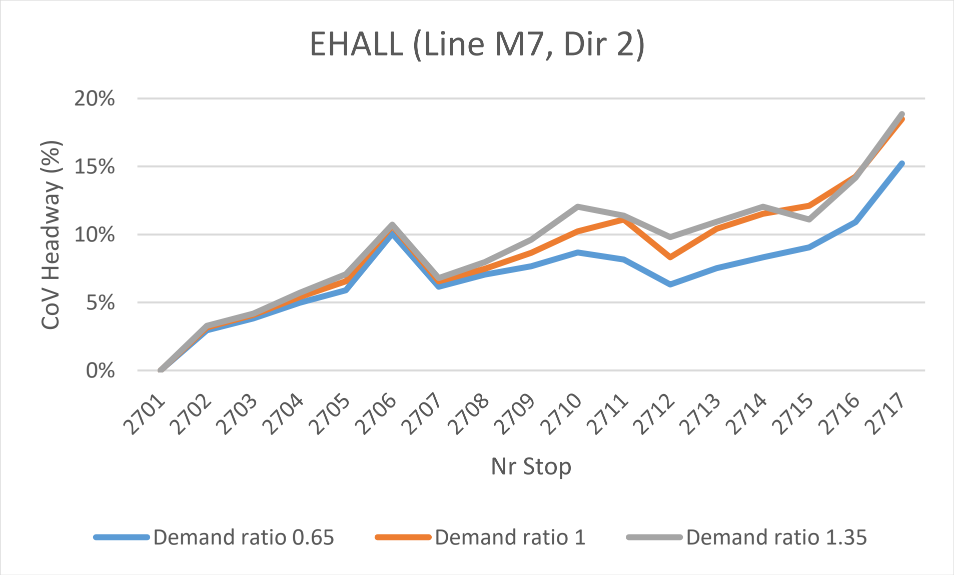

EH1 (Line M7, Dir 2)
CoV Headway (%)
25%
20%
15%
10%
5%
0%
2701 2702 2703 2704 2705 2706 2707 2708 2709 2710 2711 2712 2713 2714 2715 2716 2717
Nr Stop
Demand ratio 0.65
Demand ratio 1
Demand ratio 1.35

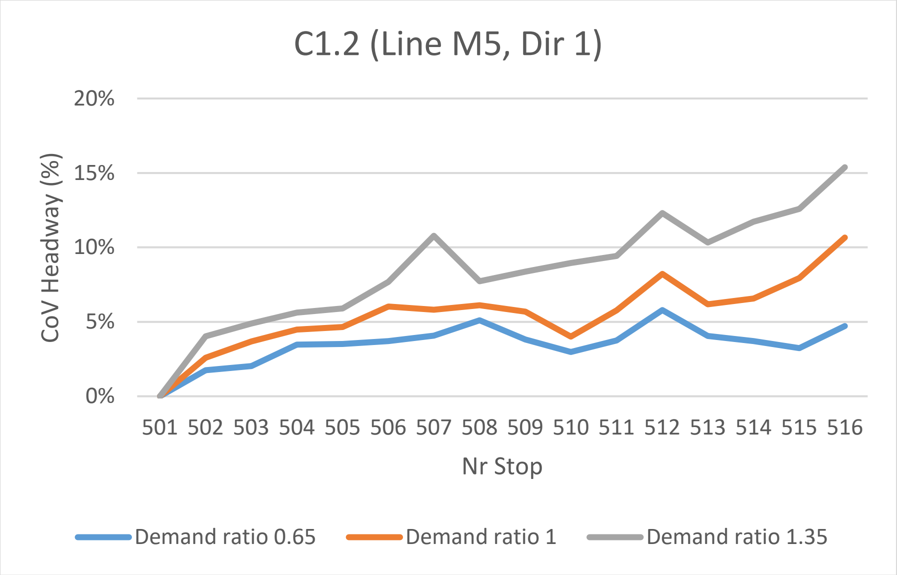
U

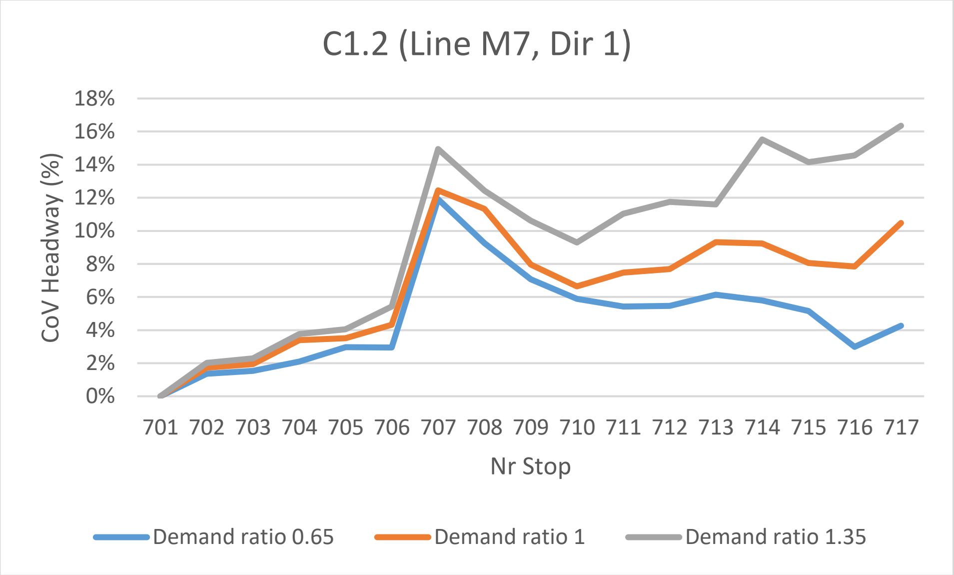

EHALL (Line M5, Dir 1)
CoV Headway (%)
0%
5%
10%
15%
20%
501
502
503
504
505
506
507
508
509
510
511
512
513
514
515
516
Nr Stop
Demand ratio 0.65
Demand ratio 1
Demand ratio 1.35

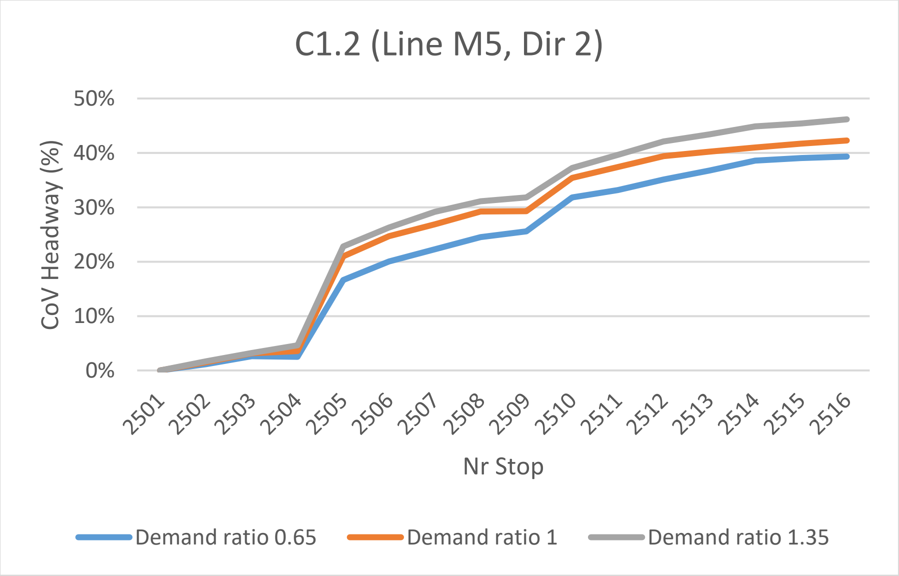

EHALL (Line M7, Dir 1)
CoV Headway (%)
0%
2%
4%
6%
8%
10%
12%
14%
16%
18%
701
702
703
704
705
706
707
708
709
710
711
712
713
714
715
716
717
Nr Stop
Demand ratio 0.65
Demand ratio 1
Demand ratio 1.35

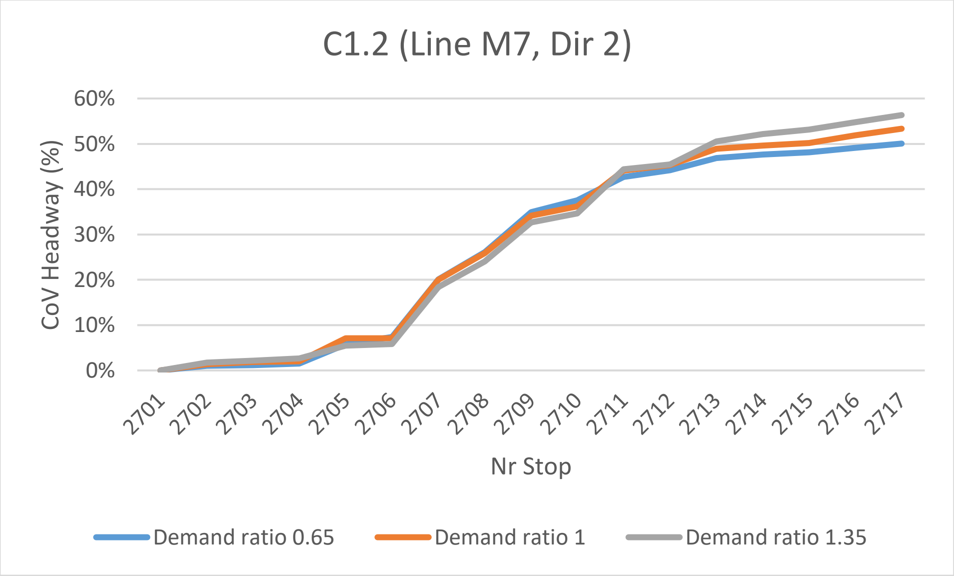

EHALL (Line M5, Dir 2)
CoV Headway (%)
0%
2%
4%
6%
8%
10%
12%
14%
2501
2502
2503
2504
2505
2506
2507
2508
2509
2510
2511
2512
2513
2514
2515
2516
Nr Stop
Demand ratio 0.65
Demand ratio 1
Demand ratio 1.35


EHALL (Line M7, Dir 2)
CoV Headway (%)
0%
5%
10%
15%
20%
2701
2702
2703
2704
2705
2706
2707
2708
2709
2710
2711
2712
2713
2714
2715
2716
2717
Nr Stop
Demand ratio 0.65
Demand ratio 1
Demand ratio 1.35

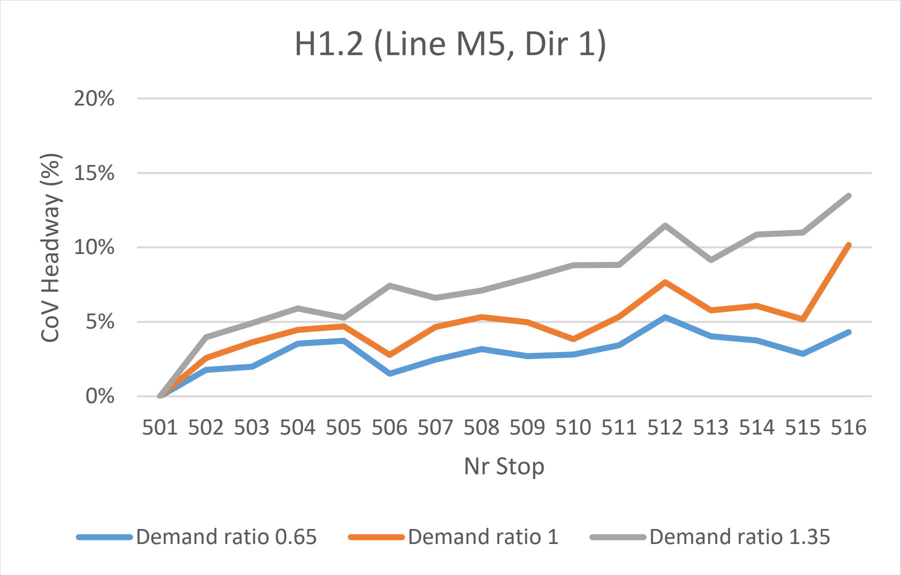

C1.2 (Line M5, Dir 1)

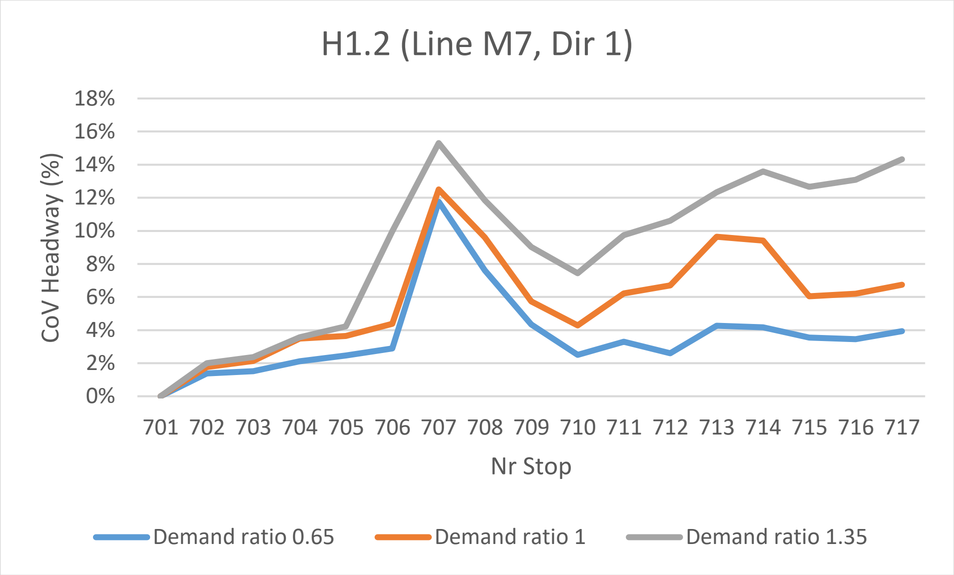

C1.2 (Line M7, Dir 1)

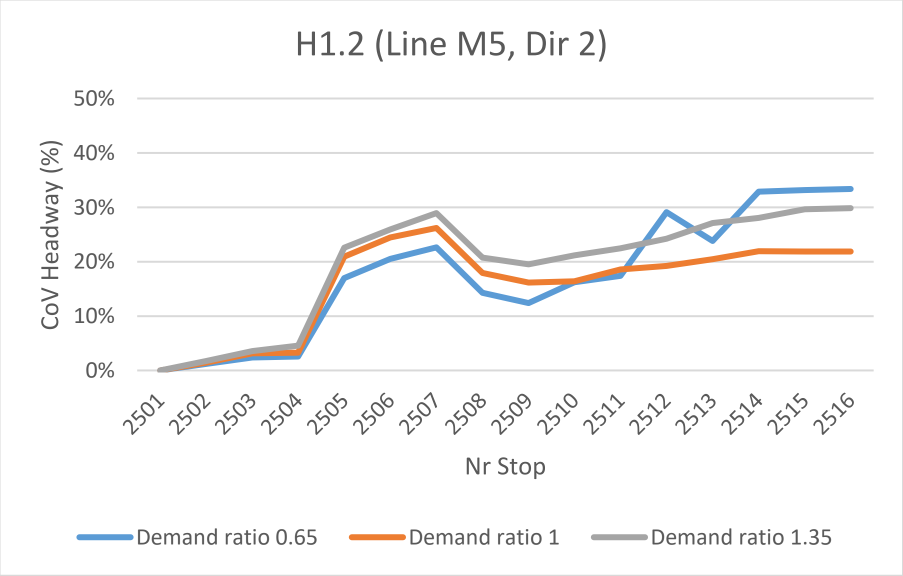

C1.2 (Line M5, Dir 2)

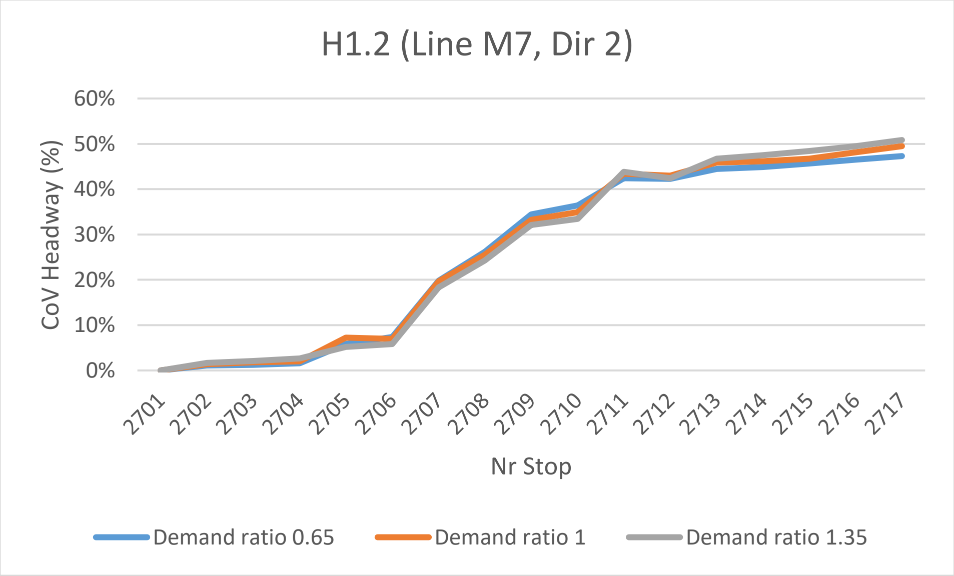

C1.2 (Line M7, Dir 2)

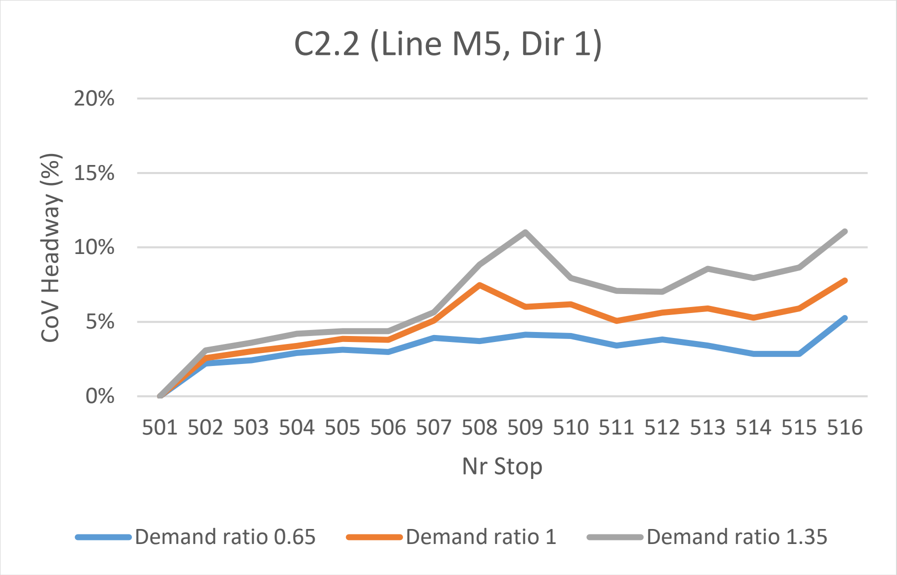
W

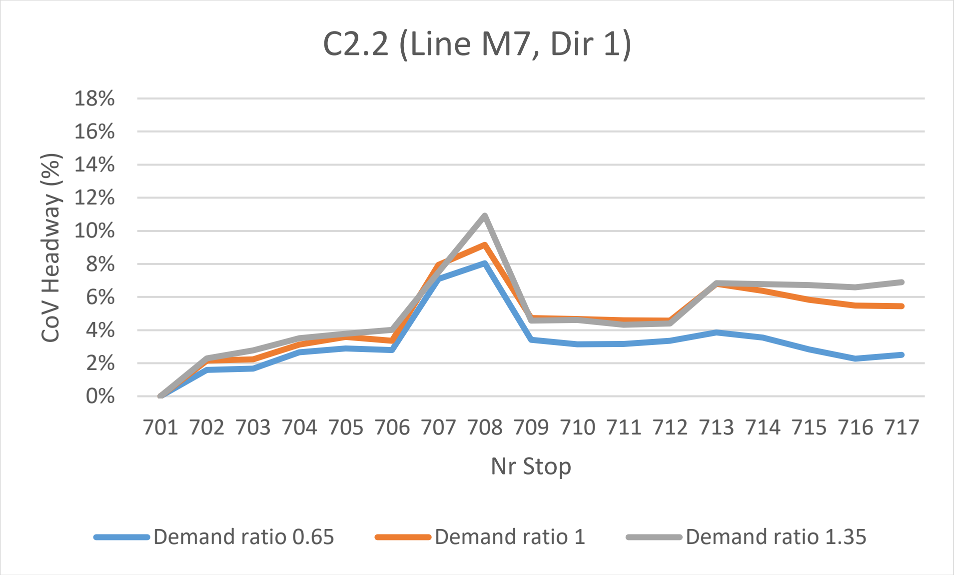

H1.2 (Line M5, Dir 1)

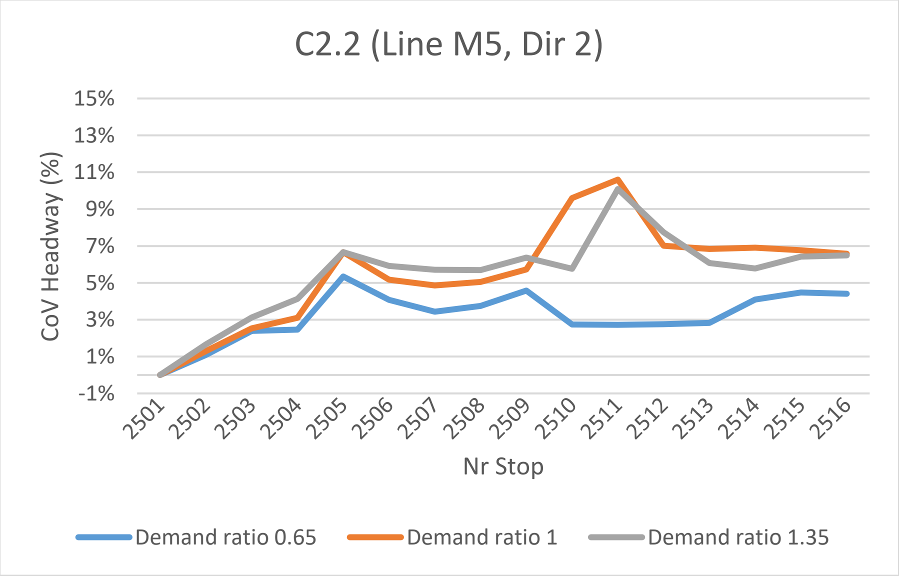

H1.2 (Line M7, Dir 1)

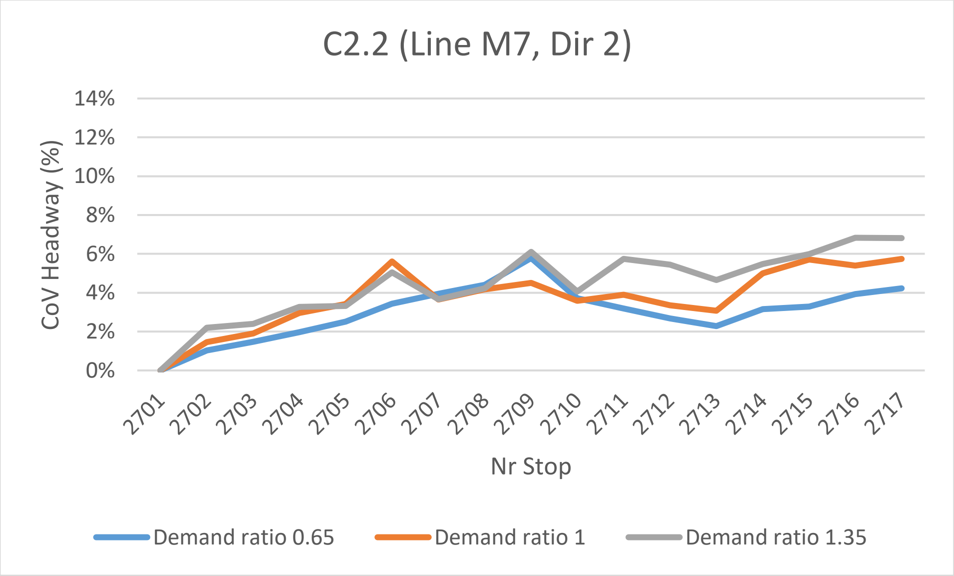

H1.2 (Line M5, Dir 2)

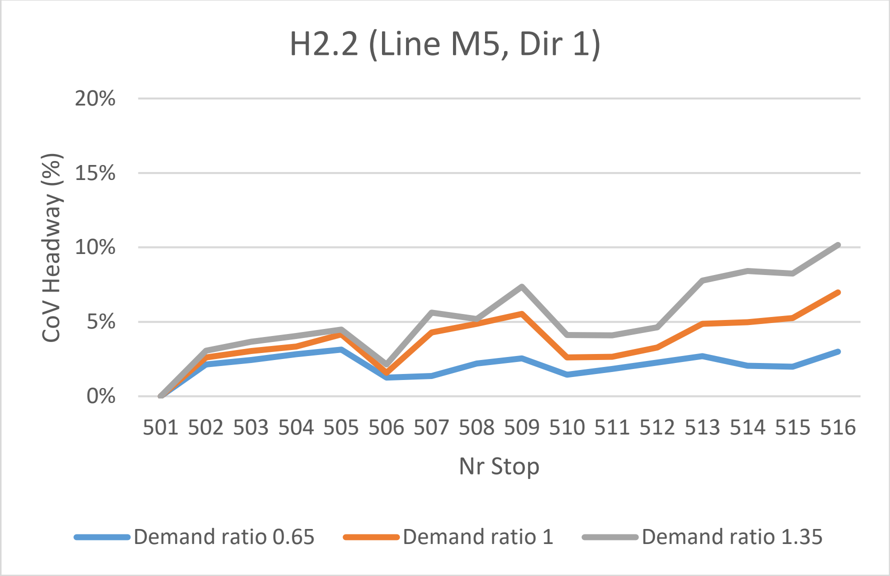

H1.2 (Line M7, Dir 2)

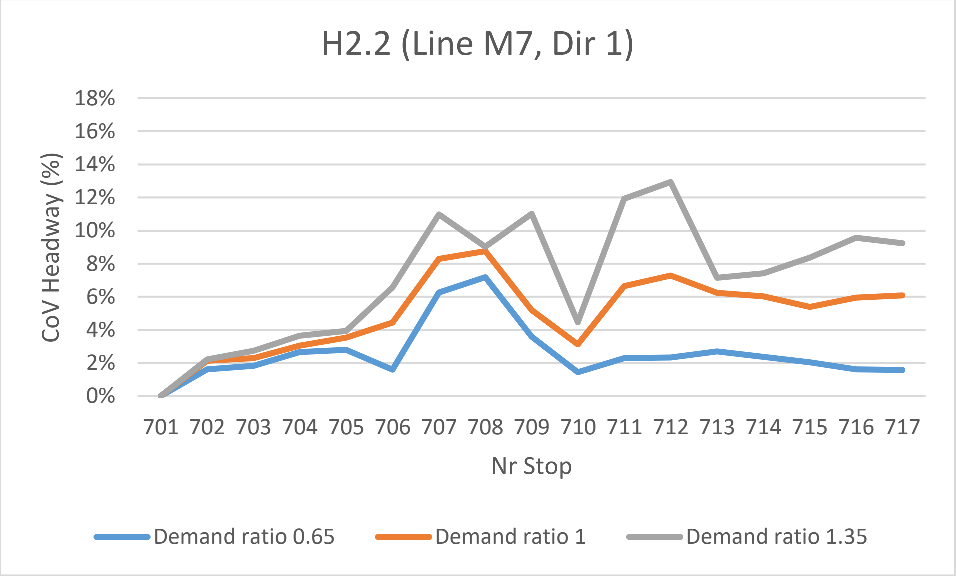

C2.2 (Line M5, Dir 1)
CoV Headway (%)
20%
15%
10%
5%
0%
501 502 503 504 505 506 507 508 509 510 511 512 513 514 515 516
Nr Stop
Demand ratio 0.65
Demand ratio 1
Demand ratio 1.35

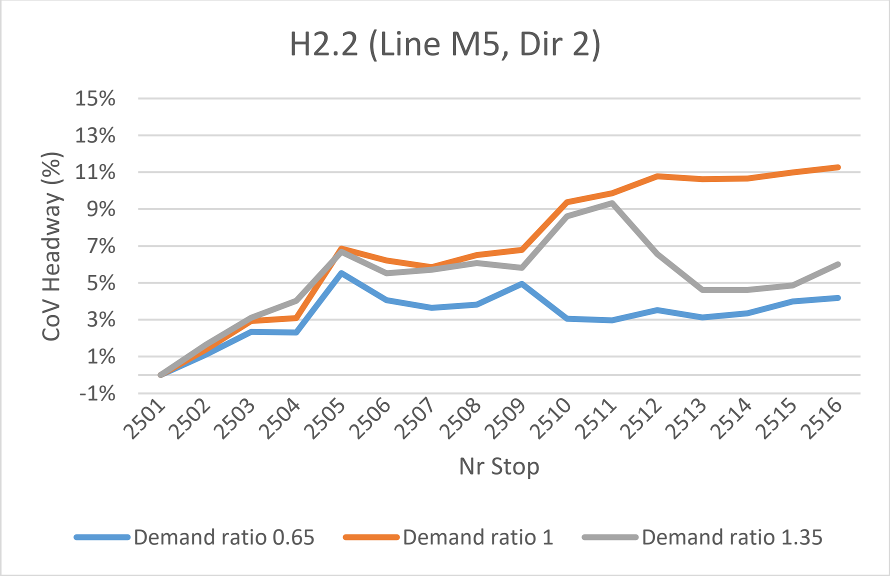

C2.2 (Line M7, Dir 1)
CoV Headway (%)
18%
16%
14%
12%
10%
8%
6%
4%
2%
0%
701 702 703 704 705 706 707 708 709 710 711 712 713 714 715 716 717
Nr Stop
Demand ratio 0.65
Demand ratio 1
Demand ratio 1.35

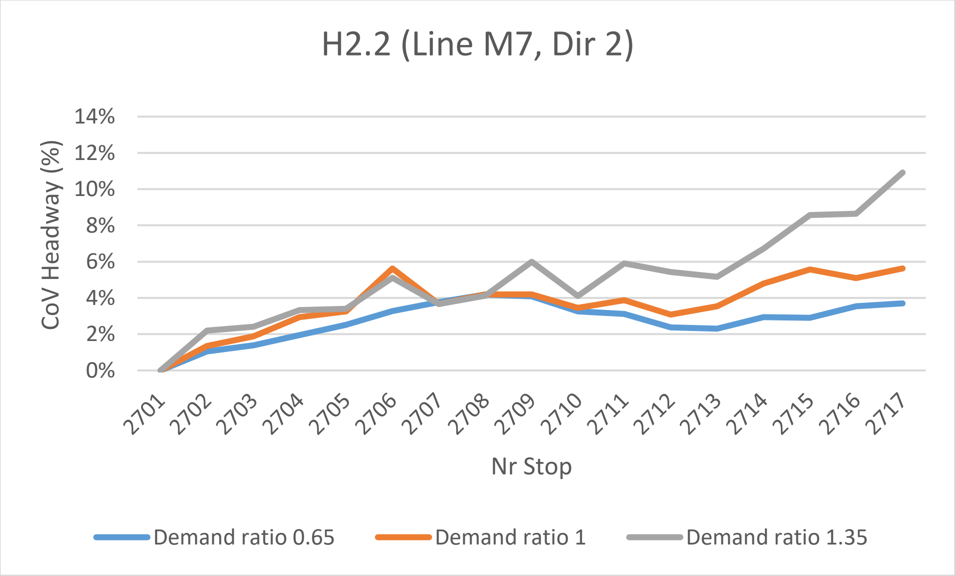

C2.2 (Line M5, Dir 2)
CoV Headway (%)
15%
13%
11%
9%
7%
5%
3%
1%
-1%
2501 2502 2503 2504 2505 2506 2507 2508 2509 2510 2511 2512 2513 2514 2515 2516
Nr Stop
Demand ratio 0.65
Demand ratio 1
Demand ratio 1.35


C2.2 (Line M7, Dir 2)
CoV Headway (%)
14%
12%
10%
8%
6%
4%
2%
0%
2701 2702 2703 2704 2705 2706 2707 2708 2709 2710 2711 2712 2713 2714 2715 2716 2717
Nr Stop
Demand ratio 0.65
Demand ratio 1
Demand ratio 1.35

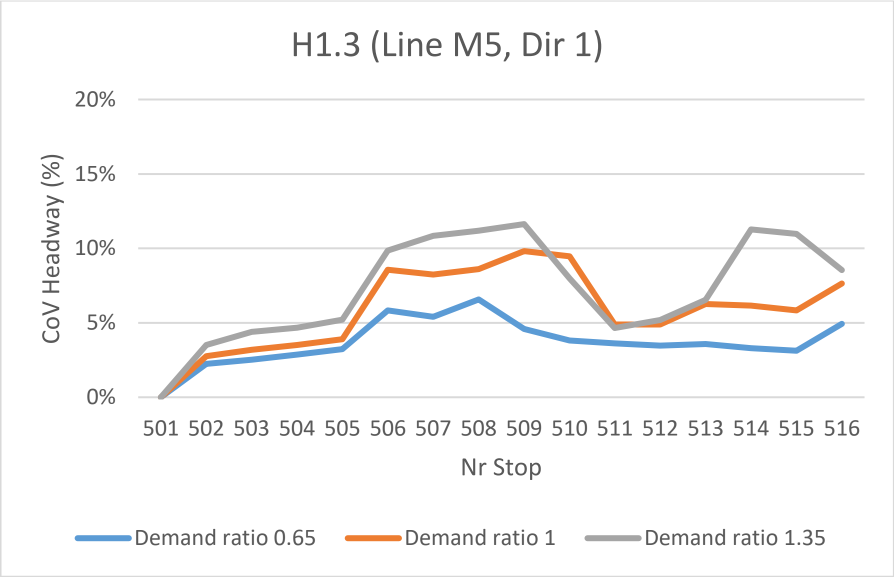

H2.2 (Line M5, Dir 1)
CoV Headway (%)
20%
15%
10%
5%
0%
501 502 503 504 505 506 507 508 509 510 511 512 513 514 515 516
Nr Stop
Demand ratio 0.65
Demand ratio 1
Demand ratio 1.35

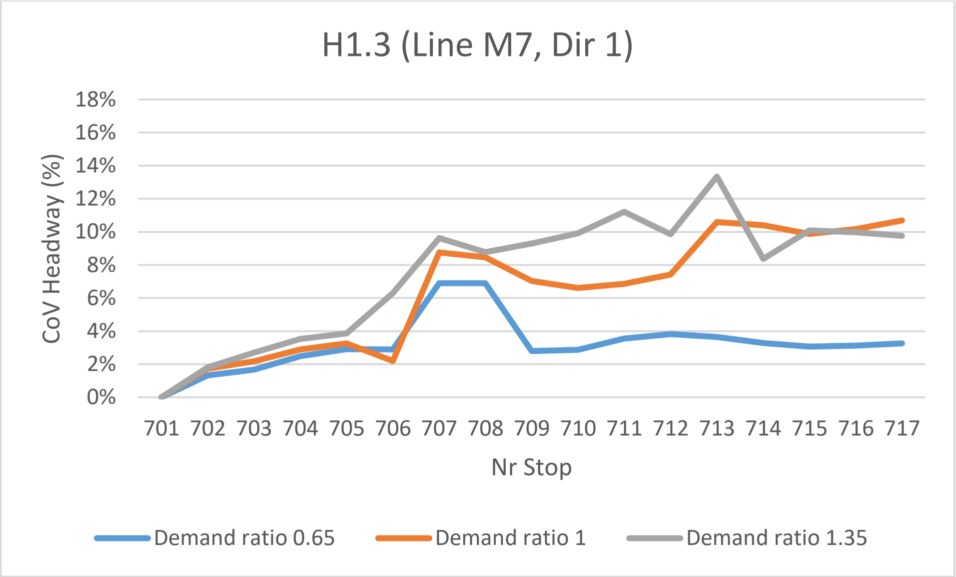

H2.2 (Line M7, Dir 1)
CoV Headway (%)
18%
16%
14%
12%
10%
8%
6%
4%
2%
0%
701 702 703 704 705 706 707 708 709 710 711 712 713 714 715 716 717
Nr Stop
Demand ratio 0.65
Demand ratio 1
Demand ratio 1.35

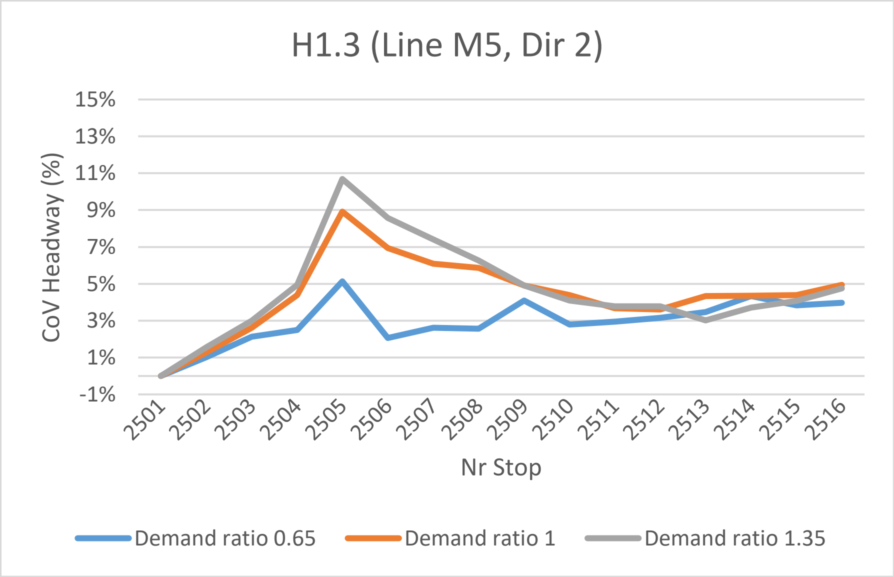

H2.2 (Line M5, Dir 2)
CoV Headway (%)
15%
13%
11%
9%
7%
5%
3%
1%
-1%
2501 2502 2503 2504 2505 2506 2507 2508 2509 2510 2511 2512 2513 2514 2515 2516
Nr Stop
Demand ratio 0.65
Demand ratio 1
Demand ratio 1.35

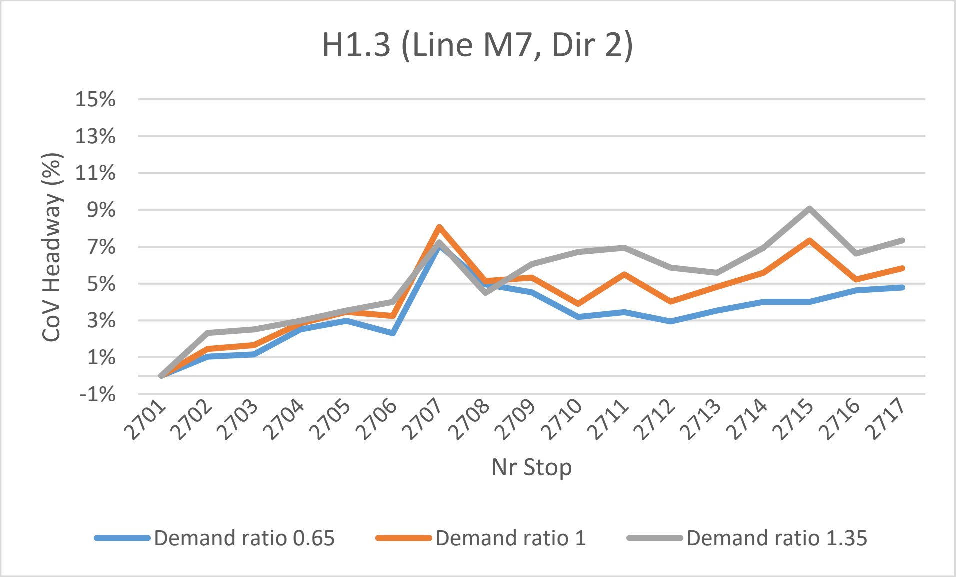

H2.2 (Line M7, Dir 2)
CoV Headway (%)
14%
12%
10%
8%
6%
4%
2%
0%
2701 2702 2703 2704 2705 2706 2707 2708 2709 2710 2711 2712 2713 2714 2715 2716 2717
Nr Stop
Demand ratio 0.65
Demand ratio 1
Demand ratio 1.35

Z

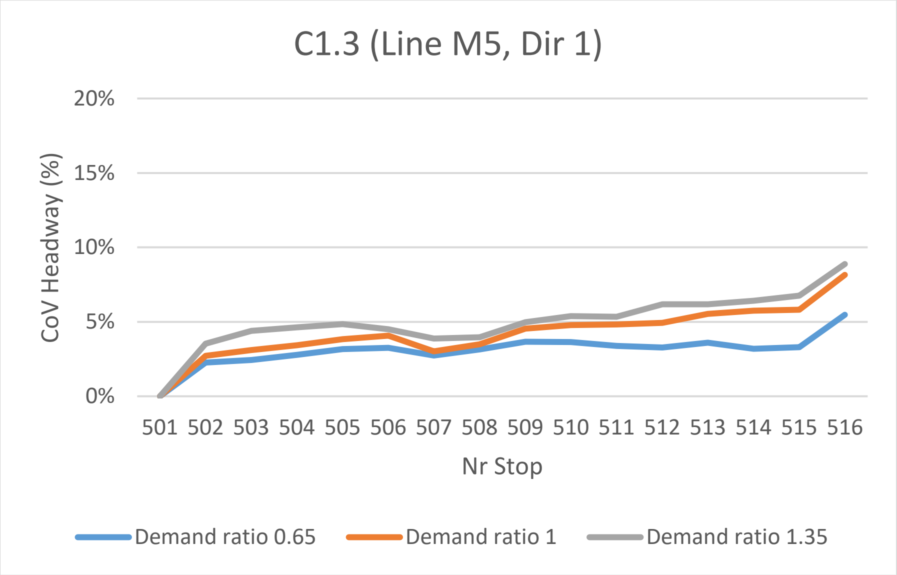

H1.3 (Line M5, Dir 1)

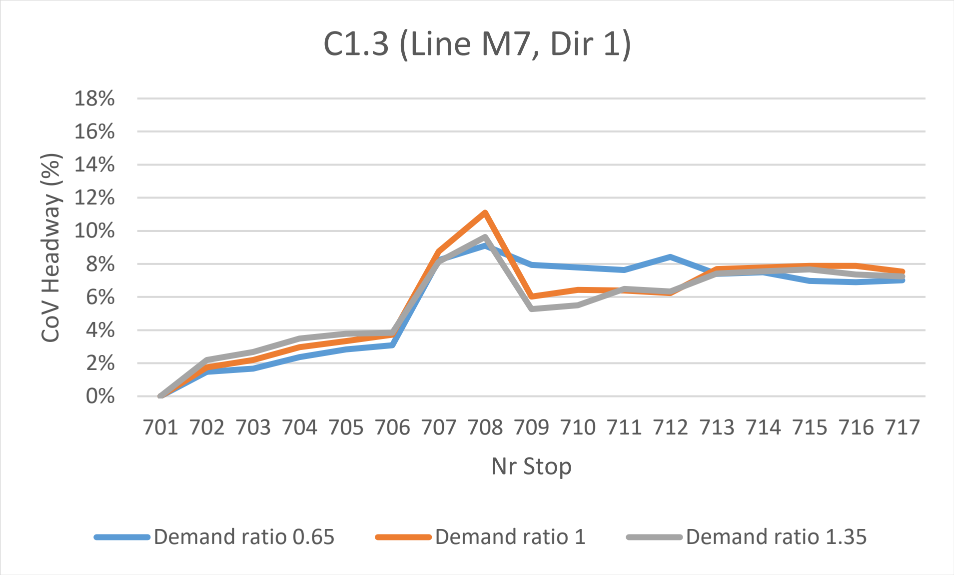

H1.3 (Line M7, Dir 1)

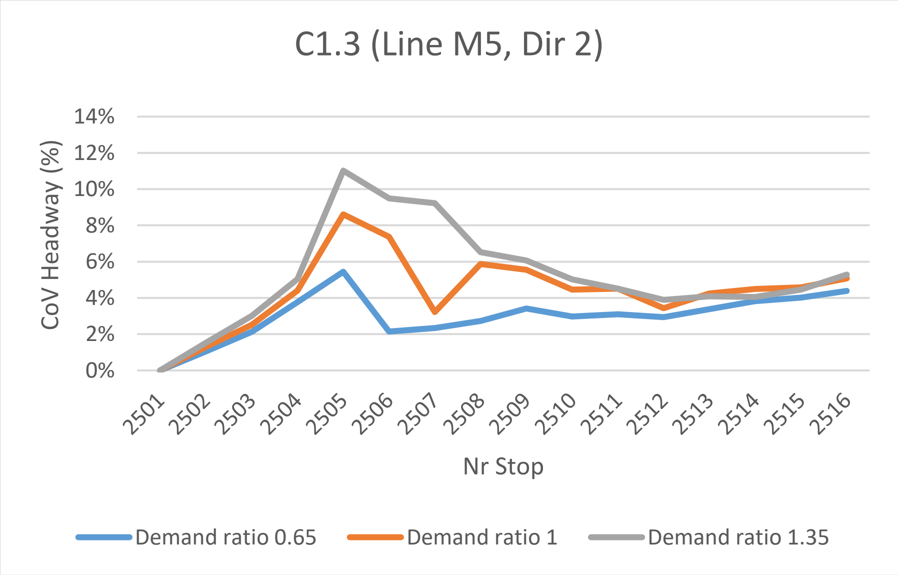

H1.3 (Line M5, Dir 2)

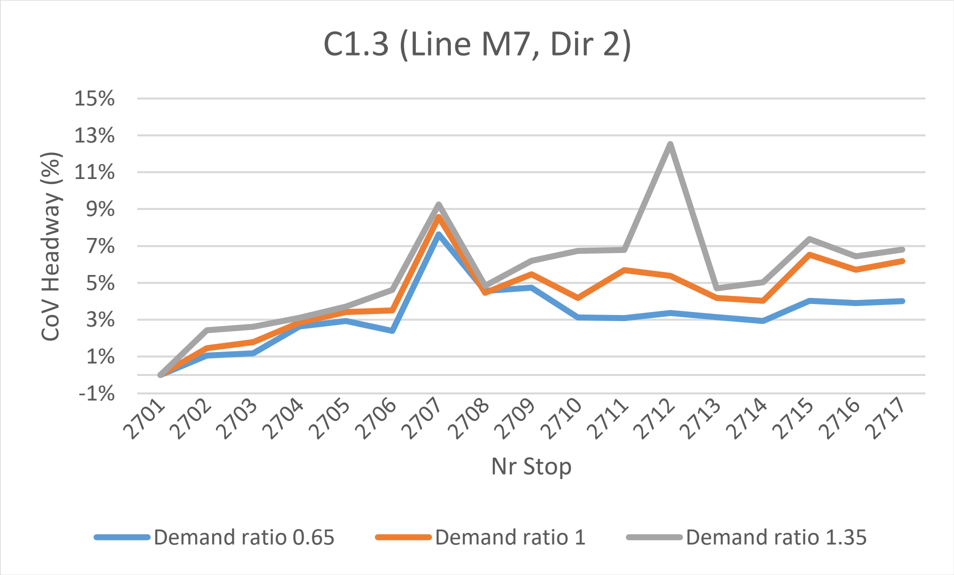

H1.3 (Line M7, Dir 2)

AA


C1.3 (Line M5, Dir 1)
CoV Headway (%)
20%
15%
10%
5%
0%
501 502 503 504 505 506 507 508 509 510 511 512 513 514 515 516
Nr Stop
Demand ratio 0.65
Demand ratio 1
Demand ratio 1.35


C1.3 (Line M7, Dir 1)
CoV Headway (%)
18%
16%
14%
12%
10%
8%
6%
4%
2%
0%
701 702 703 704 705 706 707 708 709 710 711 712 713 714 715 716 717
Nr Stop
Demand ratio 0.65
Demand ratio 1
Demand ratio 1.35


C1.3 (Line M5, Dir 2)
CoV Headway (%)
14%
12%
10%
8%
6%
4%
2%
0%
2501 2502 2503 2504 2505 2506 2507 2508 2509 2510 2511 2512 2513 2514 2515 2516
Nr Stop
Demand ratio 0.65
Demand ratio 1
Demand ratio 1.35


C1.3 (Line M7, Dir 2)
CoV Headway (%)
15%
13%
11%
9%
7%
5%
3%
1%
-1%
2701 2702 2703 2704 2705 2706 2707 2708 2709 2710 2711 2712 2713 2714 2715 2716 2717
Nr Stop
Demand ratio 0.65
Demand ratio 1
Demand ratio 1.35

Appendix E: Interview summary

Interview process

The purpose of the interview is to verify the potential applicability of the proposed concept and the realness of the result from the practical perspective. For this purpose, an interview with an expert in public transport operation was done. The interview took around 30 minutes and was semi-structured. The first section of the interview discusses the comparison of performance result for different strategies. The second section of the interview discusses the potential of applying the strategies from the practical perspective.

Interview results

This section provides the result of the interview in a descriptive analysis.

Performance of the strategies based on different perspectives

In relation to the passengers and the operators, passengers as the customer, is the main priority in public transport operation. For most passengers in public transport, travel time is very important. On the other hand, the operators concern on the operating cost. Several strategies in the evaluation based on simulation showed a better regularity, as one reliability indicator, comes with a cost of higher number of fleet requirement. For the operator, higher operational cost is not a problem as long as the strategy can provide a better service for the passengers, and hence lead them to get a higher number of passengers as the consequence. Nevertheless, one should assure that the benefit gained from the strategy is worth compared to the cost that has to be spent.

In addition, when comparing different services in term of travel time, the passengers may not be aware of a slight difference, for example 1 – 2 minutes travel time delay. This small difference can be ignored when assessing the best strategy. However, obviously, a larger difference than that will be undesirable. The delay should be kept in a reasonable number, otherwise it can reduce the attractiveness of using public transport system itself and the passengers may change their preference into using their personal car.

From the perspective of the authority, schedule-based control is still preferable, concerning on the punctuality indicator. Even though there is no plan to migrate into regularity, showing them the high percentage of regular trips that can be achieve through different strategies might initiate the idea of applying regularity-based operation.

Implementing regularity-based bus operation in AllGo network

As a system operated with a dedicated lane, speed adjustment was expected to be working well in this network. However, the result from the simulation shows that the schedule-based holding strategy can outperform the speed adjustment by looking at the overall performance. The same condition applied for headway-based holding control. This actually can be predicted already, considering the high punctuality that the system currently has.

To change a system into regularity-based operation, there are already many risks to take. The problem is not only related to the control strategy itself, but also related to the strategic planning and requires changes in the every aspect of the public transport system. Hence, for a dedicated lane bus operation such as Almere, it seems better to keep the punctuality high so that the regularity can be achieved, rather than changing the whole system into regularity, while the gain is insignificant.

Implementing regularity-based bus operation in general

Apart from the case in Almere, it is still possible to apply a regularity-based operation in other networks. Still, there are many things to consider before applying it, which is not captured in the simulation, as followed.

Burden for the drivers

The drivers are very difficult to accept changes. As the executors of the system, mainly they just want to keep working based on the existing system. Speed adjustment-holding developed in this study, might be difficult to apply due to this issue, because it also requires many changes in the way the drivers work.

ICT system -- C-ITS system (Cooperative Intelligent Transport System)

In the simulation, information exchange works as an event-based. However, it is better to have a system that can continuously exchange the vehicle state on a time-based, thus, the input for control decision can be more accurate. Continuous exchange of information will help to monitor the recent state of the vehicle, and produce a more robust prediction for a better control system. The existing technology has been able to do this kind of interaction, thus, technology will no longer be a problem for the system. A reference for this is the C-ITS system where there is a cooperation between vehicle.

Passenger adaptation

From the passenger perspective, it does not seem that many changes are required based on the developed control. The most important thing is to keep them informed about their travel time to their destination.

Conflict with operational scheduling

The issue regarding the operational scheduling, it seems more important to consider how to convince the people behind it to redesign the way they schedule. The issue with the drivers are more complex since they are working under an organization, which also has their own requirements for employing drivers relating to workload and rest time.

Coordination with other actors

With regularity, it is also possible to have a coordination with other stakeholder, for example the road controller, to help controlling the traffic light along the route in such a way it supports the desirable headway.

Concessionaires

With the concessionaire, it is important to determine a certain bandwidth for the regularity. Until what boundaries the headway can be acceptable, regardless the variation. A headway-based operation can have a low regularity, but it may be not acceptable if the deviation (in average) is much higher than the initial planning. Imagine a case in which having an initial headway of 5 minutes, but then has an actual average headway of 10 minutes but is very regular. It should be considered to what extent the regularity itself is can be approved.