Kungliga Tekniska Högskolan

Boarding and bunching

The impact of boarding procedure on bus regularity and performance

Jens West

2011-04-08

Master thesis
Transport Systems programme
Transport Science Department
School of Architecture and the Built Environment

Abstract

The aim of this thesis is to study how different boarding procedures on buses affect bus bunching, passenger travel time and waiting time, taking the effects on the whole transit network in mind. To achieve this it is important to be able to quantify the bunching problems in situations with different boarding procedures and demand.

Video recording of bus boarding and alighting in Stockholm and Gothenburg was used to calibrate and validate dwell time models. Identification of suitable dwell time functions was based on the data and former experience. The network performance analysis is based on simulation of two bus lines with different supply and demand running partially parallel.

The simulation shows that in a system with many passengers and overlapping bus lines, free boarding through all doors can decrease average passenger travel time and vehicle circulation time by 20 - 25 per cent during rush hour. At the same time better regularity means less crowded buses, and for each bus and stop 0.5 passengers less were left behind due to overcrowding.

Allowing the passengers to board through all doors can in combination with a good holding strategy give large benefits in a transit network in the size of Stockholm. Even though bus bunching is a well-known phenomenon, it is seldom considered when evaluating new transit policies and this can lead to underestimation of the effects.

Acknowledgements

The idea behind this thesis was born after reading Trafikplan 2020 (SL 2010), where page 43 is devoted to the future need for higher capacity in the trunk bus network in Stockholm. Once again, allowing boarding through all doors is mentioned as a possible way of improving service. After discussions with Karl Kottenhoff and Oded Cats at KTH and Paulina Eriksson at Trivector Traffic AB, the subject evolved. Oded Cats became the thesis supervisor. I would like to thank these persons for their contribution.

I would also like to thank Malin Gibrand and all her colleagues at Trivector Traffic, for giving me support and a pleasant work environment at their office in Stockholm.

Table of contents

Table of figures

1. Introduction

1.1. Background

Turning bus transit into a faster and more reliable mode of transport has for good reasons been a major goal for transport researchers, planners and politicians for many years. An efficient bus network is necessary to prevent the streets of the larger cities from being clogged up by cars. Furthermore, for people without access to a car, buses are often vital for travelling. The long-time trend has often been that the bus mode has become less attractive, when it in terms of travel time, comfort and reliability has lost ground to the car.

Improving bus service has many aspects. Bus Rapid Transit (BRT) is a concept that aims for the same standard in a bus service as in a rail service. The key to this is that the transit service should be completely separated in space from car traffic, thus avoiding obstacles such as car queues, traffic lights and parked cars. Other BRT elements are stations (in contrast to stops), special vehicles, an efficient fare system, a good information system and a clear operation plan and image. (Kottenhoff, Andersson and Gibrand 2009)

An important aspect of BRT is that the dwell times at stations should preferably be as short as they are at a subway or tram station. This means that passengers are free to board and alight the vehicle unhindered and through many door channels simultaneously.

In Sweden local buses are normally boarded only through the front door, and alighted through all other existing doors, which are often two or at most three single or double doors. In rural or small town settings, the passenger often has the opportunity to purchase the ticket from the driver, but in larger cities it is common to be required to show a prepaid ticket.

Passenger vehicles on rail (e.g., trams, light rail and commuter trains), on the other hand, are always boarded and alighted through all doors. In the Gothenburg and Norrköping tramway systems, passengers can board without showing their transit ticket to anyone, while in Stockholm all rail vehicles have either station barrier guards or on-board conductors.

Since 1967, street cars have not been in regular service in Stockholm, which is a result of both the development of the subway system and of competition with cars. In August 2010 the first new tramline in Stockholm inner city was opened, and the plan is to continue building tramways. This follows a trend that has been observable in large parts of Western Europe in recent years.

There is no bus service in Stockholm so far that implements the full BRT concept. The trunk lines ("blue buses") have a relatively high degree of signal priority, bus lanes and high service frequency. The most important trunk lines run through the city core, which makes the room for physical improvements limited. So far the blue buses are boarded only through the front door at most stops, just like the other local bus lines. On major transfer nodes, boarding is eased by “traffic hosts”, who verify tickets and let passengers board through one of the rear doors. New bus lines with more BRT-like features than the current blue buses are currently being planned in Stockholm.

Figure 1: S:t Eriksplan, a typical inner-city bus stop in Stockholm, used by several lines

1.2. Problem description

Bunching is a common problem in high frequency bus services (and can be so in rail service as well), which is caused by random variations in ride and dwell times (Kronborg, Andersson, et al. 2000). A bus that faces a random delay will get more boarding passengers at each stop, causing more and more delay. The following bus will get fewer passengers at each stop, causing it to catch up the bus ahead of it.

The dwell time is the time a transit vehicle spends at a stop. The length of the dwell time at each stop depends on many factors. However, dwell time is generally assumed to be shorter when boarding is allowed through all doors (Sundberg and Peterson 1989). Although formulas exist for calculating dwell times, contributing factors that are not included in the formulas make direct observations necessary for exact estimations of a dwell time model that is valid for Swedish conditions.

It is difficult to compare the magnitude of the influence that different factors have on service regularity and bunching, as most of they are not easily controlled systematically. The fact that Gothenburg has another type of boarding procedure on trunk line buses than Stockholm does not allow direct comparisons of caused bus bunching, as none of the other parameters are likely to be identical. Measures that have been taken to improve regularity have often coincided with other changes, such as increased passenger numbers (Wendle and ter Schure 2004) and schedule adjustments not connected to the measures taken (Ingemarson 2010).

As a changed boarding procedure is assumed to affect regularity, and regularity is assumed to affect passenger travel time (including waiting time), the relationship between a changed boarding procedure and travel time is not straightforward in high frequency bus services.

Simulation is one way towards better understanding of how different factors influence travel time and regularity. Until recently, these simulations have been limited to very simplified models (Daganzo 2009). Considering that the performance of one transit line is influenced by the whole traffic network, including other transit lines, lack of computational power and available data (in an appropriate format) still limits the possibilities to simulate bus network performance.

A common-line problem deals with transit riders that have several options for their journey (Chirqui and Robillard 1975). The riders choose between bus options with both reasonable travel time and waiting time. Today, when passenger information systems are common, the transit riders can-not be assumed to be unaware of the waiting time for the next bus, but the waiting time for a faster bus is of course sometimes long enough to motivate taking the slower alternative. In practice the solution to a common-line problem will depend on the passenger demand as well, because crowding and delays will make lines less or more attractive (Cominetti and Correa 2001).

There are several reasons why alternatives are not always equally fast. The buses can take different routes, or one of them can require a change. One of them can be an express line that has fewer stops. Lastly, one of them can have a faster boarding procedure. This last scenario might seem hypothetical, but when street trams and more BRT-like bus lines become more common in Stockholm where buses traditionally allow boarding only through the front door, there will be competition between normal buses and new lines using the same physical path.

When a line with boarding through all doors (with unsupervised ticket validation or no ticket validation at all) and a line with boarding only through the front door (with ticket validation supervised by the driver) share a common line segment, the transit users will be subject to a special case of the common-line problem. If the lines have different stop patterns, this will naturally counteract bunching, because the lines will then serve different purposes to a higher degree and the possibilities to pass another vehicle will be greater. However, if they have the same stop pattern, persistent bunching might be the result.

It is reasonable to assume that holding strategies will be more complicated to implement in this case, because if the faster vehicle was forced to keep the headway to the slower one constant, it would not be fast anymore. If the slower vehicle is forced to keep a radically slower timetable than the fast service (and let faster vehicles pass) to avoid bunching, its passengers will be treated unfairly. Especially those travelling beyond the shared line segment will lose time unnecessarily.

Bunching with several lines involved has been very little studied before; most simulation models only include one simplified line. There are also very few previous attempts to quantify any of the factors that cause bunching. Crowding effects on dwell time and bunching is seldom taken into consideration when evaluating transit networks, and analysis is in many cases on the vehicle level and seldom on the passenger level.

1.3. Objectives of this study

- To validate the commonly available dwell time functions in a Stockholm context
- To analyse boarding procedure effects on
    - dwell time
    - bus bunching, crowding and waiting time
    - the whole network performance on a passenger level
- To quantify the bunching problems in situations with different demand and boarding procedures
- To discuss the implications of the relation between boarding procedure and bus regularity, in particular in the context of Swedish transit systems

2. Literature review

The main sources of information on bus dwell times and bus bunching were found from the libraries at Kungliga Tekniska Högskolan and VTI, Statens väg- och transportforskningsinstitut. Additional material was available from the collections of Karl Kottenhoff at KTH and Trivector Traffic AB.

The Transit Capacity and Quality of Service Manual (Kittelson & Associates 2003) was accessed from http://www.trb.org/Main/Blurbs/153590.aspx.

2.1. Dwell time

The time it takes for an average passenger to board or alight a vehicle depends on a number of factors. These include the number of available doors, the payment method, crowding effects and vehicle geometry (e.g., floor height).

A high number of available door channels affects the boarding and alighting time positively. The numbers in Table 1 are taken from Transit Capacity and Quality of Service Manual (Kittelson & Associates 2003). A door channel is either a single door or one half of a double door (Sundberg and Peterson 1989). In sources from USA (e.g., TCQSM and Milkovits 2008) much focus is on whether passengers alight in the rear or the front door. This might not be an important issue in Stockholm, because the front door is used almost exclusively for boarding.

	Available	**Default Passenger Service Time (s/p)**		
	Door Channels	Boarding	Front Alighting	Rear Alighting
With smart card	1	3.0	2.8	1.6
Free boarding	1	2.0	2.8	1.6
	2	1.2	1.5	0.9
	3	0.9	1.3	0.7
	4	0.7	0.9	0.5
	6	0.5	0.6	0.4

Table 1: TCQSM default passenger service time for low-floor buses

These numbers are supported by the Swedish studies reviewed by Sundberg and Peterson (1989), except that the Swedish numbers are consequently 20 per cent lower. A study made in Örebro revealed that these numbers can be significantly higher for a line with a different fare system and relatively low numbers of boarding passengers per stop (Wendle and ter Schure 2004). The difference between one and two doors available for boarding was very small in this study (both numbers were around ten seconds).

A low-floor bus is estimated to have 20 per cent faster boarding in TCQSM. This corresponds to 0.5 seconds for an average boarding. Johansson and Liljemark obtained the same result in Gothenburg in 1980. The alighting is approximately 25 per cent faster in a low-floor bus. In an experiment in Uppsala (Eklund 1992) the effect was not this high. In this experiment the boarding and alighting was only 7 – 13 per cent faster with a low-floor bus. A reason for this could be that the experiment participants were young students with good mobility.

The fare payment system also affects the service time. The Swedish study by Blomqvist and Larsson (1980) supports TCQSM, which suggests service times of between 2.5 (for free boarding) and 4.2 seconds (for swipe cards) for normal buses (not low-floor) depending on the payment method. The number of available door channels explains the differences that exist for some of the studied cities. A study in Chicago (Milkovits 2008) found boarding times of 3.1 seconds for smart cards and 4.2 for swipe cards on low-floor buses, 0.5 seconds more than TCQSM. In a laboratory experiment by Fernández (2010) the boarding time was only 1.5 seconds with free boarding, and 1.7 with smart cards on low-floor buses. Surprisingly, a vertical gap of 150 millimetres speeded up the boarding time further. However, real life data showed that boarding with a combination of smart card ticket verification and free boarding took 2.1 seconds and alighting 1.3 seconds.

In TCQSM, a constant time penalty for each boarding passenger is added when standees are present in the bus. Several authors have tried to give a better approximation of the increased boarding and alighting times when the bus is crowded. Sundberg and Peterson (1989), Weidmann (1994), Puong (2000) and Milkovits (2008) all agree on a non-linear effect from standing passengers. Puong agrees with TCQSM on that only boarding times are affected by crowding, while Sundberg and Peterson, Weidmann and Milkovits have found indications that alighting time is affected as well.

Sundberg and Peterson point out that the impact should be vehicle-specific, because a bus with less floor space will be more crowded than a bus with more floor space. This can be generalized with a formula including the number of standees per square metre, and such a formula is suggested but not proved by Sundberg and Peterson. A similar model is suggested by Weidmann, in which the crowding effect is a second grade function of the number of standees per square metre. The other studies are done with specific vehicle types and there is no attempt to generalize the results to other vehicles.

Milkovits found that in crowded situations the ticket verification method does not affect the boarding time. This makes sense, because when the boarding passengers are already slowed down by crowding, they are not able to pass the ticket verification point any faster in any case. This situation occurs when the crowding time addition is larger than the ticket type time addition.

A Swedish study showed that whether the bus has a large floor space for standees or many available seats does not seem to affect the boarding time in non-crowded situations. However, the study confirmed the assumption that double doors lead to shorter alighting time (Kronborg, Carlbring, et al. 1986).

Except boarding and alighting time, dwell time is also affected by the door opening and closing time. Airaksinen and Kuukka-Ruotsalainen (2008) showed that door opening times vary between 3 and 10 seconds for different bus models. Clearance time is often separated from dwell time and consists of the time it takes for the bus to enter and leave the stop. Clearance time depends on the configuration of the stop area. The clearance time is between 5 and 12 seconds for different stop types (Linderholm 2004).

2.1.1. Free boarding and fare evasion experience

In Sweden, the standard is to allow boarding only through the front door. This is motivated mostly by the increased risk of fare evasion related to free boarding. In Gothenburg, the experience is that ten per cent cheat when boarding is free, compared to two or three per cent with boarding only through the front door. On the trunk lines the increased passenger numbers due to the travel time gain is estimated to make the faster boarding procedure economically beneficial. (Wendle and ter Schure 2004)

In Jönköping, where boarding is allowed through several doors, the fare evasion is only 0.5 - 1 per cent in the whole system, and the faster boarding procedure in combination with other measures on the trunk lines are estimated to be economically beneficial. In Linköping where boarding was free on the buses between 1998 and 2002, the experience was not as good. After it was discovered that fare evasion increased from 1 - 3 per cent to ten per cent, the system was changed back. (Wendle and ter Schure 2004)

In Germany and France it is common to allow boarding through all doors. However, in some small French cities this policy has been abandoned due to increased fare evasion. (Wendle and ter Schure 2004)

2.2. Bus bunching

Buses that do not arrive when expected are a well-known cause of frustration and delays for transit riders all over the world. Bus delays can be caused by traffic congestion, incidents and accidents along the route. Such problems can be minimized by building better infrastructure (e.g., improved roads, bus roads, and stop areas) and by better transit priority (e.g., dedicated lanes and signal priority in intersections). Unusually large numbers of passengers or passengers with unusual characteristics (e.g., passengers with lower mobility) can cause delays as well. Such problems can be minimized by easing vehicle boarding. The bus can also be delayed already from the start, due to technical problems or because the driver is late. Differences in driver behaviour and ability can also cause delays along the way. (Kronborg, Andersson, et al. 2000)

In low-frequency bus services, passengers are usually aware of the timetable and arrive at the stop shortly before they expect the bus to arrive. Delays cannot be completely avoided, but if the bus is not extremely late, only passengers waiting for that late bus are affected.

If the frequency is high enough (ten minutes or more frequent according to TRAST 2007), the passengers can be assumed to arrive continuously to the stop, neglecting the actual schedule. Hence they do not care if the bus is late according to a schedule, because the waiting time depends only on the headway between arriving buses. The headway deteriorates if one bus is late but the consecutive bus is not. More passengers will then board the first bus than the following one, which will worsen the problem further, causing the latter to catch up the former. This phenomenon is called bus bunching and has been analysed for many decades. Vuchic (1969) developed a deterministic model to show that even the smallest disturbances inevitably lead to bunches.

Larger headway variations do not only lead to longer waiting times, but also to more uneven bus occupancies , which means that more passengers have to stand and ultimately means that more buses are needed to serve the same number of passengers. The slowest buses will be the ones that carry many passengers, which means that passenger travel times will increase. The problem will be further increased by the fact that crowded buses take longer to board.

The higher the frequency, the more likely it is that buses bunch (Osuna and Newell 1972). Turnquist and Bowman (1980) found that when there are large deviations in inter-stop travel times this is not only a disadvantage for very high frequency lines. If the buses bunch very quickly, they will be less sensitive to external disturbances than they are when running singly. However, this model assumes that buses can overtake each other repeatedly ("leap-frog"). In some cities (e.g., in Turku, Finland) were bay stops are common, several buses even have the same departure time to be able to leap-frog from the start. If the buses have alighting passengers at every stop, this method works less efficiently. Increasing vehicle capacity is a more common method to avoid very high frequencies (e.g., introducing articulated buses or light rail).

2.2.1. Reducing bunching

The traditional way of dealing with the bunching problem is to insert slack in the timetable, and to hold buses that are early (Eberlein, Wilson and Bernstein 2001). In this way, small schedule deviations can be erased and bunching can be avoided. Inserting excessive slack affects travel time negatively, so the amount of slack is an optimization problem where regularity and travel time should be balanced. For the same reason, holding cannot be performed at every stop. The stops where buses are held are called time points.

If the deviations are too large, the slack becomes insufficient, and regularity decreases along the route nevertheless. Another problematic situation is when all buses are late (e.g., due to weather conditions or congestion). Then none of the buses are held, and bunches can start forming.

Strategies to deal with regularity issues include short turning (i.e., turning the bus before it reaches the terminal), skipping stops and inserting extra buses (Kronborg, Andersson, et al. 2000). The former two of these measures are unacceptable from the passengers' point of view, while the latter is very resource consuming.

Another control strategy for high frequency bus services is headway-based holding. Instead of having a schedule that regulates the departure from time points, the departure time is decided from the headway to the preceding and possibly also the succeeding bus. With automated vehicle location (AVL) systems, this is achievable essentially without increasing the labour.

If the dwell time would not grow with the number of boarding passengers, it is easy to assume that problems with bunching would not be as severe, as they would not grow systematically. According to Vuchic (1969), the most effective way to deal with bunching is to reduce boarding times. However, external disturbances can never be completely avoided, and to break bunches that have already been formed, at least some of the control strategies must still be available regardless of a changed boarding procedure.

2.2.2. Experience from Stockholm

In Stockholm, several measures have been introduced with improved regularity as at least one of the goals. Bus lanes were an important part of the trunk line concept that was introduced in 1998 (Fredriksson and Andersson 2002).

Signal priority was introduced with the trunk lines as well (Ingemarson 2010). In 2002, a project called RETT had the objective to evaluate different methods for improved regularity (SL 2003). One of the methods was adaptive signal priority, which means that the signals do not prioritize early vehicles. The trial was successful, and adaptive signal priority was implemented on all the trunk lines.

Traffic hosts, whose role is to shorten dwell times at important stops by checking tickets and to hold early buses existed before 2000, but when a new contract was made with the bus operator the financing was withdrawn (Kronborg, Andersson, et al. 2000). Traffic hosts were included in the RETT project (SL 2003). The conclusion was that having traffic hosts at important stops was not an efficient method. Still, the method was tested again on line 4 in 2004, and again the result was meagre (Ingemarson 2010). Neither regularity nor dwell times were shorter in general. However, this measure was later made permanent for all the trunk lines.

Having extra buses on standby were also a part of the RETT project, but the result was that it was not efficient either. Instead RETT gave a number of suggested new measures. They were headway-based control, driver relieves only at terminal stops, boarding through all doors, and to convince the drivers to open both front doors. None of these suggestions have been implemented so far (Ingemarson 2010). Instead, traffic hosts and extra buses, which were not recommended measures, are used today to reduce waiting times.

2.3. Shared transit corridors

Assigning passengers correctly to lines that serve the same OD-pair and to estimate the average travel time is an important part of transit modelling, which requires good assumptions about passenger decision making. This topic is known as the common-line problem and has been studied by many.

Chriqui and Robbillard (1975) suggested that passengers are able to bundle together the headways of lines that share the same stop and board the first vehicle to arrive in order to achieve shorter waiting time. This idea was further developed by Spiess and Florian (1989) with an algorithm to find the passenger share among lines that produces the optimal average travel time. This algorithm is possible to use when link travel time is a function of the passenger flow as well. Cominetti and Correa (2001) and others have presented more advanced models with basically the same properties.

All of these analytical methods require the relation between passenger flow and travel time to be a well-defined function and hence they cannot easily deal with issues such as bunching, lack of timetable synchronization and holding. However, the ability of the passengers to predict travel time is certainly limited as well.

Other authors have dealt with the issue of optimizing bus allocation to different lines on shared transit corridors, based on the analytical approach to common-line passenger assignment (Han and Wilson 1982) and new heuristic algorithms (Teng and Yang 2009).

Timetable synchronization between different lines has been dealt with by Ceder, Golany and Tal (2001). The goal of this research has been to minimize passenger waiting time at transfers. The proposed algorithm assumes deterministic link travel times and ignores the problem with bunching. The only literature that has been found on the subject of bunching involving two or more lines sharing the same corridor is by van Oort and van Nes (2009). They briefly describe the problem and how to analyse it.

3. Methodology

3.1. Data collection

To compare boarding through the front door and boarding through all doors, dwell time data was collected in Stockholm and in Gothenburg. Both cities have basically the same ticket alternatives, where smart card tickets are the dominant form and a minority of less frequent travellers uses either paper or SMS tickets. In Stockholm all travellers are required to prove to the driver that they have a valid ticket. Smart cards are held against a card reader to verify its validity while paper and SMS tickets are shown directly to the driver. In Gothenburg travellers are not required to do any ticket verification. However, if the traveller uses a smart card that is not a period card (e.g., a single or 5-trip ticket) it has to be held against a card reader for the ticket to be activated.

The boarding and alighting processes were recorded with a digital video camera. All the data was analysed later, except from the level of crowding on the bus, which was not possible to observe on the video recording, and was instead estimated directly on the location. The crowding level was estimated after the bus had left the stop, and the crowding before boarding started was calculated by subtracting the number of boarding passengers (from the recording) from the estimated crowding afterwards.

The data was collected at four stops in Stockholm(S:t Eriksplan, Västerbroplan, Gullmarsplan and Odenplan) and one in Gothenburg (Nordstan). All the data collection locations except Gullmarsplan have a traffic signal directly after the stop. All stops except Västerbroplan and S:t Eriksplan are points where the schedule is regulated, and Gullmarsplan is even the starting point for the bus lines. When the driver for these reasons has to wait after the last passenger has boarded the bus, it is very common that the front door is left open for more passengers to board. In many cases there are actually more passengers arriving to the stop during this time. Sometimes waiting for late arrivals can be the sole reason for the driver to wait at the stop, but it is practically impossible to verify if and when this is the case. Time lost due to traffic signals, schedule regulation and waiting for additional passengers is not part of the boarding procedure and independent of the vehicle capacity, but varies depending on which stops and lines are studied.

Due to these reasons, a boarding or alighting process was determined to start when the first door was opened, but not to end when the last door was closed, but rather when the last passenger had either entered or left the vehicle completely. Ideally the driver then closes the doors and drives off, but the time it takes depends both on how fast the driver is and how fast the door closing mechanism is. These processes are arguably independent of boarding procedure and vehicle capacity as well. The difference between the total dwell time and the time spent on passenger boarding and alighting was studied separately.

3.1.1. Stockholm

The first data collection occasion was on November 25th, 07:40 – 08:30, at S:t Eriksplan, Stockholm, in the direction towards Odenplan and Karolinska sjukhuset. This location was chosen because of the large number of both boarding and alighting passengers. Data was recorded from 23 buses belonging to lines 3, 4, 72 and 77, out of 35 buses that passed the stop during the recording. Most of the buses that are not included in the record arrived while another bus was still at the stop, so it stopped outside of the camera range. In some cases the camera view was obscured by people. The record includes 143 boarding passengers and 55 alighting passengers.

Figure 2: Data collection at S:t Eriksplan, Stockholm

The second data collection occasion was on November 25th, 16:10 – 17:50, at Västerbroplan, Stockholm, in the direction towards Hornstull. This location was chosen because of the high degree of crowding on the buses and the large number of boarding passengers. Data was recorded from 33 buses belonging to lines 4, 40, 77, 151, 153, 726, 743 and 745. In total 68 buses passed the stop, but many of them were not possible to record due to the same reasons as at S:t Eriksplan, and some of the buses did not stop at all. The record includes 309 boarding passengers.

Figure 3: Data collection at Västerbroplan, Stockholm

The third data collection occasion was on November 26th, 16:30 – 17:30, at platform M, Gullmarsplan, Stockholm. This location was chosen because of the large number of boarding passengers. Data was recorded from 14 buses belonging to lines 873 and 875. No buses are missing from the record. The record includes 274 boarding passengers.

Figure 4: Data collection at Gullmarsplan, Stockholm

The fourth data collection occasion was on November 29th, 16:30 – 17:40, at Odenplan, in the direction towards S:t Eriksplan and Norrtull. This location was chosen because of the large number of alighting passengers. Data was recorded from 24 buses belonging to lines 2, 4, 70 and 515, out of 35 buses in total that passed the data collection point. The record includes 73 boarding passengers and 235 alighting passengers.

Figure 5: Data collection at Odenplan, Stockholm

3.1.2. Gothenburg

The fifth data collection occasion was on December 10th, 07:30 – 08:15, at Nordstan, in the direction towards Brunnsparken and Centralstationen. . This location was chosen because of the large number of both boarding and alighting passengers. The recording had to be aborted because the battery was discharged (due to the cold weather). Data was recorded from eight buses belonging to lines 16, 17, 21 and 52. The number of vehicles that were not recorded was not counted, but it includes tram line 6 which also passes the stop. The record includes 60 boarding passengers and 121 alighting passengers.

Figure 6: Data collection at Nordstan, Gothenburg

The sixth data collection occasion was on December 10th, 15:44 – 17:30, also at Nordstan, in the direction towards Brunnsparken and Centralstationen. Data was recorded from 27 buses belonging to lines 16, 16X, 17, 21, 25 and 52. The record includes 284 boarding passengers and 497 alighting passengers. Two of the buses on line 16 were double-articulated.

3.2. Simulation

To study the effects of different boarding procedures in various situations, simulation was used. The clear advantage of this method over studying empirical data is that the input parameters can be better controlled, and the impact of different measures can be quantified with a higher certainty.

The tool within which the dwell time model was implemented is BusMezzo, the transit simulation model built on Mezzo, a mesoscopic traffic simulation model (Burghout 2004). In Mezzo individual vehicles are modelled, but not their second-by-second movements. The time it takes for a vehicle to move along a link is mainly based on two functions, the speed-density function and the queuing function. The speed-density function is used on a fraction of the link that is determined by the extent of the downstream queue. The queue length and speed is determined by a stochastic queue server for each turning movement.

BusMezzo uses the traffic network of Mezzo for analysing transit performance (Cats, Burghout, et al. 2010). The impact of other traffic can be modelled directly as vehicles, but it can also be modelled implicitly as random distributions in the link travel times. In this way the correlation between travel times on different links is not captured, but this correlation has in practical applications been found to be low (Cats, Larijani, et al. 2011).

As the dwell time is the focal point of this study, the implicit way of modelling traffic conditions was chosen. To make these conditions as realistic as possible, run time distributions were based on real bus line data. Bus line 1 in Stockholm has been used in BusMezzo simulations before in order to study different holding strategies, and the run time between each stop was then found to follow the log-normal distribution, with individual parameters for each link (Cats, Larijani, et al. 2011). These parameters were used to model the link run times in this study.

3.2.1. Network

Bus stops in Stockholm are very seldom used by only one bus line. An example of this is seen in Table 2, where all the bus lines that share one or more stops with line 4 are listed. Not all of these bus lines use exactly the same stop area, but in many cases (e.g., lines 40, 72, 74 and 77) they do.

Radiohuset													
Garnisonen													
Banérgatan													
Värtavägen	1									72			
Jungfrugatan	▨									▨			
Musikhögskolan										▨			
Stadion										▨	73		
Östra station										▨	▨		
Odengatan										▨			
Roslagsgatan		2			42	53				▨			
Stadsbiblioteket		▨			▨	▨			70	▨			
Odenplan		▨			▨	▨			▨	▨			
Dalagatan									▨	▨			
S:t Eriksplan			3							▨			77
Fleminggatan			▨										▨
Fridhemsplan	1			40									▨
Mariebergsgatan	▨			▨									▨
Västerbroplan				▨									▨
Högalidsgatan				▨									▨
Hornstull				▨									▨
Lignagatan													
Varvsgatan													
Ansgariegatan													
Zinkensdamm								66					
Rosenlundsgatan								▨				74	
Wollmar Yxkullsgatan								▨				▨	
Södra station								▨				▨	
Rosenlund			3									▨	
Eriksdal			▨				55					▨	
Skanstull			▨				▨					▨	
Gullmarsplan													

Table 2: Bus lines in Stockholm that run parallel with line 4

The network in the simulation consists of two lines, A and B, which partially run parallel (see Figure 7). On this shared section, they use the same stop areas, and the passengers travelling along the shared corridor can choose freely between the two lines and thus will they board the first vehicle to arrive.

In the simulation, both lines have 32 stops, whereof 16 are shared with the other line. This is a longer shared section than those existing in Stockholm, but on the other hand there are only two lines sharing stops and potential passengers, and not three or four which is common in many places in Stockholm.

The lines are only run one way, from stop 1 to stop 32, because the simulation only covers peak hour, so there is not enough time to capture the whole trip-chaining circulation (one round trip is estimated to take at least one and a half hour). The first half hour no passengers are generated, in order for the buses to spread out on the line. Thereafter, passengers are generated according to an even distribution during one and a half hour.

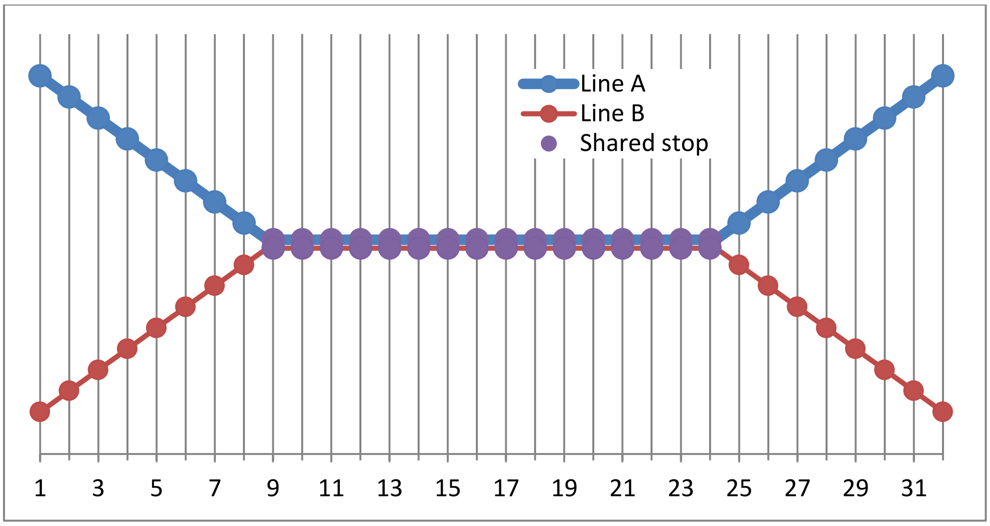

Figure 7: Simulated transit network

Three stops are time point stops, number 9, 17 and 25. On these stops the buses are held if they are too early, while on other stops the buses leave as soon as it is possible. A line with 32 stops (whereof three time points) can be described as a typical trunk bus line (cf. Table 3).

		Line			
	Direction	**1**	**2**	**3**	**4**
Number of stops	a	33	24	25	31
	b	31	22	26	30
Number of time points	both	3	2	3	4

Table 3: Number of stops on the trunk lines in Stockholm

The buses cannot pass each other at the stops, except at the time point stops, where they are able to leave either when they are ready to do so or when the timetable allows them to. This was chosen because it resembles reality for inner-city bus lines. If not impossible, it is often very difficult for the buses to pass each other. There is in most cases only one bus lane, and in order to pass another bus the bus behind has to use a car lane, and that is in general not only a time consuming manoeuvre, but often there are also physical barriers between the car lane and the bus lane. At time point stops there is generally more space for overtaking.

3.2.2. Demand and service frequency

A generic OD-matrix was created to imitate typical peak hour boarding patterns and passenger loads on busy inner-city bus lines (see figures Figure 8 and Figure 9). In reality, boarding patterns are seldom this smooth, since they often include considerable peaks (e.g., at transfer nodes). However, as long as the total number of boarding passengers and maximum passenger load is the same, such pattern differences should not affect regularity in any dramatic way.

The most frequent trip length in the OD-matrix is four stops, but due to the high number of OD-pairs with longer trip length, the average trip length is almost six stops. In a city such as Stockholm, where buses are mainly a complement to the main transit mode subway, such trips lengths can be regarded as typical. Comparing the total number of boarding passengers with the trunk lines in Stockholm during peak hour confirms that the pattern is realistic.

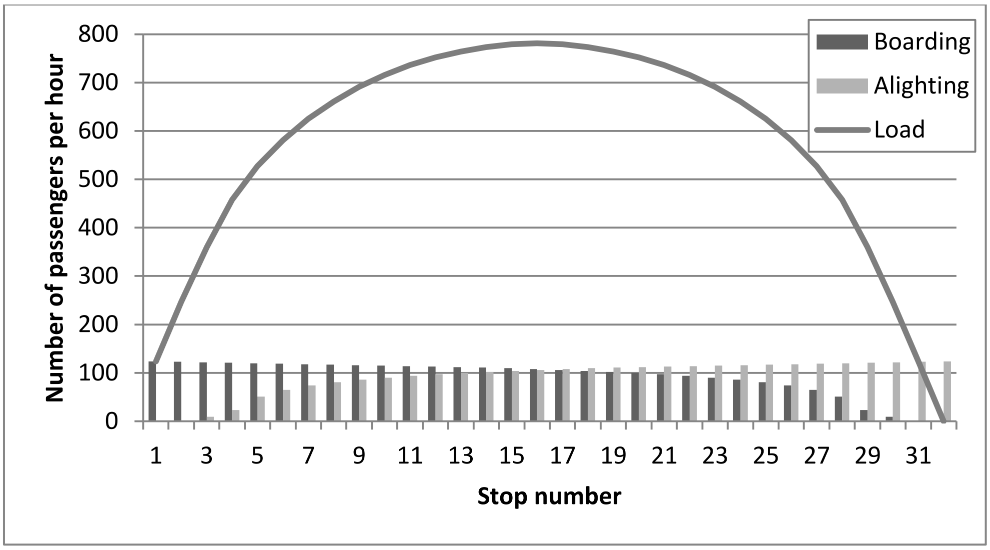

Figure 8: Demand pattern for line A in the simulation

To meet a demand where the peak hour load is almost 800 passengers at the maximum passenger load section, articulated buses are needed. According to the norms that are followed in Stockholm (SL 2006), the average number of passengers during one hour should not be higher than the total seat capacity.

A standard articulated bus takes 55 seated passengers, and this means that a headway of four minutes is required (15 buses per hour) for line A. The total seat capacity is then $15 \times 55 = 825$. This demand and corresponding supply is very similar to the conditions on bus lines 1 and 4 in Stockholm during rush hour (line 1 has a maximum load of 950 passengers during the morning peak hour and 700 during the afternoon peak hour while the maximum for line 4 is 800 passengers per hour in both morning and afternoon).

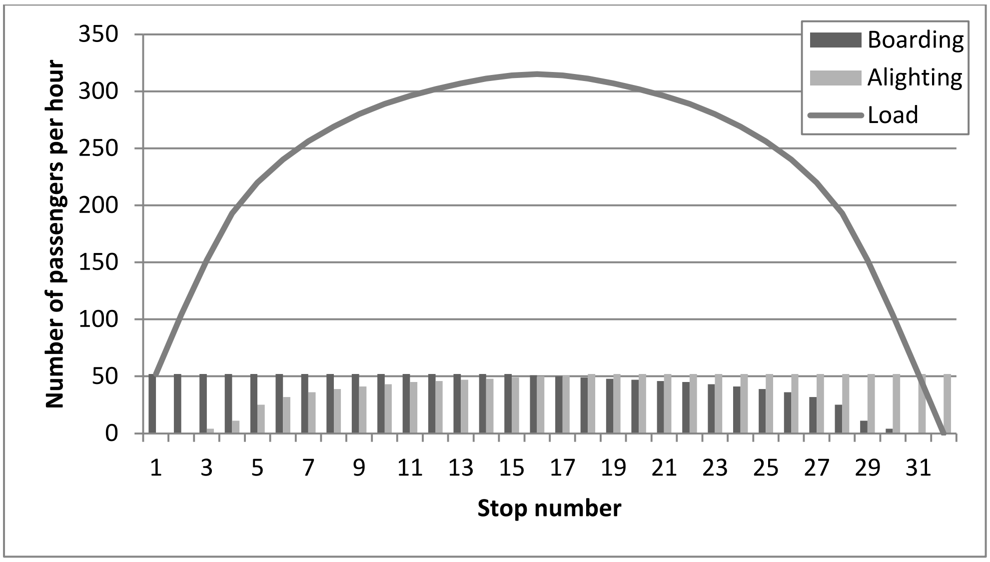

Figure 9: Demand pattern for line B in the simulation

If line A corresponds to one of the busiest bus lines in Stockholm, line B is more of a normal inner-city commuter bus line (cf. Table 4). Normal buses with seat capacity of 35 and headway eight minutes have a total capacity of $7.5 \times 35 = 263$ passengers per hour.

Line	Direction	Max load	Number of buses	Average headway	Average max load per bus
72	Östhammarsgatan	389	10	6 min	39
73	Karolinska sjh	317	7	8.6 min	45
74	Krukmakargatan	230	6	10 min	38
77	Karoliska Sjh	290	6	10 min	48

Table 4: Description of a set of inner-city bus lines in Stockholm during the morning peak hour

3.2.3. Scenarios

To see how the lines perform when they are not disturbed by other lines, they were first simulated separately, with the demand according to figures Figure 8 and Figure 9. These scenarios are named S0, S0H, S2 and S2H. In these simulations there is no shared corridor and no interaction of any kind between the two lines. Because the passenger load on line B is higher than the stipulated norm, this line was also run with five minutes headway to compare the results with the eight minute headway.

In the following scenarios (0, 0H, 1, 1H, 2, 2H), the two lines are run simultaneously, with the passenger demand on the shared section combined (i.e., a passenger going from a shared stop to another shared stop is indifferent between the two lines and boards the first vehicle to arrive). The passenger load reaches its maximum between stops 16 and 17. Here the average number of total transit riders is 1,100 per hour. The total seat capacity per hour is slightly lower, 1,088.

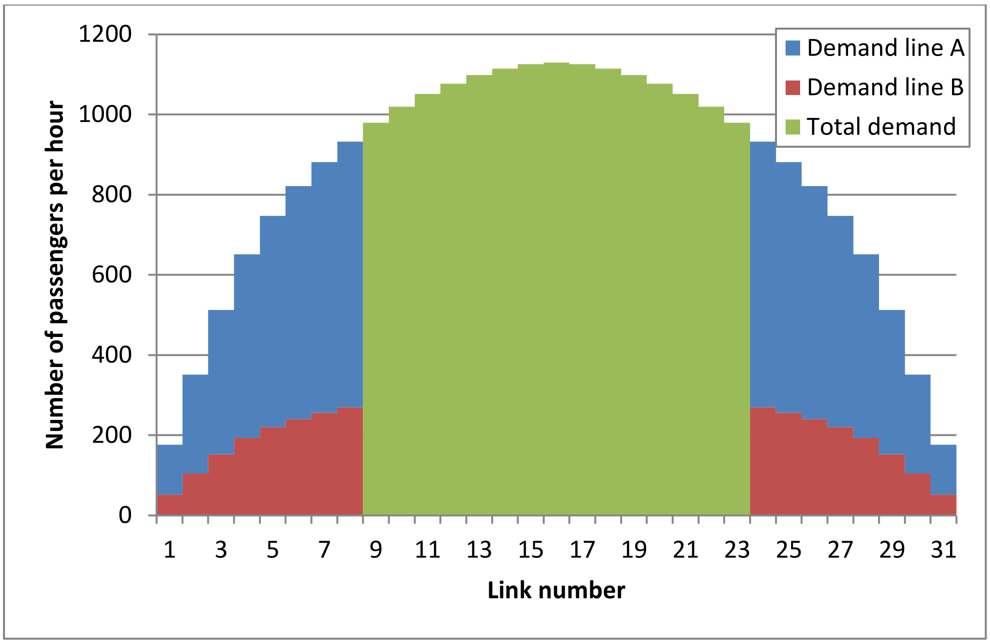

Figure 10: Total load pattern for lines A and B in the simulation

The total number of boarding passengers is 4,300 per hour. Of these, 1,900 can only use line A to reach their destination, 800 can only use line B and the last 1,600 passengers have both the origin and the destination on the shared section and hence have the opportunity to use both lines.

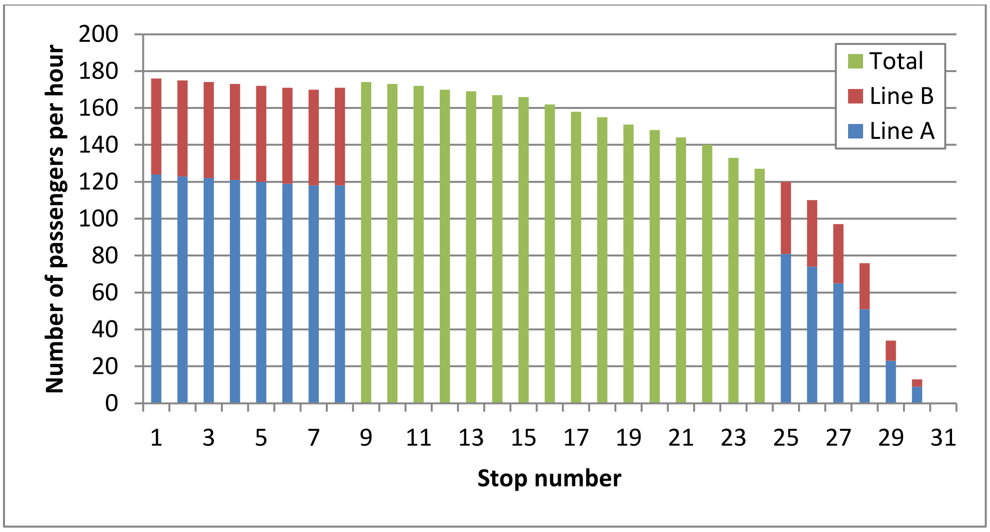

Figure 11: Total boarding pattern for lines A and B in the simulation

Scenario 0 is the base scenario, where boarding is allowed only through the front door. In scenario 1, the type of boarding procedure is changed for only the high-frequency line (line A). Line B keeps the front door boarding procedure. In scenario 2, boarding is allowed through all doors for both lines. The schedule was recalculated for the scenarios where boarding was allowed through all doors, otherwise most of the reduced dwell time would have appeared as increased holding time.

In the base scenario (S0 and 0), a schedule based holding strategy is implemented, as in Stockholm. To create a schedule, the buses were first run without holding at the time points. The 85th percentile of the run time from the beginning of the line to the first stop (number 9) was decided as the scheduled time[1]. Thereafter, the lines were simulated with holding at the first time point to decide the 85th percentile run time to the second time point (stop number 17). The run time to the third time point (stop number 25) was decided last, after holding at the first two time point stops was utilized.

To study how the regularity can be improved by other means than by allowing boarding through all doors, a state-of-the-art headway-based holding strategy was implemented on the high-frequency line. In these scenarios, the buses are not held with respect to a fixed schedule, but with respect to the headway both to the preceeding and the subsequent vehicle (Cats, Larijani, et al. 2011). The time point stops, where the holding takes place, are the same as before.

Headway-based holding works best for high frequency services, where bunching is a severe problem (Daganzo 2009). Test simulations showed that headway-based holding did not improve neither regularity nor travel times for line B. It was decided that in the scenarios, headway-based holding would only be implemented on line A.

		Holding strategy		**Boarding procedure**	
Scenario	**Simulation procedure**	**Line A**	**Line B**	**Line A**	**Line B**
S0	Separate lines	Schedule	Schedule	Front door	Front door
S0H	Separate lines	Headway	Headway	Front door	Front door
S2	Separate lines	Schedule	Schedule	Free	Free
S2H	Separate lines	Headway	Headway	Free	Free
0	Combined lines	Schedule	Schedule	Front door	Front door
0H	Combined lines	Headway	Schedule	Front door	Front door
1	Combined lines	Schedule	Schedule	Free	Front door
1H	Combined lines	Headway	Schedule	Free	Front door
2	Combined lines	Schedule	Schedule	Free	Free
2H	Combined lines	Headway	Schedule	Free	Free

Table 5: Scenario description

In all the scenarios, buses belonging to line A are dispatched every four minutes and buses belonging to line B every eight minutes (except in the separate scenarios, which have two versions, one where line B was dispatched every eight and one where it was dispatched every five minutes). In the shared corridor, where the two lines in practice act as one single line, the average headway for all buses should ideally be 160 seconds. In cases where two lines merge, the schedules are often synchronized to achieve even headways. However,

---

[1] The practice of determining scheduled run times is approached differently in different cities, depending on what objectives are prioritized. In Stockholm the 90th percentile is used, which was discovered only after simulations had started. The 85th percentile is another common practice and is used categorically throughout this paper.

synchronizing two lines requires them to have the same headway. These lines have different headways, hence synchronizing the schedule of line A with line B (i.e., by dispatching the buses with 160 and 320 seconds headway in turns) leads to immediate bunching problems.

Another possible control method would be to have separate control strategies along the separate routes, and then to synchronize the two lines along the shared route. This would increase the holding time drastically, and the consequences of such a method could become very awkward in situations when some of the vehicles are late. Additionally, if other lines also run parallel, the task of synchronizing them all soon becomes overwhelming.

A test simulation of the base scenario was performed with two alternative dispatching times, one where buses belonging to line B arrive at the merge point simultaneously with a bus belonging to line A, and one where they arrive right between two buses belonging to line A. The simulation showed that the most optimal dispatching scheme is the one where buses on line B arrive at the merge point at the same time as a bus belonging to line A.

The conclusion is that it is better to not try to avoid bunching between vehicles belonging to different lines, and to concentrate on keeping even headways on line A (because the capacity on line A is considerably higher). This is best achieved by trying to make buses on line B arrive at the merge point at the same time as a bus belonging to line A. If a bus belonging to line B instead goes in right between two buses belonging to line A, they will be likely to bunch up all three very quickly.

3.2.4. Simulation repetitions

Each simulation run is spanning two hours of bus service. The first 30 minutes no passengers arrive at the stops, so the bus service can be initiated along the whole line. Hence the time period that is evaluated is 90 minutes long, and throughout this time the passenger demand follows the same distribution, which is a peak hour distribution.

To ensure that the result from each scenario is accurate, it needs to be simulated several times. The required number of simulation runs in one batch can be calculated from the formula (Cats, Burghout, et al. 2010)

$$N(m) = \left(\frac{S(m)\cdot t_{m-1,(1-\alpha)/2}}{\overline{X(m)}\cdot \varepsilon}\right)^2,$$

where $N(m)$ is the number of runs required (estimated based on m initial simulation runs), $\overline{X(m)}$ and $S(m)$ are the estimated mean and standard deviation from a sample of m simulation runs, ε is the allowable percentage error of $\overline{X(m)}$ and α is the level of significance.

The simulation was run on a netbook with the Intel Atom D525 dual core 1.8 GHz CPU and 2 GB of RAM. Running the simulation once took around 30 seconds. Creating the schedule and evaluating the scenario output requires four different simulation batches for each scenario. The scenario output includes 1,440 stop visits per run. Unfortunately, these circumstances made running batches of more than ten simulation runs very time consuming (five minutes only for running the simulation) and unstable (handling records of tens of thousands of rows makes the software slow and increases the risk for software crashes).

To achieve results that are significant on the 95 per cent level, allowing only 10 per cent errors in the most important output variables, it would be necessary to do at least 30 replications. Fluctuation in holding time is so large that this variable would call for 150 replications.

It was decided that ten replications were sufficient for the purpose of this study. Though this leads to some results being statistically more uncertain, this number of replications enables identification of trends and analysis patterns. Anyhow, increasing the level of significance in a simulation by doing many replications is by no means a guarantee that the result becomes more realistic. This depends entirely on how good the model is, and that is not possible to determine by doing more replications.

4. Data collection results

Here the results are presented from the collection of dwell time data in Stockholm and Gothenburg. In Stockholm, boarding and alighting processes are separated between the front door and the rear doors, and hence it is possible to present separate results for boarding and alighting service time. In Gothenburg it would not be possible to separate boarding and alighting, as it occurs seamlessly through all the doors. Instead a linear regression model of the whole process was estimated.

4.1. Stockholm

For buses that were not overcrowded the results from the data collection were surprisingly clear-cut. In all the locations in Stockholm that had mostly low-floor inner-city buses (S:t Eriksplan, Västerbroplan and Odenplan) the average boarding time per passenger was exactly the same in uncrowded situations, 2.4 seconds, regardless of different passenger numbers and time of the day. At Gullmarsplan, the average boarding time was 2.8 seconds, but there a majority of the buses were not low-floor.

The total passenger service time when the bus is not crowded is clearly a linear function of the number of boarding passengers (see Figure 12). In a linear regression model for low-floor buses the intercept is -0.2, with a t-value that is only -0.1. The R^2 is exactly the same (0.93) without this constant, so it was removed from the model (i.e., the constant is zero).

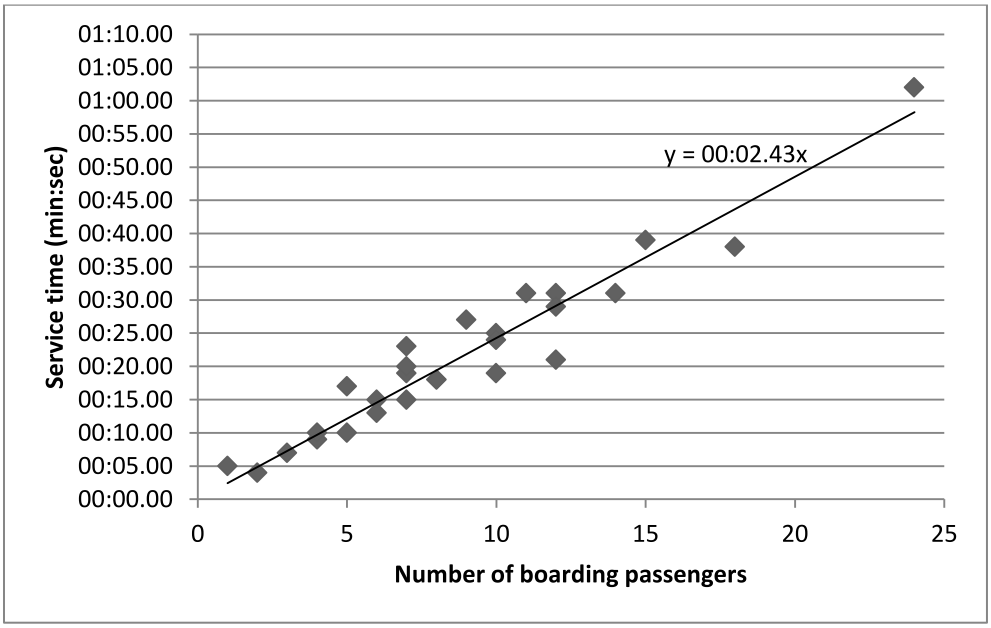

Figure 12: Service time for boarding passengers on uncrowded low-floor buses in Stockholm, R^2 for the line fit is 0.93

Inner-city buses in Stockholm generally have two front door halves (channels). Some of the drivers opened both, while some only opened one of them. This could potentially lead to different service times, but the data did not back up this theory. No significant difference was observed between one and two open door halves. The reason for this is probably that the passengers need to form one queue up to the ticket verification machine, and this means that the number of door channels is in practice always one.

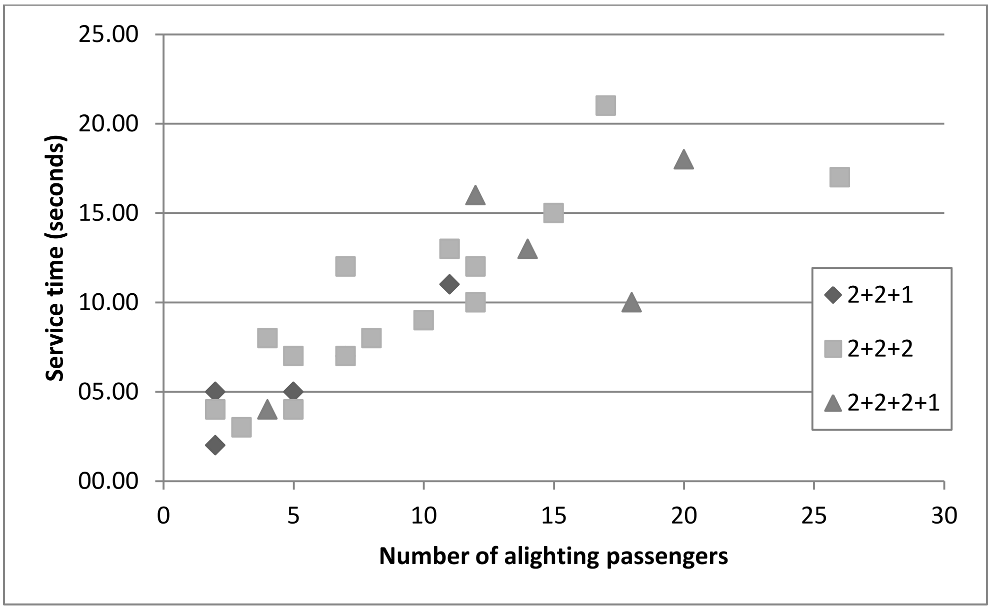

Figure 13: Service time for alighting passengers in Stockholm with different door configurations

The data concerning alighting passengers is restricted in Stockholm, especially for buses with other door configurations than 2+2+2 (with the front door reserved for boarding). For the data that is available, the alighting time for one passenger was 0.9 seconds with 2+2+2+1 and with 2+2+2 and 1.0 seconds with 2+2+1 door channels. The front door was practically never used for alighting.

	Passenger service time (sec)			
Door configuration	**Boarding**	R^2	**Alighting**	R^2
2+2+1	2.4	0.93	1.03	0.80
2+2+2			0.94	0.59
2+2+2+1			0.86	0.47

Table 6: Passenger service time for uncrowded low-floor buses in Stockholm

4.1.1. Crowding

Crowding had a clear effect on the boarding speed, but the magnitude of this effect shows a large variance. This is not surprising; it is natural that crowding leads to larger variance in boarding times, but the small amount of available data with very crowded buses makes the estimation of a crowding factor uncertain. However, the result clearly supports the Swiss formula (Weidmann 1994) for crowding effects on boarding speed. If the cases where the number of boarding passengers was less than six are removed, the two curves in Figure 14 are even closer to each other, as the extreme values often come from situations with only a few passenger movements.

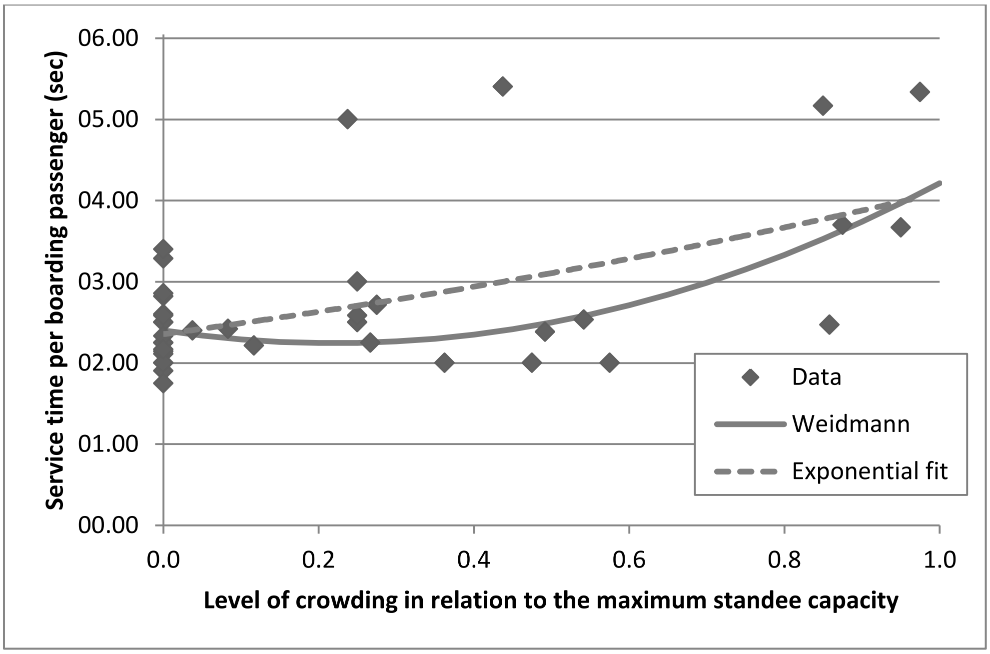

Figure 14: Crowding effect on boarding time in Stockholm

4.2. Gothenburg

In Gothenburg, all the data was collected at the same stop. It has the same physical properties as the data collection spots in Stockholm (i.e., an in-lane stop with a wind shelter and a long low platform), and the buses were mostly articulated low-floor buses, just as in Stockholm. All the articulated buses (except the two double-articulated buses that passed) had 2+2+2 door channels. The number of normal buses was unfortunately too small to draw any conclusion about boarding and alighting rates for them. None of the buses were completely full (even if the busiest bus lines in Gothenburg pass the stop and it was rush hour), so crowding effects were not possible to measure.

For articulated buses under normal conditions, the service time for boarding and alighting passengers was possible to determine with high accuracy in Gothenburg (see Table 7). The R^2 for the linear regression model is 0.94. A linear model might not the most suitable for representing only a few boarding or alighting passengers, but based on the data it is not clear what function would be better, so the intercept from the linear regression model (three seconds) can serve as a substitute for the longer service time per passenger in such situations.

4.3. Comparison

In Stockholm, the total dwell time (when no passengers are standing in the bus) is determined by

$$DT = MAX(t_b P_b, t_a P_a),$$

and in Gothenburg by

$$DT = C + t_b P_b + t_a P_a,$$

where t_a is alighting passenger service time, t_b is boarding passenger service time, P_a is the number of alighting passengers, P_b is the number of boarding passengers and C is a constant. The data analysis did not produce any constant significantly different from zero for the first equation. The faster alighting in Gothenburg can naturally be explained by the fact that there is one more door available for alighting (i.e., the front door).

				Passenger Service time (seconds)					
	C	St Err	t-stat	t_b	St Err	t-stat	t_a	St Err	t-stat
Stockholm	N/A			2.4	0.1	22.4	0.94	0.06	14.8
Gothenburg	3.3	1.1	3.4	0.86	0.06	15.2	0.49	0.04	11.1

Table 7: Dwell time model parameters

Using these dwell time formulas means that when the ratio between the number of boarding and the number of alighting passengers is close to 0.375 (i.e.,$\frac{0.9}{2.4}$), front door boarding is generally not less efficient than free boarding. Table 8 compares the service times in Stockholm and Gothenburg for hypothetical situations with different numbers of boarding and alighting passengers.

		Number of boarding passengers																				
		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Number of alighting passengers	0	-3	-2	0	2	3	5	6	8	9	11	12	14	15	17	18	20	21	23	24	26	27
	1	-3	-2	-1	1	3	4	6	7	9	10	12	13	15	16	18	19	21	22	24	25	27
	2	-2	-3	-1	0	2	4	5	7	8	10	11	13	14	16	17	19	20	22	23	25	26
	3	-2	-3	-2	0	2	3	5	6	8	9	11	12	14	15	17	18	20	21	23	24	26
	4	-1	-2	-2	-1	1	3	4	6	7	9	10	12	13	15	16	18	19	21	22	24	25
	5	-1	-2	-3	-1	1	2	4	5	7	8	10	11	13	14	16	17	19	20	22	23	25
	6	-1	-2	-2	-2	0	2	3	5	6	8	9	11	12	14	15	17	18	20	21	23	24
	7	0	-1	-2	-2	-1	1	3	4	6	7	9	10	12	13	15	16	18	19	21	22	24
	8	0	-1	-2	-3	-1	1	2	4	5	7	8	10	11	13	14	16	17	19	20	22	23
	9	1	0	-1	-2	-2	0	2	3	5	6	8	9	11	12	14	15	17	18	20	21	23
	10	1	0	-1	-2	-2	-1	1	3	4	6	7	9	10	12	13	15	16	18	19	21	22
	11	1	1	0	-1	-2	-1	0	2	4	5	7	8	10	11	13	14	16	17	19	20	22
	12	2	1	0	-1	-2	-2	0	2	3	5	6	8	9	11	12	14	15	17	18	20	21
	13	2	1	0	0	-1	-2	-1	1	3	4	6	7	9	10	12	13	15	16	18	19	21
	14	3	2	1	0	-1	-2	-1	1	2	4	5	7	8	10	11	13	14	16	17	19	20
	15	3	2	1	0	-1	-2	-2	0	2	3	5	6	8	9	11	12	14	15	17	18	20
	16	3	3	2	1	0	-1	-2	-1	1	3	4	6	7	9	10	12	13	15	16	18	19
	17	4	3	2	1	0	-1	-2	-1	1	2	4	5	7	8	10	11	13	14	16	17	19
	18	4	3	2	2	1	0	-1	-2	0	2	3	5	6	8	9	11	12	14	15	17	18
	19	5	4	3	2	1	0	-1	-2	-1	1	3	4	6	7	9	10	12	13	15	16	18
	20	5	4	3	2	1	1	0	-1	-1	0	2	4	5	7	8	10	11	13	14	16	17

Table 8: Difference in terms of dwell time (in seconds) between the two boarding procedures, cyan coloured fields represent combinations of boarding and alighting passengers when free boarding is faster, while orange fields represent combinations when front door boarding is faster

Both in Stockholm and Gothenburg, a large majority of the passengers were clearly work commuters with period cards. Only a few were children or babies in strollers, and their effect on the result is insignificant. No wheelchairs were recorded.

The result presented here is for articulated buses with 2+2+2 door channels. Normal buses with 2+2+1 door channels seem to be very close to these numbers and this might not be unreasonable considering that the doors are less spread, so the passengers have a shorter average distance to a door. The main difference between normal and articulated buses is probably the different tolerances to crowding caused by the different maximum standee capacities.

4.3.1. Comparison with TCQSM

If the dwell time model from TCQSM (Kittelson & Associates 2003) is used with parameters corresponding to Swedish conditions, service time values would be 3.0 seconds for boarding and 0.5 seconds for alighting in Stockholm. The fact that boarding was faster than what TCQSM suggests is in line with what Sundberg and Peterson noted in 1989.

The only satisfying explanation to why alighting is slower than suggested by TCQSM is that the double door in its current design does not work as two door channels, but as single door channel. According to TCQSM, two low-floor rear door channels have a default passenger service time of 0.9 seconds, which is the same result as for buses in Stockholm with 2+2+2 door channels and no front door alighting. The observed buses were not crowded.

The hypothesis that Swedish double doors work practically as single door channels was confirmed in Gothenburg. The service times recorded correspond to three channels in TCQSM for boarding and four channels when alighting. A reason why the alighting was so fast in Gothenburg could be the high number of alighting passengers per bus (eighteen on average, compared to nine in Stockholm). Previous studies have shown that alighting might not be an entirely linear process for large numbers of passengers (Sundberg and Peterson 1989). This could be one of the explanations for the constant of three seconds in the regression model.

5. Dwell time model

To model the dwell times in Stockholm, the Transit Capacity and Quality of Service Manual (Kittelson & Associates 2003) offers a good base formula. However, the parameter values were taken from the collected data (see Table 7). Because the data was mostly collected from articulated buses with 2+2+2 door channels, and no reliable data was available for normal buses (2+2+1), it was decided that the same dwell time model would be used for articulated and normal buses. This can be motivated if double doors in fact work essentially as single channels.

Applying these formulas on all the passengers and buses in the simulation model, without the crowding effect and without other factors that can prolong the dwell time (e.g., other buses blocking the way) gives an average dwell time of 27.2 seconds with front door boarding and 23.5 seconds with free boarding. This is a 14 per cent decrease in total dwell times.

5.1. Crowding

Based on the sources mentioned earlier and the collected data, the crowding effect was judged to be insufficiently modelled by TCQSM, and the used crowding factor was instead based on the one proposed by Weidmann (1994). This crowding factor is best presented as a second grade function of the ratio between the number of standees and the total standee capacity, which has a maximum of one when the bus is completely full. The function maximum is then according to Weidmann's study on average 1.75, but with a large variation.

Weidmann's regression model included a small negative first grade term, but it is more reasonable to assume that this term originates from random variation or correlations in the data than that more crowding to a certain level actually would cause faster boarding. To create a formula suitable for simulation, the first grade term was removed and the second grade term adjusted accordingly to keep the maximum at 1.75. Additionally, this formula fits the collected data better. The simplified formula is:

$$Crowding\ factor = 1 + 0.75\left(\frac{no.of\ standees}{standee\ capacity}\right)^2$$

For the boarding process, the number of standees is an average of the number before the boarding starts (with the alighting passengers subtracted) and after it is over. For the alighting process, the number of standees is the number of through standees (i.e., the theoretical number of standees after the alighting process but before the boarding process, if they would be separated in time).

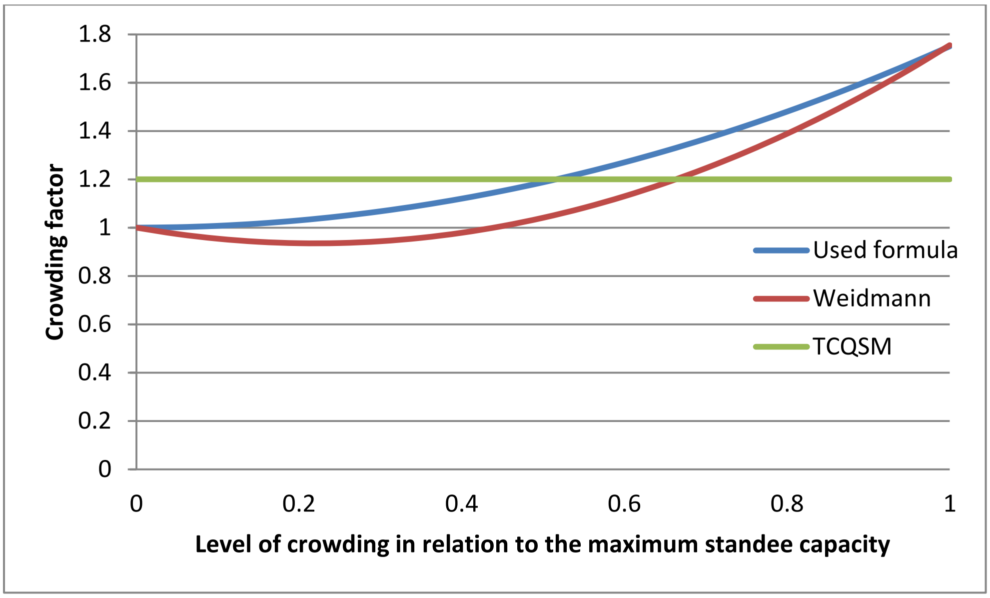

Figure 15: Crowding effect on boarding time

5.2. Dwell time constant

So far, the description of the dwell time model has been focused on passenger boarding and alighting. All the other dwell time components (most importantly door opening and closing time and clearance time), are in BusMezzo included as a constant. There are several reasons why this might not be optimal. One is that different bus types can have different door opening and closing times. Another is that some drivers might wait longer for late passengers than others. None of these issues have been in the scope of this study, but it can be pointed out that bus types are relatively homogenous on a line level. Driver behaviour is an interesting topic, but very difficult to quantify. Hopefully the variation in link ride time is sufficient for simulating random variation on a vehicle level.

To approximate the dwell time constant (which in this case means all the time that passes from that the bus stops moving until it starts moving again, with the time for boarding and alighting excluded), automatic passenger count (APC) data from line 1 in Stockholm was studied. The dwell time model was applied on the recorded passenger numbers, and the result was subtracted from the recorded dwell time. The difference was twelve seconds per stop, which if the dwell time model and the data are correct should be the dwell time constant. In the APC data, clearance time is part of the link ride time, and that is how it is treated here as well.

A constant of three seconds is already included in the dwell time model for boarding through all doors. The two constants were added, so the constant for this model is 15 seconds. For low passenger numbers this means that this boarding procedure is slower than boarding only through the front door. This is in several ways reasonable, as the passenger circulation is probably better with front door boarding and it is easier for the driver to time the door closing immediately after the last boarding passenger.

6. Simulation results

This chapter summarizes the output from all the scenarios described in section 2.3.3 that have been simulated in BusMezzo. Sections 6.1 and 6.2 describe the results from scenarios S0, S0H, S2 and S2H, where there is no interaction between the two lines, and hence the results are presented individually for the two lines. In section 6.3 the results from the simulations of the whole network are presented and discussed.

6.1. Line A separate

Line A has a total average run time of 44 minutes in the separated base scenario (scenario 0). When boarding is allowed through all doors and the schedule is adjusted accordingly (scenario 2), the average run time decreases to 37 minutes, a decrease by 15 per cent. The average dwell time decreases from 35.3 seconds to 24.2 seconds, down by 31 per cent. This improvement is twice as high as the arithmetic sum of the reduction in boarding and alighting time suggests, and is a result of better regularity (i.e., a combination of less waiting behind other buses at stops and less crowding effects).

Scen.	**Ride**	St D	**Dwell**	St D	**Wait**	St D	**Hold**	St D	**Total**	St D
S0	219.1	40.9	264.9	44.5	178.1	32.3	44.2	16.7	706.3	95.5
S0H	218.3	40.8	233.5	50.6	157.3	25.8	43.7	10.8	652.9	107.0
S2	210.0	37.3	170.1	20.0	164.8	39.8	24.6	7.6	569.4	90.1
S2H	201.9	18.4	168.8	20.8	151.1	22.3	21.9	4.9	543.6	53.3

Table 9: Average passenger travel time in seconds for line A (separate simulations)

Moreover, the decrease in average passenger travel time in scenario 2 is 19 per cent and the passenger dwell time goes down by 36 per cent. The reason why the impact on the passenger level is larger is that the effect of shorter boarding times is larger when there are many passengers boarding or alighting, which correlates with more crowded buses.

Unfortunately, the passenger waiting time output from BusMezzo does not consider that some passengers are forced to wait for more than one bus because the first bus to arrive is overcrowded. The amount of lost time can be roughly estimated by multiplying the number of passengers left behind by the average headway. In practice, waiting time for the overcrowded bus is probably longer than the average waiting time, but waiting time for the second bus is on the other hand probably shorter than the average. This estimate is included in the passengers waiting time presented in this paper.

Scenario	**Ride time**	**Dwell time**	**Waiting time**	**Holding time**	**Total time**
S0	219.1	264.9	178.1	44.2	691.8
S0H	0%	-12%	-12%	-1%	-8%
S2	-4%	-36%	-7%	-44%	-19%
S2H	-8%	-36%	-15%	-51%	-23%

Table 10: Average passenger travel time change for line A compared to scenario 0, green fields represent results significant on the 95 % level

The headway-based control strategy (scenario 0H) also reduces the average run time substantially, by ten per cent down to 39 minutes. But the effect on passenger travel time is lower, only eight per cent, because the flexible timetable mostly shortens run times for buses that are not overcrowded. When regularity is disturbed, a headway-based control strategy reacts by slowing down the other buses, which affects the travel time of many passengers negatively, even if the effect for passengers on the delayed bus is positive. The eight per cent travel time decrease is not statistically significant, because of the large deviation in the relatively small sample of simulation runs.

The best results are reached when a headway-based control strategy is combined with allowing boarding through all doors (scenario 2H). The average vehicle run time decreases by 22 per cent and the average passenger travel time decreases by 23 per cent. The dwell time and holding time is approximately the same as is in scenario 2, but the regularity is improved further (see Table 11), which leads to decreases in both waiting time and ride time (however, this decrease is only significant on the 75 per cent level).

Regularity can be measured in different ways. The variable that is directly influenced by the type of boarding procedure is dwell time variation. It is obvious that absolute dwell time variation will decrease when the passenger service time decreases, because the marginal time contribution for each additional passenger on the dwell time is smaller. But as Table 11 shows, the dwell time coefficient of variation, CV (DT), is radically decreased as well. This indicates that the buses arrive more regularly (i.e., the passenger distribution between the buses is more even).

A variable that might be regarded as the most natural measure of regularity is the headway coefficient of variation, CV (h). The number in Table 11 is an average over all stop visits for all vehicles. The corresponding level of service (LOS) is according to the CV (h) intervals defined in TCQSM (Kittelson & Associates 2003). In Figure 16 the headway coefficient of variation for each individual stop is shown. A high headway variation means that vehicles are bunched. In Table 11, a bunched stop visit is defined as one having a headway that is more than 50 per cent shorter or longer than the scheduled headway (in agreement with TCQSM). The presented share is an average over all stop visits (e.g., if half of the vehicles are bunched half of the stop visits the total bunching ratio is one fourth).

When buses have reached their maximum passenger capacity, passengers trying to board are forced to wait for the next bus. This can happen with perfect headways as well, because passengers arrive randomly at stops, but with a large headway variation it happens more frequently. Once again, the number for passengers left behind presented in Table 11 is an average over all stop visits.

Scenario	CV (DT)	CV (h)	LOS	Bunching	Left behind pass.
S0	0.66	0.60	E	23%	0.30
S0H	0.63	0.52	D	20%	0.17
S2	0.38	0.53	E	19%	0.17
S2H	0.36	0.42	D	16%	0.15

Table 11: Regularity comparison for line A (separate simulations)

The regularity indicators show that scenarios S0H and S2 are basically equivalent. In scenario S2, the good regularity is clearly a result of the small deviation in dwell times, while the headway-based control strategy in scenario S0H alleviates external disturbances in link ride times.

From Figure 16 it is easy to see that the headway-based strategy reduces the headway variation more efficiently at the time point stops, while the free boarding procedure causes the variation to grow slower between the time point stops. The difference between the different scenarios is most obvious after stop 17, where the passenger load has passed its maximum but the number of boarding passengers is still high. With boarding only through the front door, headway variation grows faster.

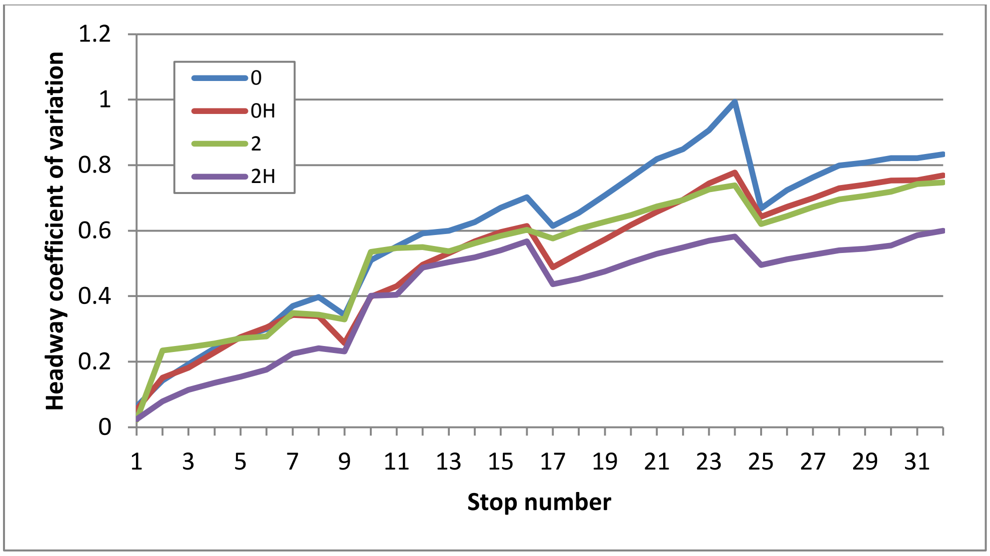

Figure 16: Headway variation for line A (separate simulations)

6.2. Line B separate

In the base scenario, the average run time for line B is 37 minutes, and the average dwell time is 23.8 seconds. By allowing boarding through all doors, the average run time goes down to 34 minutes and the average dwell time to 21.7 seconds. The percentage change is six for the run time and seven for the dwell time. Passenger dwell time decreases by eight per cent (significant only on the 75 per cent level).However, the total passenger travel time increases by one per cent, due to increased waiting time.

Scenario	Ride	St D	Dwell	St D	Wait	St D	Hold	St D	Total	St D
S0	202.1	8.0	159.4	12.7	260.4	10.5	11.8	4.4	633.7	24.0
S2	203.0	14.7	146.0	26.0	287.2	11.9	4.6	2.2	640.8	43.7
Change	**0%**		**-8%**		**10%**		**-61%**		**1%**	

Table 12: Average passenger travel times in seconds for line B (separate simulations) and percentile changes, green fields represent results significant on the 95 % level

Judging from how the holding time is sharply decreased, but the regularity is not improved, random variation seems to have either resulted in a too tight schedule or in more external disturbances in scenario 2. Still, considering the number of passengers and the available supply, the regularity in both scenarios can be regarded as very good. The high passenger demand in relation to the available bus supply makes the system sensitive to irregularities, which is why many passengers are left behind in scenario 2 and why the dwell time does not decrease more than it does.

Scenario	CV (DT)	CV (h)	LOS	Bunching	Left behind pass.
S0	0.40	0.16	A	8%	0.08
S2	0.28	0.18	A	9%	0.27

Table 13: Regularity comparison for line B (separate simulations)

Based on this result, the changed boarding procedure does not have any significant positive effect for the passengers on this line, when it is run separate. However, when a bus line is this popular, the frequency is usually raised, which might give other results. To investigate this, the headway was decreased to five minutes, while the passenger demand was kept constant.

6.2.1. Line B separate with higher frequency

Five minute headway clearly justifies headway-based holding, and the resulting passenger travel time is accordingly better with headway-based holding. Moreover, with headway-based holding, the changed boarding procedure has a clearer effect on passenger travel times.

Scenario	Ride time	Dwell time	Waiting time	Holding time	Total time
S0	209.4	146.8	167.1	30.0	553.3
S0H	203.6	141.8	185.8	20.5	551.7
S2	208.8	115.3	164.8	44.4	533.3
S2H	208.6	118.7	168.9	13.5	509.6

Table 14: Average passenger travel time in seconds for line B with higher frequency (separate simulations)

The conclusion from these results is that headway-based holding is not an effective method to prevent systematic bunching (i.e., bunching caused by Poisson passenger arrivals), but when sudden random delays occur, headway-based holding can alleviate the consequences. When boarding is allowed through all doors, buses are less systematically bunched, and this makes schedule-based holding an inefficient method to deal with delays and the potential of headway-based holding is better made use of.

Scenario	Ride time	Dwell time	Waiting time	Holding time	Total time
S0	209.4	146.8	167.1	30.0	553.3
S0H	-3%	-3%	11%	-32%	0%
S2	0%	-21%	-1%	48%	-4%
S2H	0%	-19%	1%	-55%	-8%

Table 15: Average passenger travel time change for line B compared to scenario 0, green fields represent results significant on the 95 % level

Compared to eight minute headway, the higher passenger capacity of the five minute headway makes bus line B less sensitive to bunching, and a small increase in headway variation does not immediately lead to overfull buses. This makes the result more reliable.

Scenario	CV (DT)	CV (h)	LOS	Bunching	Left behind pass.
S0	0.38	0.23	B	10%	0.04
S0H	0.39	0.27	B	10%	0.15
S2	0.17	0.22	B	10%	0.01
S2H	0.19	0.20	A	8%	0.05

Table 16: Regularity comparison for line B with higher frequency (separate simulations)

6.3. Combined lines

6.3.1. Scenario 0 (base)

When the two lines are combined, some of the passenger demand moves from line B to line A, due to the higher frequency on line A. However, this does not result in shorter dwell times or travel times on line B, because the congestion and bunching problems increase drastically. Line B, which used to have a much tighter schedule than line A, now requires a slower timetable than line A, and the average run time is now 45 minutes instead of 37 minutes. The average run time for line A is still 44 minutes.

The passengers face longer ride times than when the lines were separate, because of more congestion in the bus lane and queuing into stops. However, the average dwell times do not increase significantly. The waiting time goes down because of the higher total frequency, and this leads to shorter total travel time for the passengers than when the lines are separate from each other.

Line	Ride time	Dwell time	Waiting time	Holding time	Total time
A	230.4	253.5	191.5	27.8	703.2
B	262.4	204.2	224.0	24.6	715.2
Average	**238.8**	**240.6**	**200.0**	**26.9**	**706.3**

Table 17: Average passenger travel time in seconds in scenario 0

All the regularity indicators give a clear message; regularity becomes a key problem when many buses use the same stops and compete for the same passengers. Line B that used to have a headway coefficient of variation of 0.16 now has 0.50, which explains why the average holding time is longer. However, the number of passengers left behind cannot be compared between the separate and the combined scenarios, as some passengers stay behind because they need to take the other bus to go beyond the shared section. Unfortunately, it is difficult to tell what group a waiting passenger belongs to. The bunching percentage presented here is only within the lines, bunching between buses that belong to different lines is presented later.

Line	CV (DT)	CV (h)	LOS	Bunching	Passenger share	Left behind pass.
A	0.65	0.76	F	34%	74%	1.22
B	0.65	0.50	D	26%	26%	1.31

Table 18: Regularity comparison in scenario 0

6.3.2. Scenario 0H

When headway-based control is introduced for line A, all travel time components except holding time decrease. The mean run time for line A decreases by five per cent and for line B by four per cent. Line B gets a larger share of passengers in this scenario, which indicates that the buses of line B are more likely to be the first bus in a bunch than when line A has schedule-based holding. This is supported by the fact that waiting time increases for passengers boarding line B.

Line	Ride time	Dwell time	Waiting time	Holding time	Total time
A	220.8	225.2	169.0	34.0	649.0
B	244.4	201.9	228.6	32.2	707.1
Average	**227.7**	**218.4**	**186.3**	**33.5**	**665.9**

Table 19: Average passenger travel time in seconds in scenario 0H

Even if line B gets a larger share of passengers than in scenario 0, the regularity is better for this line as well. The variation in headway is smaller and fewer buses are bunched. Fewer passengers are left behind.

Line	CV (DT)	CV (h)	LOS	Bunching	Passenger share	Left behind pass.
A	0.64	0.67	E	28%	71%	0.83
B	0.62	0.37	C	20%	29%	1.33

Table 20: Regularity comparison in scenario 0H

6.3.3. Scenario 1

The average vehicle run time for line A decreases to 35 minutes when boarding is allowed through all doors. This is 20 per cent shorter than in the base scenario. Even if the holding time for line A is reduced as well, regularity is improved. Instead, holding time for line B has increased considerably, which makes this scenario unique. In all the other scenarios, the holding time per passenger is longer for line A than for line B. The average run time for line B decreases by seven per cent compared to the base scenario.

Line	Ride time	Dwell time	Waiting time	Holding time	Total time
A	215.2	179.7	149.5	14.2	558.6
B	221.4	174.7	196.1	44.9	637.0
Average	**216.9**	**178.3**	**162.7**	**22.9**	**580.8**

Table 21: Average passenger travel time in seconds in scenario 1

The headway coefficient of variation has decreased for both lines compared to both scenarios 0 and 0H. Bunching has decreased substantially for both lines, from 34 per cent for line A and 26 per cent for line B in scenario 0 to 24 and 16 per cent in scenario 1. The number of passengers left behind has decreased for both lines as well.

Line	CV (DT)	CV (h)	LOS	Bunching	Passenger share	Left behind pass.
A	0.37	0.50	D	24%	72%	0.76
B	0.47	0.31	C	16%	28%	0.95

Table 22: Regularity comparison in scenario 1

6.3.4. Scenario 1H

In scenario 1H, line B has a passenger share of 30 per cent, which is a clear sign that its vehicles are caught up by vehicles belonging to line A. However, vehicles belonging to line A that are ahead of these bunches are held by the headway-based control strategy, which makes line B less crowded than in scenario 1. For line A, the average vehicle run time decreases by 20 per cent compared to the base scenario, just like in scenario 1, and for line B it decreases by 14 per cent.

Line	Ride time	Dwell time	Waiting time	Holding time	Total time
A	218.0	169.9	150.0	21.8	559.7
B	236.4	184.9	198.4	4.7	624.3
Average	**223.5**	**174.4**	**164.6**	**16.7**	**579.1**

Table 23: Average passenger travel time in seconds in scenario 1H

It is interesting to compare the regularity on line B in scenarios 1 and 1H. By increasing holding time for line B and letting the faster buses pass, it is possible to avoid severe bunching problems in scenario 1. With headway-based control this is not as easy to achieve, but the performance is still acceptable due to the better handling of regularity problems.

Line	CV (DT)	CV (h)	LOS	Bunching	Passenger share	Left behind pass.
A	0.34	0.48	D	19%	70%	0.75
B	0.49	0.41	D	25%	30%	0.89

Table 24: Regularity comparison in scenario 1H

6.3.5. Scenario 2

When boarding is allowed through all doors, the average run time for line A is 38 minutes, 13 per cent less than in the base scenario. The average run time for line B is 40 minutes, eleven per cent less than in the base scenario. The average passenger travel time is approximately the same as in scenarios 1 and 1H.

Line	Ride time	Dwell time	Waiting time	Holding time	Total time
A	215.8	169.0	150.9	41.5	577.1
B	245.3	148.3	190.6	35.7	619.8
Average	**223.4**	**163.6**	**161.1**	**40.0**	**588.2**

Table 25: Average passenger travel time in seconds in scenario 2

The headway variation is lower in scenario 2 than in any of the other scenarios. Holding time is considerably longer as well, so it cannot be taken as evidence that regularity is improved by the changed boarding procedure (at least not compared to scenarios 1 and 1H). The low number of replications is a problem here.

Line	CV (DT)	CV (h)	LOS	Bunching	Passenger share	Left behind pass.
A	0.41	0.42	D	18%	74%	0.76
B	0.38	0.28	B	16%	26%	0.75

Table 26: Regularity comparison in scenario 2

6.3.6. Scenario 2H

In scenario 2H, the average vehicle run time for line A is 34 minutes, shorter than in any other scenario. The average vehicle run time for line B is 37 minutes, which is lower than in any other scenario as well. The headway-based holding strategy seems to be optimal in this case, where it can alleviate large externally caused delays, but where bunching is not as systematic as with the slower boarding procedure.

Line	Ride time	Dwell time	Waiting time	Holding time	Total time
A	193.3	155.9	147.6	19.7	516.5
B	218.0	138.6	194.6	10.9	562.1
Average	**199.9**	**151.2**	**160.2**	**17.3**	**528.7**

Table 27: Average passenger travel time in seconds in scenario 2H

Scenario 2H has less bunching and less passengers left behind than any of the other scenarios. Nevertheless, holding time is almost as short as in scenario 1H and considerably shorter than in scenario 2.

Line	CV (DT)	CV (h)	LOS	Bunching	Passenger share	Left behind pass.
A	0.31	0.45	D	18%	73%	0.66
B	0.33	0.31	C	17%	27%	0.83

Table 28: Regularity comparison in scenario 2H

6.3.7. Run time comparison

In Table 29, the vehicle run time distribution is summarized. Scenario 1 is exceptional, with line B having a very small deviation from the mean. The 85th percentile run time, which is the base for scheduled vehicle circulation, decreases by 26 per cent form scenario 0 to scenario 2H for line A. For line B the decrease is 24 per cent.

	Line 1			**Line 2**		
Scenario	**Mean run time**	**St D**	**85-perc**	**Mean run time**	**St D**	**85-perc**
0	44	8	50	45	7	50
0H	41	8	47	43	6	45
1	35	4	38	42	2	42
1H	35	5	38	39	5	42
2	38	5	39	40	5	42
2H	34	4	37	37	4	38

Table 29: Run time comparison (in minutes)

6.3.8. Travel time comparison for line A

For line A, passenger travel time decreases significantly compared to the base scenario in all scenarios except scenario 0H. The ride time decreases significantly only in scenario 2H. The dwell time decrease is significant in all scenarios. Waiting time decreases significantly in all scenarios except scenario 0H.

Scenario	Ride time	Dwell time	Waiting time	Holding time	Total time
0	230.4	253.5	191.5	27.8	703.2
0H	-4%	-11%	-12%	22%	-8%
1	-7%	-29%	-22%	-49%	-21%
1H	-5%	-33%	-22%	-21%	-20%
2	-6%	-33%	-21%	49%	-18%
2H	-16%	-39%	-23%	-29%	-27%

Table 30: Average passenger travel time change for line A compared to scenario 0, green fields represent results significant on the 95 % level and yellow on the 90 % level

When it comes to holding time, random variation in ride times has a large impact on both setting the schedule and on the simulation itself. This is why the significance levels are lower, even for substantial differences in holding time. It can be argued that scenario 2 has a schedule with an excessive amount of slack or that scenario 0 has an insufficient amount of slack. These problems are hard to avoid when setting schedules both in reality and in simulations, but are avoided with the headway-based holding strategy. However, the difference in total travel time between scenarios 2 and 2H cannot be explained by the reduced holding time, as the difference between them in ride time and dwell time is also significant.

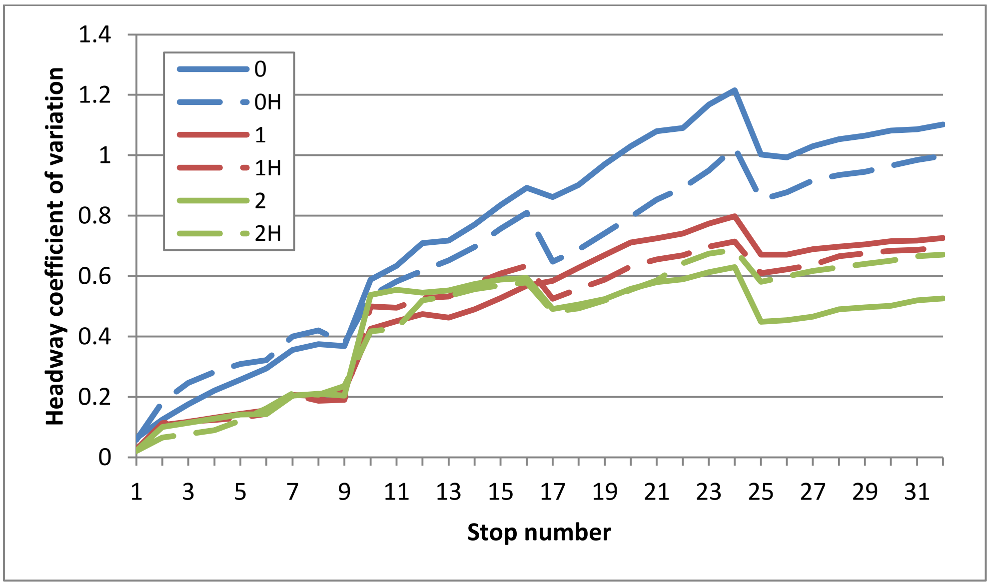

Figure 17: Headway variation for line A

Figure 17 shows how the headway variation for line A increases along the journey. All scenarios experience large externally caused delays between stop 9 and stop 10 and at some other random links, but with the changed boarding procedure, the delays grow slower. The schedule-based holding seems to be unsuccessful in some cases, most notably at stop 17 in scenario 1. This can to some extent be related to the interaction with line B, which has the slower boarding procedure. This interaction seems to have a positive effect on regularity for line A, while the holding time is reduced.

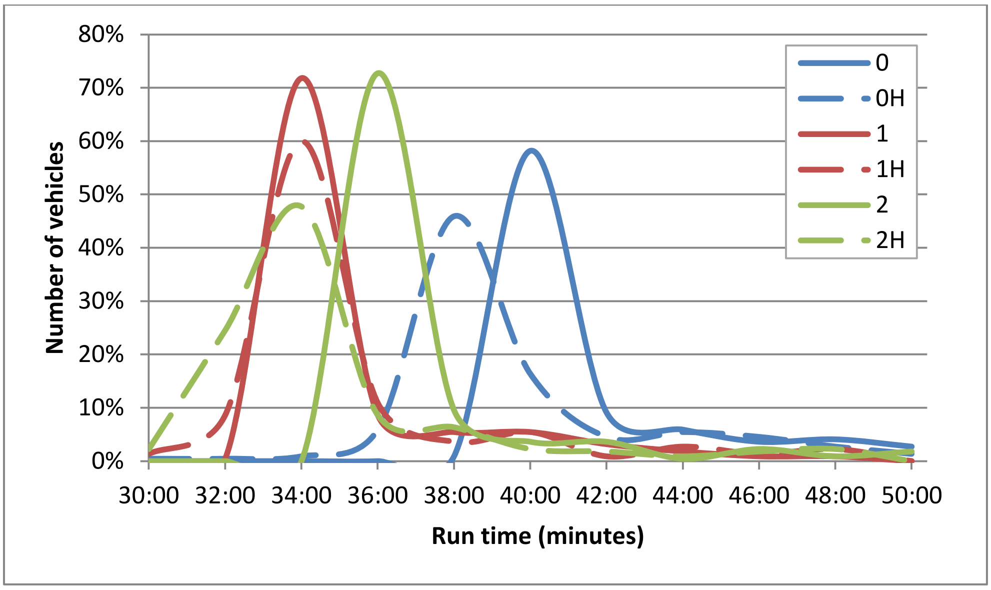

Figure 18: Vehicle run time histogram for line A

Figure 18 shows how the vehicle run time variation (which is described in more detail in Table 29) is shifted to lower values of the run time distribution (i.e., more run times are substantially shorter than the mode) in the scenarios with headway-based holding. In the scenarios with schedule-based holding, the run time variation is almost entirely towards longer run times than the mode. The shortest run times in terms of average, median and 85th percentile are all in scenario 2H.

6.3.9. Travel time comparison for line B

It is surprising to see that there is a significant decrease in passenger travel times on line B in scenarios 1 and 1H. The improved regularity on line A seems to help line B as well, causing less waiting time, less overcrowded buses and less congestion.

Scenario	Ride time	Dwell time	Waiting time	Holding time	Total time
0	262.4	204.2	224.0	24.6	715.2
0H	-7%	-1%	2%	31%	-1%
1	-16%	-14%	-12%	82%	-11%
1H	-10%	-9%	-11%	-81%	-13%
2	-7%	-27%	-15%	45%	-13%
2H	-17%	-32%	-13%	-56%	-21%

Table 31: Average passenger travel time change for line B compared to scenario 0, green fields represent results significant on the 95 % level

When line B was run separately, there was no decrease in travel time caused by the new boarding procedure. The same can be said about the change in total travel time between scenarios 1 and 2 (between which the only difference is the boarding procedure for line B). However, the difference between scenarios 1 and 2H is twelve per cent. The difference between scenarios 1H and 2H is ten per cent. Both results are significant on the 0.995 level.

6.3.10. Average travel time comparison

Looking at the total effect for lines A and B, scenarios 1 and 1H have very similar results. Scenario 2 is slightly slower, but the difference is smaller than the difference in holding time. Scenario 2H has a clearly significant decrease in all travel time components, and even if the headway variation is slightly larger than in scenario 2, less buses are bunched and less passengers are left behind than in any of the other scenarios. Scenario 2H has nine per cent shorter average passenger travel time than scenarios 1 and 1H.

Scenario	Ride time	Dwell time	Waiting time	Holding time	Total time
0	238.8	240.6	200.0	26.9	706.3
0H	-5%	-9%	-7%	24%	-6%
1	-9%	-26%	-19%	-15%	-18%
1H	-6%	-28%	-18%	-38%	-18%
2	-6%	-32%	-19%	48%	-17%
2H	-16%	-37%	-20%	-36%	-25%

Table 32: Average passenger travel time change for both lines compared to scenario 0, green fields represent results significant on the 95 % level and yellow on the 90 % level

Figure 19 visualises the contribution from the different travel time components on average passenger travel time. Holding time is a very small part of the total travel time, but it is still causes the travel time to be longer in scenario 2 than in scenarios 1 and 1H.

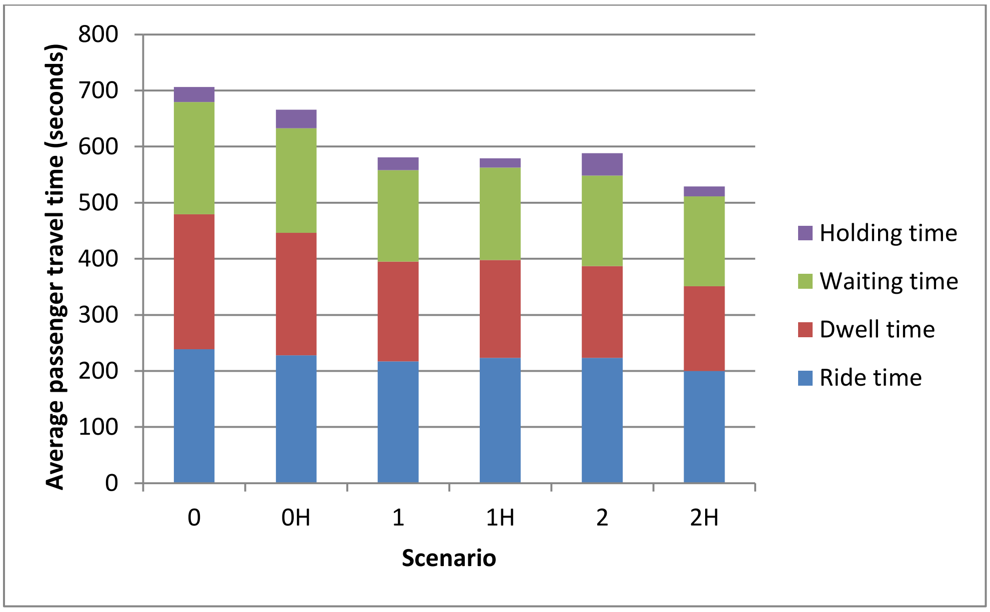

Figure 19: Average passenger travel time comparison (both lines included)

To isolate the effect of the changed boarding procedure, it is probably better to compare the scenarios with headway-based holding strategy than the ones with schedule-based holding, as they are clearly better at handling random delays that are not caused by boarding passengers.

Scenario	Ride time	Dwell time	Waiting time	Holding time	Total time
0H	227.7	218.4	186.3	33.5	665.9
1H	-2%	-20%	-12%	-50%	-13%
2H	-12%	-31%	-14%	-48%	-21%

Table 33: Average passenger travel time change for both lines compared to scenario 0H, green fields represent results significant on the 95 % level and yellow on the 90 % level

6.3.11. Combined regularity

In the shared corridor, the ideal headway for all buses is 160 seconds. No measures are taken to enforce this headway in any of the scenarios, as the two lines have their own control strategies. Still, the combined headway variation decreases compared to the base scenario in all the other scenarios.

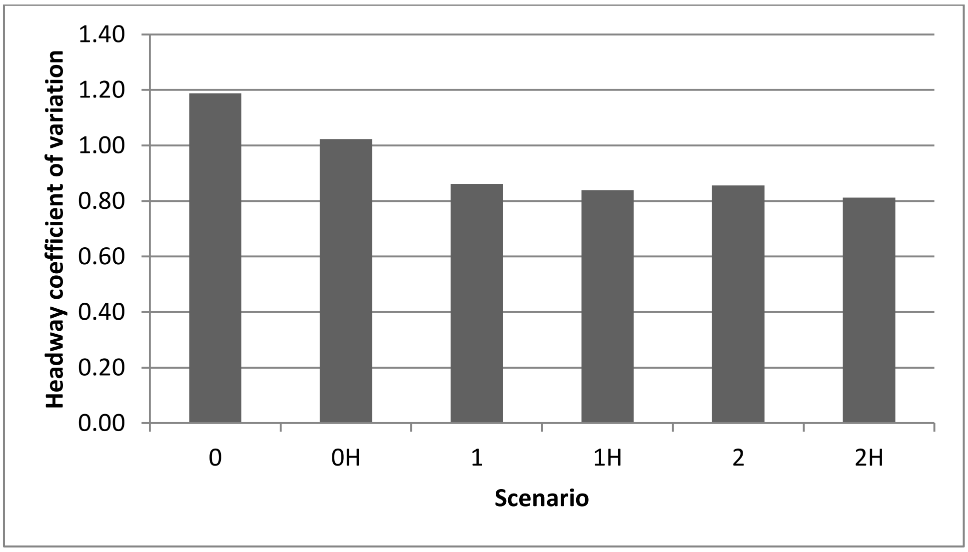

Figure 20: Combined headway variation for both lines in the shared corridor

Table 34 shows the share of the stops visits in the shared corridor when the buses arrive in bunches, according to the same definition as before. However, in this table buses belonging to the other line are also taken into consideration. This means that if a bus belonging to line A arrives at a stop less than 80 seconds (half the ideal combined headway) after a bus belonging to line B (or vice versa), they are regarded as bunched. As noted before, scenario 1 is exceptional in the way that line B is able to avoid bunching.

Scenario	0	0H	1	1H	2	2H
Line A	64%	58%	62%	56%	51%	50%
Line B	82%	72%	47%	58%	81%	70%
Total	**70%**	**63%**	**57%**	**57%**	**61%**	**57%**

Table 34: Share of the stop visits on the shared section where the bus is bunched with another bus

6.3.12. The impact of uneven headways

The fact that buses of lines A and B arrive at stop 9 with different headways (line A four minutes and line B eight minutes) means that there is an underlying asymmetry in the combined headway distribution that leads to more bunching. To prove this, the results from scenario 0 can be compared to a scenario where both bus lines have a frequency of five minutes. In all the scenarios so far, this variable has been kept constant, and passengers have been served by 22.5 buses per hour with a total seat capacity of 1088 per hour. If both lines have a frequency of five minutes, there will be 24 buses per hour with a total seat capacity of 1080 per hour.

The results show that for line A the change to five minute headway does not affect travel times significantly, but the regularity is improved. For line B, the travel time is 18 per cent shorter and the regularity is better as well.

It is easy to suggest that lines that run parallel should have the same frequency when possible, but in a real city (e.g., Stockholm) lines are overlapping in a far more complex way, and applying this rule strictly would probably require all lines in the inner city to have the same frequency. Furthermore, with only two lines and one parallel stretch, it is relatively easy to synchronize the timetables so they act as one timetable on the shared section (i.e., in the way the Stockholm subway and many suburban and rural bus lines work). With a whole system of overlapping bus lines this becomes an impossible task.

7. Discussion

The transit simulations show that bunching and poor regularity is an important factor leading to long waiting and travel time for the passengers. With perfect headways the average waiting time for passengers on line A would be 95 seconds and on line B 150 seconds (weighted averages for the shared corridor and the branches). In the base scenario, where the regularity is the worst, the average waiting time is 190 seconds for line A and 220 seconds for line B. Even in the best scenario the waiting time is still 150 seconds on line A and 190 seconds on line B. The most important reason for this is the frequent bunching in the shared corridor, and that complication is seldom mentioned in literature on the common-line problem.

Studying the travel time on a passenger level gives a completely different share between link ride time and dwell time than on the vehicle level. Even though dwell time for some reason is a slightly larger part of the total vehicle run time in the base scenario of this simulation (36 per cent) than empirical data from Stockholm show (which are not for peak hour and could be affected by the traffic hosts), it is surprising that dwell time constitutes half of the passenger travel time. This means that the importance of reducing dwell times can easily be underestimated when not looking from the passenger perspective.

The data collection analysis showed that the marginal dwell time increase that each individual passenger causes is radically decreased when boarding is allowed through all doors. However, for stops with only a few boarding passengers, the net effect of free boarding is very small or can even be negative. An interesting side result is that there is no correlation in the data between boarding time and if the driver opens either both front doors or only one.

For line B separate, the highest recorded passenger travel time effect of the changed boarding procedure was eight per cent. Whether this is a notable improvement or not is open for debate, but considering that this eight per cent change required the introduction of headway-based holding as well, it would probably be a disappointment to many. The regularity problems experienced on this line were actually not eased by any of the measures. In cases such as this the cost of fare evasion and ticket controls would probably outweigh the gains.

When line B is part of a larger system, the effects of the changed boarding procedure are substantially larger. The travel time saving is not only larger for the passengers on line B, but passengers on line A are clearly benefited as well. Regularity is improved for both lines.

In scenarios 1 and 1H, the a-priori expectation was that the different boarding procedures on lines A and B would create more bunching problems. This turned out to be a completely wrong assumption. On the contrary, the regularity was substantially better in 1 and 1H than in the base scenario and in terms of bunching between the two lines, scenario 1 was the best of all the scenarios.

Instead, the results clearly indicate that allowing boarding through all doors on one of the lines is beneficial for the other line as well. Regularity is better and waiting times and even ride times are shorter for line B.

7.1. Importance of the holding strategy

If boarding and alighting would take no time at all (zero seconds per passenger), simulation shows that the link ride time variability still makes six per cent of the buses on line A arrive at the terminal bunched when no control strategy is implemented. In this extreme case, schedule-based holding would delay the buses by on average 129 seconds, and still four per cent of them would be bunched. With headway-based control, the average holding time would be only 16 seconds, and bunching would be reduced to three per cent at the terminal.

With the standard dwell time model for boarding through only the front door, no holding strategy makes 60 per cent of the buses on line A arrive at the terminal bunched. The conclusion from this is that ten per cent of the bunching cannot be prevented from being formed; it is caused purely by random variation in link travel time. This bunching cannot be prevented, but half of it can later be dissolved with a good holding strategy. The last 90 per cent of the bunching is caused by combinations of random delays in link travel time, dwell time variance and accumulated bunching. By keeping down the dwell time delays, much of this bunching can be prevented.

Headway-based control and fast boarding seems to be an especially good combination. The conclusion from this is that headway-based holding is a very effective way of alleviating large random delays (i.e., sudden delays of the same magnitude as the headway). More systematic bunching on the other hand, which according to the argument above is 90 per cent of the total bunching problems with boarding only through the front door, can potentially be handled well by scheduled-based holding (if the vehicles are not later than the 85th percentile there is always slack to use for this), but based on this study, headway-based holding is generally better than schedule-based holding in these situations as well.

7.2. Positive feedback effects

Bus bunching is an example of positive feedback. The more variables are considered in the simulation, the larger this effect is, because they all contribute to bunching. Table 35 shows how the effect from the changed boarding procedure is accumulated with simulation complexity. Looking at an individual passenger boarding or alighting (keeping the crowding level constant), boarding through all doors saves only 14 per cent time on average. When considering that the boarding and alighting process is just a fraction of the total run time, this might lead to the conclusion that changing the boarding procedure is completely pointless.

Level of complexity	1H	2H
Average time saving per passenger movement without crowding	-9%	-14%
Bus dwell time saving with crowding effect with separate lines	-16%	-19%
Total bus dwell time saving with combined lines	-18%	-24%
Average passenger dwell time saving	-20%	-31%

Table 35: Total time saving in scenarios 1H and 2H compared to scenario 0H

When regularity issues (i.e., bunching, crowding and queuing) are taken into account, delays affected by the type of boarding procedure make the dwell time reduction climb to 19 per cent. Furthermore, by combining two lines and taking the delay caused by this into account, dwell time is reduced furthermore compared to the base case.

Finally, when realising that the buses with many passengers on board also are the slowest buses (i.e., studying dwell time for individual passengers and not for vehicles), the riders save as much as 31 per cent of the dwell time from the changed boarding procedure. Altogether, not only the dwell time is reduced, but to a smaller extent also ride time, waiting time and holding time, which gives an average passenger 21 per cent shorter travel time.

7.3. Traffic hosts

As previous studies have shown, placing traffic hosts at important stops have not had the sought effect on dwell time and regularity. It would be interesting to study their effect by simulation, but constructing a realistic dwell time model for a situation with traffic hosts is not as straightforward as for the two already studied situations. The dwell time with an assisting traffic host can be modelled as a linear function of the number of boarding and alighting passengers if it is assumed that boarding always takes longer time than alighting. Traffic hosts are located specifically at such stops, so this assumption is reasonable.

However, such a model would need to predict which buses the traffic host chooses to assist. Their task is to assist mainly the late buses, but exactly which buses they choose to assist is up to their personal judgment and is prone to human errors. This is the main reason why such a model has not been constructed.

However, it is possible to use the available data to estimate how much the traffic hosts could reduce dwell time if they were there to assist every bus. This is only valid if the passengers are assumed to be able to choose which door to use as effectively as with free boarding. This is highly unlikely, as many boarding passengers do not even recognise the opportunity to use the rear door. Based on data from line 4 in Stockholm around half of the passengers board at a stop with a traffic host.

In the ideal case the total dwell time saving for a bus with average passenger load could be at most nine per cent (compared to 14 per cent with free boarding through all doors). This calculation assumes that boarding through the front door takes 2.4 seconds per passenger and that the marginal contribution of one passenger is only 60 per cent of 2.4 seconds when passengers board through both the front door and one of the rear doors (i.e., 1.4 seconds per passenger on average). It should be noted that the total dwell time is calculated analytically and is not based on simulation. Full buses are more frequent when regularity is poor, which means that the dwell time for a bus with average passenger load is not the same as the average dwell time for all buses.

However, from a regularity point of view it is not the average bus that is the most interesting to study. A very full bus could theoretically save up to twelve per cent of the dwell time because of the traffic hosts. Here is the key to why traffic hosts are not efficient in improving regularity, because with free boarding the dwell time for the full bus would be reduced by 27 per cent compared to front door boarding.

	Front door boarding	Traffic hosts at important stops	Free boarding through all doors
Average load	13:26	12:11	11:30
Twice the average load	23:00	20:20	16:47
Increase in dwell time	**71 %**	**67 %**	**46 %**

Table 36: Total dwell time for a bus on line 4 in Stockholm, calculated from the dwell time models

Even if the decisions traffic hosts make about which buses to assist would be perfectly optimal from a regularity point of view, they cannot even under ideal conditions reach the same low dwell time variance that free boarding has by default. The result is more bunching, and more bunching means even more dwell time variance. Furthermore, because the traffic hosts only assist a fraction of the buses, their contribution to reducing overall passenger travel time is certainly considerably smaller than what free boarding would have.

7.4. Limitations of the results

The accuracy of the results is in general not as good as one would wish for, because the number of repetitions is only ten and variation turned out to be large between repetitions. This means that small differences in travel time or regularity are not significant and cannot be taken into account. However, in many cases the difference in travel time and regularity between two scenarios is large enough to be significant.

The setup of the simulation experiment is very simplified. Only two transit lines are included, and to compensate for this, they are parallel along a very long section. This could lead to other results than a situation with many lines running parallel for shorter stretches.

The dwell time function for boarding through all doors is not fully satisfying for low numbers of passengers. To compensate for this, the dwell time constant is three seconds longer than for boarding through the front door. This is a rough estimation that might lead to errors when modelling small passenger numbers.

The effect of driver behaviour on regularity is not taken into consideration in this study. A better control strategy, which headway-based holding seems to be, can hopefully minimize the effects of differing driver behaviour as well.

Fare evasion and safety issues are likely to increase with free boarding through all doors. This should be prevented by increased security and ticket supervision, which leads to higher costs. On the other hand, shorter vehicle run times makes it possible to save vehicle and driver hours. Improving the transit network also changes the demand for transit trips. How this changes the load profile for the bus network and the ticket revenues is not considered in this study.

In the end, what holding strategy is chosen depends on how the contract between the transit authority and the transit operator is formulated. If the transit operator has economic incentives for schedule-based holding, it will not be easy to introduce headway-based holding.

8. Conclusion

This study shows very large benefits for the passengers on crowded inner-city bus lines from changing the boarding procedure and allowing boarding through all doors, which might seem exaggerated in the light of what previous studies have showed. For one vehicle taken out of context, this study would not give large benefits either. However, this study has taken bunching and regularity problems into consideration in a way that is rarely done, which might explain this difference and justify the results of this study.

It is important to remember that for boarding through all doors to be this clearly beneficial, a good holding strategy is required. For this to work, the contract with the operator must have a clear focus on improving regularity and travel time, ideally permitting headway-based holding.

However, this simulation study shows that for the benefits to be substantial (and to ultimately be able to cover the lost revenue due to fare evasion) the system needs to be large and the passenger numbers more or less exceptional for Swedish conditions. In practice the trunk lines in Stockholm and Gothenburg are the only lines that can match the passenger numbers that are necessary according to this study. However, the passenger numbers in Stockholm are large enough for the benefits to be considerable.

Applying these policies together (free boarding through all doors and headway-based holding) on the trunk lines or the whole inner-city bus network of Stockholm could potentially lead to large gains for the passengers. Even if fare evasion would become as common in Stockholm as it is on the trunk lines in Gothenburg (ten per cent), the positive net results that have been experienced in Gothenburg could certainly be at least as good in Stockholm. Based on this study, the travel time and vehicle circulation time gain could be as much as 25 per cent during peak hour, which would both save considerable resources and increase ridership.

As improving the bus service would increase passenger numbers further, some of the positive effects would be lost due to more crowding. In the long run tram or subway (or BRT) might be the only solution for some of the busiest sections. The conclusion from simulation with two different boarding procedures is that introducing vehicles with faster boarding does not cause more regularity problems. This conclusion should be applicable on a mix of trams and buses as well. This means that there are no disadvantages of introducing trams parallel to buses with slow boarding in the city. However, a faster boarding procedure on the buses would be advantageous for all passengers in the system, including the tram riders.

8.1. Suggestions for future studies

To fully understand how different lines interact and together cause regularity problems, more complex transit networks should be simulated, ideally with car traffic simulation included to capture link travel time variations in more detail. Assigning driver and vehicle attributes to individual buses might also be a way to better understanding of how bunching is caused.

An in-depth study of the concept with traffic hosts at important stops is necessary to motivate their existence (or to reject them). A study of which conditions are central factors leading to fare evasion problems would be important when advocating free boarding.

The only way to verify the results of this paper is to perform a full scale test of free boarding through all doors with headway-based holding in Stockholm. This could also give insight into how fare evasion is affected and how large the increase in demand would be.

9. References

Airaksinen, S., and V. Kuukka-Ruotsalainen. "Bus priority as a competitive factor." 2008. http://best2005.net/content/download/910/4181/file/Bus%20priority%20as%20a%20competitive%20factor.pdf (accessed November 2010).

Bernås, M., and H. Pettersson. *Studium av hållplatstider – en studie av faktorer som förlänger bussens hållplatstider.* Unpublished report, 1976.

Blomquist, P., and A. Larsson. *Uppehållstid vid busshållplats – En jämförande studie mellan olika betalningssystem.* Thesis work, Gothenburg: Avdelningen för trafikplanering, Chalmers Tekniska Högskola, 1980.

Burghout, W. *Hybrid mesoscopic-microscopic traffic simulation.* CTR2004:04, Stockholm: Kungliga Tekniska Högskolan, 2004.

Cats, O., N. L. Larijani, W. Burghout, and H. N. Koutsopoulos. "Impacts of holding control strategies on transit performance: A bus simulation model analysis." *Proceeding of the 90th annual meeting of the Transportation Research Board.* Washington, DC, 2011.

Cats, O., W. Burghout, T. Toledo, and H. N. Koutsopoulos. "Mesoscopic modeling of bus public transport." *Transportation Research Record 2188*, 2010: 9-18.

Ceder, A., B. Golany, and O. Tal. "Creating bus timetables with maximal synchronization." *Transportation Research Part A 35*, 2001: 913-928.

Chirqui, C., and P. Robillard. "Common bus lines." *Transportation Science 9*, 1975: 115-121.

Cominetti, R., and J. Correa. "Common lines and passenger assignment in congested transit networks." *Transportation Science 35 (2)*, 2001: 250-267.

Daganzo, C. F. "A headway-based approach to eliminate bus bunching: Systematic analysis and comparisons." *Transportation Research Part B 43 (10)*, 2009: 913-921.

Eberlein, X. J., N. H. M. Wilson, and D. Bernstein. "The holding problem with real-time information available." *Transportation Science 35 (1)*, 2001: 1-18.

Eklund, P. *Trafikantcirkulation och låga golv i stadsbussar.* KFB-rapport 1994:18, Stockholm: Kommunikationsforskningsberedningen, 1992.

Fernández, R., P. Zegers, G. Weber, and N. Tyler. "Influence of Platform Height, Door Width, and Fare Collection on Bus Dwell Time." *Transportation Research Record 2143*, 2010: 59-66.

Fredriksson, L., and P. G. Andersson. *Stombussprinciper – Erfarenheter och slutsatser.* Rapport 2002:40, Lund: Trivector Traffic AB, 2002.

Han, A. F., and N. H. M. Wilson. “The allocation of buses in heavily utilized networks with overlapping routes.” *Transportation Research Part B 16B (3)*, 1982: 221-232.

Ingemarson, M. *Körtider för busstrafik - En körtidsstudie av stombusstrafiken i Stockholms innerstad.* Thesis work, Lund: Thesis 201, Institutionen för teknik och samhälle, Lunds Tekniska Högskola, 2010.

Johansson, B., and S. Liljemark. *JOLIM – Matematisk modell för bestämning av hållplatsuppehålls längd.* Thesis work, Gothenburg: Institutionen för transportteknik, Chalmers Tekniska Högskola, 1980.

Kittelson & Associates, KFH Group, Parsons Brinkkerhoff Quade & Douglass, Hunter-Zawarski, K. *Transit Capacity and Quality of Service Manual, second ed.* Washington, DC: Transit Cooperative Research Program, Report 100, 2003.

Kottenhoff, K., P. G. Andersson, and M. Gibrand. *Bus Rapid Transit – kunskapssammanställning med identifiering av forskningsfrågor.* Stockholm: Kungliga Tekniska Högskolan, 2009.

Kronborg, P., P. G. Andersson, C. Bolinder, and D. Svanfelt. *Hopklumpning av bussar vid tät stadsbusstrafik.* TFK-rapport 2000:2, Stockholm: Institutet för transportforskning, 2000.

Kronborg, P., Ö. Carlbring, G. Lind, and M. Gedda. *Möbleringens betydelse för stadsbussars effektivitet.* TFB-stencil 20, Stockholm: Transportforskningsberedningen, 1986.

Li, M., F. Zhao, L. Chow, H. Zhang, and S Li. “Simulation model for estimating bus dwell time by simultaneously considering numbers of disembarking and boarding passengers.” *Transportation Research Record 1971* (Transportation Research Record 1971), 2006: 59-65.

Linderholm, L. *Busshållplatser i tätort - effekter på framkomlighet och säkerhet vid olika utformning.* Publikation 2004:36, Borlänge: Vägverket, 2004.

Milkovits, M. “Modeling the Factors Affecting Bus Stop Dwell Time - Use of Automatic Passenger Counting, Automatic Fare Counting, and Automatic Vehicle Location Data.” *Transportation Research Record 2072*, 2008: 125-130.

Osuna, E. E., and G. F. Newell. “Control strategies for an idealized public transport system.” *Transportation Science 6*, 1972: 52-72.

Puong, A. “Dwell time model and analysis for the MBTA Red Line.” 2000. http://www.bb.ustc.edu.cn/ocw/NR/rdonlyres/Civil-and-Environmental-Engineering/1-258JPublic-Transportation-Service-and-Operations-PlanningFall2003/D9613FBC-9279-4F31-A46D-8DB2E037E9E4/0/a3_dwelltim.pdf (accessed November 2010).

SL. *RETT – Ett pilotprojekt för bättre regularitet på Stomlinje 1.* Stockholm: AB Storstockholms Lokaltrafik, 2003.

SL. *RIPLAN - Riktlinjer för planering av kollektivtrafiken i Stockholms län.* PLAN – Rapport 2006:10, Stockholm: AB Storstockholms Lokaltrafik, 2006.

SL. *Trafikplan 2020.* Stockholm: AB Storstockholms Lokaltrafik, 2010.

Sundberg, J., and B. Peterson. *Kapacitet i kollektiva trafiksystem - Del 3 - Uppehåll vid hållplats.* Trafikplanering meddelande 69, Stockholm: Kungliga Tekniska Högskolan, 1989.

Teng, J., and X. Yang. "Coordinated optimization of bus headways for passenger corridors." *2009 International Joint Conference on Computational Sciences and Optimization.* Sanya, Hainan, China: IEEE Computer Society, 2009. 981-985.

TRAST. *Trafik för en attraktiv stad, utgåva 2.* Stockholm: Sveriges kommuner och landsting, 2007.

Turnquist, M. A., and L. A. Bowman. "The effects of network structure on reliability of transit service." *Transportation Research Part B 14B*, 1980: 79-86.

van Oort, N., and R. van Nes. "Regularity analysis for optimizing urban transit network design." *Public Transport 1 (2)*, 2009: 155-168.

Weidmann, U. "Der Fahrgastwechsel im öffentlichen Personenverkehr." IVT nr.99, Zürich, 1994.

Wendle, B., and J. ter Schure. *Effektivare på- och avstigning i stadsbusstrafik.* Publikation 2004:35, Borlänge: Vägverket, 2004.

Vuchic, V. R. "Propagation of schedule disturbances in line-haul passenger transportation." *Revue de l'UITP*, 1969: 281-284.