Bus Service Performance Analysis
Case Study: Bus Line 1 in Stockholm, Sweden

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ABSTRACT

Transit reliability is one of the key factors in running a successful transit system from both passengers’ and operators’ perspective. To improve the reliability of a transit service a performance analysis is necessary. There are several service measures that can be applied to evaluate the performance of a transit service, both in relation to service punctuality and service regularity. Punctuality can be considered of higher importance on low frequency lines and regularity on high frequency lines. Bunching is used to describe how vehicles occupying the same bus route tend to bunch up and consequently the reliability decreases. For improving reliability several holding control strategies can be applied such as schedule-based holding, where early vehicles are held at time points, and headway-based holding, where vehicles are held to retrieve even headways between consecutive vehicles.

This thesis provides an overview of several different performance measures that can be analyzed using Automatic Vehicle Location data (AVL) and Automatic Passenger Counters data (APC) collected from bus vehicles. As a case study, bus line 1 in Stockholm was analyzed. The line is a high frequency, inner city bus line, where schedule based holding is the current holding control strategy.

The performance analysis included an analysis of service regularity, service punctuality, dwell times, passenger boarding/alighting and load, and run times. A linear regression analysis was applied to evaluate the effects of passenger activity on the dwell times.

The results showed that the overall service performance decreased along the line for both directions. Vehicle trajectories revealed increased bunching along the line. The drivers’ compliance to holding analysis showed that there was room for improvement. Overall, the analysis showed that the current holding control strategy does not retrieve headway regularity and that the schedule for vehicle run times was too tight and needs revision. Furthermore, switching to headway-based holding was suggested.
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LIST OF TERMS AND ABBREVIATIONS

APC: Automatic Passenger Counters

AVL: Automatic Vehicle Location

Bunching: A term used to describe how vehicles occupying the same bus route tend to bunch up

BussPC: A computer located in the drivers’ cabin, providing the driver with information about how late/early they are etc and enables communication with the control center

CV: Coefficient of variation, the ratio of standard deviation to the mean, can be used to measure the variability of data

Dwell time: Used to describe how long buses dwell at each stop. Dwell time could include both service time and holding time

Headway: The time that passes between when two vehicles occupying the same bus route pass a specific point on the route

Headway-based holding: A holding control strategy where vehicles are held if they are too close to the preceding vehicle

Holding time: Used to describe the time duration a bus stays at a particular stop due to holding

Punctuality: Used to describe how well vehicles are following the time table. On-time performance and schedule adherence are also used to describe punctuality

Regularity: Used to describe the regularity of buses arriving or departing at stops, thus the regularity of the headways

Schedule-based holding: A holding control strategy where vehicles are held if they are ahead of schedule

Service time: Used to describe the time duration a bus stays at a particular stop due to passenger boarding and alighting


TCQSM: Transit Capacity and Quality of Service Manual

Time points: Specific stops on the line where vehicles are held
1 INTRODUCTION

1.1 OVERVIEW AND MOTIVATION

In today’s society, the requirements for European cities to provide their inhabitants with environmentally friendly living conditions are continually increasing. In addition to high requirements regarding environmental consideration, people demand fast transportations and high mobility. By offering good public transport systems, cities can reduce the space needed for traffic structures, emissions from car traffic and congestion problems that are common in larger cities.

Transit reliability is one of the most important factors for a transit system to be successful both from passengers and operators perspective. A reliable transit system results in less waiting time for passengers, more satisfied customers, better utilization of vehicles, and thus less operational costs for the operators.

One important concept in relation to transit reliability is bus bunching. Bunching is used to describe how vehicles occupying the same bus route tend to bunch up. That is, a vehicle that is late tends to get later and a vehicle that is early tends to get earlier. More passengers will be waiting for a late vehicle at each stop than for an early vehicle, assuming that passengers arrive randomly at stops. This results in longer dwell times for the late vehicle at each stop, since more passengers will be boarding and alighting, which then leads to the vehicle being even later. Finally, the vehicle will both be late and crowded, causing unsatisfied passengers and poor vehicle fleet utilization. To counteract bunching, various holding control strategies can be applied.

The County of Stockholm, Sweden has several different modes for public transport, e.g. the underground, commuter trains and buses. There are four so-called blue bus routes (lines 1, 2, 3 and 4) in the inner city of Stockholm. Those routes get their names from their blue colored buses, which are larger than the regular Stockholm city bus. They are all highly occupied and intended to offer frequent and fast trips within the inner city. The current holding control strategy used for the blue bus lines in Stockholm is schedule based holding.
Using that strategy vehicles are only held at specific stops, called time points, if they are ahead of schedule.

Considering the continuous residential growth in the County of Stockholm, there is a need for constant revision and enhancement of the public transport system, for it to be a successful one. The main objective of this project is to evaluate the service performance of blue bus line 1 in Stockholm along with analyzing the effects passenger boarding and alighting have on the service performance. The analysis was based on two different empirical datasets from SL’s (Stockholm Public Transport) database, an Automatic Vehicle Location (AVL) dataset and an Automatic Passenger Counters dataset (APC).

The service performance of bus line 1 is analyzed using various measures. The analysis is aimed at highlighting how bunching originates and accumulates along the line. In addition to the service performance analysis, an analysis of the effects of passengers boarding and alighting is done providing formulas that describe the relationships between dwell times at stops and passenger load/boarding/alighting. The analysis is then concluded with recommendations for improvements.

1.2 OBJECTIVE AND SCOPE

The main objectives of this study are the following:

- To analyze different indicators of service performance of bus line 1 in Stockholm, such as:
  - Dwell times
  - Drivers compliance to holding
  - Service punctuality
  - Service regularity
  - Run times
- To analyze the effects of passenger boarding/alighting/load on service performance, i.e. bus bunching and dwell times. Explain relationships between passenger boarding/alighting/load and dwell times at stops using regression.
- Give recommendations for improvements on the current blue line 1 operation.

Empirical data was used for all the analysis.
1.3 **Thesis Outline**

The thesis is made out of six main chapters. Chapter 1, *Introduction*, gives a brief overview on the background of this study and the objective and scope. Chapter 2, *Literature Review*, provides an overview on previous studies and literature published on the thesis topic. Chapter 3, *Methodology*, describes the different steps in carrying out this project, data collection, and how the data analysis was performed. Chapter 4, *Case Study Description*, provides an overview of public transport in Stockholm as well as describing the characteristics of bus line 1. In chapter 5, *Results*, the results of the data analysis are presented and summarized. Finally, in chapter 6, *Conclusions*, those results are discussed and some recommendations for further developments of the system are given.
2 LITERATURE REVIEW

Service reliability can be considered as one of the main objectives for transit operators and agencies. However, there are other parties, such as passengers and drivers, that have different interests and thus different perspectives on what is a reliable and a good transit service. Several performance indicators, or measures, can be used for analyzing bus service. In this project, the purpose is to analyze some of the performance measures that can be studied using AVL and APC data. Consequently, the main focus of the literature review is on those measures. The literature review is divided into three main sections. The first section, Bus Service Performance, reviews the literature on the different measures for bus service performance. In the second section, Different Perspectives on Service Performance, literature on passengers’, operators’ and agencies’ perspectives on service performance is discussed. The final section, Stockholm Experience, discusses previous studies that have been conducted on bus line 1 in Stockholm.

2.1 BUS SERVICE PERFORMANCE

Measuring performance of transit systems can be useful in several different ways. It can be done for reporting purposes, for operators to improve their services and reach pre-defined goals, and to make decisions on where and when service needs to be provided or improved (Transportation Research Board, 2002). One of the biggest enhancements in the operations of bus services in relation to service reliability has been the emergence of AVL and APC systems. Transit providers have increasingly been implementing and relying on the technology. (Tétrault & El-Geneidy, 2010; El-Geneidy, et al., 2010). This more widespread adoption of AVL and APC data has opened new venues in transit operations and system monitoring. Despite this, there have been little efforts in employing collected AVL data in evaluating transit performance (El-Geneidy et al., 2010). Transit service reliability could be assessed at various levels of aggregation ranging from the route as a whole (route-based reliability) to specific stops (stop-based reliability) (Chen, et al., 2009, p. 724).

Punctuality, or on-time performance, and regularity are two different aspects of the performance of a transit service. It can be found in the literature that the importance of service measures varies between long headway routes and short headway routes. For long headway routes the most common measure of reliability is punctuality (Furth & Muller,
2007). However, for high-frequency routes, it is important to monitor headway regularity (Transportation Research Board, 2002; van Oort & van Nes, 2009; Trompet et al., 2010). “On-time performance is often measured only on routes with longer headways (e.g., longer than 10 minutes), while headway regularity is often measured for routes with shorter headways.” (Transportation Research Board, 2002, p. 207). On short headway routes, customers should not have to rely on the schedule. (Transportation Research Board, 2002).

Both the service regularity and punctuality are analyzed in this project. Some of the measures used in analyzing the regularity are: coefficient of variation of headways, headway distributions, vehicle trajectories (illustrating the occurrence of bunching) and correlations between consecutive arrivals. Some of the measures used in analyzing service punctuality are percentage of on-time arrival and departure. Other aspects such as dwell time, passenger boarding/alighting and load, and run times are analyzed separately.

**Service Punctuality**

Schedule adherence is a term used to describe how well vehicles are following the timetable. Agencies/operators consider a vehicle to be on-time if it departs from a stop within a certain time window relative to the schedule. Some agencies/operators do not even consider a vehicle to be on-time if it departs before the scheduled time. Furthermore, from passengers’ perspective, an early departing vehicle could mean waiting a full headway for the next vehicle (Transportation Research Board, 2002). The definitions of on-time arrivals can vary. For instance, in Strathman and Hopper (1993), a vehicle is considered to be on-time if it arrives no more than one minute early or no more than five minutes late. This definition is also the most common definition according to Transportation Research Board (2002). They also add that usually, on-time performance is only measured at specific locations such as time points, but it is possible to measure it for all stops for a regular bus service (Transportation Research Board, 2002, p. 206). On-time performance could moreover be weighted by number of passengers. That is, the percent of on-time arriving passengers instead of the percent of on-time arriving vehicles (Henderson, Kwong & Adkins, 1991 cited in Transportation Research Board, 2002, p. 206).
Running time deviation measures the uncertainty in running time to each location and how the variation in running time changes along the route. The variation in the end of the route can be useful to plan the slack in the schedule. (Abkowitz & Engelstein, 1983)

According to Strathman and Hopper (1993) several actions/remedies, both short term and long term, can be taken to improve poor on-time performance. Short term remedies are those that aim to return service to schedule in the event of an occasional ”unanticipated” failure, such as holding for early arrivals, and inserting an additional bus for late arrivals. Long time remedies are focused on systematic on-time failures. This can be done by changing run times or adding layover times. Passenger load can affect on-time performance and it is more likely to have on-time failures if the peak load point occurs at the beginning of the run (Strathman and Hopper, 1993, p. 94).

**Service Regularity**

As previously described, service (or headway) regularity is more important than punctuality on high frequency routes. Even headways should lead to more even on-board load, shorter average passenger waiting times at stops as well as shorter dwell times, and thus, a shorter travel time (SL & Busslink, 2003). Passenger waiting time would be minimized if vehicle headways are identical, assuming constant arrival rates during a short time period (Eberlein, et al., 2001). Uneven headways can lead to uneven passenger loadings and bunching, which is irritating both to passengers of the bunched buses and those waiting at the stops (TCQSM, 2003). In recent years, real-time information display has been implemented on some bus lines, such as line 1 in Stockholm. The real-time information provides passengers with information about the upcoming bus arrivals at the bus stop. Passengers can also access real-time information via their mobile phones or on the internet. The availability of real-time information may affect passengers’ decisions in the context of bunching. That is, when bunching occurs, the passenger might choose not to board the first (often crowded in cases of bunching) vehicle if he/she knows that another vehicle (often less crowded) will arrive in 1 or 2 minutes (TCQSM, 2003, p. 3-17).
In practice, headways are almost always irregular. According to Eberlein, et al. (2001) the reasons for headway irregularity are mainly due to three types of variations: dispatching headway variation, dwell time variation, and inter-station running time variation between vehicles. Furthermore, data analysis indicated the first two types of variations being the dominant sources of headway irregularity (Eberlein, et al., 2001, p. 3).

It is well known that headway variations amplify along the transit route due to uneven demand at different stops (Eberlein, et al., 2001, p. 5). Bellei and Gkoumas (2010) also showed that headway distributions get more spread downstream using a stochastic simulation model for a one way transit line, which accounts for some transit service characteristics such as dwell time at stops, capacity constraints and arrivals during the dwell time. They simulated a long, medium-high frequency virtual bus line, which is operated in mixed traffic, and the passengers flow is close to capacity in the most loaded sections. Furthermore, the results from their model showed that the occurrences of bunching increases as the vehicles travel further along the line.

**Dwell Time**

*Dwell time* has been identified as one of the major factors for bunching on high frequency lines (Bellei & Gkoumas, 2010). According to TCQSM dwell time is proportional to the boarding and/or alighting volumes as well as the amount of time required to serve each passenger. There five main factors influencing dwell time are shortly described below (source: TCQSM, p. 4-3):

- **Passenger Demand and Loading:** The number of passengers that pass through the highest-volume door. Identified as a key factor in how long it will take for all passengers to be served. One of the determinants for the passenger load profile is the number of stops, which affects the number of boarding/alighting passengers. A small number of stops result in a greater number of passengers at each stop. However, a high number of stops could result in reduced travel speeds. Thus, there needs to be a balance between the planning of stop number and passenger walking times.
- **Fare Payment Procedures**: The fare payment system can have a major influence on the time needed to serve each passenger. Some systems allow boarding through more than one door.
- **Vehicle Types**: The time required to serve each passenger increases if ascending or descending is necessary.
- **In-Vehicle Circulation**: Boarding takes more time when standees are present onboard.

According to TCQSM the dwell time at each stop can be estimated using the following formula:

\[ t_d = P_a t_a + P_b t_b + t_{oc} \quad [1] \]

where:
- \( t_d \): average dwell time (s);
- \( P_a \): alighting passengers per bus through the busiest door (p);
- \( t_a \): alighting passengers service time (s/p);
- \( P_b \): boarding passengers per bus through the busiest door (p);
- \( t_b \): boarding passenger service time (s/p); and
- \( t_{oc} \): door opening and closing time (s)

The buses on line 1 are low floor and boarding is usually through a single door, i.e. the front door. Alighting is usually through rear doors. Furthermore, smart card tickets are the dominant form of payment procedures and a smaller number of less frequent travelers use paper or SMS tickets (West, 2011). For a case like Stockholm, with low floor buses, single door boarding. TCQSM (p.4-5) suggests 3,0 seconds per each boarding passenger, assuming no standees. Moreover, it is suggested that each alighting passenger adds 0,5 - 0,7 seconds, for 3 or 4 door channels respectively. In TCQSM (p. 4-6) it is suggested that the value of 2 to 5 seconds would be reasonable for door opening and closing, under normal operations. Thus, the TCQSM dwell time model in the case of line 1 would be:

\[ t_d = P_a \cdot (0,5 \text{ to } 0,7) + P_b \cdot 3,0 + (2 \text{ to } 5) \quad [2] \]
However, the range of values of door opening and closing time could even be higher. For an example, Airaksinen and Kuukka-Routsalainen (n.d.) state that door opening and closing should take 3-10 seconds, depending on the bus model.

A common practice used by SL is to assume that each boarding passenger adds 2 seconds to the dwell time and each alighting passenger adds 1 second.

West (2011) studied passenger boarding and alighting for several bus stops in Stockholm. Data was collected using video recording. West collected data at four bus stops in Stockholm (S:t Eriksplan, Västerbroplan, Gullmarsplan and Odenplan). All of those stops have a traffic signal directly after the stop, except for Gullmarsplan. Furthermore, both Gullmarsplan and Odenplan are regulation stops (time points). Most of the buses that stopped at the inner-city bus stops (S:t Eriksplan, Västerbroplan and Odenplan) were low floor. For the inner-city stops West found the average boarding time per passenger being 2,4 seconds both in crowded and non-crowded situations. The door configuration of the observed buses varied in the study. In the case of 2+2+2+1 and 2+2+2 buses\(^1\), which correspond to most of the buses on line 1, West found that the alighting time per passenger was 0,94 seconds. West added a constant of 12 seconds to the model (i.e. the model intercept), which represented all the time from when the bus stopped moving until it started moving again, excluding the time of passenger boarding and alighting. Thus if the results from West (2011) would be presented in a similar form as in TCQSM, the dwell time model would be:

\[
t_d = P_a \cdot 0,94 + P_b \cdot 2,4 + 12 \quad [3]
\]

Video recorded data has some limitations such as, if two buses stopped at the bus stop at the same time the camera range only captured one of them and sometimes the camera view was obscured by people. Moreover, the boarding and alighting times were measured manually from the video recordings, which can bring about human error. The APC data, which was used in this project, was however collected automatically. In addition to that, the APC date has records for all stops on the line.

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\(^1\) The door configuration on a 2+2+2+1 bus: One front door with 2 channels. Three rear doors, two with 2 channels each and one with one channel

The door configuration on a 2+2+2 bus: One front door with 2 channels. Two rear doors with 2 channels each.
**Holding**

Holding is a common operational strategy used to improve service reliability. Headway-based and schedule-based holding are two common holding control strategies. Headway-based holding is when vehicles are held if they are too close to the preceding vehicle. That is done to restore a regular service. It is assumed that vehicles cannot speed up and therefore no action is taken for vehicles with long headways (van Oort, et al., 2010, p. 4). Counter to headway-based holding, schedule-based holding involves analyzing only one vehicle at a time, where each vehicles schedule adherence is checked at time points and vehicles are held if they are ahead of schedule (van Oort, et al., 2010, p. 5).

The effect of schedule-based holding is patently related to the schedule design. Schedule design is very important when schedule-based holding is applied. If the schedule is tight, few vehicles will be ahead of schedule and little holding is necessary. However, if the schedule is loose it is likely that most vehicles will be ahead of schedule and therefore held. A percentile value of the cumulative distribution of the actual previous trip times is often used to determine scheduled trip times. (van Oort, et al., 2010, p. 5).

Furth and Muller (2007, p. 55) describe schedule-based holding in the following way: “Holding at time points truncates the early part of the departure time distribution, converting what would be early departures into on-time departures. The more slack time is inserted into the schedule, the greater the reliability, because slack time raises the probability of an early arrival and therefore (with holding) an on-time departure.” On the down side, holding lowers operating speed, which can affect the riding time and potentially the operating cost. Furthermore, they discuss the optimal slack to insert into the time points at the terminal, in the form of layover and recovery time. Their analysis is aimed at longer headway routes where passengers target a particular schedule departure. They state that time point holding can help prevent small disturbance from becoming major disturbances that routinely afflict most transit lines, and that schedule-based holding results in nonstandard shapes of departure and arrival time distributions (Furth & Muller, 2007, p. 55-56).
Drivers’ compliance is essential for any holding control strategy to have presumptive effects. Furthermore, the transit schedule needs to be realistic and allow for holding at time points. Furth and Muller (2007, p. 56) describe possible reasons for poor holding discipline, such as the difficulty of enforcement or unrealistic running time schedule.

**Run Times and Route Length**

Abkowitz and Engelstein (1983) found that trip distance, number of boarding and alighting passengers and signalized intersections are all factors that strongly influence mean running time. They also found that running time deviation on early points on the bus route influence running time deviations further downstream and that running time variations increases with route length.

Chen, et al. (2009) looked at the service reliability for several different bus routes in Beijing. They proposed three different performance parameters (a punctuality index based on routes, deviation index based on stops and an evenness index based on routes) to analyze the route performance. Their results showed that in general all three performance parameters decreased with the increase of route length. This indicates that the longer the bus route the lower the reliability. Moreover, they find that the decline in performance is most significant up to 30 km route length. Furthermore, the reliability at the stop-based level decreases along the route. The further downstream the stop is the lower the reliability.

Furth and Muller (2007, p. 56) discuss how planners often have to decide on running times without having adequate historical data, and base their decisions on a single day’s observations or in reaction to complaints. One common rule of thumb, also discussed in TCQSM, is to set the running time between time points equal to the mean observed running time (Furth & Muller, 2007, p. 56). Another common rule of thumb is to set the route running time at 85-percentile uncontrolled running time. Recovery time at the end of a bus line is then commonly determined using a fixed percentage (often 15% or 20%) of the scheduled running time.
2.2 **DIFFERENT PERSPECTIVES ON SERVICE PERFORMANCE**

One can look at transit performance from several perspectives. Those perspectives are customer, community, agency and vehicle/driver (Transportation Research Board, 2002, p. 5). The literature and this project are mostly focused on the perspectives of customers and agencies. Therefore, they are discussed below.

As described in the guidebook (Transportation Research Board, 2002, p. 5), a transit mode has to be competitive to other available transit modes for a given trip so that the customer might choose the given mode. There are several areas that are of greatest concern to passengers if they are to choose public transport, i.e. availability of the public transport service, and if it is available the convenience and comfort of the service. Some of the aspects affecting the customers’ decisions are under the control of the transit agency. Those are: Service delivery, travel time, safety and security, and maintenance. All of the above-mentioned, except for safety and security, directly relate to service reliability. Service delivery reflects on the day-to-day basis aspects of how well the service meets the customers’ expectations, i.e. how well the actual service corresponds to timetables. The same goes for the travel times and how well the actual travel times fit the schedule, as well as if the travel times are scheduled in such a way that the trip length is competitive to other modes. The maintenance part can be related to service reliability on an incident-basis, e.g. if a vehicle breaks down while in service and how the transit agency deals with the scenario. Customer satisfaction is a keystone in running a successful public transport system. For the system to be effective and economic the number of passengers has to be sufficient.). As previously described, service reliability is linked to customers’ reflections in several ways and thus a prime factor in customer satisfaction. (Transportation Research Board, 2002).

One of the main differences on how passengers perceive service reliability differently from the operators is described by Chen, et al. (2009, p. 723). They discuss how transit operators may have a distorted view of the transit service reliability since, in practice, reliability assessment are route based, measuring bus terminal on-time performance, or in other words, the schedule adherence of the whole running time along the routes. Passengers are more sensitive to the stop-based reliability than the route-based. Thus, from a passenger’s
perspective, regularity is more important than schedule adherence if the buses run frequently (Chen, et al., 2009, p. 726).

Casello, et al. (2009, p. 136) state that transit reliability, from the user’s perspective, involves departing from the origin station on time, having reasonable on board travel time, and arriving at the destination station within a time frame that allows them to be at their destination without being late.

From the transit agencies’ point of view the objective will be on running efficient and effective operations. “Individuals within the agency will normally be committed to the success of the mission of transit, which is to provide service and be an asset to the community.” (Transportation Research Board, 2002, p. 8). Transit agencies also try to be competitive with the personal automobile to attract more choice passengers. To do so they need to provide reliable services (short wait time, less variation). (Tétrault & El-Geneidy, 2010, p. 390).

2.3 Stockholm Experience

The trunk bus lines in Stockholm have been somewhat studied in the previous years, mostly line 1. However, this report, to the author’s knowledge, is the most comprehensive service performance analysis on one of the trunk lines, where AVL and APC data, released yet.

In 2002 SL and Busslink\(^2\) did a trial on the line in attempt to improve the regularity, especially to aim at keeping more even headways. The hope was even that improved regularity would bring about increased ridership. The measures taken during the trial included e.g. offering two more flex-buses to insert in the routes traffic if needed, applying more traffic controllers on the line during peaks, adjustments on traffic sign bus-priority so that buses that were more than 2 minutes ahead of schedule didn’t get priority and a lower tolerance for when the BussPC screen (see more on BussPC in chapter 3.1) in the drivers’ cabin informed the drivers on not being on-time. Some of the results from the trial showed that the regularity somewhat improved but there still were cases of bunching and the number of “full” buses was lower. The analysis aimed at comparing the before and after period of the trial and

\(^2\) Busslink is the name of the operator Keolis in Sweden (Keolis, n.d.) Keolis is the operator for line 1 in Stockholm.
included only analysis of data for several stops on the line. The analysis included number of late and early departures for the time points, vehicle trajectories only including four stops (time points and Stureplan) and total dwell times at a few of the stops on the line. The waiting times did not reduce to such extent that it gave economic grounds for continuing with all of the trial measures. (SL & Busslink, 2003). However, the adjustments on the traffic signal priority were permanently implemented (West, 2011).

Ingemarson (2010) wrote a master’s thesis with the aim to study the run times for the blue buses in Stockholm and factors affecting the run times. The factors taken into consideration were some of the changes on Stockholm’s traffic system in recent years, such as congestion charges (adopted in August 2007). Empirical data for two of the blue bus lines were studied, line 1 and line 4. The data for line 1 includes the months August-September in the years 2004-2008 for the time periods 07:00-08:00, 16:00-17:00 and 21:00-23:00. Ingemarson analyzed the run times over the whole line (route based) and the results showed that the overall runtime had increased over the 4 year period. The number of boarding and alighting passengers was also studied at two stops (Fridhemsplan and Hötorget) over the three 1-hour periods. By comparing the planned run time and the mean actual run time for line 1, Ingemarson found that in most cases over the four year period, the planned run time was longer than the actual run time. The difference usually was between 0-2 minutes.

The current holding control strategy used for the blue bus lines in Stockholm is schedule-based holding control. However, Larijani (2010) showed using simulation that reliability of buses could be increased if even headway holding control, was applied instead of the current holding control. Even headway holding control aims at keeping even headways between consequent vehicles regardless of the schedule.
3 METHODOLOGY

The working process used in this project involved the following main steps; literature search, literature review, data collection and data analysis. The last two steps are described on the following pages.

3.1 DATA COLLECTION

Two main empirical datasets were used to evaluate bus line 1: AVL-data, *Automatic Vehicle Location* data from bus vehicles and APC-data, *Automatic Passenger Counters* data from bus vehicles.

The AVL data was collected through a computer, called bussPC, which has been installed in all busses in Stockholm. The computer is located in the driver’s cabin and provides the driver with information about how late/early they are according to schedule (on a half-minute level), the next three time points, distance to the next stop in meters etc. The system also enables communication with the control center, i.e. through radio and text messaging. The AVL dataset contains data for all trips that had scheduled departure time from the original terminal between 10:30 and 18:00 (10:30 AM – 6:00 PM, i.e. 7.5 hours period) during May 26th-2008 – May 29th-2008 (Monday-Thursday). The dataset included trip ID, vehicle ID, date, scheduled departure time from original terminal, stop number, scheduled arrival time, scheduled departure time, actual arrival time and actual departure at all stops. The dataset included 18,452 records in total. Those records represent 664 trips, both whole trips, from origin terminal to end terminal, and shorter trips (some are scheduled to start later on the route, thus not at the origin terminal, some vehicles do not finish their trips as can be seen in the vehicle trajectories in chapter 5.4.). Out of those 664 trips, 233 (35%) started within the afternoon peak period, 15:30-18:00.

The APC dataset was derived from SL’s database. It included all data available for line 1 for the entire month of April 2011, and the records where for buses starting their trips between 05:00-01:30 (5:00 AM and 1:30 AM, i.e. 20.5 hours period). However, APC equipment is currently only installed in around 10% of the blue buses, and thus the records from the dataset only represent a sample of the vehicles that are assigned to line 1. The dataset included e.g. actual arrival time, actual departure time, scheduled arrival time, scheduled
departure time, number of boarding passengers, number of alighting passengers and passenger load for each stop on the line. The dataset included around 26,300 records in total. Those records represent 963 trips, out of those only 74 (8%) trips started within the peak period, 15:30-18:00.

3.2 DATA ANALYSIS

3.2.1 AVL-data Analysis

Before any evaluations could be made the AVL-dataset had to be prepared for further use. The main focus of the AVL-data analysis was on the following:

- Holding and dwell times at stops: Dwell times could be calculated using values for actual bus arrival and departure at stops. Consequently the average, standard deviation and coefficient of variations of dwell times could be calculated. It was not possible to directly calculate holding at time points, since holding time is included in the total dwell time in the dataset.

- Drivers’ compliance: Drivers’ compliance could be investigated by comparing the proportion of buses that both arrived ahead of schedule and departed ahead of schedule at time points on one hand and non-time points on the other.

- Schedule Adherence: Schedule adherence could be derived by comparing the values for actual arrival/departure and schedule arrival/departure.

- Headway Regularity: By sorting the data for each stop in chronological order the headways could be calculated, both the scheduled headways and the actual. Then the correlation between consecutive headways could be calculated and correlation between arrival and departure headways at each stop. To get an even better overview of the headways and how/if bunching accumulated along the line the vehicle trajectories were plotted for certain time periods using the arrival/departure times for individual buses at all stops along with the distances between the stops.

- Travel times: The calculation of the total travel time required to sort out whole trips from the dataset, i.e. trips that started at one terminal and ended at another. Using the actual departure times at origin terminals and actual arrival times at end terminals, the travel time for each direction could be calculated and the travel time distribution for the dataset could be plotted.
The software Microsoft Excel was used for all calculations. Calculations were made both for the whole time period and the afternoon peak period, which was defined as the time period from 15:30 to 18:00 o’clock.

3.2.2 APC-data Analysis

The APC data was processed in order to enable an analysis of passenger loads and the dwell time function. Fridays, Saturdays, Sundays and other holidays/red days were excluded from the dataset. That was done so that the results would be comparable to the AVL data results, which only included records for Monday-Thursday. The analysis of the APC data was twofold: A descriptive analysis and a regression analysis on the effects of passenger flows on dwell time at stops.

The descriptive analysis included several calculations and plots that described the characteristics of passenger boarding/alighting and load along the line. The average and standard deviations of both boarding and alighting passengers along with the load was calculated for different time periods and different stops. The distribution of average boarding/alighting passengers and load was plotted over the stops on the line for different time periods.

In order to describe the relationship between passenger boarding/alighting/load on one hand and the dwell time at stops on the other, Excel’s built-in data analysis tool for regression was used to evaluate different variable combinations and perform a linear regression analysis.

The software Microsoft Excel was used for all calculations. Calculations were made both for the whole time period and the afternoon peak period.
4 Case Study Description

4.1 Public Transport in Stockholm

Stockholm is Sweden’s capital and it’s most populous city, with around 850,000 inhabitants\(^3\) in the municipality and a total of 2 million in the larger Stockholm region. The population in the Stockholm region is growing fast, with over 300,000 people in the last 10 years. (Stockholms stad, 2011).

SL, Stockholm Public Transport, is responsible for public transport in the whole Stockholm County\(^4\). However, the operations are procured through international competition and therefore managed by different operators. The operators are compensated based on their performance, i.e. service punctuality and other quality factors, such as customer treatment and service, and they sometimes get fined based on other factors such as missed trips and crowding level. The public transport system in Stockholm can be divided into four different travel modes: commuter trains, local lines, the underground and buses. The commuter trains provide services to those living in the northern and southern parts of the county, often connecting areas located far from Stockholm’s centre to the rest of the county. The local lines provide services to travelers in many suburban areas of Stockholm, such as Danderyd, Täby, Vallentuna, Bromma etc. The underground, connecting most suburban areas around Stockholm to the city centre, has the highest number of passengers within SL’s traffic network but the bus network carries almost as many passengers as the underground, offering 450 bus routes. Furthermore, the bus network is the most widespread out of those above-mentioned networks. In general the usage of the public transport is high. For instance, 75% of all travelers going to the central parts of Stockholm during the morning peak periods choose SL’s public transport. (SL-AB Storstockholms Lokaltrafik, n.d.)

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\(^3\) Number of inhabitants from December 2010

\(^4\) Stockholm county consists of 26 municipalities including the municipality of Stockholm
4.2 **Bus Line 1**

Blue bus routes 1, 2, 3 and 4 are located in Stockholm’s inner-city and are defined as trunk lines (in Swedish: stombusslinjer). They are intended to offer fast and attractive trips, with high trip frequency and high level of passenger comfort. The buses are articulated and take more passengers than the regular Stockholm city bus. The standard articulated bus has seats for 55 passengers (West, 2011, p. 24).

SL has implemented a real time information system both inside the buses for the drivers, and online and on electric signs at the bus stop shelters, for passengers. The real time information system provides information about the location of the buses. Thus, it provides information to the waiting passengers on how many minutes they have to wait till the next bus arrives, based on the bus location. According to guidelines the buses should, during peak periods, have trip frequency of 5-7 minutes and their medium speed, including dwell time, should be at least 18 km/hour (SL-AB Storstockholms Lokaltrafik, 2006, p. 6). These four trunk lines account for 58% of the total number of bus travelers in the inner city of Stockholm (SL-AB Storstockholms Lokaltrafik, 2006, p. 4). The blue buses in Stockholm have some traffic priority such as signalized priority and specific bus lanes.

Out of all bus lines in Stockholm in 2006, line 1 had the second largest number of passengers, around 35.000, after blue line nr 4, with around 60.000 passengers. The average travel speed of line 1 was 14 km/hour the same year. (SL-AB Storstockholms Lokaltrafik, 2006, p. 9-10). The line operates between the two terminals: Essingetorget and Frihamnen. The eastbound direction, from Essingetorget to Frihamnen has 33 stops and westbound direction, from Frihamnen to Essingetorget has 31 stops (including origin- and end-terminals). The lines two different directions will hereafter be referred to as EF33 (the eastbound direction) and FE31 (the westbound direction). The current holding control strategy used on line 1 is schedule based holding control, where vehicles are only held at time point stops, if they are early according to schedule. Line 1 has three time point stops in each direction. All stops on bus route 1 are shown in Table 1. Map of the route is shown in Figure 1.
Figure 1: Blue bus line 1 with its time points (source: Cats et al., 2011)
### Table 1: Names and numbers of stops on bus route 1

<table>
<thead>
<tr>
<th>Essingetorget-Frihamnen Eastbound (EF33)</th>
<th>Frihamnen-Essingetorget Westbound (FE31)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Essingetorget</td>
<td>1. Frihamnen</td>
</tr>
<tr>
<td>2. Flottbrovågen</td>
<td>2. Frihamnsporten</td>
</tr>
<tr>
<td>4. Primusgatan</td>
<td>4. Östhammarsgatan</td>
</tr>
<tr>
<td>5. Lilla Essingen</td>
<td>5. Rökubbsgatan</td>
</tr>
<tr>
<td>7. Fyrverkarbacken</td>
<td>7. Gärdet</td>
</tr>
<tr>
<td>8. Västerbroplan</td>
<td>8. Kampementsbacken</td>
</tr>
<tr>
<td><strong>10. Fridhemsplan</strong></td>
<td><strong>10. Värtavägen</strong></td>
</tr>
<tr>
<td>15. Cityterminalen</td>
<td>15. Norrlandsgatan</td>
</tr>
<tr>
<td><strong>17. Hötorget</strong></td>
<td><strong>17. Hötorget</strong></td>
</tr>
<tr>
<td>18. Norrlandsgatan</td>
<td>18. Vasagatan</td>
</tr>
<tr>
<td>20. Linnégatan</td>
<td>20. Scheelegatan</td>
</tr>
<tr>
<td>22. Nybrogatan</td>
<td>22. S:t Eriksgatan</td>
</tr>
<tr>
<td>23. Jungfrugatan</td>
<td>23. Fridhemsplan</td>
</tr>
<tr>
<td><strong>24. Värtavägen</strong></td>
<td><strong>24. Västerbroplan</strong></td>
</tr>
<tr>
<td>25. Storskärsgatan</td>
<td>25. Fyrverkarbacken</td>
</tr>
<tr>
<td>27. Gärdet</td>
<td>27. Lilla Essingen</td>
</tr>
<tr>
<td>28. Sandhamnsplan</td>
<td>28. Primusgatan</td>
</tr>
<tr>
<td>29. Rökubbsgatan</td>
<td>29. Broparken</td>
</tr>
<tr>
<td>30. Östhammarsgatan</td>
<td>30. Flottbrovågen</td>
</tr>
<tr>
<td>31. Sehlstedtsgatan</td>
<td>31. Essingetorget</td>
</tr>
<tr>
<td>32. Frihamnsporten</td>
<td></td>
</tr>
<tr>
<td>33. Frihamnen</td>
<td></td>
</tr>
</tbody>
</table>

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5 Note: This table corresponds to the stop line up as it was in 2008, i.e. for the AVL data. In 2011 one stop has been added to direction FE31, i.e. after stop nr 23 Fridhemsplan there is an additional stop nr 24 Mariebergsgatan. The stop line-up for the APC data is shown in appendix D.
SL-AB Storstockholms Lokaltrafik (2006, p.3) describe how SL’s traffic system continually needs revising both due to the massive increase in the areas population and because of new constructions like the Stockholm City Line⁶ (Citybanan) that is currently being constructed. According to the rapport the overall dwell times of the four blue buses correspond to 20% of the total run time. In the report they present a map of roads where the blue bus traffic had congestion problems during the fall of 2005, thus low speed (between 10-15 km/hour). The figure is presented below.

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⁶The Stockholm City Line is a 6 km long commuter train tunnel currently being constructed under the city. These changes will require two new commuter train station at Odenplan and T-Centralen (Trafikverket, 2011)
5 RESULTS

This chapter presents the results of all the data analysis. It is divided into 5 sections followed by a summary. The first section, *Dwell Times and Holding Times*, presents the dwell time and a passenger activity analysis at each stop. The chapter also provides an analysis of the relation between dwell times and passenger boarding and alighting volumes. The second section, *Drivers’ Compliance*, contains an analysis of the overall drivers’ compliance to the holding control strategy. The third one, *Service Punctuality*, presents the results of the on-time performance analysis along the line. The fourth section, *Service Regularity*, provides an analysis of the headway distributions at time points, the relationship between consecutive headways as well as arrival and departure headways. The section also presents the time-space relationships between consecutive vehicles in the form of vehicle trajectories which illustrates the bunching phenomenon. The fifth chapter, *Vehicle Run Times*, presents a short analysis of the total travel time for both route directions. Finally, a summary of the main results is given for each time point stop on both directions.

The analysis was done for different periods of the day if that was considered necessary. The main focus was on the peak period 15:30-18:00. Most of the analysis was also done for the whole time period, i.e. the entire dataset (including the peak-period). Some of the analysis was also done for off-peak periods. The relevant time period of each analysis section is always noted.
5.1 **Dwell Times and Holding Times**

5.1.1 **Dwell Times**

*Dwell time* is a term used to describe how long buses dwell at each stop. *Service time* is used to describe the time duration a bus stays at a particular stop due to passenger boarding and alighting processes. *Holding time* is used to describe the time duration a bus stays at a particular stop due to holding, which should occur at time points for early buses. Thus, *dwell time* could include both *service time* and *holding time* at time points. In addition to that, dwell times at all stops could be affected by coincidental traffic condition.

Dwell time variability can be measured with the so-called coefficient of variation, given by the following formula:

\[
CV = \frac{SD}{\mu}
\]  

Where SD represents the standard deviation of the dwell time and \( \mu \) represents the mean dwell time. The coefficient of variation of dwell times at each stop is shown in Figure 4.

The average dwell time at each stop, both directions, along with the standard deviations, are shown in Figure 3 (note: the origin and end terminals do not have any dwell time and are therefore not included). The average length of the dwell time peaks around the time points, indicating holding of some degree or passenger activity. For both directions, the whole time period, the time point Fridhemsplan has the longest average dwell time and the highest standard deviation. Fridhemsplan also has the longest average dwell time (101 sec for EF33 and 118 for FE31) and a high standard deviation (94 sec for EF33 and 196 sec for FE31) for the peak period.\(^7\) This could be explained by high passenger activity at Fridhemsplan, which is presented in the following section.

The average dwell time was calculated both for the whole time period and for the peak period only. The average was lower and the standard deviation higher for the peak period than the whole time period, all stops (average dwell time = 31 seconds and 27 for the peak, standard deviation = 36 seconds and 44 for the peak). This might be explained by traffic

\(^7\) The average of dwell time for the peak period is not plotted.
conditions during the peak. That is, a shorter average dwell time during the peak might be because buses are more likely to encounter traffic congestions between stops. Therefore, they would have to depart from the stop as soon as all passengers have boarded/alighted. A higher standard deviation during the peak could be related to bunching occurring and irregular passenger flows. Furthermore, it would be rational to expect, due to holding, that the average dwell time would be higher for time points than other stops. The average dwell time for the time points only was 66 seconds with standard deviation of 87 seconds for the whole time period, and during the peak period 76 seconds with standard deviation of 115.

Figure 3: The average of dwell times at each stop, represented with blue bars for regular stops and orange for time points. The standard deviation is shown in black.
Figure 4 shows how the dwell time variability, measured with the coefficient of variation (CV), changes along the line. It is evident that the CV is generally higher at time points than other stops. However, there are some non-time point stops that have a high CV. For EF33, stop nr 15, Cityterminalen, evidently has a much higher CV than other stops, or over 1.4. This might be related to the fact that Cityterminalen is the largest bus station in the city and next to Cityterminalen is T-Centralen and Stockholm Central Station, giving connections to the underground and other trains (Stockholms Terminal AB, n.d.). The stops 16, Vasagatan, and 23, Jungfrugatan, have high CV. They are both located right before time points (Hötorget, 17, and Värtavägen, 24) and Jungfrugatan is occasionally used as a drivers’ relief point. However, if there is a relationship, between those two stops having a high CV and being located just before time points, it is not clearly identifiable.

For the other direction, FE31, the CV at time points are distinctly higher than for nearby non-time points.

Since the dwell times could include both service time and holding time at time points, it is impossible to identify the exact holding time at time points and distinguish it from the remaining time spent at the stop. If the average dwell times are higher at time points than other stops, it indicates holding. It is well known that the passenger boarding and/or alighting have the highest effect on dwell time (e.g. TCQSM, p.4-3). In the following two chapters an analysis of passenger activity and dwell time is provided. It was not possible to directly link the two datasets, the AVL data (used in the dwell time analysis) and the APC (used for boarding/alighting/load analysis), since the two dataset covered different time periods. Furthermore, as previously described APC equipment was only available for a fraction of the bus fleet.
Figure 4: Coefficient of variation of dwell times. Blue bars represent regular stops and orange the time points.
5.1.2 Boarding, Alighting and Load

On average the onboard load between all stops was 19.8 passengers per bus. This applies for both directions, the whole time period. For off-peak periods the average load was 18.4 passengers, while for the peak-period it was 25.6 passengers. The average number of alighting passengers per stop was 3.2 for the whole time period (including peak), 4.1 for the peak and 3.0 for off-peak periods. The average of the load along the line was plotted with the average number of boarding and alighting at each stop. The plots for off-peak periods are presented in Figure 5 and the plots for the peak are presented in Figure 6.

Figure 5: Average number of boarding and alighting passengers (blue and red bars) and the average load (green line) at all stops during the whole time period.
Figure 5 and Figure 6 clearly show, as expected, how the majority of the passengers board at the beginning of the line and alight further downstream. There are some stops that stand out having higher average number of boarding and/or alighting passengers. All time points had more than 10 boarding and/or alighting passengers on average during the peak, except for Värtavägen in EF33. Other stops that had more than 10 boarding and/or alighting passengers during the peak were the terminal Essingetorget and St: Eriksgatan for both directions and Lilla Essingen for FE31.
The load profiles for both directions peak around the same geographical area, between Wivalliusgatan and Hötorget for EF33 and between Hötorget and Wivalliusgatan for FE31. There are some sub-routes offered on line 1, i.e. buses that are only operated on parts of the route and not between origin and end terminals. The average load differs substantially between the directions during the peak. For EF33 it is 20,7 and for FE31 it is 30,2 during the peak. For the peak period the average maximum load was 52,4 passengers and a standard deviation of 21,7 (only taking into account whole trips). For the non-peak period the average maximum load was 37,8 passengers with a standard deviation of 14,1.

To get a better overview of the passenger load and alighting/boarding profiles at the time points the average passenger activity was plotted over the whole day. The graphs are presented in Figure 7 and Figure 8.

The boarding and alighting patterns over the whole day are revealed in the figures. It is interesting to see how different the patterns for boarding and alighting are between the time points. Fridhemsplan has the most intensive passenger activity. For EF33 the majority of the passengers are alighting and for FE31 boarding. The reason for that might be that Fridhemsplan is the first stop for passengers travelling in the direction EF33 to connect to the underground.

Figure 7 and Figure 8 only show number of boarding and alighting passenger per bus. They do not show how passenger demand changes over the day, since the number of operating buses is different for peak and off-peak periods. Since the focus is mostly on the peak period the graphs for average number of boarding and alighting passengers and the average load at time points was also plotted separately for the peak period. The plots are presented in appendix C.
Figure 7: Average number of boarding and alighting passengers at time points for EF33
Figure 8: Average number of boarding and alighting passengers at time points for FE31
5.1.3 **Dwell Time and Passenger Boarding/Alighting**

In the literature dwell time is defined as “the time in seconds that a transit vehicle is stopped for the purpose of serving passengers. It includes the total passenger service time plus the time needed to open and close doors.” (HCM 1985, cited in Dueker et al., 2004, p. 23).

Linear regression was applied to evaluate the effects of passenger activity on the dwell times. The analysis was done to gain some perspective on the relationship between dwell time and passenger boarding/alighting. Furthermore, the results can be compared to previous literature such as West (2011) and TCQSM (see discussion in chapter 2 Literature Review), and the common practice used by SL, that each boarding passenger adds 2 seconds to the dwell time and each alighting passenger 1 second.

The APC data was used in the evaluations. The APC data included, among other things, dwell time, number of boarding and alighting, and onboard load at each stop. Those variables were used in the regression analysis. The terminals were excluded from the analysis since they do not include any records for dwell time. The time points were also excluded since the contribution of holding times to the dwell time cannot be identified. Thus, the results from the regression included boarding and alighting passengers at all other stops.

Most of the buses on line 1 are low floor buses and boarding is through the front door, which is a single door with two door halves. The passengers board through the front door and alight through the rear doors. The rear doors are usually; two doors in the middle with two door halves; and sometimes one door farthest back with one door half. These door configurations can also be called 2+2+2+1 or 2+2+2. As previously described (see chapter 2 Literature Review) smart card tickets are the dominant form of payment procedures, though some of the passengers use SMS or paper tickets. The passengers can charge their smart card, usually called **SL Access-kort** by SL, with various amounts and thus travel within the SL public transport system over a certain time period (SL-AB, 2011). In the front of each bus, alongside the drivers’ cabin, there is a smart card reader (i.e. automatic machine). While boarding the passenger needs to hold his/her smart card on the reader, which validates the

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8 The paper ticket can be a one trip ticket or several trip ticket which needs to be stamped by the driver. The several trip paper ticket (in Swedish: försköpsremsa) will in the future be replaced by the smart card (SL-AB, 2011).
card. The passengers are not able to buy tickets on board the busses. As noted by West (2011, p. 31) even though the front door has two door halves it works, in practice, as a door with one channel, since the passengers need to form a queue to the smart card reader.

Several regressions were performed, using different combinations of explanatory variables, to obtain the dwell time model. The different variable combinations that were tried are listed below (note: a more detailed description of the different regression attempts are provided in Appendix D):

- To start with a regression was made for a simple variable combination of explanatory variables, i.e. only number of boarding and alighting passengers.
- A regression was made where boarding, alighting and load were the explanatory variables.
- It is presumed that the effect of on-board passenger load is not linear. In other words, that the load does not start to affect passenger boarding/alighting until the number of on-board passengers has reached a certain level. Therefore a regression was tried where instead of using a plain load-variable for load the logarithm of the load, Log(L), was used.
- It was tried to create dummy variables for load. Two different dummy variables were created for load. First a dummy for the onboard load minus boarding passengers. The second dummy for load minus boarding passengers plus alighting passengers. The dummies were only taken into account if the load exceeded a certain number of passengers (n). Around 40 regressions were run for the two different dummy variables where different values for onboard passengers (n) were tried. The highest $R^2$ was obtained when n=71 passenger.
- Based on the previous regressions a new variable for load was introduced, where boarding was only taken into account if the load minus boarding exceeded 71.
All regression results and corresponding formulas are presented in Appendix D. The attempts of introducing load in the dwell time model had marginal effects on the explanatory power (R²-values, t-stat and P-values) of the model. Therefore, the recommended formula for dwell time model was the first model from the first regression:

\[ t_d = 17,30 + 0,87 \cdot P_a + 2,18 \cdot P_b \]  \[5\]

where:

- \( t_d \): average dwell time (s);
- \( P_a \): alighting passengers (p);
- \( P_b \): boarding passengers (p);

The dwell time regression analysis implied that each boarding passenger had a higher effect on the dwell time than the alighting passenger. That is, each boarding passenger adds 2,18 seconds and each alighting passenger adds 0,87 seconds to the dwell time. The constant of the model, 17,30 seconds, accounts for everything that cannot be explained by boarding and/or alighting, such as door opening and closing.

The results presented here were not in consistency with TCQSM, where each alighting passenger added 0,5 to 0,7 seconds and each boarding passenger 3,0 seconds to the dwell time. Furthermore the constant of the TCQSM model was much lower, i.e. 2 to 5 seconds. However, the results were consistent with West (2011) and SL’s common practice. West suggested that each alighting passenger added 0,94 seconds to the dwell time and each boarding passenger 2,4 seconds, which is slightly higher than the results presented here. On the other hand, West results implied a lower constant, i.e. 12 seconds. This analysis has some advantages over the analysis presented in West, i.e. that this analysis was based on larger dataset than in West, where only around 100 records for buses in Stockholm were used. The dwell time model presented in this thesis, West’s model and SL’s common practice are all based on the conditions of Stockholm and therefore it should be expected that they were consistent with each other. The TCQSM model however is not based on Stockholm conditions, which might explain the suggested values of TCQSM being different.
5.2 **Drivers Compliance**

According to the current holding control strategy, schedule-based holding, the drivers are supposed to stop and hold the bus at time points if arriving early. It can be difficult to infer when it comes to drivers’ compliance since dwell times at time points can both include service time and holding time. Thus, the dwell times could be caused by holding but they could also merely be caused by service time. The following analysis on drivers’ compliance was only based on data for the peak period.

The most straightforward way to check drivers’ compliance is to calculate the proportion of buses that arrive ahead of schedule and also depart ahead of schedule. Two definitions were made for early arrivals/departures, i.e. a 1 minute time limit and a 30 second time limit. The results, which are presented below, only indicate the upper bound of the drivers’ compliance rate. In other words, if we consider the 1 minute time frame, at least 37% of the drivers are not complying with the holding control strategy. Similarly, for the 30 second time frame, 45% are not complying with the strategy. Thus, the actual percentage of drivers not complying could be higher but never lower, considering the two time frames. The reason for this is that in some cases an early arriving bus might stop at the time point merely for passenger loading (service time) not due to holding, and thus depart on-time.

For time points:
- Out of those buses that arrived at time points more than 1 minute ahead of schedule, 37% also departed more than 1 minute ahead of schedule.
- Out of those buses that arrived at time points more than 30 seconds ahead of schedule 45% also departed more than 30 minutes ahead of schedule.

To see if there was any difference in the behavior of drivers at time points or non-time points, similar calculations were done for non-time points. The results were the following:

For non-time points (excluding terminals):
- Out of those buses that arrived at time points more than 1 minute ahead of schedule, 70% also departed more than 1 minute ahead of schedule.
- Out of those buses that arrived at time points more than 1 minute ahead of schedule, 75% also departed more than 1 minute ahead of schedule.
These results indicate that drivers are more likely to depart early if they arrived early at non-time points than at time points. This could be an indicator of drivers behaving differently at time points than at non-time points. However, this could simply be because of longer service times at time points. Furthermore, when interpreting those results one has to keep in mind how service time affects the results, as previously explained, and that in theory dwell times for early arriving buses are shorter than for late buses due to fewer passengers waiting for an early arriving bus than a late one (assuming passengers arriving randomly).
To visualize the holding, all early arrivals during the peak period were plotted along with the corresponding dwell time. Figure 9 shows both early arrivals at time points and non-time points, during the peak period. Dwell times were only plotted up to 3 minutes. The reason for that was that both few buses had dwell times exceeding 3 minutes and such long dwell times were considered unrealistic in relation to holding. The figure only shows dwell times that were under 3 minutes. It can be seen from the figure that early buses dwell longer at time points than non-time points. The red line represents the relationship (trend line) between early arriving busses and their dwell time, at time points. An $R^2$ value of 1.0 is an indicator of the regression line perfectly fitting the data. In our case, the $R^2$ value of the line is 0.1681 which cannot be considered to be high. Thus, there is not a strong linear relationship between early arriving busses and dwell time at time points. Even though the graph shows that early arriving buses are more likely to dwell longer at time points than non-time points it is also evident that there are several buses arriving early and not held at time points.

![Dwell time at stops and early arrivals](image)

Figure 9: Each dot represents a bus that arrives early at stops and how long it dwells at the stop, during the peak period.
5.3 Service Punctuality

Service punctuality (or schedule adherence) is another measurement that can be used to assess bus service performance. The criterion for on-time arrivals, used by SL, is that a bus is considered to be on-time if it arrives less than 1 minute early or less than 3 minutes late. That is, if the bus arrives within the time frame [-1 minute, 3 minutes] it is considered to be on-time. The same goes for on-time departures. In the contract between SL and the operator the measure of performance is punctuality at time points (Cats et al., 2011).

The delay distribution based on departure is plotted in Figure 10. The delay was not plotted for the end terminals (Frihamnen for EF33 and Essingetorget for FE31) since it was based on departure. The buses that departed ahead of schedule are represented with a negative number and those that departed later than scheduled with a positive number. The blue bars represent those departures that are on-time, which correspond to 66 % of all departures. Late departures corresponded to 28% and early departures 6%. The average delay is 2,6 minutes and standard deviation is 5,9 minutes. However, the average does not give a perspective of the actual difference from schedule, since we are dealing with both positive and negative numbers. Therefore, the average absolute deviation from schedule is shown in Figure 11.

The average absolute deviation from schedule might get somewhat better at time points, as a result of holding, i.e. too early departures should, in theory, be eliminated. As can be seen, from Figure 11 there is no clear evidence of reduction in the absolute deviation from scheduled departure. However, the average absolute deviation from schedule is over 4 minutes for most of the stops on the second part of the line (which is close to the average headway frequency during the peak). This applies for both directions and implies uneven headway regularity. Even at the origin terminal the average absolute deviation is around 2 minutes.

Furthermore, to gain a better perspective over schedule adherence, the percentage of on-time departures and arrivals were plotted for every stop. This was done both for the whole data set and for the peak period from 15:30-18:00 o’clock. The graphs are presented in Figure 12.
Figure 10: Delay distribution per bus per stop, based on departure. The blue bars represent on-time departures.

Figure 11: The average absolute deviation from scheduled departures for every stop.
Figure 12: On-time performance for all time periods and peak period, both directions.
Scheduled arrival and departure times are the same for all stops. That is, the scheduled timings do not allow for bus dwell time at stops, directly affecting the calculated on-time performance. However, it can be difficult to pin down if this affects the on-time performance of either arrival or departure, positively or negatively. Despite this, by looking at Figure 12 it is evident that the on-time performance based on departure is generally higher than the on-time performance based on arrival. That is an indicator of that some buses arriving early at stops, then after the dwell time departing on-time leading to higher percentage of on-time departures. Note that the on-time performance at the terminals were not plotted, since for origin terminals it is only realistic to plot the on-time performance based on departure and vice versa for the end terminals.

The overall on-time performance drops along the line in all four cases (both directions, all periods and peak period). The overall on-time performance for the whole time period is higher (59% for FE31 and 53% for EF33) compared to the on-time performance for the peak period (49% for FE31 and 47% for EF33), as might be expected due to traffic conditions.

For all time periods, direction EF33, there are signs of the effects of holding at the two first time points, Fridhemsplan (nr.10) and Hötorget (nr. 17), where the on-time performance of departures is significantly higher than the on-time performance of arrivals. In the other direction, FE31, there are only clear signs of holding effects at the third time point Fridhemsplan (nr 10). For the peak period the signs of effects from holding are less obvious compared to the whole time period. For direction EF33, the only signs of holding effects are at the first time point, Fridhemsplan (nr. 10). For the opposite direction, FE31, there are also some signs of holding at the first stop, Värtavägen (nr. 10).

To get a better overview of the effect holding had at time points, the percentage of early, on-time and late arrivals and departures were plotted for all time points during the peak period, see Figure 13. If the scheduled-based holding strategy is working as intended there should be no early departures at time points. Figure 13 shows that at all time points early departures are less than early arrivals. However, there still are some early departures.
For the direction EF33, the early arrivals at the first time point, Fridhemsplan, are 38%, while early departures are only 7%, indicating holding. At the second time point, Hötorget, the difference is not as evident, 17% early arrivals reduced to 9% early departures. For the third time point, Värtavägen, the reduction is only 3%, i.e. from 16% early arrivals to 13% early departures, which indicates that there was not much holding taking place at the time point. Moreover, it is likely that some of the difference in early arrivals and early departures is due to the fact that the scheduled arrival times are the same as scheduled departure times. Consequently, percentage of early arrival is always somewhat higher than the percentage of early departures.

For FE31, there is also a reduction in the share of early arrivals and early departures, at all time points. For the first time point, Värtavägen, the reduction corresponds to 12%, going from 29% to 17%. For the second time point, Hötorget, it is 9%, going from 14% to 5%. Finally, for the last time point, Fridhemsplan, the early arrivals correspond to 19% and no buses departed early, which could be an indicator of buses being held at that time point.

Late departures/arrivals cannot be linked to holding, and for obvious reasons, it is impossible for a bus that arrives late to depart on-time. Therefore, the percentage of late departures should always be the same or slightly higher than the percentage of late arrivals. A large difference between late arrivals and late departures might be a result of passenger boarding/alighting or temporary/time dependant traffic conditions.

There is a clear pattern that can be seen on Figure 13. That is, that the on-time performance reduces between time points on the line for both directions. Simultaneously, late departures and late arrivals increase.
Figure 13: Percentage of early, on-time and late departures and arrivals at time points, for the whole period, both directions.
To see the trend for all stops on the line, early, on-time, and late departures were plotted for all stops, both for all time periods and the peak. Those graphs are shown in Figure 14 and Figure 15.

For both directions the on-time performance deteriorates along the line. In all four cases there are some buses that depart late from the origin terminal.

For EF33 there are no early departures from the first 5 bus stops and the percentage of on-time departures is rather constant between 84-89% (81-84% during the peak). For the last 10 stops on the line, the percentage of early departures gradually increases. For both periods there is an increase in late departures around the middle of the line. There is some improvement in the number of late departures for the stops located at the end of the line for the whole period. The improvement is not as evident for the peak period, which could be attributed to more car traffic during the peak.

For FE31, both the whole time period and the peak period, the percentage of late departures is noticeably lower for the first 16 stops (around 15-28% at the peak period and 11-19% for the whole dataset), compared to the last 15 stops (between 46 -64% for the peak period and 21-40% for the whole dataset). The percentage of late departures is distinctively higher for the peak period, than the whole time period, which is probably traceable to traffic conditions during the peak. There is a decrease in early departures at all time points for FE31 compared to the surrounding stops, both for the whole dataset and the peak period. That is a sign of some holding at time points. However, there still are some early departures at the time points, which should, in theory, be eliminated as a result of schedule-based holding.⁹

It is interesting that the early departures increase for stops that are located near the end terminals. This happens for both directions all periods and could be related to the human factor. That is, that the drivers get their break at the end terminals.

The share of late departures along the line, suggests that the schedule is too tight. As described by van Oort, et al. (2010) when schedule based holding is applied, a tight schedule

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⁹ Note that the schedule adherance was not plotted for the end terminals since the calculations were based on departure.
results in few vehicles being early and thus little holding being necessary. Thus, the holding control strategy could have more effect if the schedule was looser.
Figure 14: Percentage of early, on-time and late arrivals for the whole time period, both directions. Time points are marked with the letter T.

Figure 15: Percentage of early, on-time and late departures for the peak period, both directions. Time points are marked with the letter T.
The average difference from the actual departures from the schedule, along with the standard deviation, is shown in Figure 16. The average is always above zero for both directions, implying that most buses do not depart early. However, the standard deviation bars reach below zero for all stops. That underlines the diversity of the data for bus departure i.e. that even though on average the buses do not depart early there is a high number of buses departing earlier than scheduled. For some stops the average for schedule adherence is so high (around and over 5 minutes) that it exceeds the planned headway, at least for the peak period. This is a strong indicator of bunching.

For FE33 there is an obvious turn in the standard deviation around the middle of the route. This might be related to the special circumstances at a major transfer stop, Cityterminalen, which previously have been explained.

For FE31 there is a big difference in the standard deviation between the first half of the routes and the second half. The standard deviation is evidently much higher for stops 18-30. That is an indicator of bunching on the second part of the line. This might also be traceable to Cityterminalen, since stop nr 17, Hötorget, and nr 18, Vasagatan, where the change in standard deviation starts, are located near Cityterminalen.
Figure 16: Average difference from schedule (dots) with standard deviations (vertical bars) for the whole time period, both directions. Note: Regular stops are blue, time points are orange.
5.4 Service Regularity

For a high frequency line, like line 1, it is important that the headways between consecutive vehicles are as even as possible. If a route has high occurrence of bunching the headway variation is high. As previous studies have shown (such as Bellei & Gkoumas, 2010), occurrence of bunching is higher further along the transit line. Bunching has a direct effect on passengers’ waiting times. As described by the Transportation Research Board (2002, p. 225): “Bunching reduces the amount of usable passenger capacity provided, increases passenger loads on the first vehicle in a bunch (as it picks up its passengers as well as passengers that would normally have caught the next vehicle), increases passenger wait times, and increases overall travel times, particularly for passengers on an overcrowded vehicle.”

To analyze the occurrence of bus bunching it is necessary to plot the headway distribution. The headway distribution was plotted for all the origin- and departure terminals, along with the three time points for each direction. Figure 17 shows the headway distribution for the whole time period, which is calculated as the time difference between the departures of two consecutive vehicles. The headway calculations were made for all stops except for the end terminals (since the calculations were based on departure).

It is evident from Figure 17 that the distribution of headways is better at the origin terminals compared to time points located further along the route. However, when looking at Figure 17 one has to keep in mind that they show the headway distribution for the whole period from around 10:30 – 18:00, within which the scheduled headway varies between 4-11 minutes.
Since the duration of the scheduled headways varied within the whole time period, it was decided to plot the headway distribution only for those departures where the planned headway was between 4-5 minutes within the peak period from 15:30-18:00 o’clock. The headway distributions are shown in Figure 18. The headway average and standard deviation, for the peak period (15:30-18:00) are shown in Table 4.

A similar pattern is portrayed in Figure 18 as in Figure 17, where the headways are more concentrated to the scheduled headways (4-5 minutes here) in the original terminal than at time points located further downstream, which indicates increased occurrence of bunching along the line. However, by looking at the headway distribution for the original terminals (Essingetorget for EF33 and Frihamnen for FE31) there are still some headways that are very

Figure 17: Headway distribution for the whole dataset at time points and terminals, based on bus departure. Note: Headways at end terminals are based on bus arrival
short or very long, indicating some bunching being generated already at the beginning of these trips. This could be a result of the scheduled headway control, i.e. one bus leaves the origin terminal late and the following bus leaves according to schedule, creating a short headway between the two buses which could prolong along the line.

The average headways given in Table 2 are all between 4-5 minutes as the scheduled headways. There is an obvious pattern for an increase in standard deviation as we move further down the line (with an exception of the standard deviation for Hötorget being higher than for Värtavägen in direction EF33), which is an indicator of bunching being more frequent further down the line. However the headway variability measured with the coefficient of variation of headways can even be considered to be high at the origin terminals, or 0,6.
Figure 18: Headway distribution at time points for the departures where the planned headway is between 4-5 minutes.

Table 2: Average headways and standard deviations for the peak 15:30-18:00, only when the scheduled headway was 4-5 minutes.

<table>
<thead>
<tr>
<th>Stop name</th>
<th>Average headway [min]</th>
<th>Standard deviation [min]</th>
<th>Coefficient of variation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DIRECTION: EF33</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Essingetorget</td>
<td>4,77</td>
<td>2,92</td>
<td>0,61</td>
</tr>
<tr>
<td>Fridhemsplan</td>
<td>4,46</td>
<td>2,98</td>
<td>0,67</td>
</tr>
<tr>
<td>Hötorget</td>
<td>4,81</td>
<td>6,43</td>
<td>1,34</td>
</tr>
<tr>
<td>Värtavägen</td>
<td>4,44</td>
<td>4,30</td>
<td>0,97</td>
</tr>
<tr>
<td><strong>DIRECTION: FE31</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frihamnen</td>
<td>4,57</td>
<td>2,78</td>
<td>0,61</td>
</tr>
<tr>
<td>Värtavägen</td>
<td>4,69</td>
<td>3,27</td>
<td>0,70</td>
</tr>
<tr>
<td>Hötorget</td>
<td>4,67</td>
<td>4,27</td>
<td>0,91</td>
</tr>
<tr>
<td>Fridhemsplan</td>
<td>4,80</td>
<td>4,95</td>
<td>1,03</td>
</tr>
</tbody>
</table>
To try to assess if the headway distributions changed after buses were held at time points the headway distribution for both arrival and departure was plotted for all time points and terminals, see Figure 19. The graphs on the figure do not show any clear change in the headway distribution before and after holding, except for Fridhemsplan for the direction FE31. The data suggests that the current holding control strategy does not have an effect on retrieving headway along the line. The graphs for the time points, shown in Figure 19, are also shown in Appendix A, along with graphs for the origin and end terminals.
Figure 19: Headway distributions at time points, based on arrival and departure.
A higher coefficient of variation of headways arises from a higher tendency of buses to bunch together. The coefficient of variation of headways was plotted for the whole dataset for both directions. The graphs are shown in Figure 20. If holding would have positive effect on bunching $CV_h$ would be lower for time points than other preceding stops, if $CV_h$ is calculated for headways based on departures. As can be seen in the graphs this is not the case for the direction EF33. However, there seems to be some reduction in $CV_h$ for both time points 10 (Värtavägen) and 23 (Fridhemsplan) for the other direction, FE31.

![Coefficient of variation of headways](image)

Figure 20: The coefficient of variation of headways for the whole dataset, both directions. The values are based on bus departure. Time points are marked on the graphs as orange lines.
Another aspect that is interesting while looking at bus headways is the correlation between headways of consecutive buses. A scatter plot was created for each time point and terminals for headway $h_n$ and its following headway $h_{n+1}$, to see if there is any correlation between the two. Those plots are shown in Figure 21 and Figure 22.

There is a low negative correlation between headways of successive buses. However, they imply that if headway $h_n$ is long it is more likely that $h_{n+1}$ is short and vice-versa. The correlation graphs also show an interesting pattern along the line. For stops located earlier on the line the headways are more regular, i.e. the dots (representing $h_n$ and $h_{n+1}$) cluster around similar values. The dots then get more disperse downstream, implying bunching being more frequent downstream.

The following figures show the correlation between consecutive headways at terminals and time points for direction EF33. Note: All headways are based on departure except for the end terminals where they are based on arrival.
Figure 21: Correlations between consecutive headways at time points and terminals for EF33 (the graph for the end terminal is based on arrival).
Figure 22: Correlations between consecutive headways at time points and terminals for FE31 (the graph for the end terminal is based on arrival).
In order to get a better visualization over the time-space relationship between consecutive vehicles the vehicle trajectories were plotted during the peak period of two days, i.e. May 26th and 27th. The vehicle trajectories are presented in Figure 23 - Figure 30. Two sorts of trajectories are presented in those figures. The first four figures, Figure 23 - Figure 26, show the actual vehicle trajectories for all vehicles that started their trip during the peak period. To see how the vehicle trajectories looked in comparison to the schedule the vehicle trajectories along with the scheduled trajectories were plotted for a one hour period. They are presented in the last four figures, Figure 27 - Figure 30.

The vehicle trajectories have the distance from the origin terminal on the x-axis and the timing on the y-axis. Each line represents one bus. Thus, the bus movement starts farthest to the left and the intercept to the y-axis represents the departure time from the terminal. The slope of each line indicates the speed of the respective vehicle, i.e. steep slopes imply that the vehicle is moving at a relatively slow speed. In some cases parts of the lines are completely vertical, meaning that the vehicle has stopped, and thus implying the dwell times at stops. The vertical distance between two lines at each given point on the x-axis represents the time from when the former vehicle crossed a location till the second vehicle crossed the same location, i.e. the headway. Likewise, the horizontal distance represents the actual distance between the vehicles at each given time. Furthermore, the vehicle trajectories show if bunching has occurred and if there were any overtaking.

When interpreting these figures one has to keep in mind that these figures only represent a fragment of the data, i.e. only trips that started from the origin terminal between 16:00 and 17:00 for on May 26th and 27th.

The first four figures show that the headway regularity was much better on the 26th than on the 27th, for both directions. Some external factors, such as weather, traffic conditions etc. are the most likely a reason for this difference. This only underlines that when working with real traffic data it is affected by real life external factors, often not clearly identifiable. The trajectories show that some of the buses depart bunched, especially on May 27th. The trajectories also clearly show how bunching is more frequent as the busses get further down the line. For FE33, there is even some bunching of three buses. There are some peculiar
dwell times revealed in the figures for the 27th, for an example on Figure 24 where one of the buses (the one that is the 6th bus departing from the terminal) has a very long dwell time at the first time point (around 15 minutes) and after that the bus does not dwell at any stop further down the line. The reason for that might be that the bus broke down and was taken out of service.

The vast majority of the vehicles departed on-time from the origin terminal on May 26th as is revealed in Figure 27 and Figure 28. The figures reveal how bunching occurs, and how the current holding control strategy does not retrieve the headway regularity. For an example the first bus, departing at 16:00 from the origin terminal, is somewhat late in the beginning of the line and gets later further downstream. However, the next bus is not late and held at time points to remain adhered to the schedule. The result is that the two buses bunch up. Moreover, the figures reveal how some of the early buses are held at time points. Overall, as the buses move further along the line their schedule adherence reduces severely and bunching occurs.

The last two figures, Figure 29 and Figure 30, representing May 27th reveal a condition where buses are departing bunched from the terminal. The two buses departing between 16:15 and 16:30 for FE31, are an interesting example. They depart bunched and continue that way throughout the line, one of them being one time (on the first half of the line). Since one of the buses is on time and the other is late, neither is held according to schedule-based holding, and thus headway regularity not retrieved.
Figure 23: Vehicle trajectories for all vehicles, direction EF33, during the peak period on May 26th. The locations of the time points are marked with arrows.
Figure 24: Vehicle trajectories for all vehicles, direction EF33, during the peak period on May 27th. The locations of the time points are marked with arrows.
Figure 25: Vehicle trajectories for all vehicles, direction FE31, during the peak period on May 26th. The locations of the time points are marked with arrows.
Figure 26: Vehicle trajectories for all vehicles, direction FE31, during the peak period on May 27th. The locations of the time points are marked with arrows.
Figure 27: Vehicle trajectories for vehicles that had scheduled departures from terminals between 16:00-17:00 on May 26th, direction EF33. Whole lines represent actual vehicle trajectories and dashed lines represent the scheduled trajectories. The locations of the time points are marked with arrows.
Figure 28: Vehicle trajectories for vehicles that had scheduled departures from terminals between 16:00-17:00 on May 26th, direction FE31. Whole lines represent actual vehicle trajectories and dashed lines represent the scheduled trajectories. The locations of the time points are marked with arrows.
Figure 29: Vehicle trajectories for vehicles that had scheduled departures from terminals between 16:00-17:00 on May 27th, direction EF33. Whole lines represent actual vehicle trajectories and dashed lines represent the scheduled trajectories. The locations of the time points are marked with arrows.
Figure 30: Vehicle trajectories for vehicles that had scheduled departures from terminals between 16:00-17:00 on May 27th, direction FE31. Whole lines represent actual vehicle trajectories and dashed lines represent the scheduled trajectories. The locations of the time points are marked with arrows.
5.5 Vehicle Run Times

It is important to analyze the cycle time, especially from the operators perspective. Generally, while creating a bus route schedule, the cycle time is a crucial factor. If the cycle time used in the route planning is realistic the fleet size can be optimized which results in lower operational costs. A common practice is to aim at the so called 90-percentile cycle time when the run time schedules are designed.\(^\text{10}\) A percentile value represents the value of the cumulative distribution of the actual previous trip times (van Oort et al., 2010, p.5).

While analyzing line 1, it was decided not to plot the total cycle time (i.e. both directions) since it was difficult to exclude the layover times at terminals. In other words, some trips included drivers’ breaks, change of drivers, buses etc at the terminals. Therefore, the distribution of travel times was plotted for each direction separately. The plots represent whole trips (that start at the origin-terminal and end at the end-terminals) that were made for each direction during a four day period (May 26\(^{th}\) – May 29\(^{th}\)). For EF33 there were 252 complete trips used to create the distribution and 192 for FE31. The distributions were plotted for the whole time period, i.e. the dataset was not divided into different time periods, even though the scheduled travel time varied between different periods of the day (i.e. 51-52 minutes for EF33 and 46-50 minutes for FE31). The plots of the travel time distributions are presented in Figure 31 and Figure 32. It is evident from Figure 31 that the majority of trips have a longer travel time than scheduled. The 90\(^{th}\) percentile is 8-9 minutes longer than the scheduled travel time on the EF33 direction. The difference between the 90\(^{th}\) percentile and the scheduled run times is not as pronounced on FE31, or 4-8 minutes. The calculated 90\(^{th}\) percentile value, the average run time and standard deviation are given in Table 3. The standard deviation being so high for FE31 might be explained by the high variety in the scheduled travel times.

\[
\text{Table 3: Results from run time analysis (all values are in minutes)}
\]

<table>
<thead>
<tr>
<th></th>
<th>EF33</th>
<th>FE31</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scheduled run times</td>
<td>51-52</td>
<td>46-50</td>
</tr>
<tr>
<td>(Corresponding percentile values)</td>
<td>(18-26)</td>
<td>(50-79)</td>
</tr>
<tr>
<td>90(^{th}) percentile value</td>
<td>60,4</td>
<td>54,3</td>
</tr>
<tr>
<td>Average run time</td>
<td>54,6</td>
<td>48,9</td>
</tr>
<tr>
<td>Standard deviation of average run time</td>
<td>5,5</td>
<td>12,7</td>
</tr>
</tbody>
</table>

\(^\text{10}\) SL uses 90th percentile cycle time. 85th percentile is also a common practice.
Figure 31: Travel time distribution of trips that were made from Essingetorget to Frihamnen during the whole time period.

Figure 32: Travel time distribution of trips that were made from Frihamnen to Essingetorget during the whole time period.
Under the current holding control strategy the drivers aim at keeping to the schedule. That means, that the actual run times are highly affected by how the schedule is designed. The run time results indicate that the scheduled run times are too low. A more thorough run time analysis could be done, where the data is divided based on the different scheduled run times. Preferably a larger dataset (more than the four day dataset used here) should be used in such an analysis especially with the vehicle trajectories in mind (see chapter 5.4), which revealed very different run time patterns between different days.
5.6 Result Summary

Most of the results are separated for each direction, with a special focus was given to time points. Some of the results were not direction based or stop based, such as the regression analysis for passenger boarding/alighting/load and dwell times, drivers’. The direction based results are presented in Table 4 and Table 5. The non-direction based results are listed below:

**Passenger boarding/alighting/load:**

- The majority of the passengers board at the beginning of the line and alight further downstream, as expected. There are several stops that stand out, having more than 10 boarding and/or alighting passengers on average during the peak.
- All time points have a high average number of boarding and/or alighting passengers compared to surrounding stops. In addition to the time points there are a few stops with high passenger activity as well, such as St:Eriksgatan for both directions and Lilla Essingen and Essingetorget for FE31.
- The load profiles for both directions peak around the same geographical area. That is, between Wivalliusgatan and Hötorget.
- EF33 has a much higher average load, or 30,2 passengers, during the peak than FE31 which only has 20,7.
- A regression analysis showed that each boarding passenger adds a little less than 2,2 seconds to the dwell time, while a alighting passenger adds around 0,87 seconds.

**Drivers’ compliance:**

- There was not a strong linear relationship between early arriving busses and dwell times at time points. However the drivers are more likely to depart early if they arrived early at non-time points than at time points, which is an indicator of drivers behaving differently at time points than at non-time points.
### Table 4: A summary of results for direction EF33

<table>
<thead>
<tr>
<th>Holding and dwell times</th>
<th>Service punctuality (during peak)</th>
<th>Service regularity (during peak, planned headway 4-5 minutes)</th>
<th>Vehicle run times</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fridhemsplan</strong></td>
<td>• On-time arrivals are 35%, on-time departures 60% • Early departures are 7%</td>
<td>CV of departure-headways was 0,67</td>
<td>Does not apply to time points</td>
</tr>
<tr>
<td>The stop has the longest average dwell time (101 sec both for the whole period and the peak) compared to other stops on the line and the second highest coefficient of variation of dwell times after stop number 15, Cityterminalen, (which is not a time point). The coefficient of variation of dwell times is 1,29 and 0,93 for the peak. There are much more passengers alighting at Fridhemsplan than boarding, during the whole day. For the peak the average alighting passengers is 17,7 compared to 4,4 boarding.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Hötorg</strong></td>
<td>• On-time arrivals are 36%, on-time departures 37% • Early departures are 9%</td>
<td>During the peak when the planned headway was between 4-5 minutes the CV of departure-headways was 1,34</td>
<td>Does not apply to time points</td>
</tr>
<tr>
<td>The stop has the second longest average dwell time, 62 seconds and 55 for the peak period. The coefficient of variation is 0,55 and 0,58 for the peak. The number of alighting passengers is slightly higher than the number of boarding passengers during most of the day. There is a slight peak in boarding/alighting during the mid day (around 12:00-18:00).</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Värtavägen</strong></td>
<td>• On-time arrivals are 26%, on-time departures 26% • Early departures are 13%</td>
<td>During the peak when the planned headway was between 4-5 minutes the CV of departure-headways was 0,97</td>
<td>Does not apply to time points</td>
</tr>
<tr>
<td>The stop has the average dwell time of 37 sec and 35 for the peak. The CV is 0,59 and 0,57 for the peak. This time point has a low passenger boarding/alighting compared to the other time points on the line.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Summary for EF33</strong></td>
<td>For the first 5 stops the percentage of on-time departures is high (84-89% and 81-84% for the peak) and a very low percentage of early departures (under 2%). There is a peak in early departures at stops 9 and 15 (Mariebergsgatan and Cityterminalen). For the last 10 stops on the line, the percentage of early departures gradually increases. In general the on-time performance decreases along the line.</td>
<td>The CV of departure headways increases for stops located further along the line. There is no clear reduction in the headway CV at time points. Indicating headways not being adjusted at time points.</td>
<td>The majority of the trips have a longer travel time than scheduled. The 90th percentile is also considerably higher than the scheduled travel time. The result indicated that the schedule was too tight.</td>
</tr>
<tr>
<td>The average dwell times peak around the time points. The time point Fridhemsplan, which is the first time point on the line, is distinct from the other stops, with a much longer average dwell time. The average dwell times at time points is highest for the first one (Fridhemsplan) and lowest for the last one (Värtavägen). The average passenger load is 30,2 during the peak</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Table 5: A summary of conclusions for direction FE31

<table>
<thead>
<tr>
<th>Holding and dwell times</th>
<th>Service punctuality (during peak)</th>
<th>Service regularity (during peak, planned headway 4-5 minutes)</th>
<th>Vehicle run times</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Vårtavägen</strong></td>
<td>The average is 36 sec both for all periods and the peak. The CV is slightly higher than the average for all stops (both directions) 0,67 (0,92 for the peak). This time point has a low passenger boarding/alighting compared to the other time points on the line. The average number of alighting passengers is slightly higher than for boarding during the whole day.</td>
<td>• On-time arrivals are 51%, on-time departures 63%  • Early departures are 17%</td>
<td>During the peak when the planned headway was between 4-5 minutes the CV of departure-headways was 0,70</td>
</tr>
<tr>
<td><strong>Hötorget</strong></td>
<td>The time point has the second longest average of dwell times 62 seconds, after the time point Fridhemsplan. It has the highest CV compared to other stops 1,36 (1,71 for the peak). The average number of boarding passengers is much higher than the average number of alighting passengers. There is a peak during the mid day for both boarding and alighting.</td>
<td>• On-time arrivals are 47%, on-time departures 46%  • Early departures are 5%</td>
<td>During the peak when the planned headway was between 4-5 minutes the CV of departure-headways was 0,91</td>
</tr>
<tr>
<td><strong>Fridhemsplan</strong></td>
<td>The stop has the longest average dwell time (98 sec for the whole period and 118 sec the peak) compared to other stops on the line and the second highest CV of dwell times after the time point Hötorget. The coefficient of variation of dwell times is 1,22 and 1,66 for the peak. There are much more passengers boarding at Fridhemsplan than alighting during the whole day.</td>
<td>• On-time arrivals are 29%, on-time departures 36%  • Early departures are 0%</td>
<td>During the peak when the planned headway was between 4-5 minutes the CV of departure-headways was 1,03</td>
</tr>
</tbody>
</table>

**SUMMARY FOR FE31**

The average dwell times peak around the time points. The two last time points on the line Fridhemsplan and Hötorget have a considerably higher CV than the other stops. The average dwell times at time points is highest for the last one (Fridhemsplan) and lowest for the first one (Vårtavägen). The percentage of on-time departures for the first 5 stops is high (slightly lower though than for EF33). Decrease in early departures at all time points Peak in early departures at stop 14, Stureplan. For the final 7 stops the percentage of early departures gets gradually higher. In general the on-time performance decreases along the line.

There is some reduction in the CV of headways at the first and third time points. Indicating some headway adjustment.

The majority of the trips have a lower or similar travel time as the schedule. The result indicated that the schedule was too tight.
6 CONCLUSIONS

The main objective of this thesis was to analyze different indicators of service performance of a high frequency inner city bus line. Bus line 1 in Stockholm was used as a case study. Punctuality and regularity are two different aspects of the performance of a transit service. For long headway routes punctuality, or on-time performance, is considered more important and for short headway routes regularity is more important. Both regularity and punctuality on line 1 were analyzed along with other service performance indicators such as dwell times, drivers’ compliance and run times. The analysis was based on AVL (Automatic Vehicle Location) data. This thesis also includes an analysis on the effects of passenger boarding/alighting/load on dwell times based on APC (Automatic Passenger Counters) data.

The dwell time analysis showed that the time points generally had higher coefficient of variation of dwell times and a higher average dwell time for both directions in comparison to non-time points. Furthermore, the time points also had high average number of boarding and/or alighting passengers per vehicle, compared to other stops, both during the peak and off-peak. Therefore, some of the long average dwell times at time points could be explained by service time. Some non-time points had high coefficient of variations, especially Cityterminalen for direction EF33. That might be related to the fact that Cityterminalen is the largest bus station in the city, located next to T-Centralen and Stockholm Central Station. The number of alighting passengers was also high at that stop, especially during the peak.

The load profiles, derived from the APC data, showed that the average load differed severely between directions during the peak, i.e. being 20.7 for EF33 and 30.2 passengers for FE31. Plots of average number of boarding and alighting passengers at time points showed that Fridhemsplan was the most extreme time point regarding boarding and alighting, having many more passengers alighting than boarding for EF33 and the other way around for FE31. The reason for that might be that Fridhemsplan is the first stop for passengers travelling in the direction EF33 to connect to the underground.

The dwell time regression analysis implied that each boarding passenger had a higher effect on the dwell time than the alighting passenger. That is, that each boarding passenger adds 2.18 seconds and each alighting passenger adds 0.87 seconds to the dwell time. Attempts were made to include other explanatory variables (other than boarding and alighting) to the regression model but they were found to have marginal effects on the
explanatory power of the model. The constant of the model, which accounts for everything that cannot be explained by boarding and/or alighting, was 17.30 seconds. The regression results are in consistency to West (2011). However, the results of this analysis are based on a larger dataset. Furthermore, the results are similar to SL’s common practice of each boarding passenger adding 2 second to the dwell time and each alighting passenger adding 1 second.

The drivers’ compliance results indicated that drivers are more likely to depart early if they arrived early at non-time points than at time points. However, there was not a strong linear relationship between how early buses arrived and their dwell times. The analysis showed that 37% of buses that arrived earlier than 1 minute ahead of schedule at time points also departed more than 1 minute early. Implying that 37% of buses that should be held at time points are not held. However, the drivers are behaving differently at time points than at non-time points, as 70% of buses that arrive earlier than 1 minute at non-time points also depart more than 1 minute early. These values only indicate the percentage of drivers that are not complying, since some early arriving buses do not depart early due to passenger activity.

Out of all departures from all stops, 66% were on-time. As expected, and indicated in earlier literature (e.g. Chen et al., 2009), the on-time performance drops along the line for both directions. Furthermore, the on-time performance is lower for the peak than for the whole time period. The standard deviation of schedule adherence gets considerably higher around Cityterminalen and remains higher throughout the line. For a few stops on the line the average schedule adherence is over 5 minutes (exceeding the planned headway for the peak).

Analysis on service regularity showed that the distribution of departure-headways is more concentrated to the scheduled headways at the terminals than at time points further along the line. That is in consistency with previous literature (e.g. Eberlein et al, 2001). However, there even seems to be some generation of too short/long headways at the origin terminals. The coefficient of variation of departure-headways was lowest at the origin terminals and generally increased for time points as they were located further along the line (for both directions), indicating irregular headways and thus bunching being more frequent downstream. There was no clear change in headway distribution patterns between arrival-headways and departure-headways at time points. That is an indicator of the headway
regularity not being corrected with the current holding control strategy. Scatter plots of consecutive headways, $h_n$ and $h_{n-1}$, implied that they were not highly correlated. They also implied that bunching was more frequent downstream.

Vehicle trajectories were plotted for the peak period for May 26th and 27th. The trajectories revealed very different patterns for the two days. That is, the headway regularity was much better on May 26th than May 27th. The trajectories show in a clear graphical way how bunching and overtaking occur along the line. They revealed that bunching was more frequent downstream. However, there were even some cases of buses departing bunched from the terminal.

The run time analysis indicated that the scheduled run times were too tight. That was underlined in the punctuality analysis, where the share of late departures along the line suggested too tight scheduling.

In relation to holding, the time points were studied separately. The analysis clearly showed different results for time points and non-time points. In general they showed that the time points had higher dwell times, higher coefficient of dwell times, higher number of boarding and/or alighting passengers compared to non-time points.

To summarize, the analysis has showed that the overall service performance is decreased along the line for both directions. That is, the farther away from the terminal the lower on-time performance and more spread headway distributions. The vehicle trajectories showed how the occurrence of bunching increases along the line. In some cases the buses are even departing bunched and not on-time. The drivers’ compliance to holding analysis showed that there was room for improvement. Furthermore, the analysis provided a dwell time model for line 1 in Stockholm, based on a larger database than the previous literature (to the author’s knowledge), which could be used in future planning in the Stockholm bus system.

A public transport system needs constant revising and enhancement. This is even more important in an urban area like Stockholm, which is constantly growing, and has a high utilization of public transport. This thesis has provided an empirical analysis on several important bus service performance measures for one of the most used trunk line in Stockholm. The results can be used both to compare to other studies and in planning for
other inner city bus lines with similar attributes. As for all public transport services, there is room for improvements.

Service regularity is considered of higher importance than service punctuality on a high frequency bus line, such as line 1 in Stockholm. The service performance analysis has clearly shown that the current holding control strategy does not retrieve service regularity or reduce the occurrence of bunching. Therefore, switching to headway-based holding is suggested. It should be noted that a trial was conducted on line 1, between October 6th to October 21st 2011, where headway-based holding was tried. The results from the trial period were promising but a thorough analysis on the effects of switching holding control strategy is pending.

The results on the run time analysis showed that the timetable design could be revised and that the scheduled run times were too tight. Those results were supported by the punctuality analysis. Therefore it is suggested that the run times are revised.

The report has provided a new dwell time model based on a larger dataset than some previous dwell time models for Stockholm. The model demonstrates the effects that boarding and alighting passengers have on dwell time. The new dwell time model can be used in future planning and scheduling for the Stockholm bus system, especially the inner city.

This study has provided an overview over different service performance measures for a high frequency, inner-city line. Most of the analysis was based on AVL data from 2008. It is therefore suggested that a similar analysis would be conducted using the latest data, especially an analysis on the run times. Moreover, parts of this analysis could be used as a basis for comparing to the results of the trial conducted in October 2011.
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APPENDIX A – HEADWAY DISTRIBUTION AT TIME POINTS AND TERMINALS

The following figures show the headway distribution for terminals and time points on EF33.

![Headway Distribution EF33 (Essingetorget)](image)

![Headway Distribution EF33 (Fridhemsplan)](image)
The following figures show the headway distribution for terminals and time points on FE31.
Headway Distribution FE31 (Fridhemsplan)

Headway Distribution FE31 (Essingetorget)

Arrival
## APPENDIX B – STOP LINE-UP FOR 2011

<table>
<thead>
<tr>
<th>Essingetorget-Frihamnen Eastbound (EF33)</th>
<th>Frihamnen-Essingetorget Westbound (FE31)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Essingetorget</td>
<td>1. Frihamnen</td>
</tr>
<tr>
<td>2. Flottbrovägen</td>
<td>2. Frihamnsporten</td>
</tr>
<tr>
<td>4. Primusgatan</td>
<td>4. Östhammarsgatan</td>
</tr>
<tr>
<td>5. Lilla Essingen</td>
<td>5. Rökubbsgatan</td>
</tr>
<tr>
<td>7. Fyrverkarbacken</td>
<td>7. Gärdet</td>
</tr>
<tr>
<td>8. Västerbroplan</td>
<td>8. Kampementsbacken</td>
</tr>
<tr>
<td><strong>10. Fridhemsplan</strong></td>
<td><strong>10. Värtavägen</strong></td>
</tr>
<tr>
<td>15. Cityterminalen</td>
<td>15. Norrlandsgatan</td>
</tr>
<tr>
<td><strong>17. Hötorget</strong></td>
<td><strong>17. Hötorget</strong></td>
</tr>
<tr>
<td>18. Norrlandsgatan</td>
<td>18. Vasagatan</td>
</tr>
<tr>
<td>20. Linnégatan</td>
<td>20. Scheelelegatan</td>
</tr>
<tr>
<td>22. Nybrogatan</td>
<td>22. S:t Eriksgatan</td>
</tr>
<tr>
<td>23. Jungfrugatan</td>
<td><strong>23. Fridhemsplan</strong></td>
</tr>
<tr>
<td><strong>24. Värtavägen</strong></td>
<td></td>
</tr>
<tr>
<td>27. Gärdet</td>
<td>27. Wivalliusgatan</td>
</tr>
<tr>
<td>28. Sandhamnsplan</td>
<td>28. Lilla Essingen</td>
</tr>
<tr>
<td>29. Rökubbsgatan</td>
<td>29. Primusgatan</td>
</tr>
<tr>
<td>30. Östhammarsgatan</td>
<td>30. Broparken</td>
</tr>
<tr>
<td>31. Sehlstedtsgatan</td>
<td>31. Flottbrovägen</td>
</tr>
<tr>
<td>32. Frihamnsporten</td>
<td>32. Essingetorget</td>
</tr>
<tr>
<td>33. Frihamnen</td>
<td></td>
</tr>
</tbody>
</table>
APPENDIX C – PASSENGERS AT TIME POINTS DURING PEAK PERIOD

The following figures show the average number of boarding and alighting passengers (blue and red bars) and average load (green line) at all time points during the peak period, EF33.

**Peak period- EF33 (Fridhemsplan)**

**Peak period- EF33 (Hötorget)**

**Peak period- EF33 (Värtavägen)**
The following figures show the average number of boarding and alighting passengers (blue and red bars) and average load (green line) at all time points during the peak period, FE31.
APPENDIX D – REGRESSION RESULTS

The regression results are presented below. They were done both for the peak period and the whole time period. Formula nr 1 in table D1 is the formula that was recommended in the thesis. The variables used in the regression formulas are defined using the following letters:

- I: Intercept (constant)
- A: Alighting
- B: Boarding
- L: Load
- DT: Dwell time (in seconds)
- δ: A dummy for load
- B(new): A dummy for load and boarding

Table D1. The results for the first 3 regressions based on A, B and L

<table>
<thead>
<tr>
<th>Nr</th>
<th>Description</th>
<th>Formula</th>
<th>R²</th>
<th>t-stat</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Boarding (B) and alighting (A) as x-variables</td>
<td>[ DT = 17.298 + 2.177 \cdot B + 0.874 \cdot A ]</td>
<td>0.464877</td>
<td>I: 115,0829</td>
<td>B: 81,2897</td>
</tr>
<tr>
<td></td>
<td>Adjusted:</td>
<td>[ DT = 17.298 + 2.177 \cdot B + 0.874 \cdot A ]</td>
<td>0.464767</td>
<td>I: 115,0829</td>
<td>B: 81,2897</td>
</tr>
<tr>
<td>2</td>
<td>Boarding (B), Alighting (A) and load (L) as x-variables</td>
<td>[ DT = 16,969 + 2,144 \cdot B + 0,862 \cdot A + 0,0207 \cdot L ]</td>
<td>0.456293</td>
<td>I: 88,43753</td>
<td>B: 73,23359</td>
</tr>
<tr>
<td></td>
<td>Adjusted:</td>
<td>[ DT = 16,969 + 2,144 \cdot B + 0,862 \cdot A + 0,0207 \cdot L ]</td>
<td>0.456129</td>
<td>I: 88,43753</td>
<td>B: 73,23359</td>
</tr>
<tr>
<td>3</td>
<td>Boarding (B), Alighting (A) and log(L) as x-variables</td>
<td>[ DT = 16,053 + 2,136 \cdot B + 0,861 \cdot A + 1,143 \cdot \log (L) ]</td>
<td>0.456536</td>
<td>I: 43,81504</td>
<td>B: 73,67205</td>
</tr>
<tr>
<td></td>
<td>Adjusted:</td>
<td>[ DT = 16,053 + 2,136 \cdot B + 0,861 \cdot A + 1,143 \cdot \log (L) ]</td>
<td>0.456472</td>
<td>I: 43,81504</td>
<td>B: 73,67205</td>
</tr>
</tbody>
</table>

Since Table D1 indicates that the effects of on-board passengers on dwell time were not linear it was tried to create a dummy variable for load. Two different dummies were created. They can be described in the following way:

\[
\text{Dummy A: } \delta(A)_n = \begin{cases} 
  1 & \text{if } (L - B) > n \\
  0 & \text{otherwise}
\end{cases}
\]

\[
\text{Dummy B: } \delta(B)_n = \begin{cases} 
  1 & \text{if } (L - B + A) > n \\
  0 & \text{otherwise}
\end{cases}
\]
R² shows the proportion of the variability in the data that the model accounts for. A model with a higher R² value is more likely to predict a more correct outcome. The R² was calculated for different values for n to find the optimum that gave the highest R². The results were potted in the following graph.

The highest R² was 0.4663 for n=71:

\[ \delta(A)_{71} = \begin{cases} 1 & \text{if } (L - B) > 71 \\ 0 & \text{otherwise} \end{cases} \]

Based on this results the formula was then further developed, by introducing a new variable into the regression:

\[ B(\text{new}) = \begin{cases} B & \text{if } (L - B) > 71 \\ 0 & \text{otherwise} \end{cases} \]

Using the three variables B, A and B(new) the highest R² was achieved, 0.4673. Detailed results for the regressions that gave the best results are listed in Table D2.
Table D2: Regressions with dummies

<table>
<thead>
<tr>
<th>Description</th>
<th>Formula</th>
<th>$R^2$</th>
<th>t-stat</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>The whole dataset (weekdays), without time points and terminals. Without values when there is no boarding or alighting</td>
<td>$DT = 17,274 + 2,175 \cdot B + 0,871 \cdot A + 6,561 \cdot \delta(A)_{71}$</td>
<td>0,466328</td>
<td>81,31923</td>
<td>33,64498</td>
</tr>
<tr>
<td>Boarding [B], alighting [A] and dummy A [$\delta(A)_{71}$] as x-variables</td>
<td>Adjusted: 0,466164</td>
<td></td>
<td>5,15181</td>
<td>6,7E-235</td>
</tr>
<tr>
<td>Boarding [B], alighting [A] and $B(new)$ as x-variables</td>
<td>$DT = 17,316 + 2,164 \cdot B + 0,869 \cdot A + 1,519 \cdot B(new)$</td>
<td>0,467346</td>
<td>80,81176</td>
<td>33,61127</td>
</tr>
<tr>
<td></td>
<td>Adjusted: 0,467182</td>
<td></td>
<td>6,727228</td>
<td>1,9E-234</td>
</tr>
</tbody>
</table>

All of the regression results imply that each boarding passenger has a higher effect on the dwell time than the alighting passenger. The regression that gave the highest $R^2$ implies that each boarding adds 2,164 second to the dwell time and each alighting passenger adds 0,869. In that regression the on-board load also affects the dwell time so that each boarding passenger additionally adds 1,519 seconds to the dwell if the on-board load is more than 71 passengers. However, it should be noted that the $R^2$ did not change much between the formulas presented in tables D1 and D2.

In addition to the regression analysis presented above, separate analysis was done for the peak period. The results are presented in table D3.
### Table D3: Regression analysis for the peak period

<table>
<thead>
<tr>
<th>Nr</th>
<th>Description</th>
<th>Formula</th>
<th>$R^2$</th>
<th>t-stat</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Boarding (B) and alighting (A) as x-variables</td>
<td>$DT = 18,270 + 2,141 \cdot B + 0,819 \cdot A$</td>
<td>0,523412</td>
<td>1: 53,19675</td>
<td>B: 0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Adjusted: 0,522953</td>
<td></td>
<td>0,2643</td>
<td>A: 17,32496</td>
</tr>
<tr>
<td></td>
<td></td>
<td>I: 0</td>
<td></td>
<td>B: 1,7E-262</td>
<td>A: 6,51E-63</td>
</tr>
<tr>
<td>2</td>
<td>Max(A,B) as an x variable</td>
<td>$DT = 18,662 + 1,857 \cdot \max(A,B)$</td>
<td>0,402326</td>
<td>1: 46,67502</td>
<td>B: 0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Adjusted: 0,400238</td>
<td></td>
<td>0,2038</td>
<td>A: Max(A,B): 1,5E-234</td>
</tr>
<tr>
<td>3</td>
<td>Boarding (B), alighting (A) and load (L) as variables</td>
<td>$DT = 17,894 + 2,113 \cdot B + 0,808 \cdot A + 0,018 \cdot L$</td>
<td>0,523787</td>
<td>1: 39,57742</td>
<td>B: 0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Adjusted: 0,523099</td>
<td></td>
<td>0,2428</td>
<td>A: 16,77379</td>
</tr>
<tr>
<td></td>
<td></td>
<td>I: 9,8E-256</td>
<td></td>
<td>B: 1,3E-228</td>
<td>A: 2,55E-59</td>
</tr>
<tr>
<td></td>
<td></td>
<td>L: 0,201206</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Boarding (B), alighting (A) and log(L) as x-variables</td>
<td>$DT = 17,105 + 2,113 \cdot B + 0,809 \cdot A + 0,968 \cdot \log(L)$</td>
<td>0,523807</td>
<td>1: 17,96992</td>
<td>B: 0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Adjusted: 0,523119</td>
<td></td>
<td>0,2351</td>
<td>A: 16,93018</td>
</tr>
<tr>
<td></td>
<td></td>
<td>I: 3,19E-67</td>
<td></td>
<td>B: 9,7E-230</td>
<td>A: 2,49E-60</td>
</tr>
<tr>
<td></td>
<td></td>
<td>L: 0,189879</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Boarding (B), alighting (A) and a dummy variable for load (δ) which can be</td>
<td>$DT = 18,278 + 2,136 \cdot B + 0,800 \cdot A - 0,967 \cdot δ$</td>
<td>0,523702</td>
<td>1: 53,2114</td>
<td>B: 0</td>
</tr>
<tr>
<td></td>
<td>described in the following way:</td>
<td>Adjusted: 0,523014</td>
<td></td>
<td>0,2643</td>
<td>A: 15,87795</td>
</tr>
<tr>
<td></td>
<td>δ =</td>
<td></td>
<td></td>
<td>B: 7E-260</td>
<td>A: 1,14E-53</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td>B: 0</td>
</tr>
<tr>
<td></td>
<td>if $(L - B + A) &gt; 0$</td>
<td></td>
<td></td>
<td></td>
<td>A: 0,26141</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Note: 55 is the normal number of seats in articulated buses (blue buses)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Dataset only with peak period, (and only weekdays) without time points and terminals. Without values when there is no boarding or alighting.