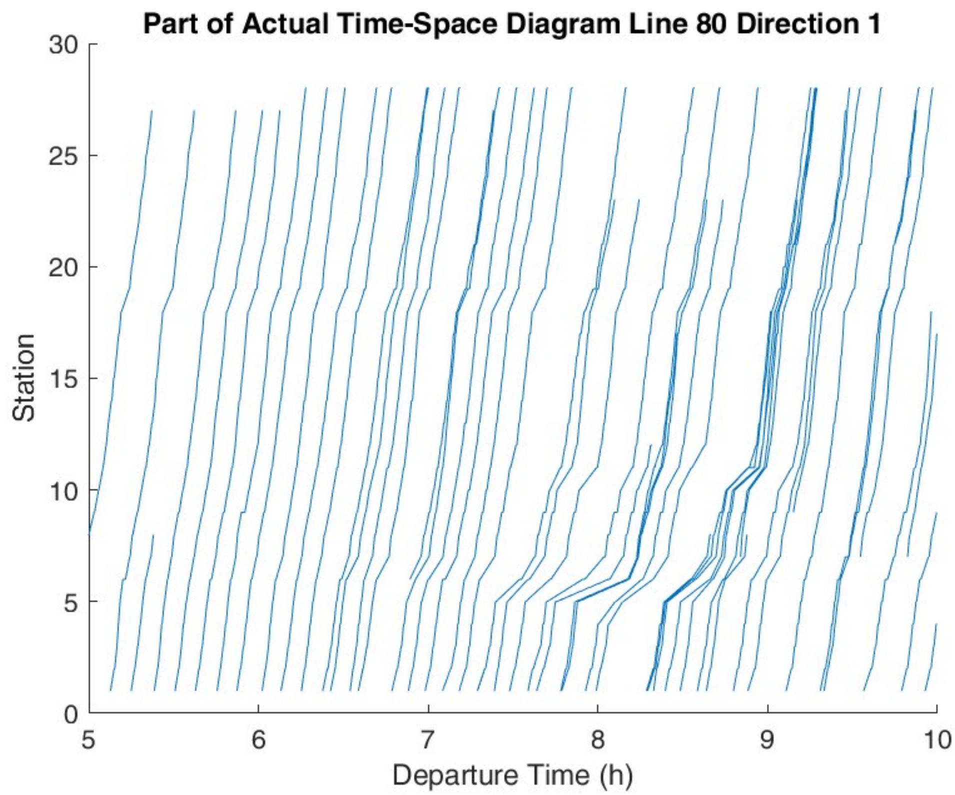

Bus bunching: the case of Zurich

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Projektarbeit M.Sc.

Civil Engineering M.Sc.

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Projektarbeit M.Sc.

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Abstract

Bus bunching can be a serious problem for many cities around the world, endangering the level of provided public transport services and consequently increasing dissatisfaction. The current project investigates the bus bunching phenomenon at the city of Zurich. The problem is identified by detecting and afterwards analyzing the most susceptible to bus bunching lines. Subsequently the potential causes of the problem are approached by measuring the delays in arrival and departure times, as well as the variation of alighting and boarding times at each station for the most suffering from bus bunching lines.

Keywords

Bus Bunching; Zurich; Delays

Preferred citation style

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1 Introduction

The provision of a high-level public transport is an index of highly developed cities. According to Ngoc et al. (2017) an efficient public transport system can contribute decisively to facing congestion, accident and pollution problems. Nevertheless, a public transport can face various problems that may endanger its efficiency. One of the most common such problems is bus bunching, where *"two or more buses of the same route arrive at the same time at a bus stop"* (Andres and Nair, 2017). Consequently, it can give rise to increased passenger dissatisfaction and to a possible switch to other transport modes.

Bus bunching situations can be triggered by various both external and internal processes. More specifically, the phenomenon can be attributed to shared infrastructure, likely to increase congestion, variations in the demand among different stations, and differences in the driving behavior of the people. The most common ways to deal with the problem include the adjustments on the timetable and the avoidance of ticket collection at the vehicle entrance and their replacement with smart cards (Corman et al., 2019).

One of the most usual causes for bus bunching, as already mentioned, is the variation of the demand at the stops along a line, translating into differences in the boarding and alighting time. Fonzone et al. (2015) studied the influence of boarding rates and arrival patterns on bus trajectories and headways investigating both cases, with or without the presence of additional delays. The passenger arrival at the stops was described by a utility function, which expresses the desire to minimize waiting time, while including the risk to miss a bus. For this purpose equations were derived to express the probability of boarding a bus, the expected waiting time and the passenger arrival distribution. Their analysis indeed highlights the presence of a strong correlation between these patterns and the headways.

Iliopoulou et al. (2020) have used two different algorithms to approach the phenomenon of bus bunching, where data from various lines in the city of Athens were analyzed. The first algorithm identified the spots with high occurrence of bus bunching and the spots where the problem starts and ends leading to a spatial and temporal clustering presented in corresponding maps. The second one defined different types of bus bunching, namely random, multi-line and systematic, according to the percentage of instances and the scheduled headways. Bunching between buses from different lines has also been investigated and clustered. Finally, suggestions for the handling of the problem alongside with their advantages and disadvantages were made based on the characteristics of each case.

The problem of bus bunching has also been studied for the city of Portland, Oregon by collecting data from Automatic Vehicle Location (AVL) and Automatic Passenger Count (APC) and extracting information, such as the headways of different lines (Jin et al., 2011). The aim of the aforementioned study was to identify the spatial and temporal spots of bus bunching along with its causes and consequences. The causes of the problem were listed and categorized according to whether the cause lies in the following or front bus and the respective percentages of occurrence were defined, showing that the most common causes were "*either the departure of the front bus from the previous station or the dwell time or passenger movement at the current stop*" (Jin et al., 2011).

An alternative approach of analyzing smart card data for detecting bus bunching was preferred by Fourie et al. (2016) for the case of Singapore. More specifically, aggregated smart card data records have been used to derive the demand and the public transport schedule to compose the supply. These comprised the input for a set of agent-based simulations, where different plans for the agents were introduced according to where the activities locations could be detected. From these simulations, information such as bus trajectories and public transport schedule were extracted and subsequently compared to the initial smart card data to identify their deviations. Once bus bunching was identified in the longest bus line of Singapore, a split of this line into two lines was proposed and considerable improvements in the trajectories and the waiting times were observed in the simulations.

Verbich et al. (2016) studied the interaction between buses running on the same corridor and how this in turn can affect bus bunching. Their analysis consists of two parts; the effect on dwell and running times and for this purpose data were collected and analyzed from AVL and APC in Oregon, Portland. More specifically, they investigated the time impact of varying from the scheduled dwell and running times on following buses in both the cases of vehicles from the same and different lines. This study included also the influence of various factors, e.g. the place of a stop and whether a station provides a shelter on the dwell and running times.

In order to face the problem of bus bunching a great variety of technological means is available, which are part of the Intelligent Transportation Systems (ITS). Iliopoulou and Kepaptsoglou (2019) propose applications of such technologies and present the respective benefits in strategic, tactical and operational level. Examples of such strategies are the optimization of the timetable and the suitable design of the network and the transfer points. Afterwards, they suggest how those can be implemented in real-time operations. The AVL and APC, which are mentioned above and used in a couple of papers are examples of ITS.

Another approach for facing bus bunching suggests the use of hybrid model predictive control (Sirmatel and Geroliminis, 2018). Hybrid implies the use of both continuous and discrete variables to describe a system. The introduced controller aims to regularize spacing and accelerate bus operation. This can be achieved through predicting passenger flows and adjusting speed and waiting times in real time. Afterwards, their performance is also compared to this of Integral (I-) and Proportional Integral (PI-) controllers, which regularize the bus headways according to the spacing error or the spacing error and its rate of change computed respectively and it is shown that the service time will be decreased, whereas headway regularity will be increased.

Moreover, Schmöcker et al. (2016) propose an alternative handling of the problem by studying bus bunching for the case of a corridor that is being served by two different lines. Variables such as demand, delays, dwell times and queues' propagation were described analytically. Different models of lines running on the same route have been examined based on the percentage of users that can be served by more than one line and whether overtaking is possible for two buses. Through their study they showed how lines running in shared corridor, even for a few stops, can contribute to the mitigation of bus bunching and how further delay decrease can be achieved by enabling bus overtaking.

Apart from schedule-based proposals for mitigating the problem, dynamic ones have also been made. For instance, Daganzo (2009) has proposed the formulation of dynamic holding times. As holding times the writer defines "*the slack into their schedules to guarantee that buses can meet the target travel times*". In addition to that, dynamic ones will be calculated according to real-time headway information and control in order to hamper problems from growing larger by adjustments i.e. on their speed, headway or stopping points. The analysis was executed using dynamic equations that describe the schedule and the suggested control and its efficiency was proved to be of high value.

Smart card data have also been used to identify and deal with the problem by Yu et al. (2016), who analyzed transit smart card data from the city of Beijing and created an algorithm in order to investigate bus bunching by predicting the headways and comparing them with the actual ones by measuring indexes, such as the Root Mean Square Error and proving a very high convergence. The variability of boarding and alighting time was also taken into consideration. This method can be of high utility for passengers by providing them with information about actual running times or overcrowded vehicles.

The goal of the current project is to study the phenomenon of bus bunching in the city of Zurich. Different lines are investigated by utilizing data publicly available by the Verkehrsbetriebe Zürich (VBZ)[1]. The data include information about planned and actual arrival and departure times, stops and stations and the trip IDs for all the bus lines in Zurich. The data used were for the year 2019. Subsequently, the data are analyzed to detect the hotspots of the problem, i.e. the stations and the hours of the day, when bunching is more often and stations, from where bunching starts or ends. Furthermore, the connection between bus bunching and alighting and boarding time variations along the day is investigated. The entire public transport network of Zurich is shown in Figure 1.1.

[1] https://data.stadt-zuerich.ch/dataset/vbz_fahrzeiten_ogd

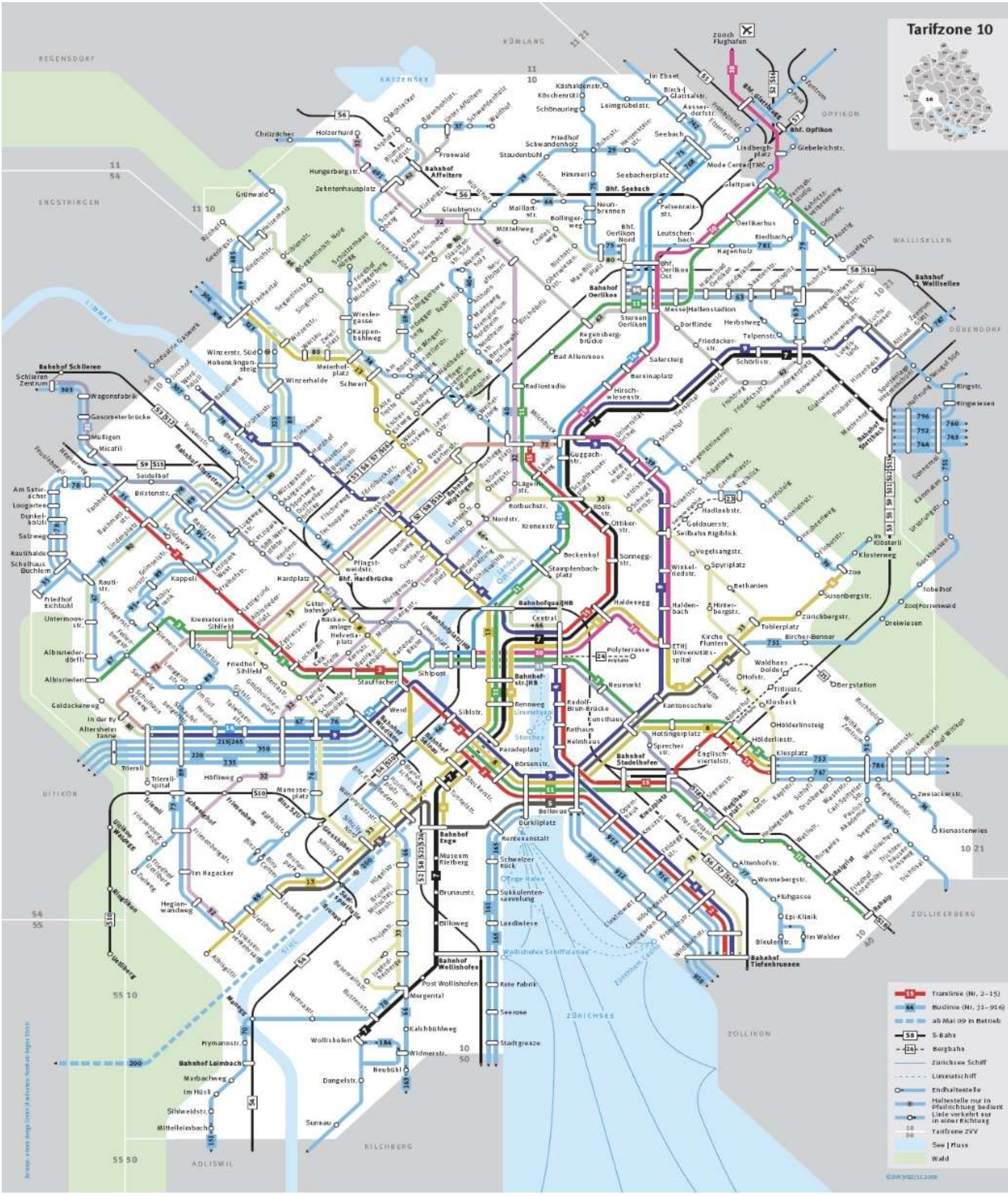

Figure 1.1: Public transport network of the city of Zurich

2 Problem Identification

The first of the investigation of the problem of bus bunching in the city of Zurich started with the identification of the problem. The aforementioned data were analyzed for a number of lines and for both directions for 3 months to investigate the variation the seasonal variation. The months decided to investigate were January, July and November. These 3 months were chosen in order to have one month with high possibility of snow and bad weather conditions, leading to increased mobility needs, one month with closed schools, universities and perhaps some businesses, implying lower demand and one month with open schools and universities and milder weather conditions. It must be mentioned that a service day is considered from 5 am until 1:30 pm the next day.

The number of lines to be investigated was chosen in order to include all the lines crossing the center of Zurich. Moreover, for every set of lines leading to a decentralized hub, one line was included in the analysis. The lines that were investigated were the following: 31, 32, 33, 40, 46, 61, 69, 72, 75, 80, 89, 94, 161 and 751. The data for the above lines were aggregated and the bus bunching instances for 4 weeks duration were defined. The bus bunching instances were firstly defined at a stop level, i.e. considering for each stop the total number of arrivals. As bus bunching the case where two buses of the same route arrive at a station with a time difference of less than or equal to two minutes. The graphs derived from this include graphs showing the total number of bus bunching instances at each station, where at least one line of the above passes (Figure 2.1 & Figure 2.2) and graphs showing the total number of bus bunching instances at each station divided by the total number of arrivals at each station, i.e. the percentage of bunching buses (Figure 2.3 ÷ Figure 2.8). More indicative for the problem are obviously the graphs with the percentages of bus bunching instances.

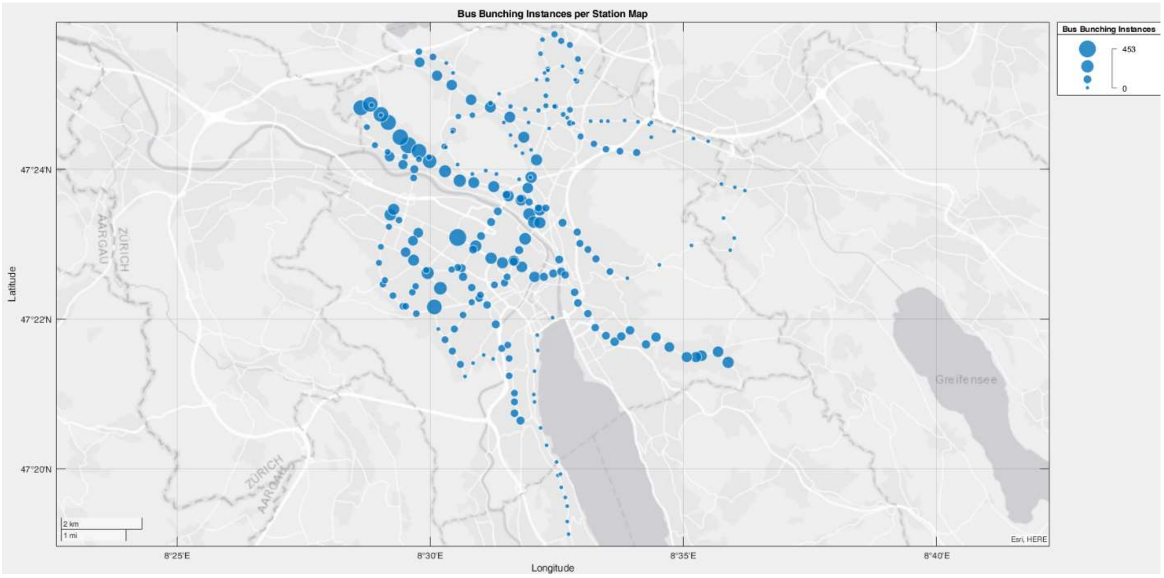

Figure 2.1: Bus Bunching Instances, January, Direction 1

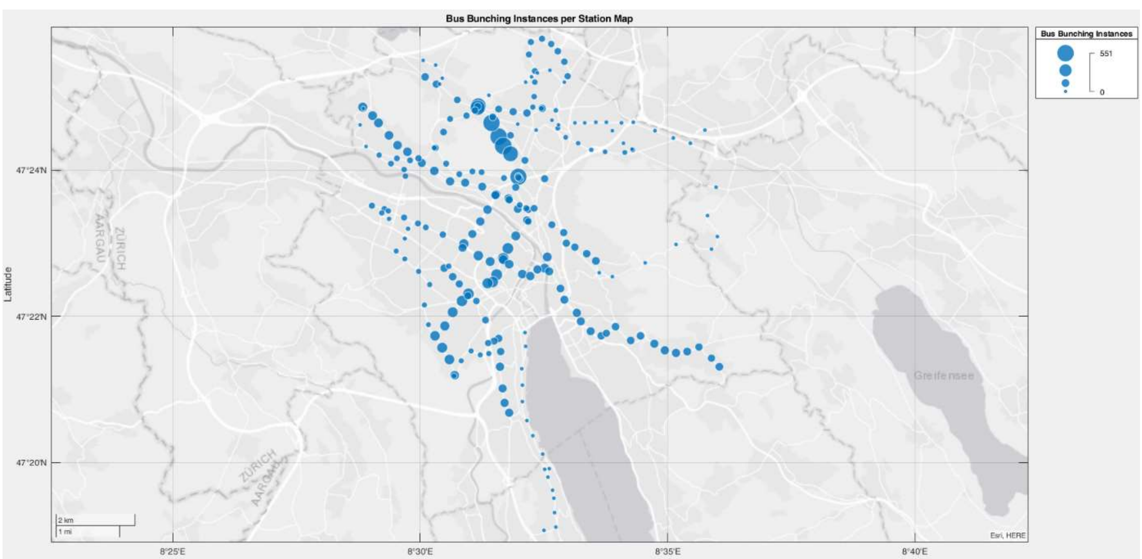

Figure 2.2: Bus Bunching Instances, January, Direction 2

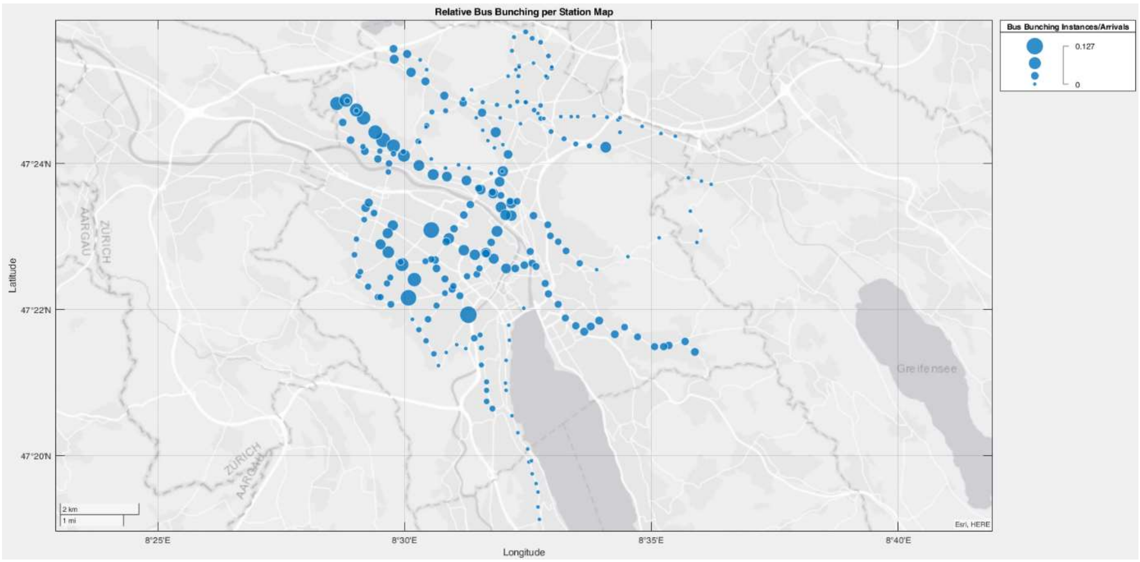

Figure 2.3: Bus Bunching Percentages, January, Direction 1

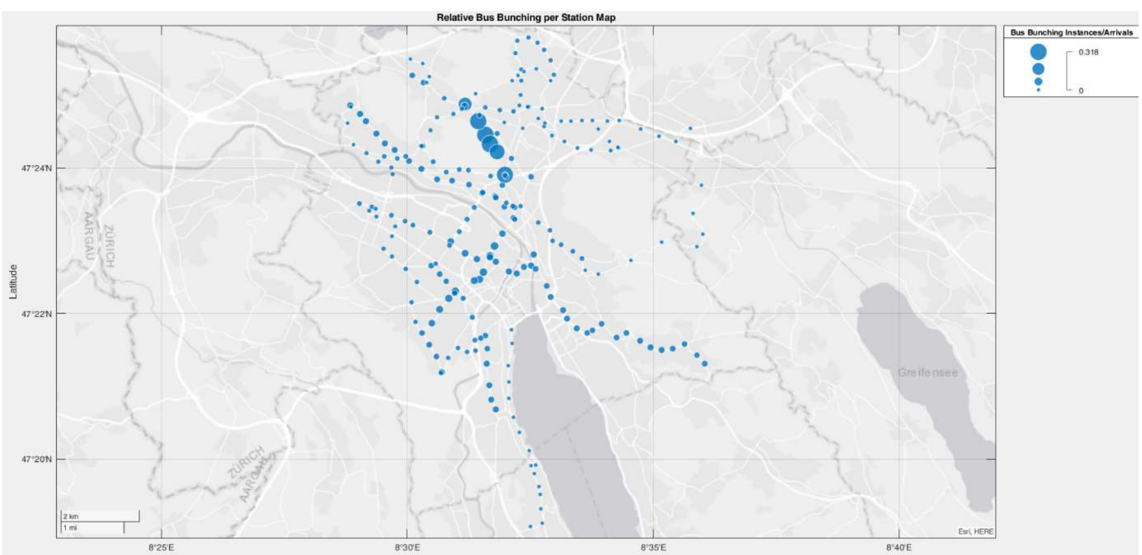

Figure 2.4: Bus Bunching Percentages, January, D2

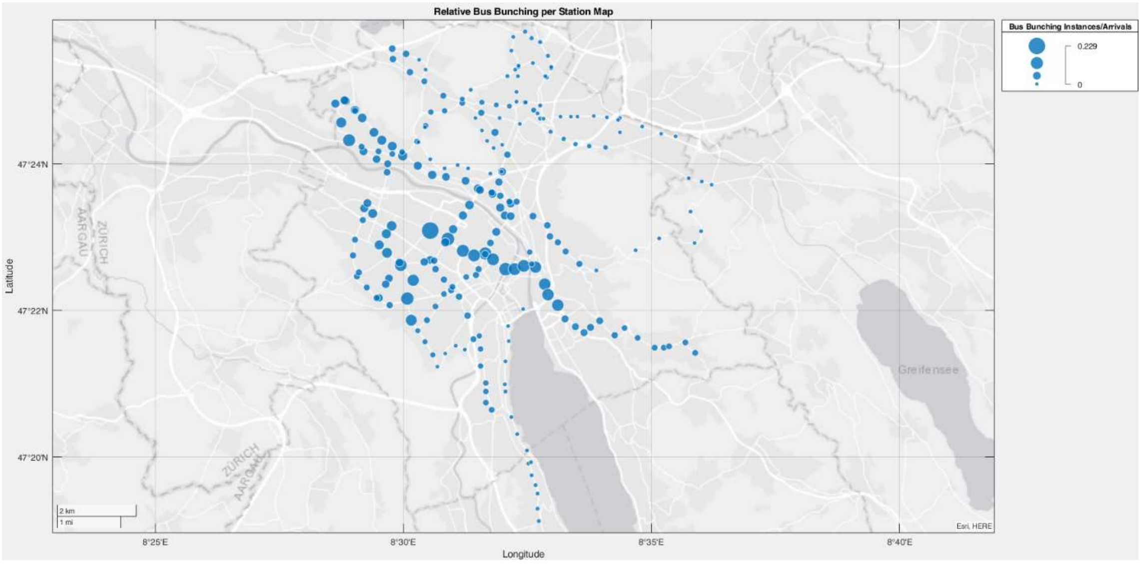

Figure 2.5: Bus Bunching Percentages, July, D1

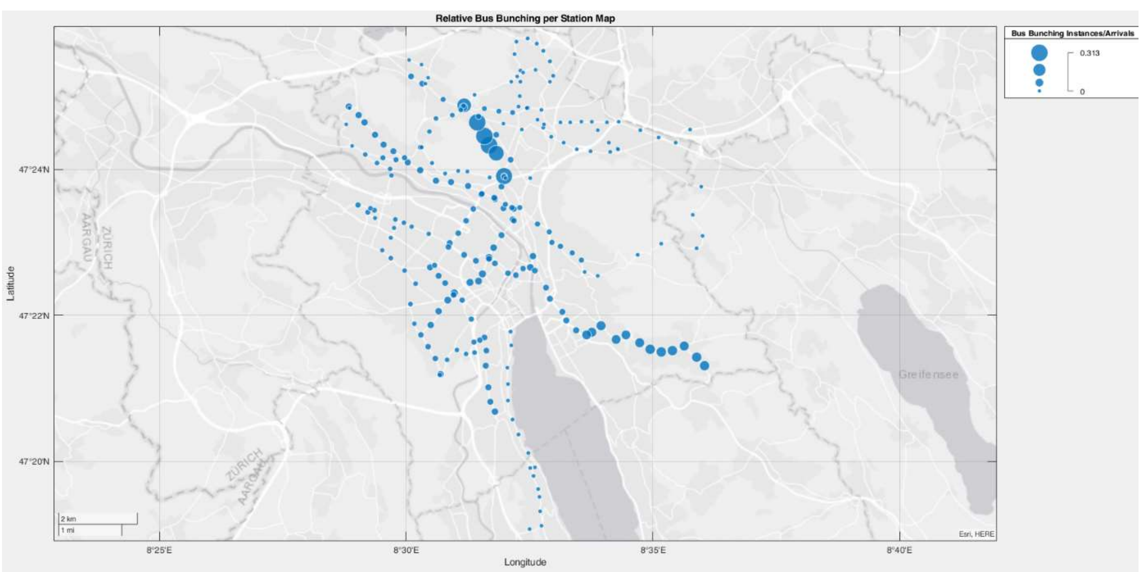

Figure 2.6: Bus Bunching Percentages, July, D2

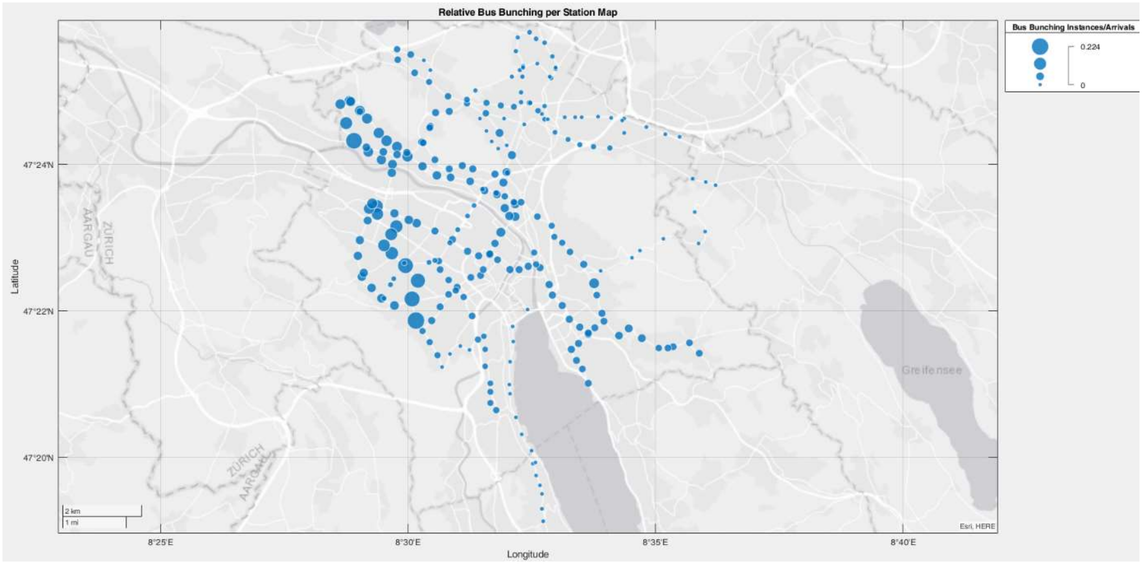

Figure 2.7: Bus Bunching Percentages, November, Direction 1

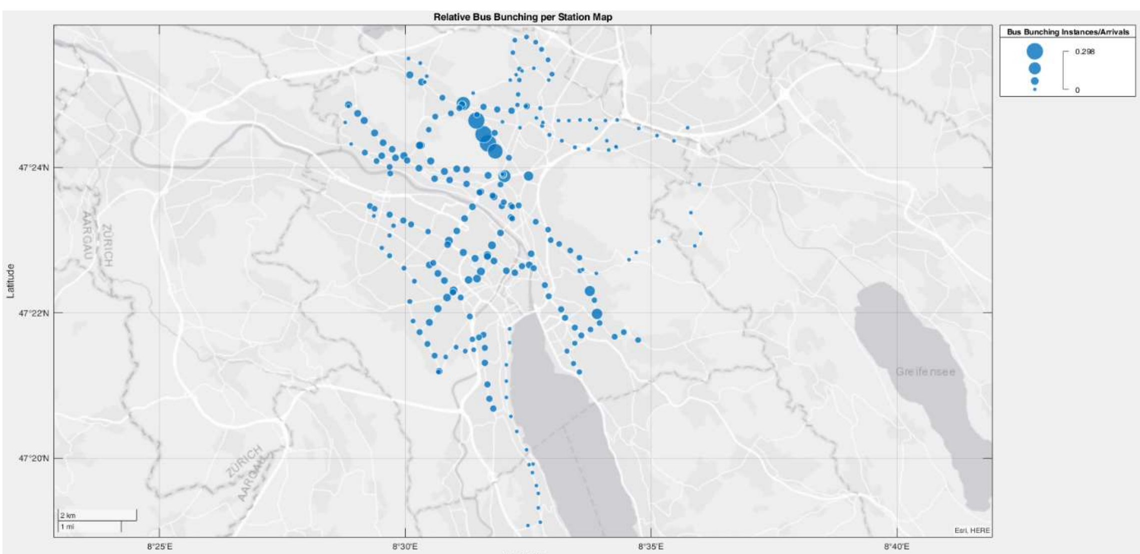

Figure 2.8: Bus Bunching Percentages, November, Direction 2

From the above graphs it can be noticed that the lines leading to decentralized hubs show no or negligible bus bunching. On the contrary, lines crossing the city center or other critical stations show much higher percentages of bus bunching. Therefore, for the next step of the analysis the lines that were chosen were the ones with more intense bus bunching problems and more specifically the more central ones, i.e. lines 31, 32, 33, 46, 69, 72 and 80. The following graphs (Figure 2.9 ÷ Figure 2.14) show the bunching instances for these lines as well as the percentage of bunched services, relative to the total amount of arrivals of the specific line at each station. From Figure 2.1 ÷ Figure 2.8 it is clear that differences can be pointed for the different months of the year related to weather conditions and demand variations. It is worth also noting that the bunching scheme, i.e. the frequency and the stations suffering the most, is not the same for the two directions, a fact attributed to demand differences.

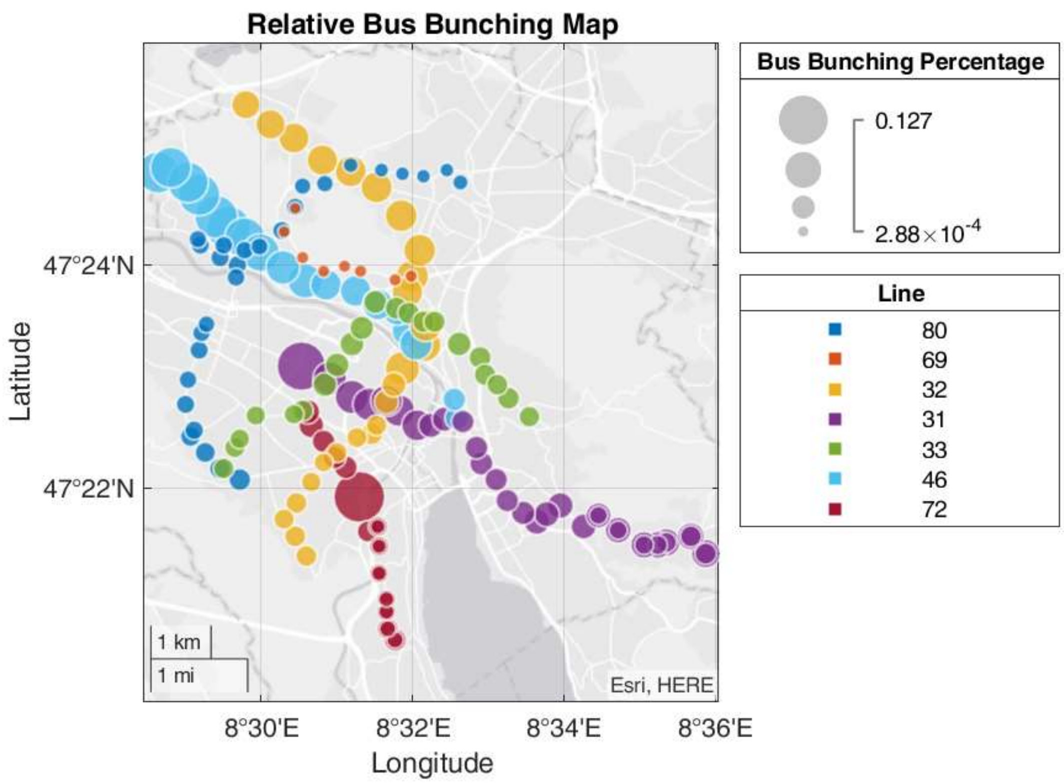

Figure 2.9: Bus Bunching Percentages per line, January, Direction 1

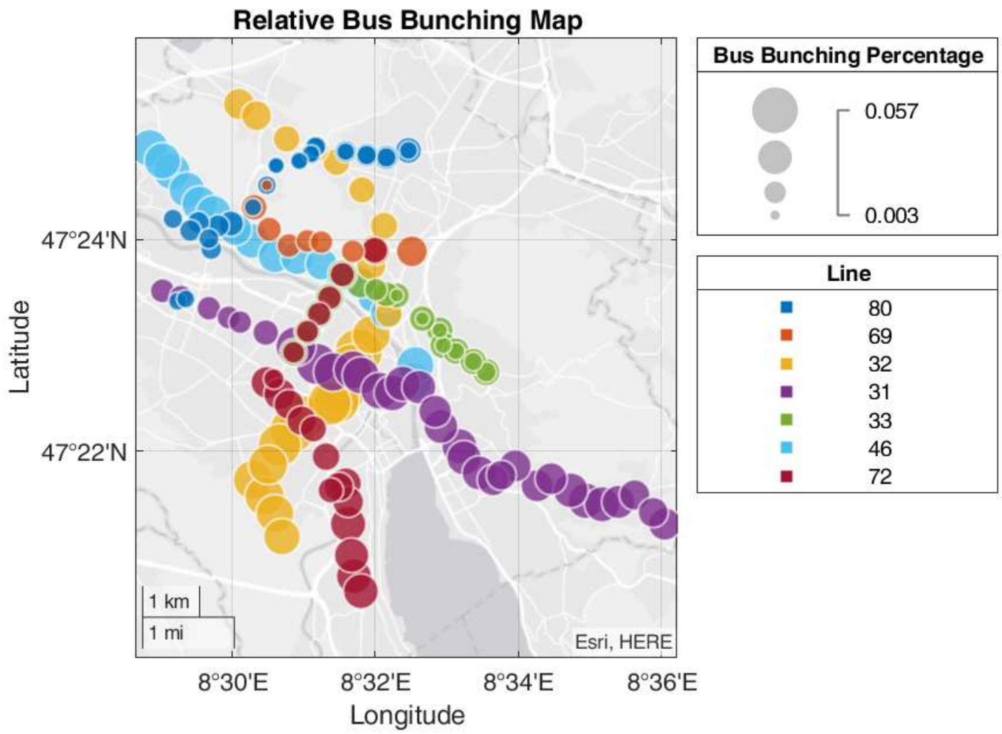

Figure 2.10: Bus Bunching Percentages per line, January, Direction 2

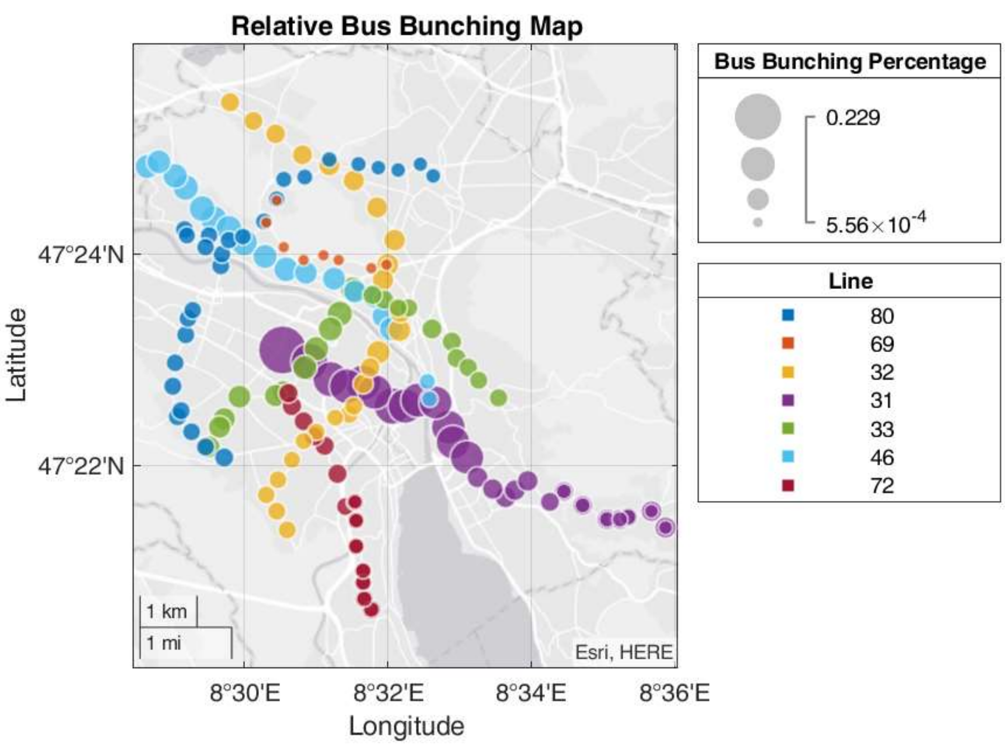

Figure 2.11: Bus Bunching Percentages per line, July, D1

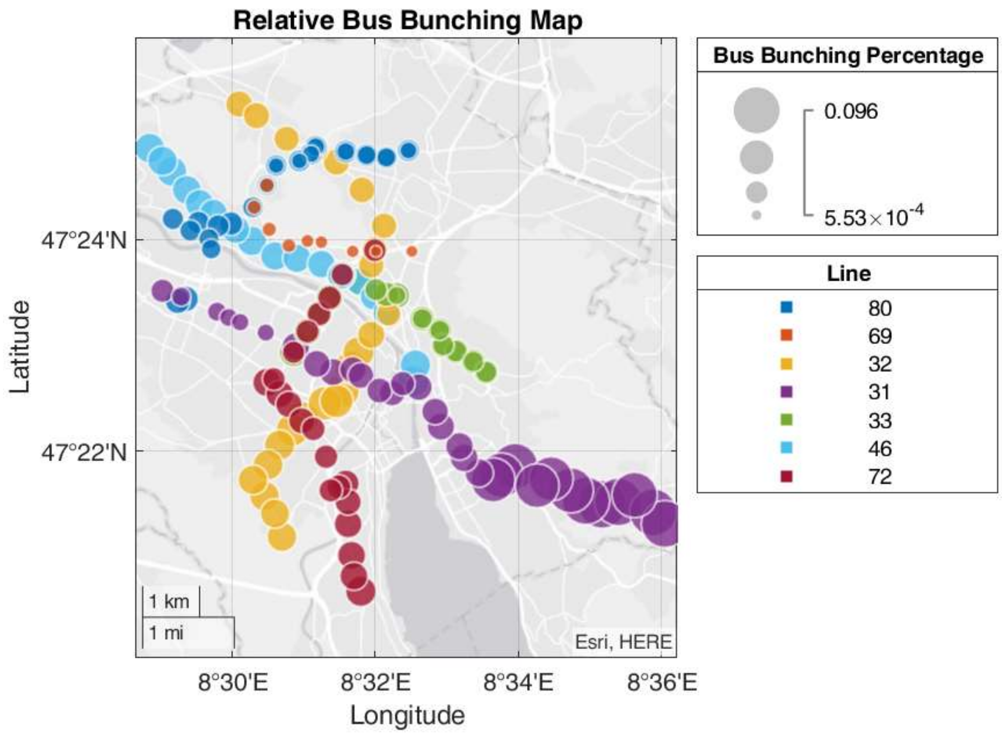

Figure 2.12: Bus Bunching Percentages per line, July, Direction 2

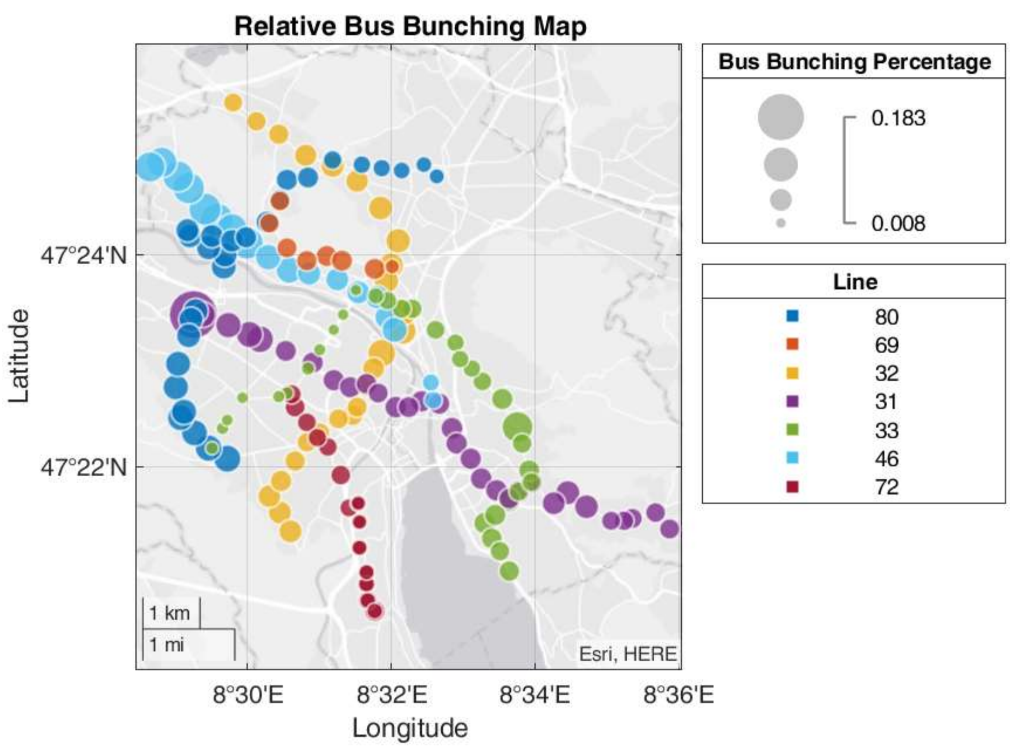

Figure 2.13: Bus Bunching Percentages per line, November, Direction 1

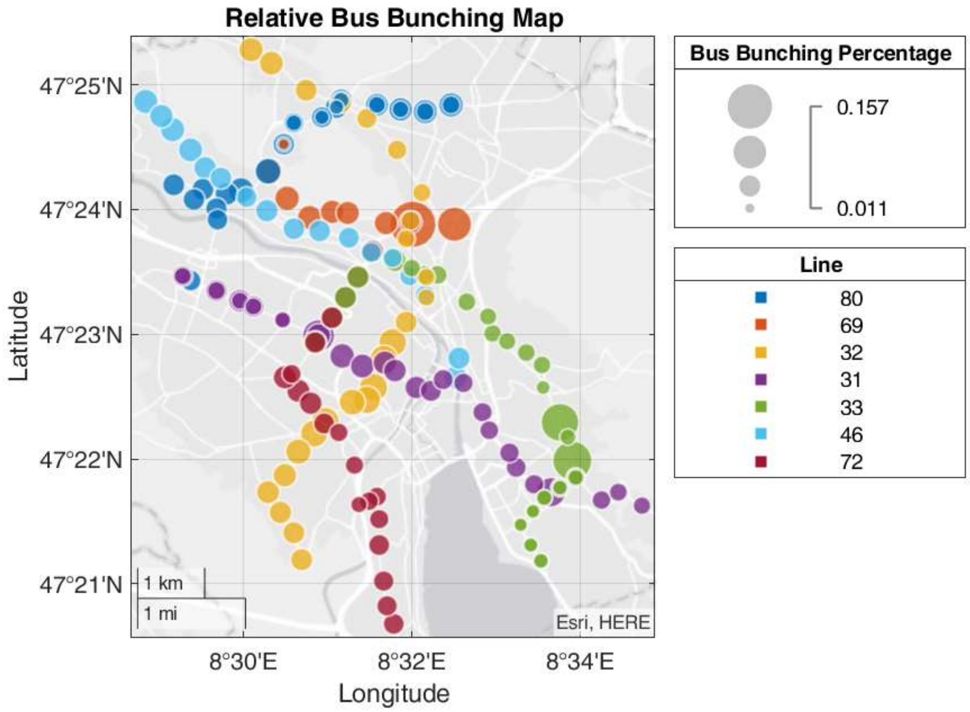

Figure 2.14: Bus Bunching Percentages per line, November, Direction 2

As detected from Figure 2.9 ÷ Figure 2.14 the lines suffering from bus bunching seem to be lines 31, 32 and 33. Intense problems are also detected for lines 69 and 80. It must be underlined that lines 31, 32 and 33 cross the center of the city. Line 80 is a line with a quite high number of stations (28) and thus quite interesting to investigate. On the contrary line 69 has only 12 stations and the increased bunched percentage of bus renders it to a very interesting case.

For these lines graphs were plotted with the mean and the standard deviation of the arrival and the departure delay, i.e. the average delay and the deviation from the average delay, in order to investigate the evolution of the phenomenon along the route (Figure 2.15 ÷ Figure 2.20). The months and directions that have been decided to be plotted were the ones with the most acute bus bunching phenomena observed. It can be noticed that the values are approximately equal for July and November and lower for January, although January could have been expected to have higher delays due to bad weather conditions. A possible reason for that can be lower mobility due to bad weather conditions. Moreover, it is remarkable that the mean values of the delays seem to increase at the sequence of the stops, whereas the standard deviation remains almost constant.

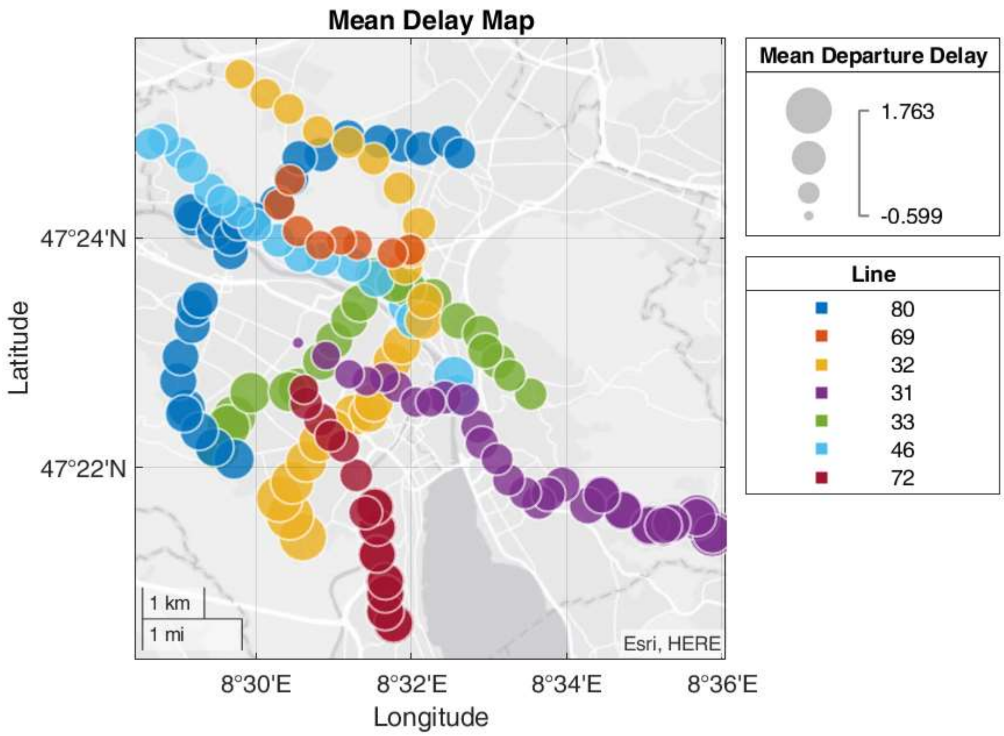

Figure 2.15: Mean Departure Delays Map, January, Direction 1

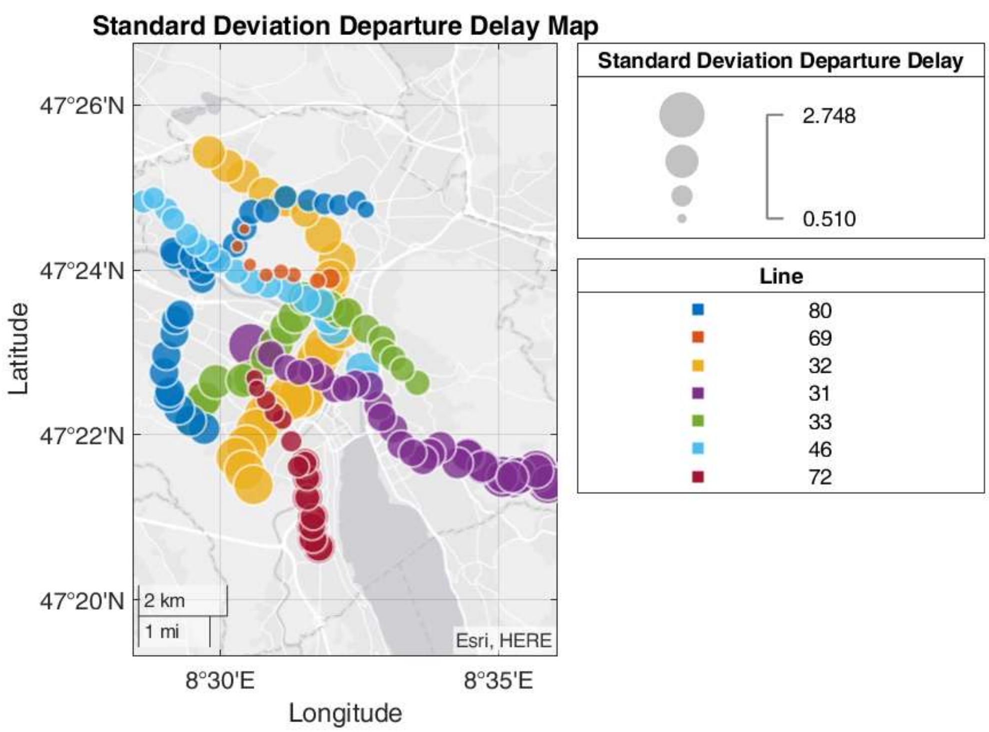

Figure 2.16: Standard Deviation Departure Delays Map, January, Direction 1

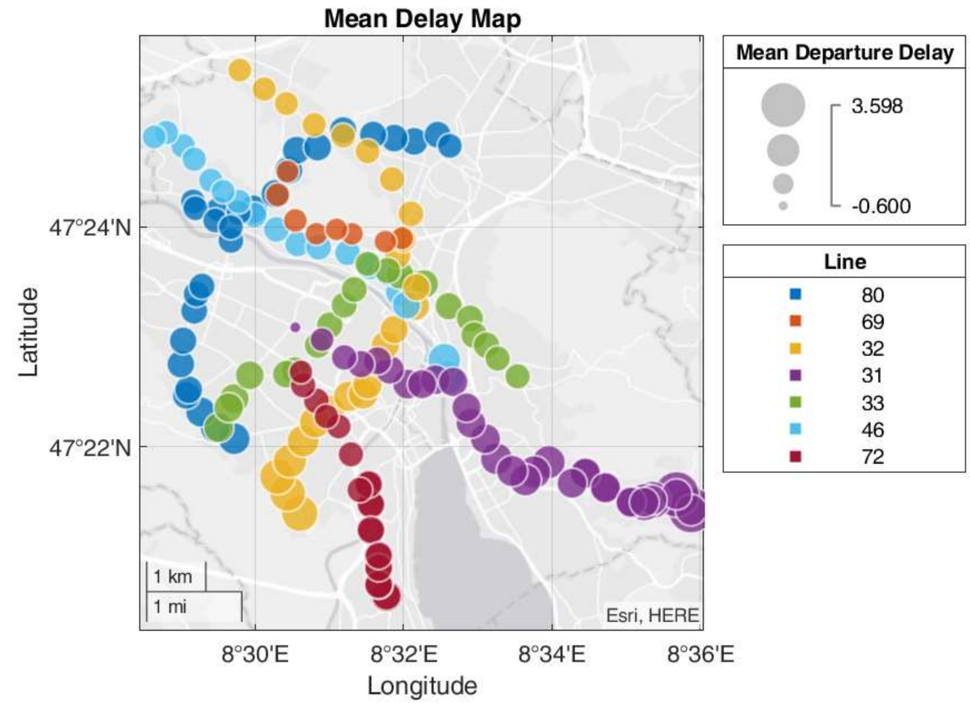

Figure 2.17: Mean Departure Delays Map, July Direction 1

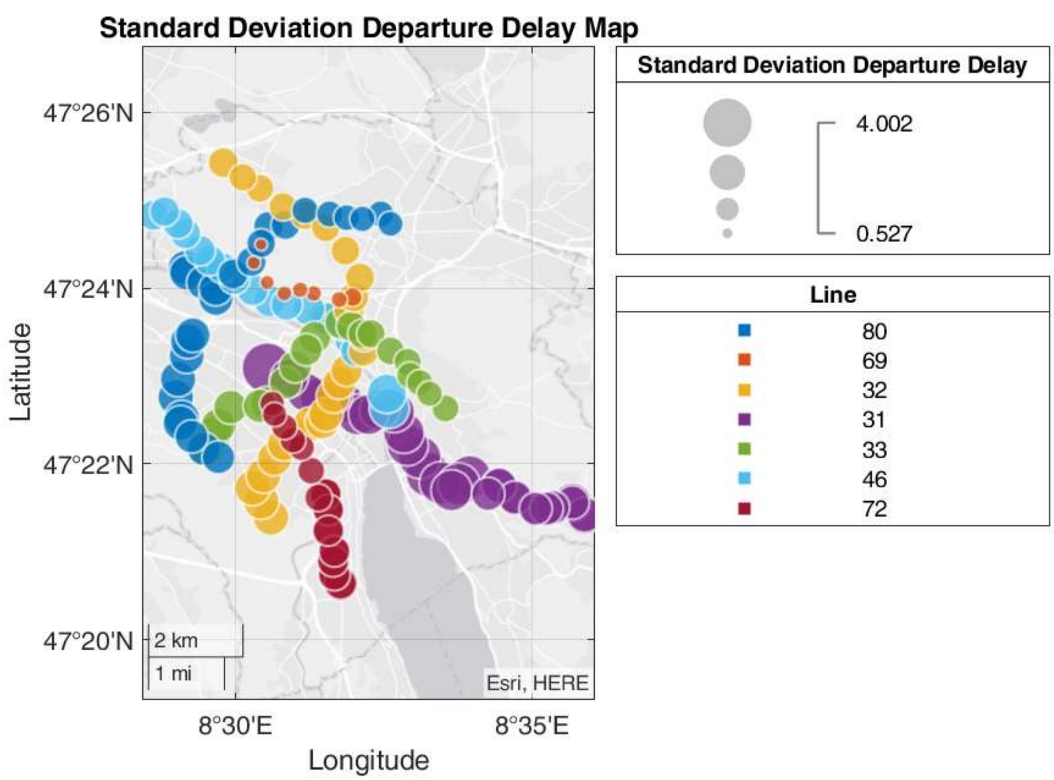

Figure 2.18: Standard Deviation Departure Delays Map, July, Direction 1

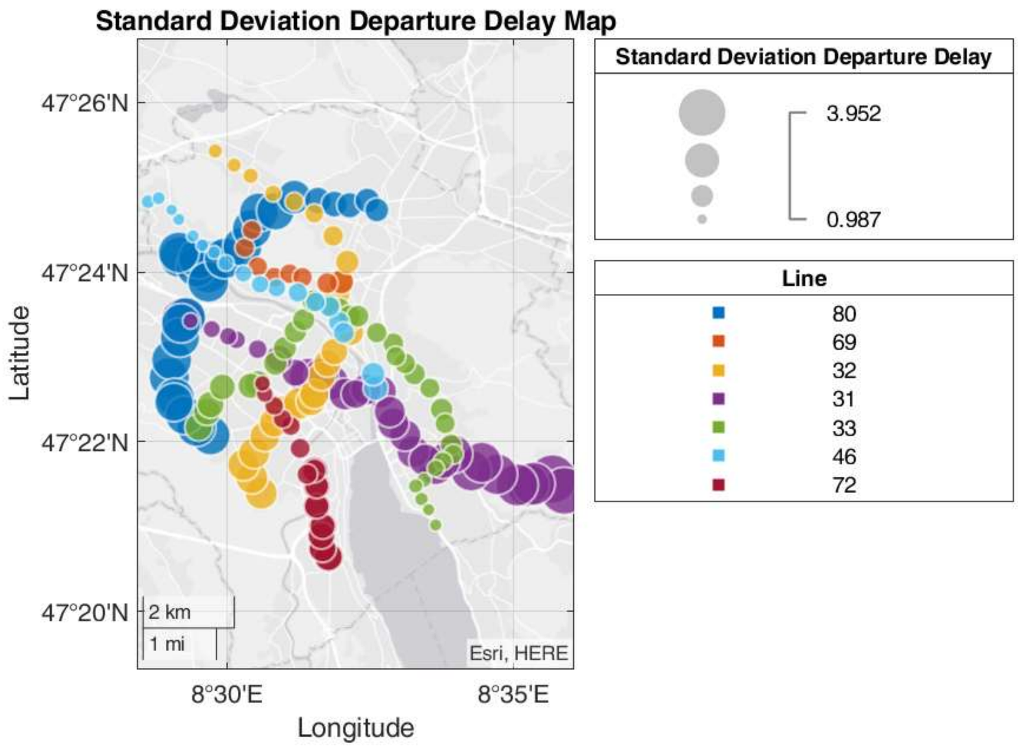

Figure 2.19: Standard Deviation Departure Delays Map, November, Direction 1

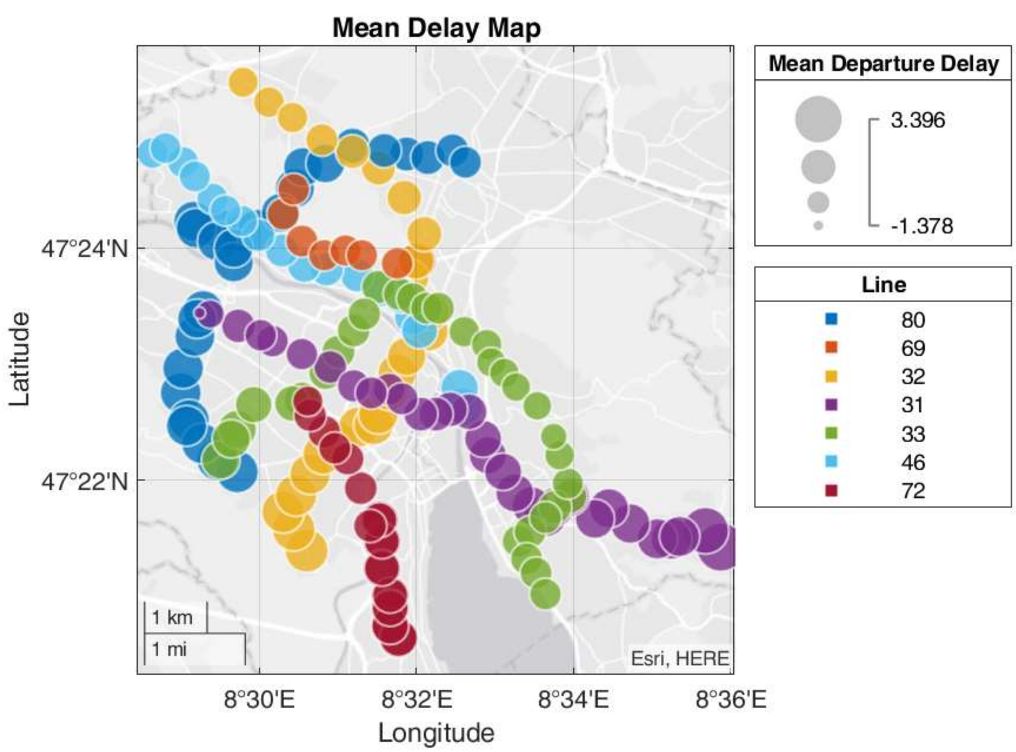

Figure 2.20: Mean Departure Delays Map, July Direction 1

The problem identification continued by concentrating on the most prone to bus bunching lines, for which the instances for all their stations were calculated by showing the differentiation if bunching is considered when two buses arrive with a time difference of less than or equal to two or three minutes (Figure 2.21 ÷ Figure 2.24). It can be seen that considering three instead of two minutes, which was the limit for the above graphs, can lead to almost double bunching instances per month. This increases the magnitude of the problem by showing how intense the delays are for these lines. All the following graphs are plotted for one of the three months: January, July or November, since not great differences exist. For comparison reasons plots of different months and directions for line 32 are placed in the Appendix (Figure A.1 ÷ Figure A.23).

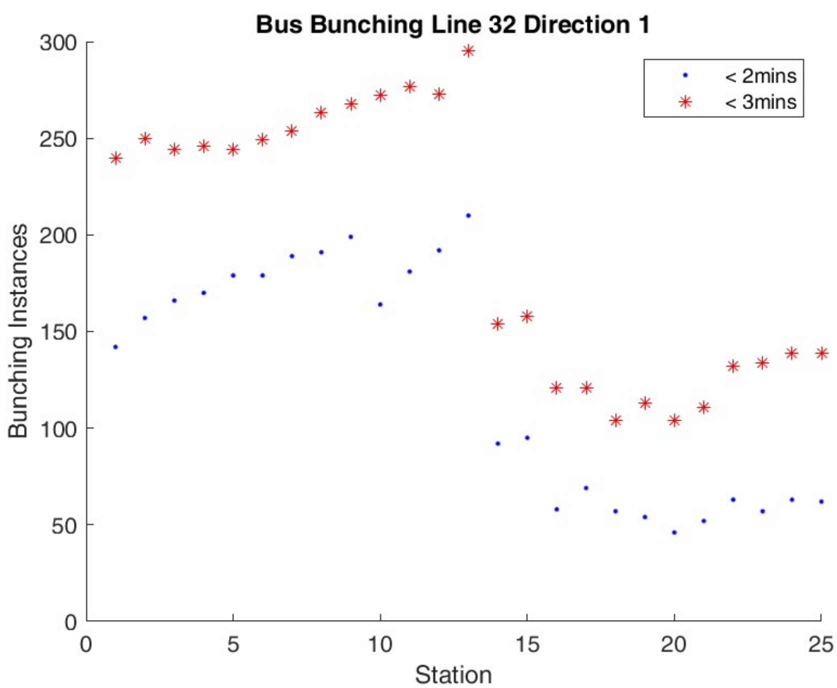

Figure 2.21: Bus Bunching Instances for 2 or 3 minutes difference, Line 32, Direction 1

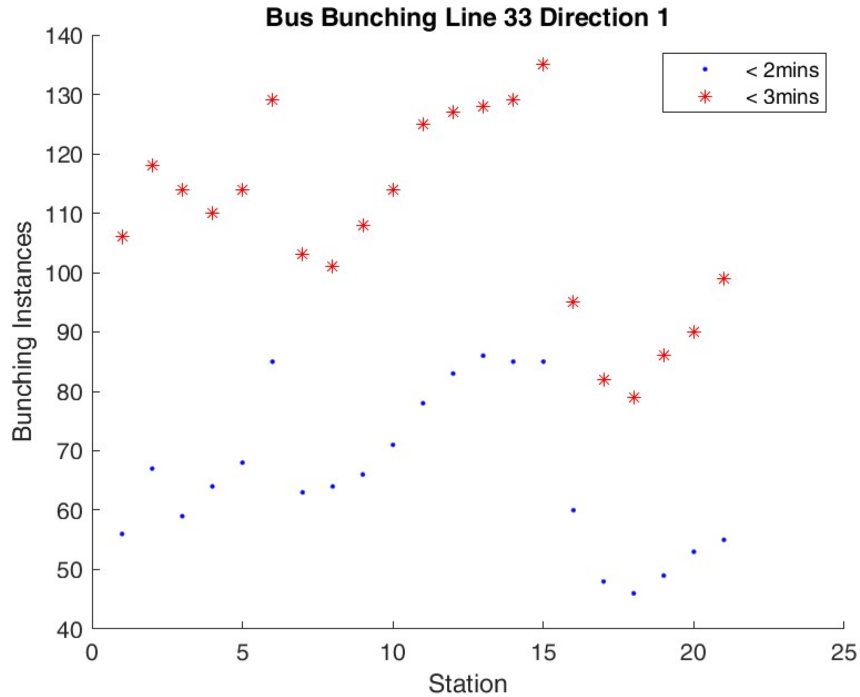

Figure 2.22: Bus Bunching Instances for 2 or 3 minutes difference, Line 33, Direction 1

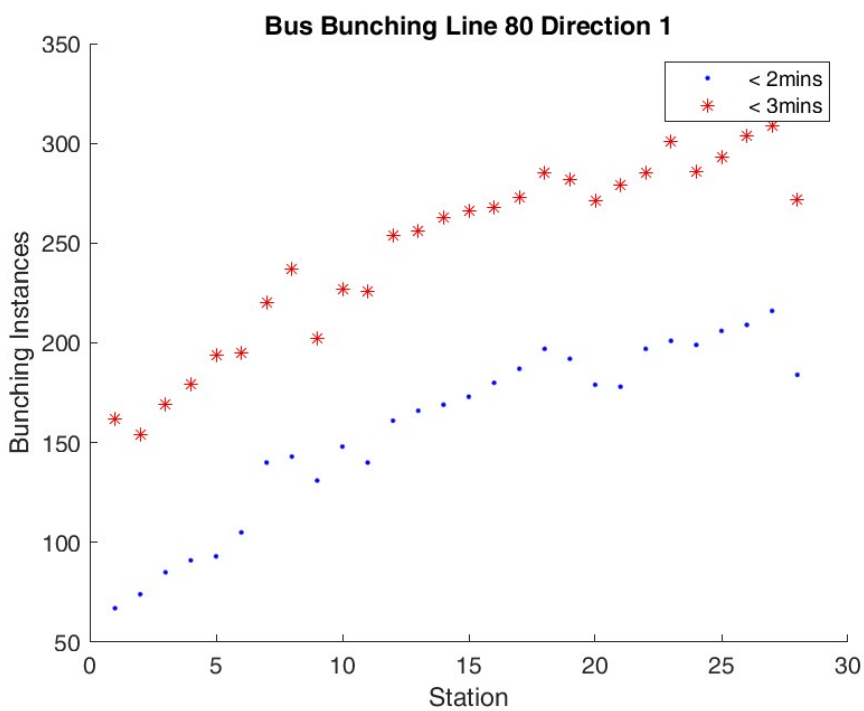

Figure 2.23: Bus Bunching Instances for 2 or 3 minutes difference, Line 80, Direction 1

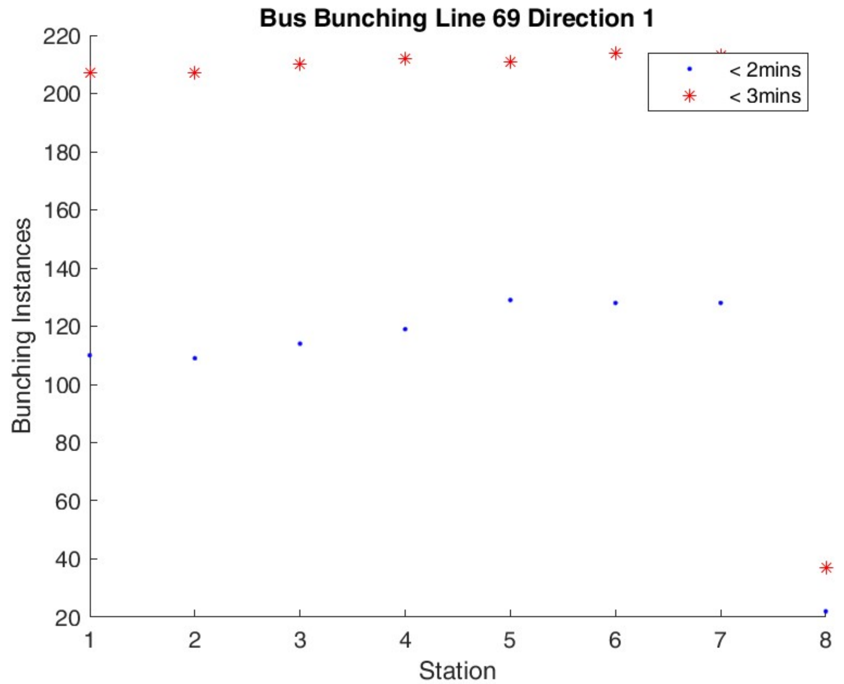

Figure 2.24: Bus Bunching Instances for 2 or 3 minutes difference, Line 69, Direction 1

Of high importance for the detection of the problem are also the time-space diagrams, showing for one day all the bunching buses and at which stops the phenomenon is more likely to begin and finish (Figure 2.25). A closer look at the morning peak hours of this graph can offer a better view to the problem (Figure 2.26 ÷ Figure 2.32). It is clear that throughout the day it can happen that two buses can travel in pairs for a part of the route or the whole route.

It should also be noticed that there are specific stations along the bus route where delays are more often, e.g. for line 32 this can be station 10 and for line 33 this can be station 12. Quite interesting is the fact that not all vehicles run the whole route, but they sometimes run only on a part of it usually the one with the highest demand and especially during the peak hours. This can be the explanation to various facts as for example to Figure 2.21, where the bunching instances show a sudden decrease at station 12. For comparison a time-space diagram has also been plotted for line 72, where bus bunching can also be observed but with a lower frequency. The following time-space diagrams are plotted for Thursday 10.01.2019 and Wednesday 06.11.2019.

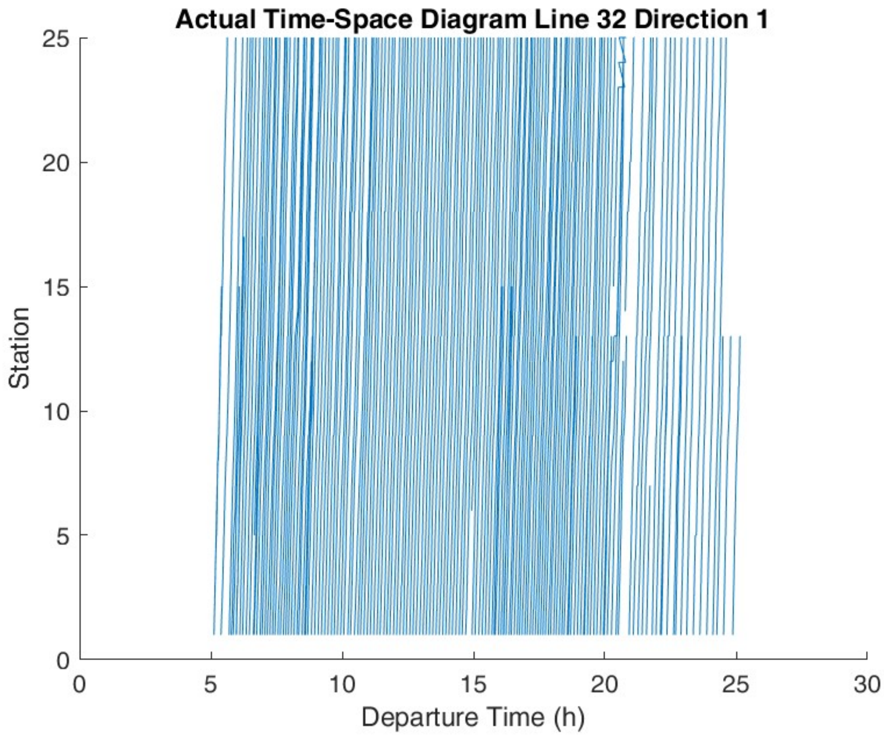

Figure 2.25: Actual Time Space Diagram, Line 32, Thursday 10.01.2019

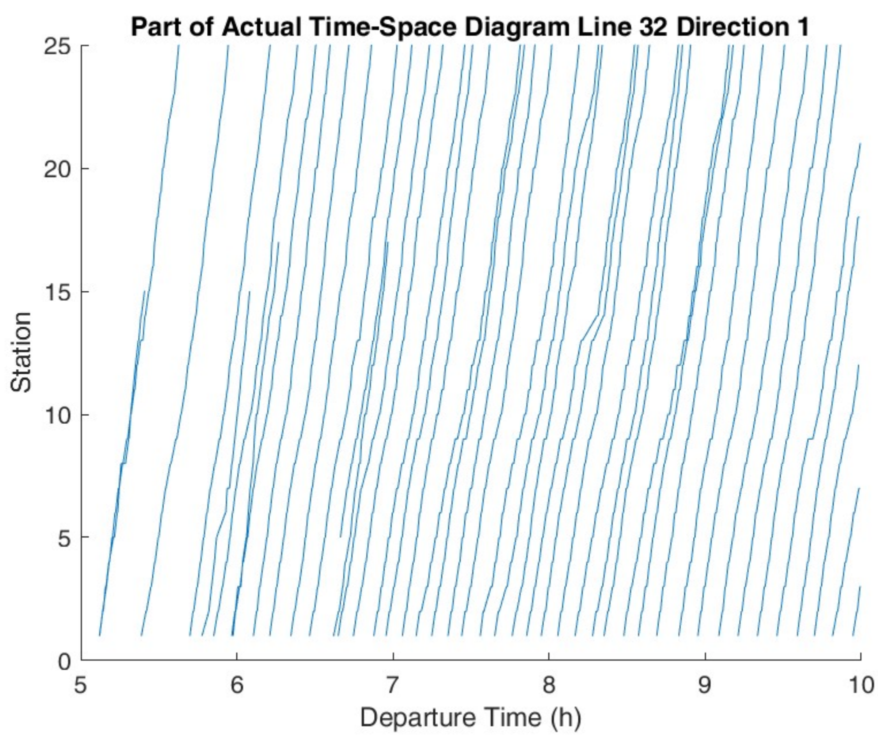

Figure 2.26: Part of Actual Time-Space Diagram, Line 32, Thursday 10.01.2019

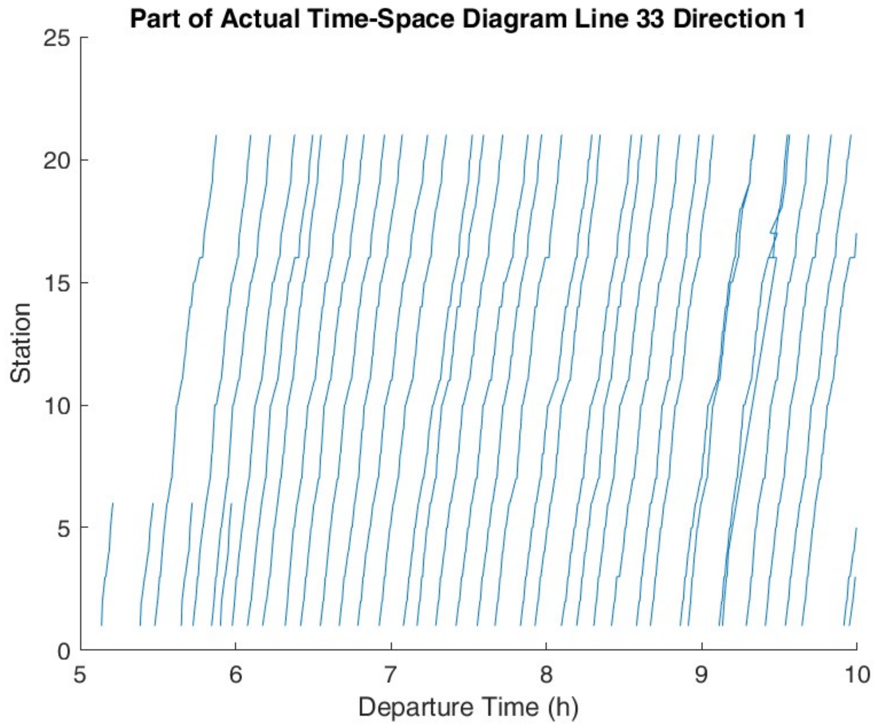

Figure 2.27: Part of Actual Time-Space Diagram, Line 33, Thursday 10.01.2019

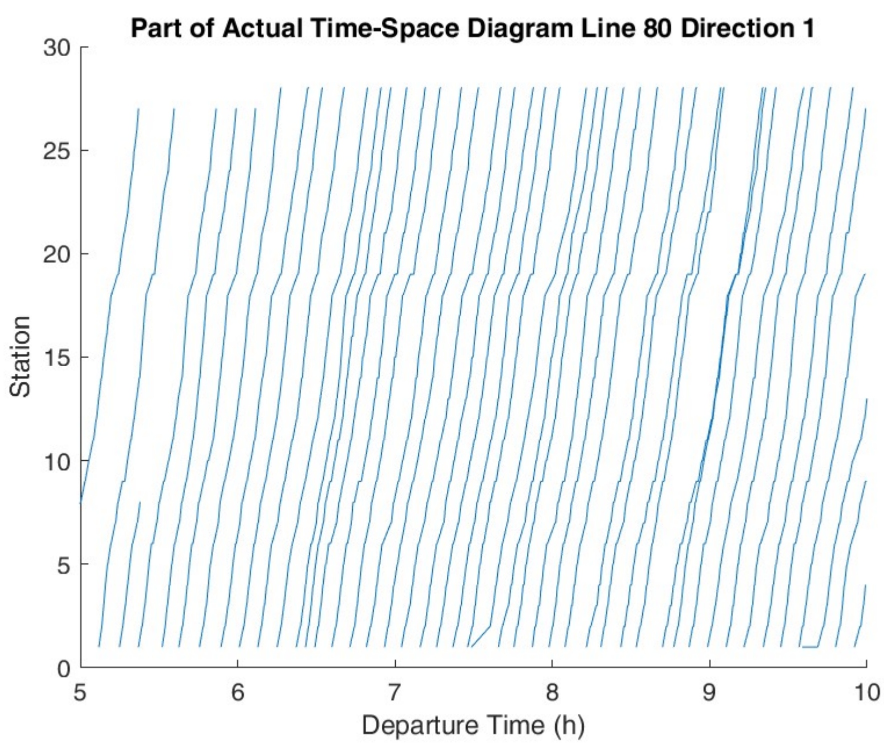

Figure 2.28: Part of Actual Time-Space Diagram, Line 80, Thursday 10.01.2019

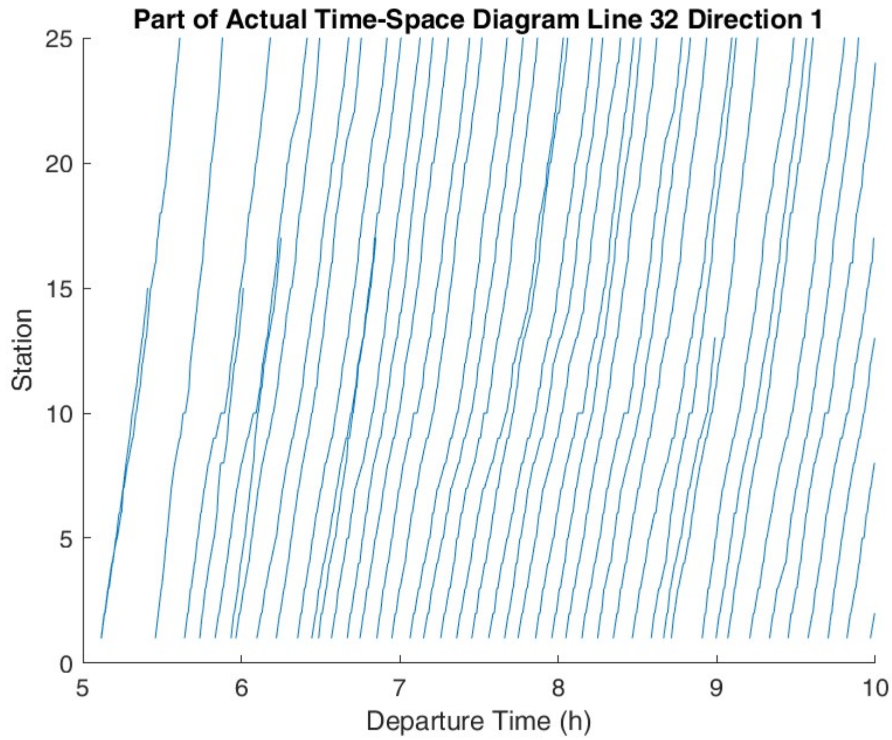

Figure 2.29: Part of Actual Time Space Diagram, Line 32, Wednesday 06.11.2019

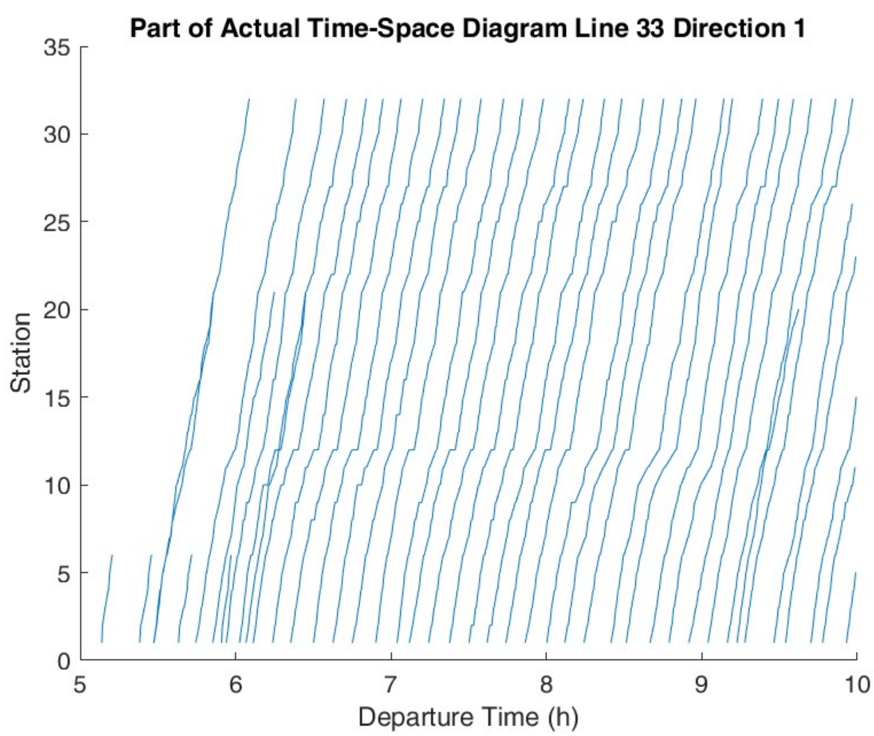

Figure 2.30: Part of Actual Time-Space Diagram, Line 33, Wednesday 06.11.2019

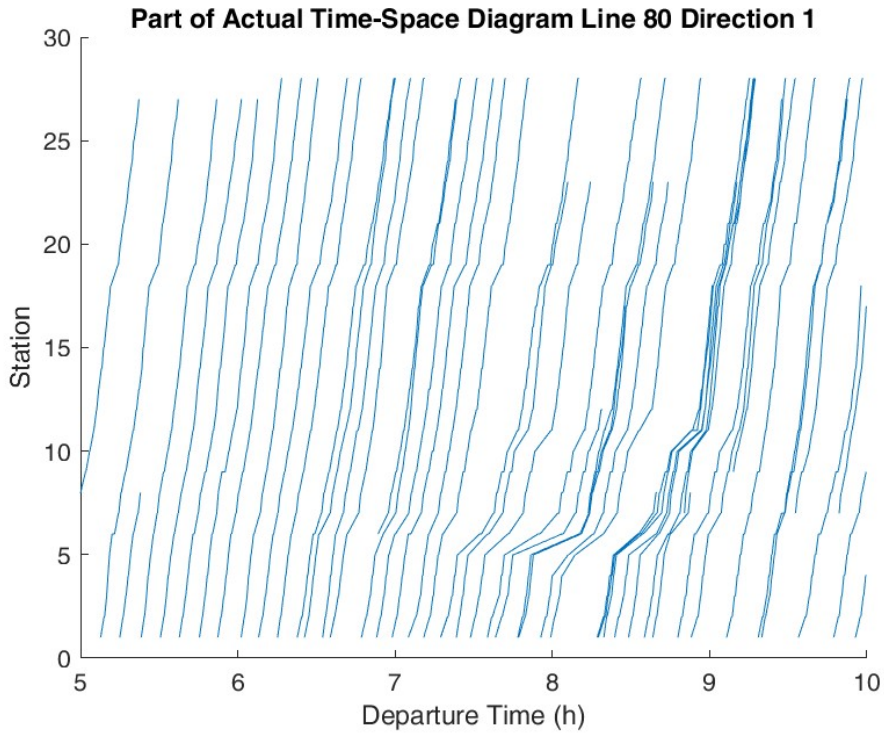

Figure 2.31: Part of Actual Time-Space Diagram, Line 80, Wednesday 06.11.2019

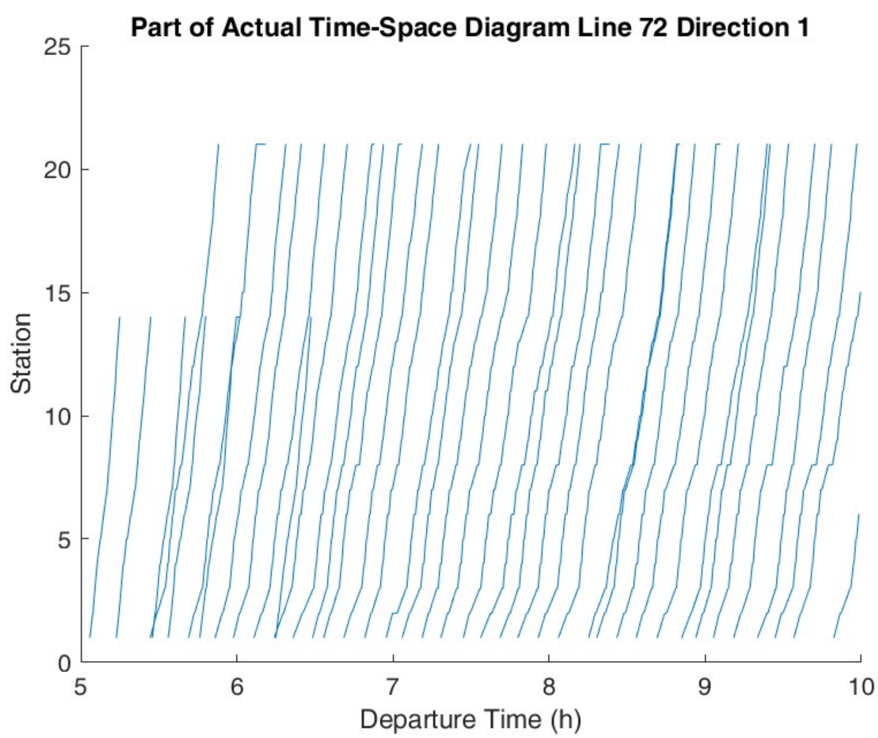

Figure 2.32: Part of Actual Time-Space Diagram, Line 72, Wednesday 06.11.2019

The deviation of the planned and the actual headways was afterwards illustrated. Box plots presenting the relative deviation, namely the aforementioned difference divided by the actual headway were plotted for each station (Figure 2.33 ÷ Figure 2.37). It should be noticed here that, although increasing deviations can be expected along the bus route, this is not necessarily always the case. The deviations are apparently more intense for long rather than short lines, which can be understood when comparing the graphs for lines 32 and 80 with this for line 69. A possible reason for this observation are delays being accumulated along the bus stops. All the diagrams refer to the same month, since the overall scheme seems to be the same.

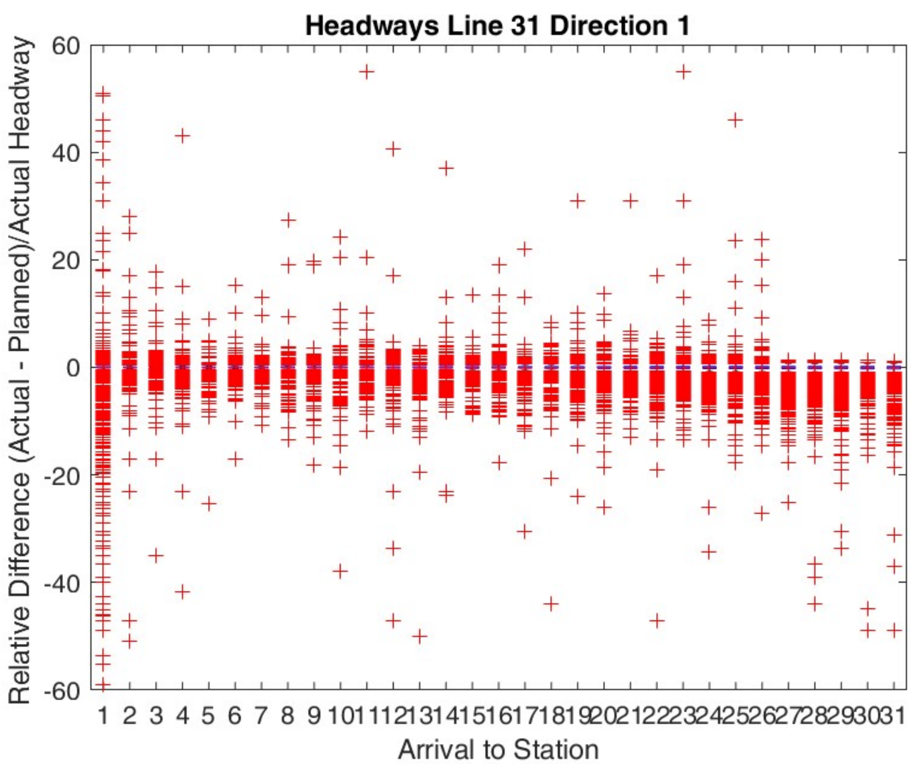

Figure 2.33: Relative Differences Actual & Planned Headways, Line 31

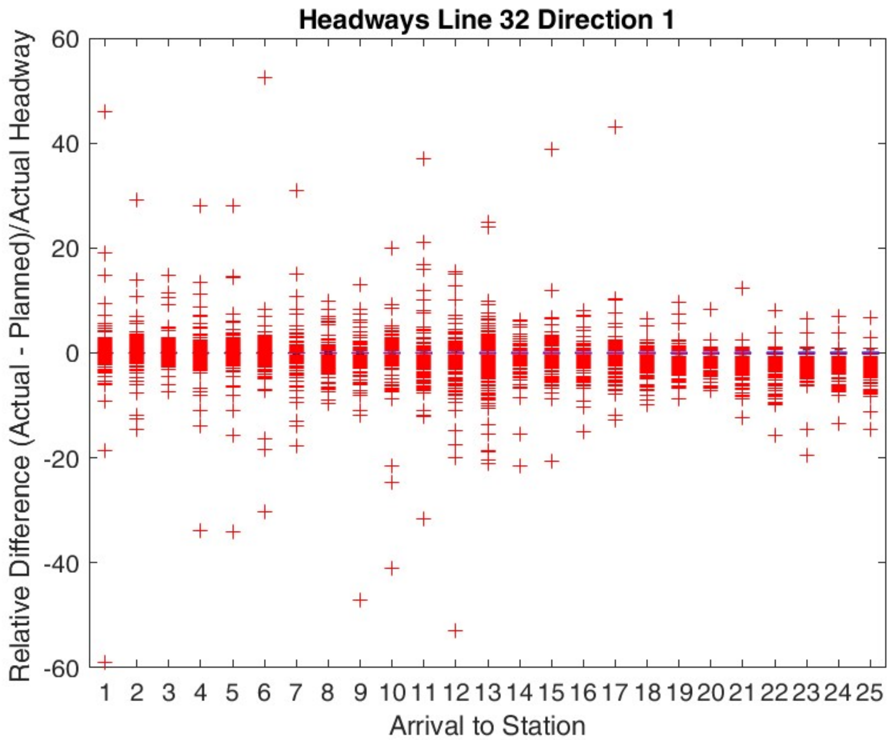

Figure 2.34: Relative Differences Actual & Planned Headways, Line 32

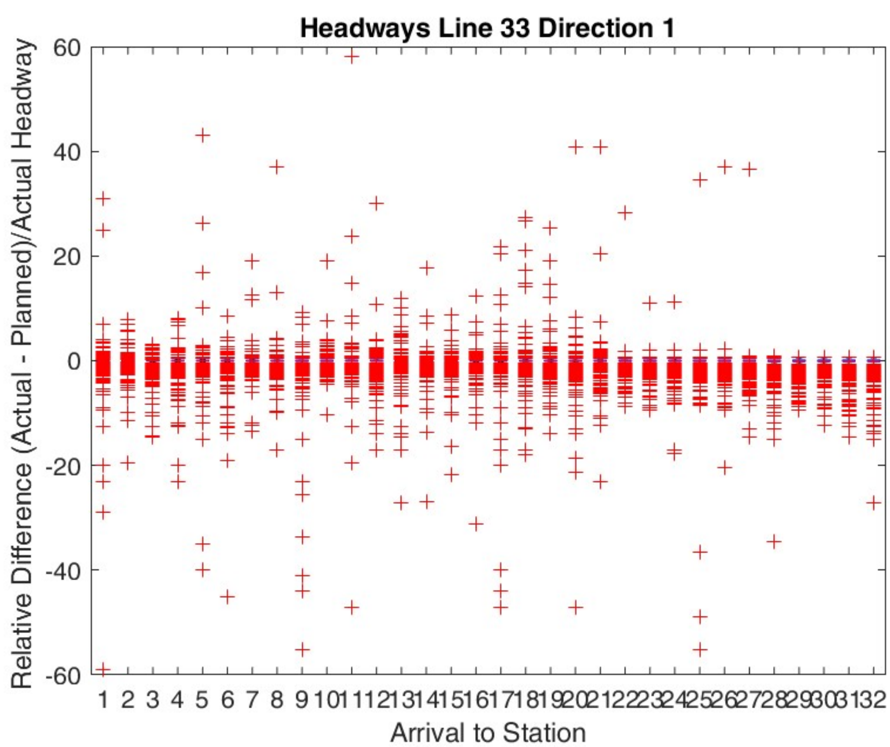

Figure 2.35: Relative Differences Actual & Planned Headways, Line 33

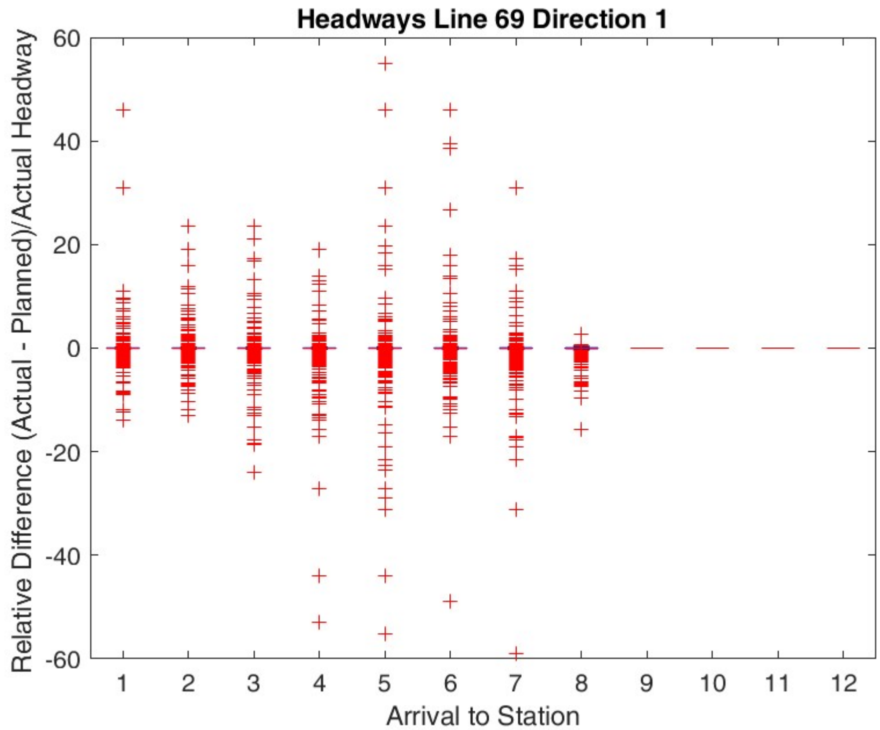

Figure 2.36: Relative Differences Actual & Planned Headways, Line 69

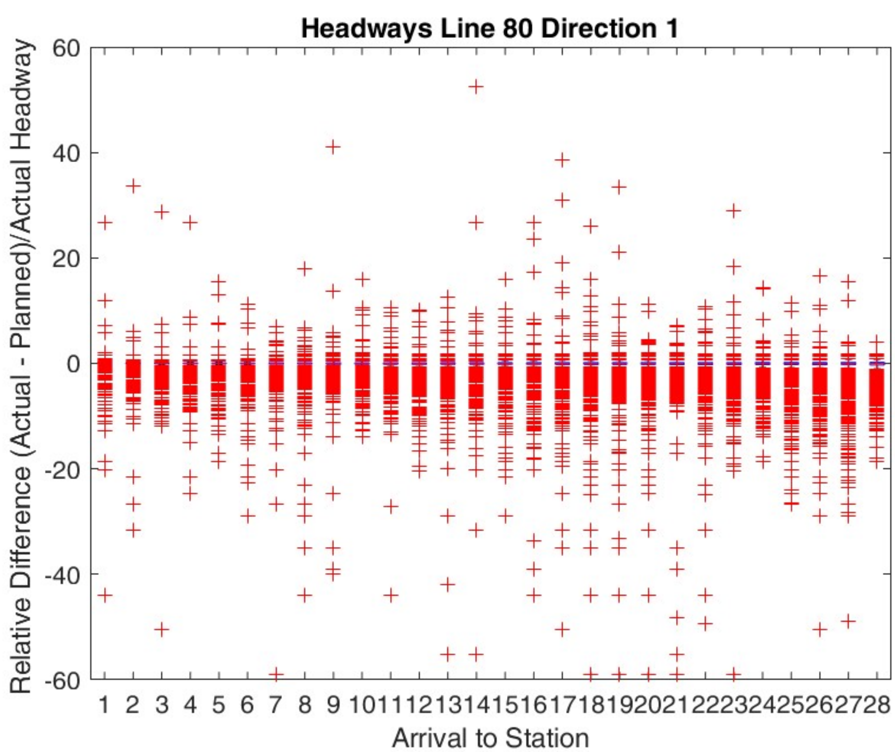

Figure 2.37: Relative Differences Actual & Planned Headways, Line 80

Indicative of the bus bunching problem can also be the following histograms (Figure 2.38 and Figure 2.39) , showing on the y axis the quantity of each bin for differences between the actual and planned headways and a normal curve fitted. From these histograms, how frequent it is for the difference between the planned and the actual headways of a line to deviate from the area of zero.

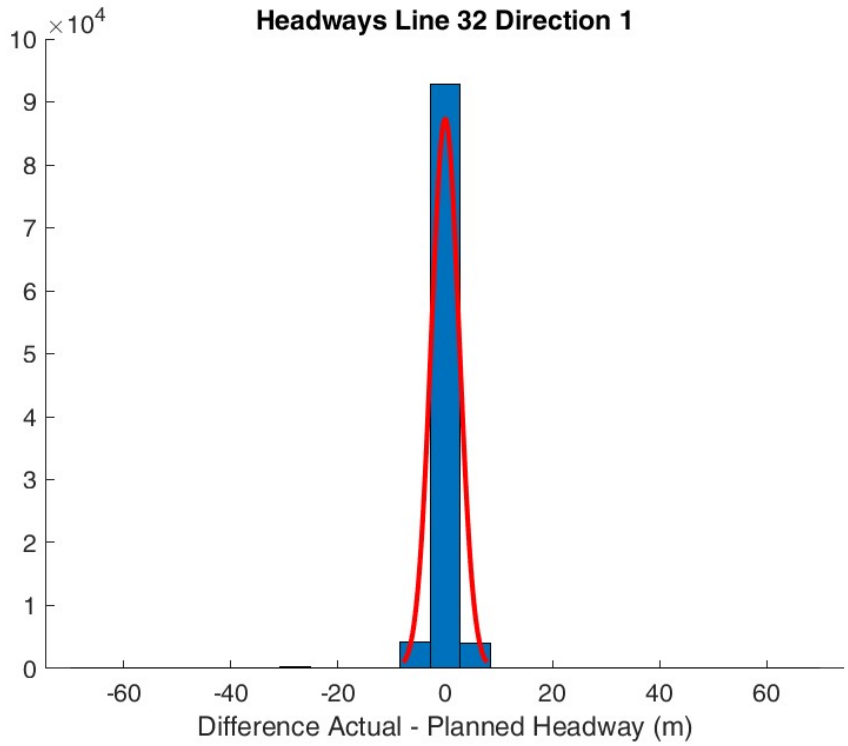

Figure 2.38: Headways Differences Histogram, Line 32

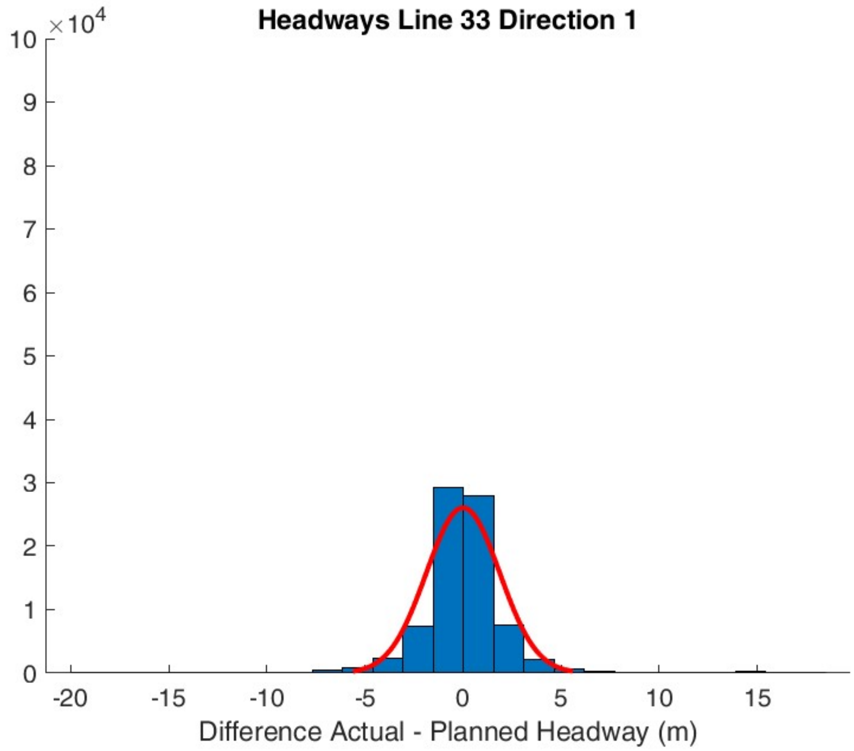

Figure 2.39: Headways Differences Histogram, Line 32

Finally, the deviation between the actual and the planned headways leading finally to bus bunching can also be seen from Figure 2.40 ÷ Figure 2.45. These graphs illustrate how the deviations increase along the bus route causing great delays at the last ones. The planned headways are not the same throughout the day and that's the reason why the red line is not straight. Moreover, the planned headways are not for all the stops, as already mentioned. For comparison reasons the same graph for line 46 has been placed, where the headway deviations are shown to be lower than for lines 31, 32 and 33. The following graphs refer to Tuesday 19.11.19 and Friday 19.07.2019. Great similarities can be observed between the two days both for lines 32 and 33.

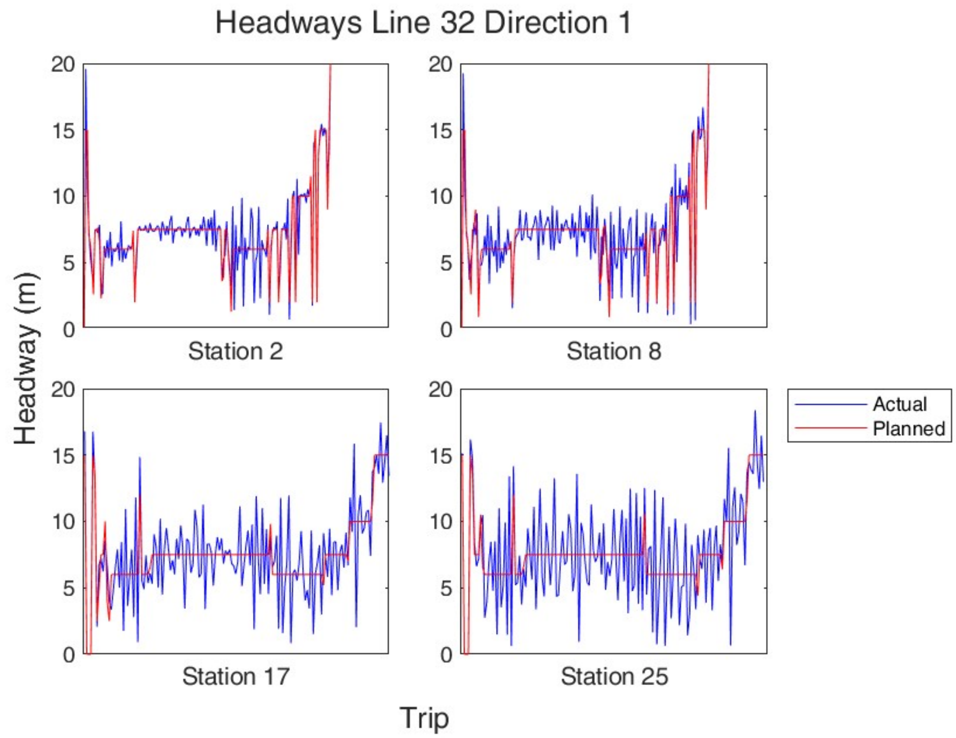

Figure 2.40: Actual & Planned Headways, Line 32, Tuesday 19.11.19

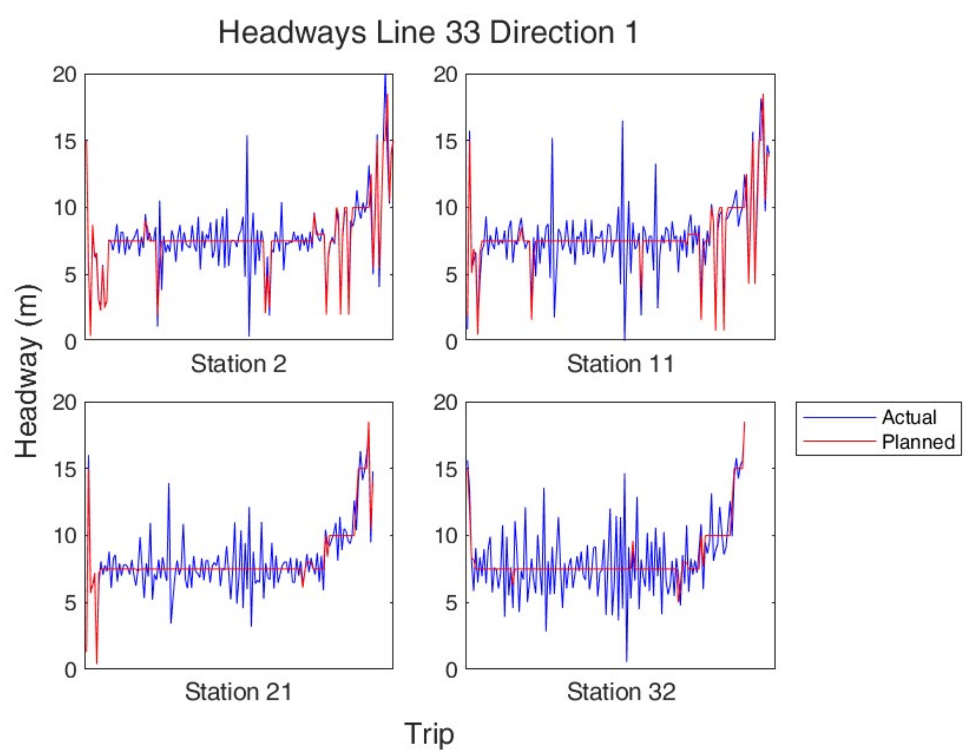

Figure 2.41: Actual & Planned Headways, Line 33, Tuesday 19.11.19

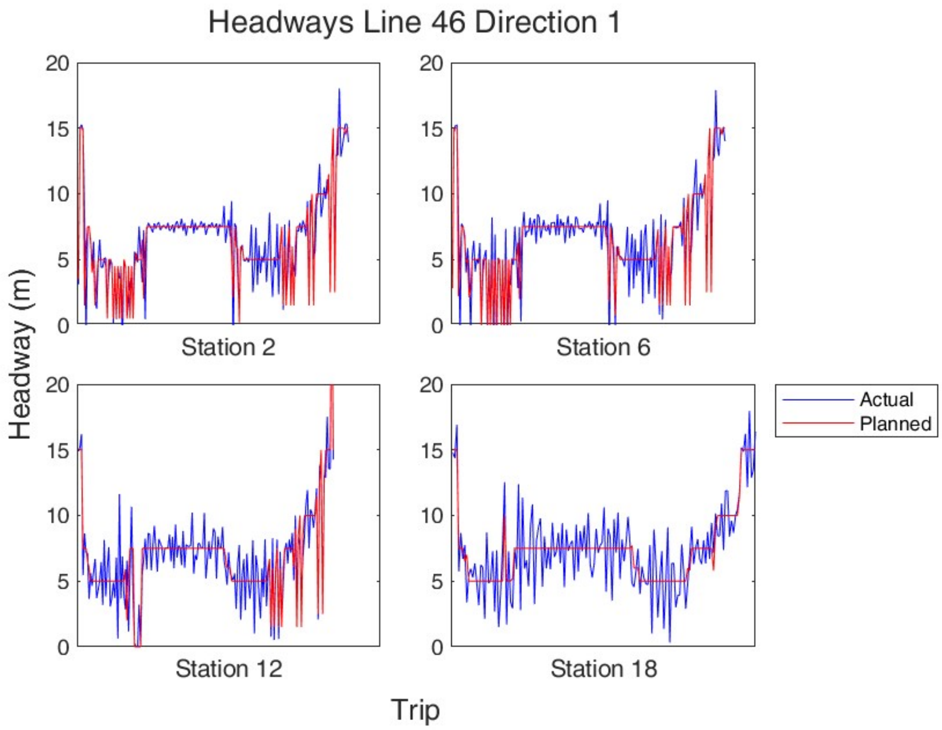

Figure 2.42: Actual & Planned Headways, Line 46, Tuesday 19.11.19

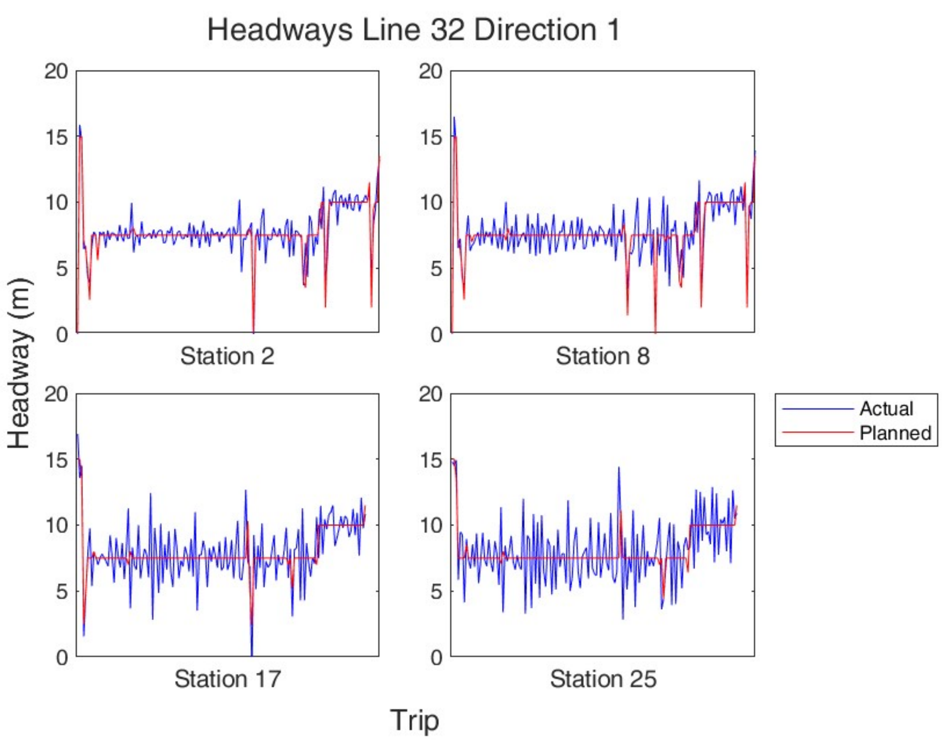

Figure 2.43: Actual & Planned Headways, Line 32, Friday 19.07.19

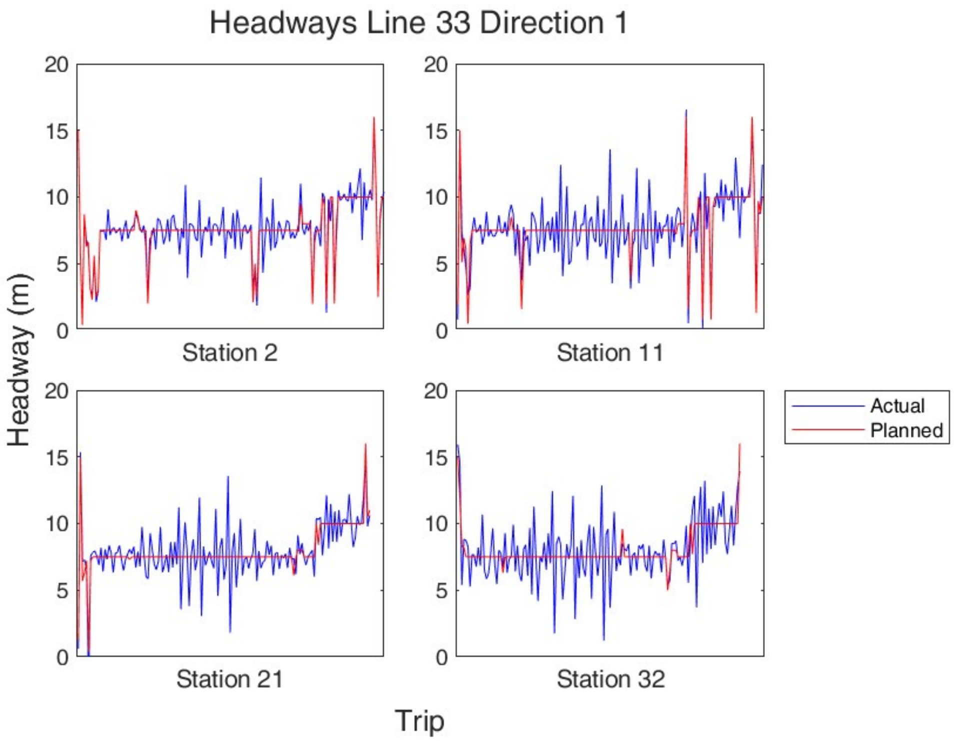

Figure 2.44: Actual & Planned Headways, Line 33, Friday 19.07.19

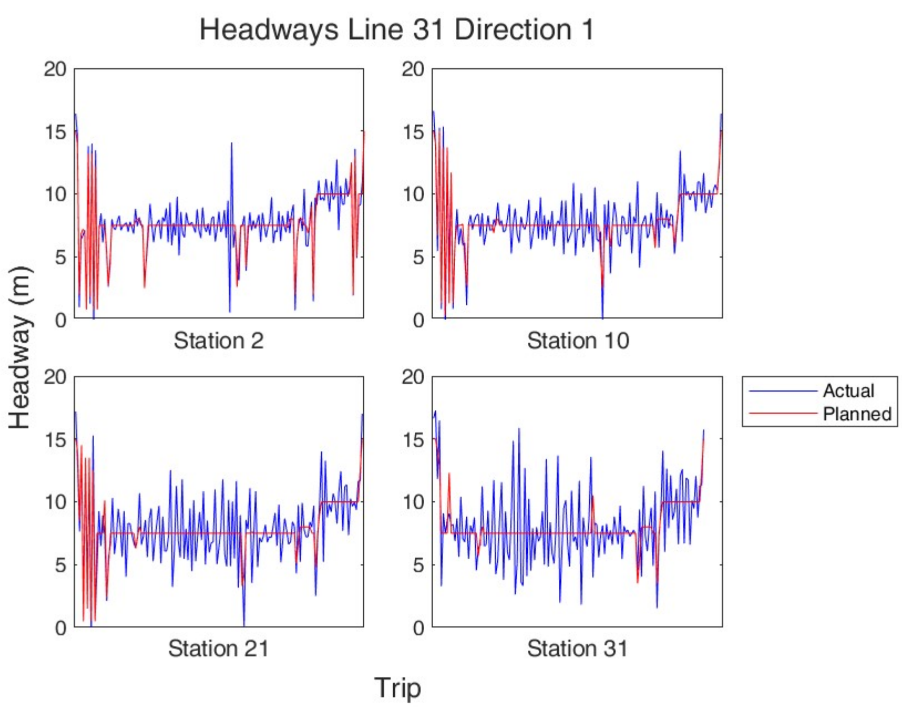

Figure 2.45: Actual & Planned Headways, Line 31, Friday 19.07.19

3 Causes Identification

The next step was the identification of possible causes for the problem. The causes investigated at the current project were the delays in the arrival or the departure and the increased alighting and boarding times. The delays in the arrival for the most suffering lines are shown in the following graphs (Figure 3.1 ÷ Figure 3.4) for a time space of four weeks.

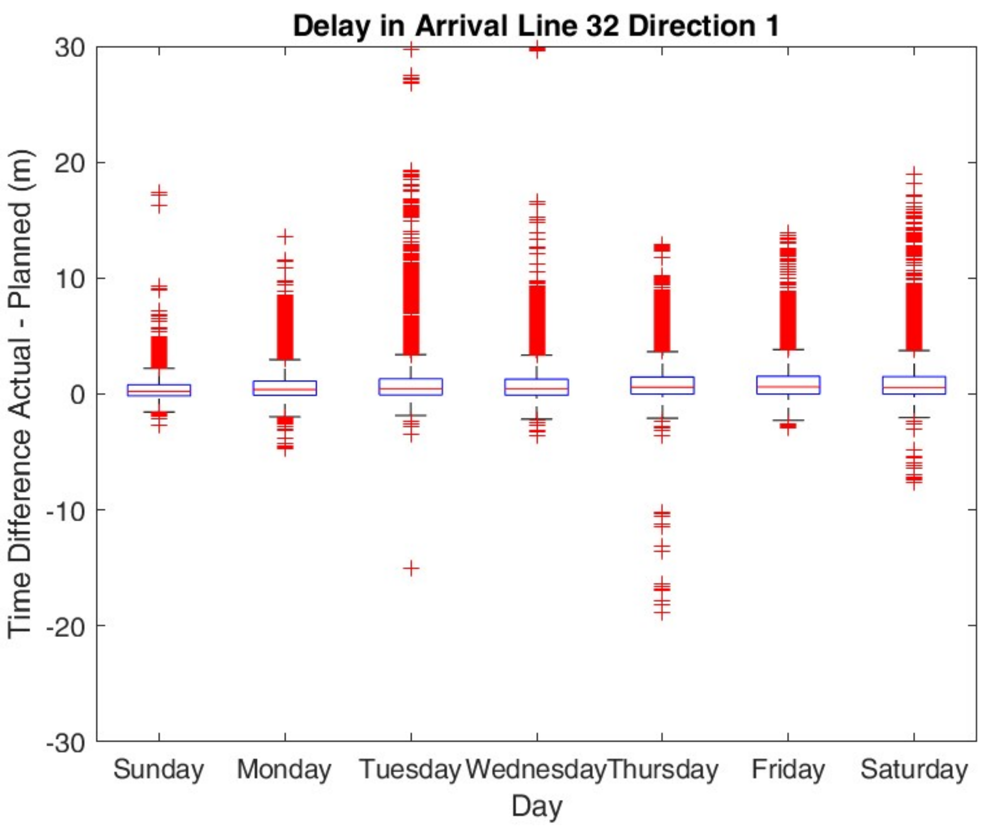

Figure 3.1: Arrival Delays per day, Line 32, Direction 1

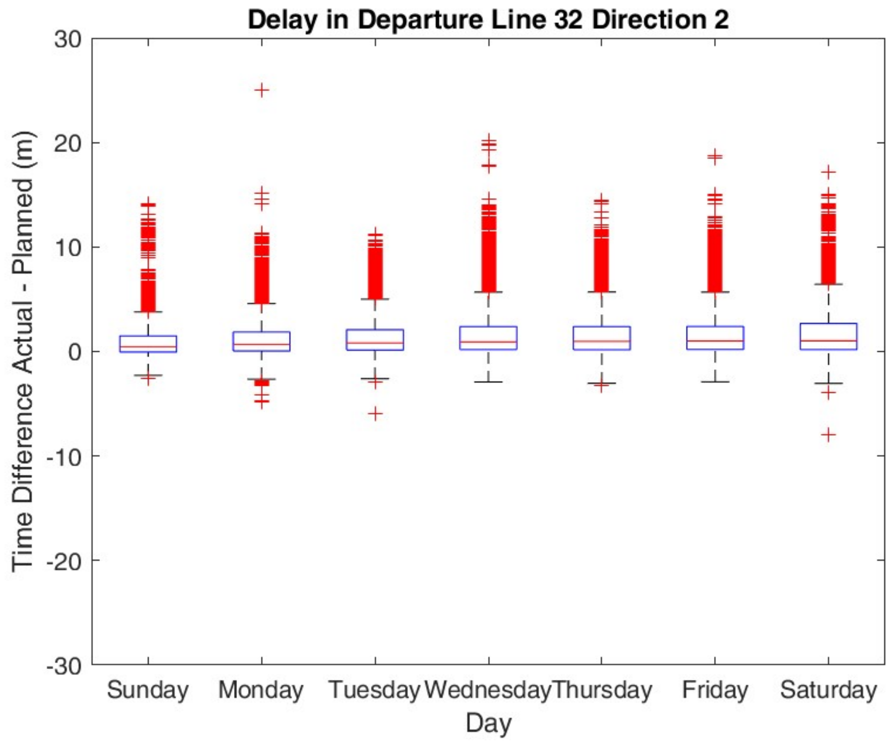

Figure 3.2: Arrival Delays per day, Line 32, Direction 1

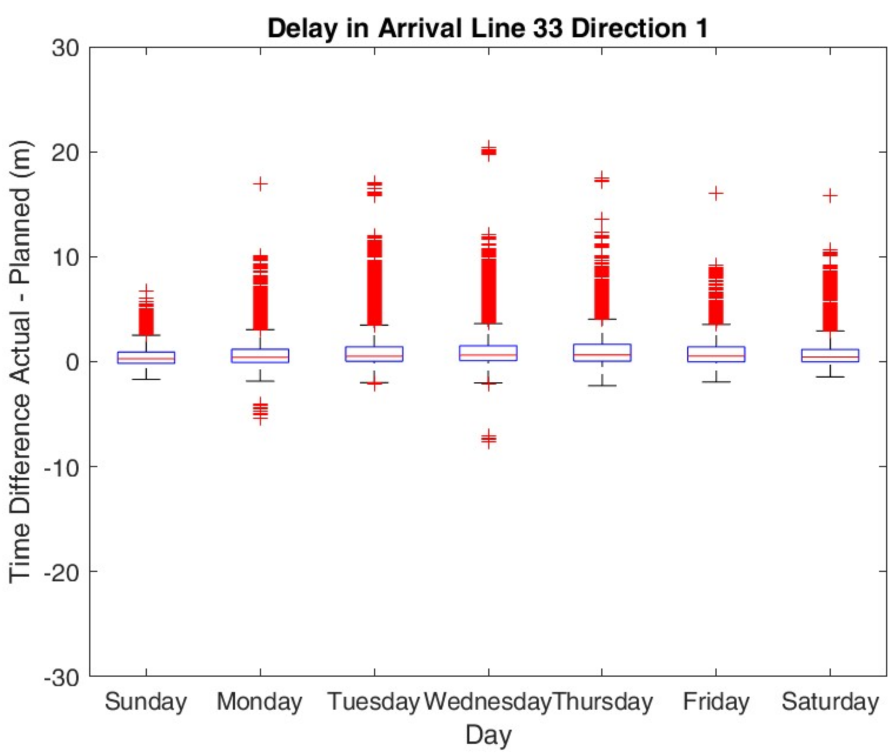

Figure 3.3: Arrival Delays per day, Line 33, Direction 1

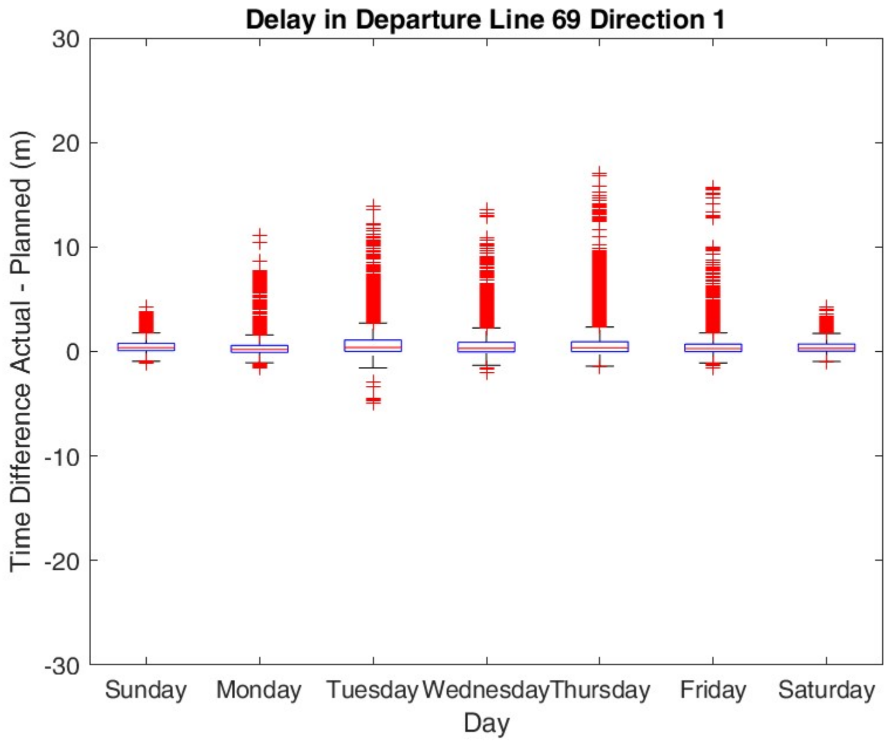

Figure 3.4: Arrival Delays per day, Line 69, Direction 1

It is worth noticing that differences are detected not only between weekdays and weekends but also between the different weekdays. This can be a random phenomenon, when taking a look at other months, but sometimes the case can be that specific days show higher mobility. Furthermore, although the delays during the weekends are lower than weekdays, as expected, one cannot take them as negligible. Differences between the two directions are obvious comparing Figure 3.1 and Figure 3.2.

The arrival delays are also plotted for each station of the line (Figure 3.5 ÷ Figure 3.8). Weekdays are only taken into consideration to account for the more acute problems. Increasing delays can be observed along the bus route due to accumulated problems, especially for long lines. However, time buffers foreseen at some stations and lines running only on the most crowded part of the route account for the drop in the delays.

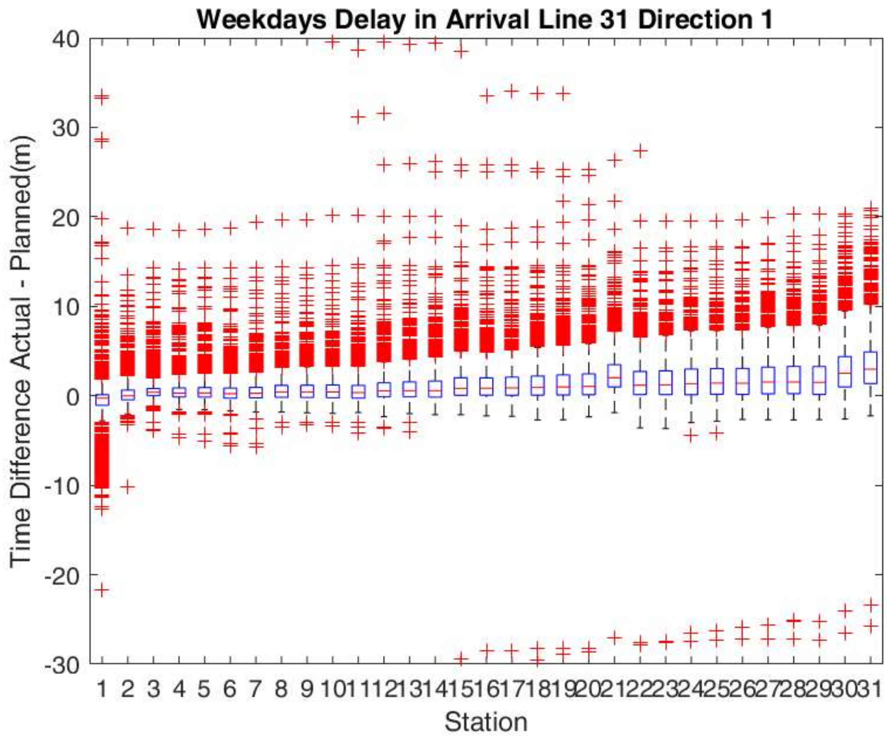

Figure 3.5: Arrival Delays per station, Line 31

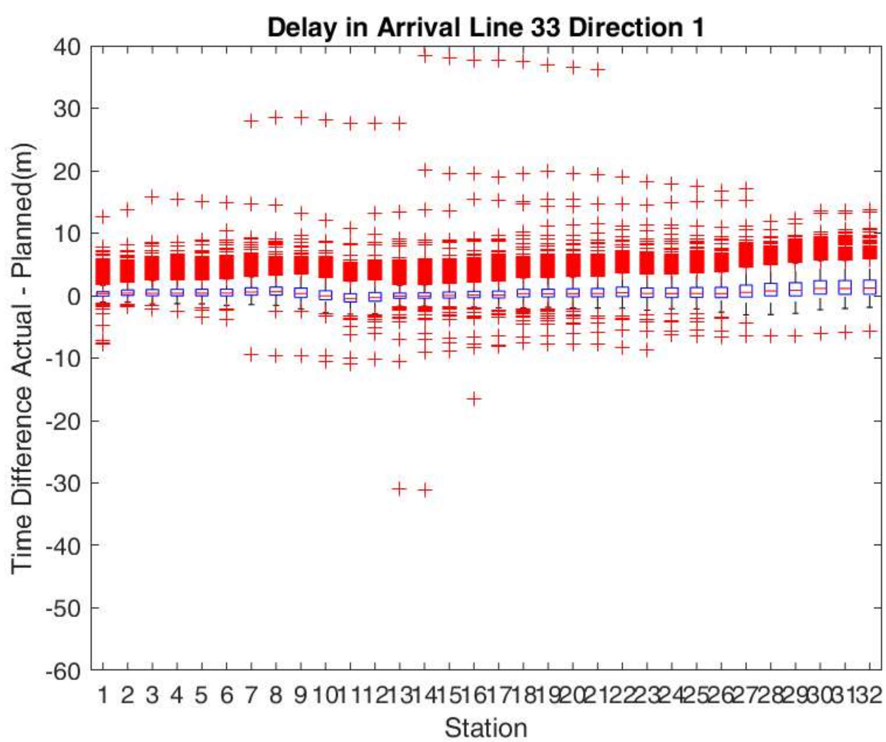

Figure 3.6: Arrival Delays per station, Line 33

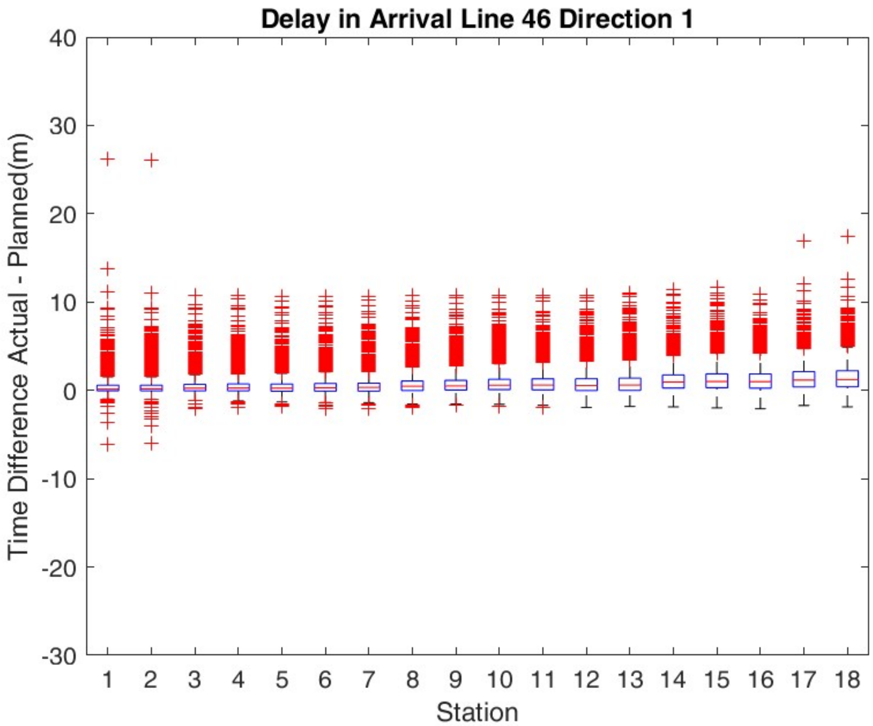

Figure 3.7: Arrival Delays per station, Line 46

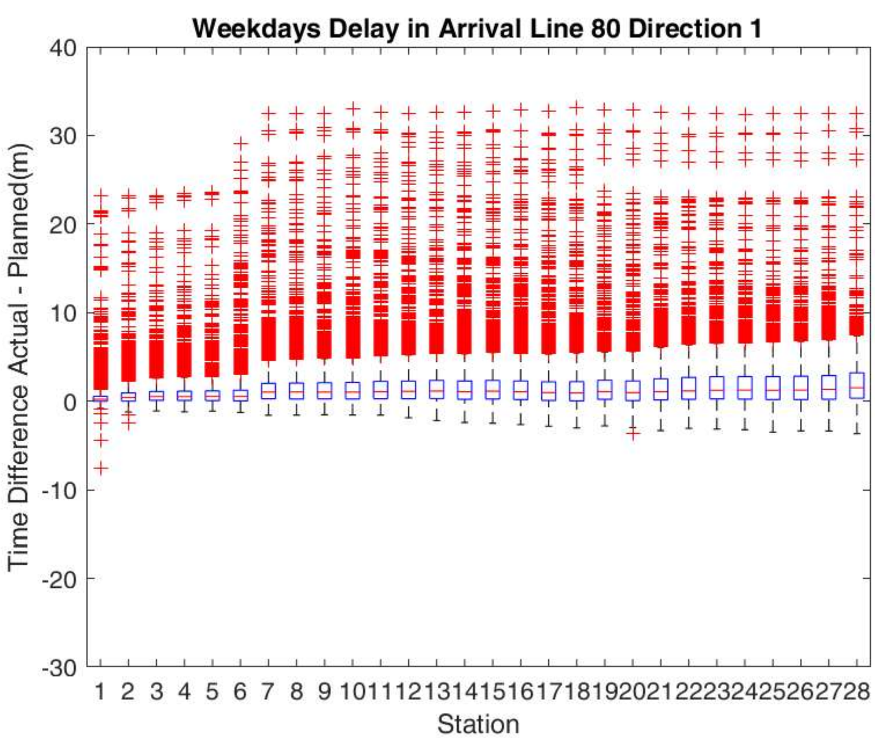

Figure 3.8: Arrival Delays per station, Line 80

Similarly, the plots for departure delays (Figure 3.9 ÷ Figure 3.12) show the same characteristics as the ones described above. Both from the departure and arrival delays graph, increased delays for lines 31, 32 and 33 in comparison e.g. to line 46.

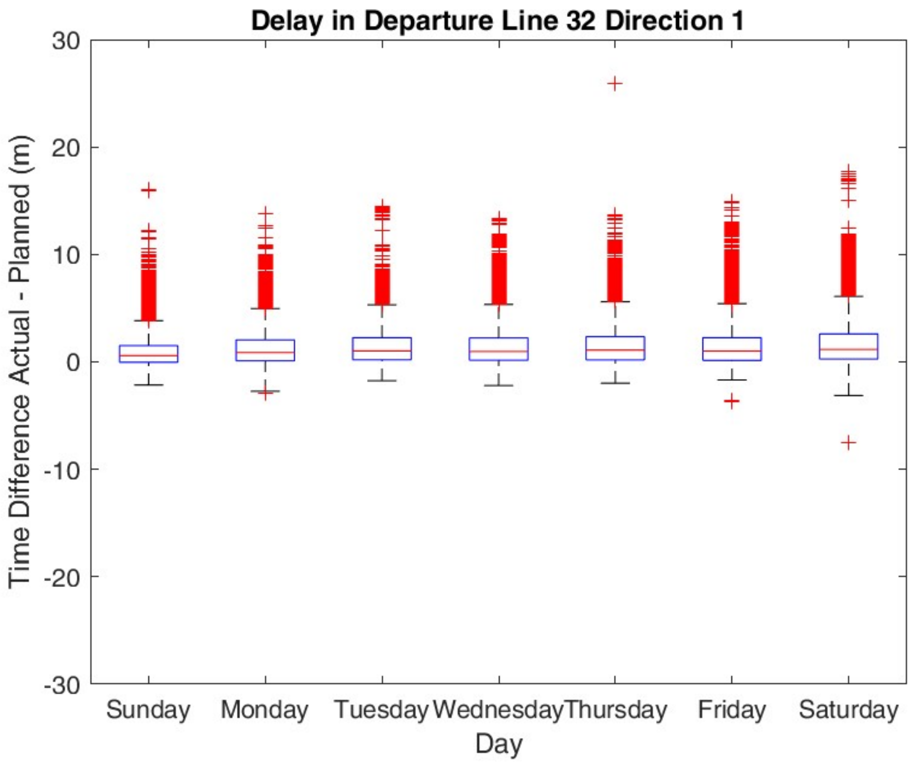

Figure 3.9: Departure Delays per day, Line 32

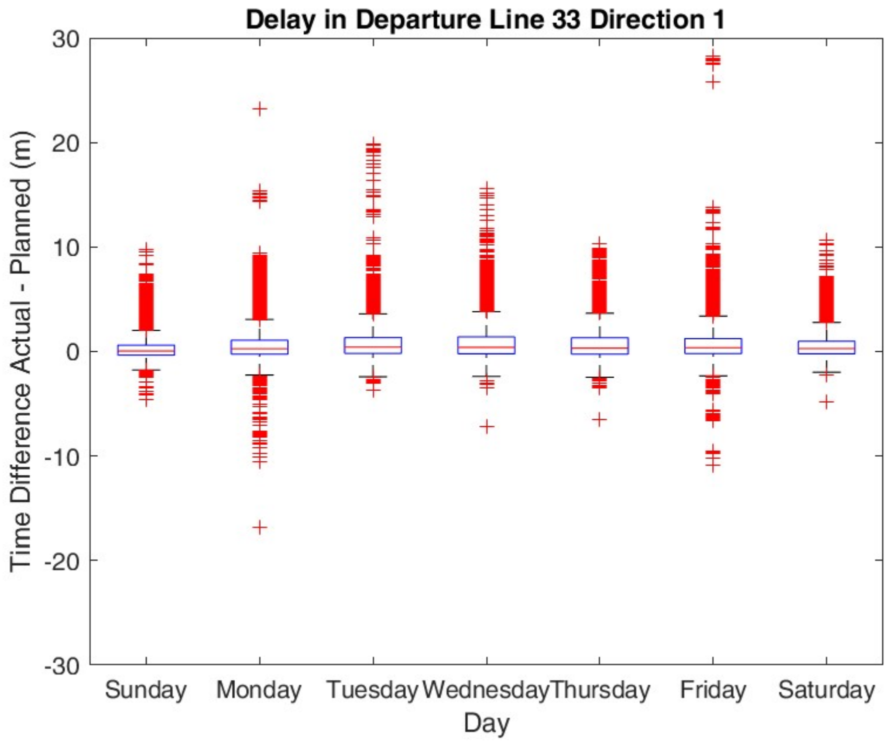

Figure 3.10: Departure Delays per day, Line 33

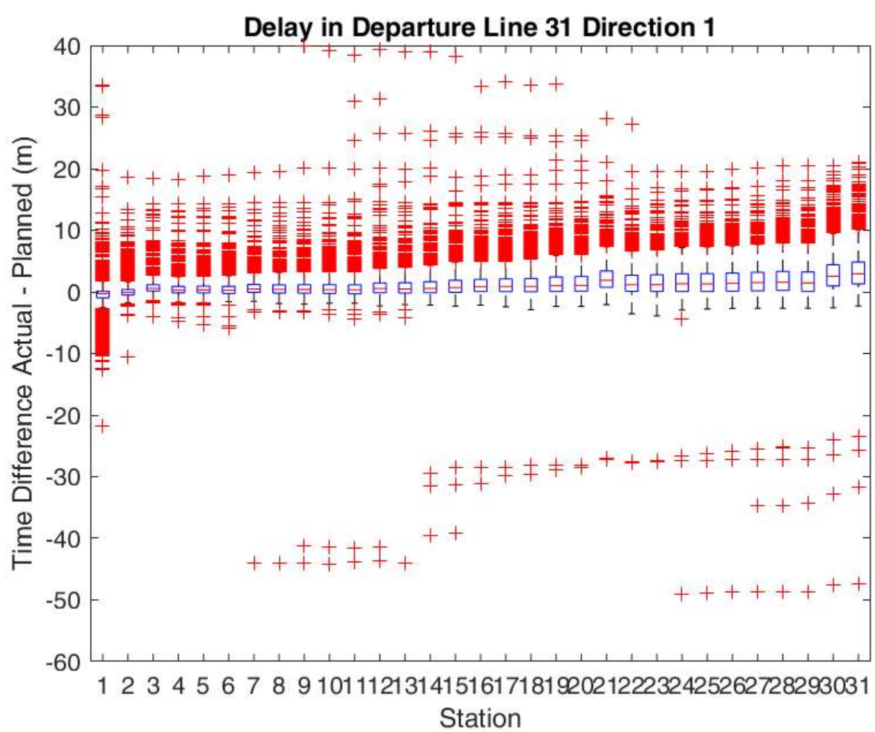

Figure 3.11: Departure Delays per station, Line 31

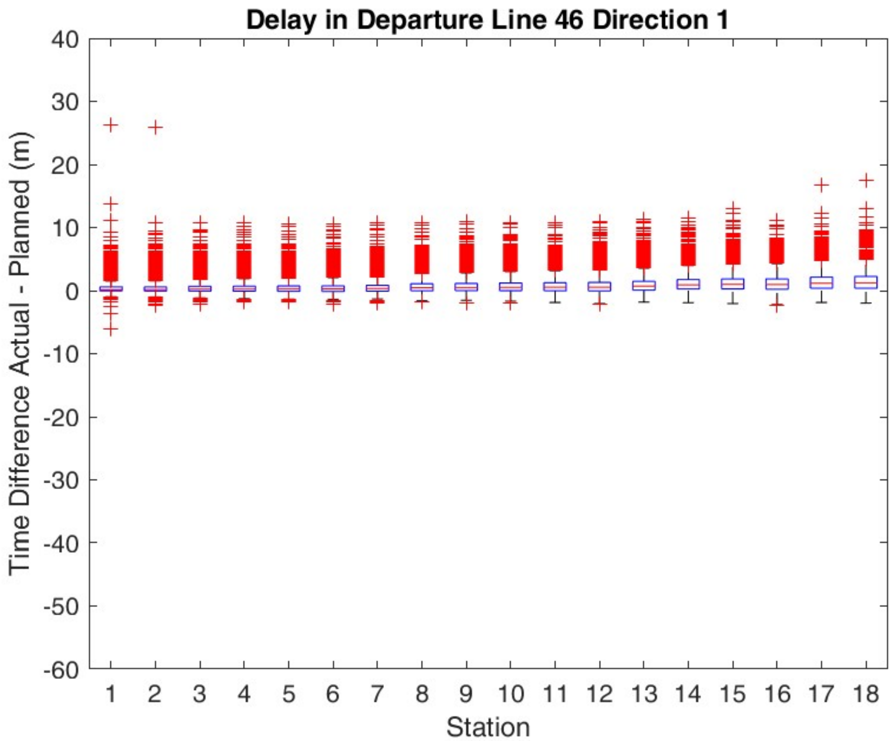

Figure 3.12: Departure Delays per station, Line 46

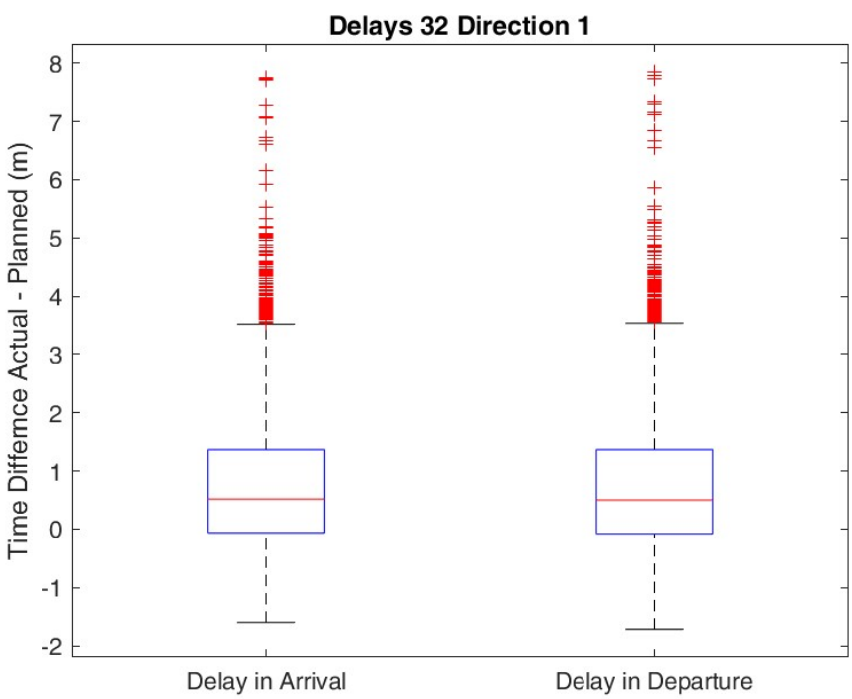

Figure 3.13: Delays in Arrival & Departure, Line 32

Figure 3.13 shows that the delays in the arrival and departure are not exactly the same, implying that the alighting and boarding times can have a crucial role to bus bunching phenomena. Boarding and alighting times seem to vary throughout the days of the week without being at all inconsiderable during the weekend. A great variation can be noticed along the route with the highest values being noticed at nodal stops such as Bucheggplatz and Milchbuck. Increased times are also met at stations with connection to railway and at university stations, e.g. ETH Hönggerberg. It is out of doubt that the two directions of each line show differences at the boarding and alighting times, as already discussed. These differences are attributed to fluctuation in the demand and the stop. Stations at intersections and stations with more than one line arriving, e.g. Glaubtenstrasse are highly possible to show higher boarding and alighting times.

Differences can also be detected between peak and off peak hours as shown in Figure 3.14 ÷ Figure 3.22. However, they are lower than expected. It is of high importance to show how the actual boarding and alighting times deviate from the planned ones. As it can be seen from Figure 3.5 ÷ Figure 3.8 this deviation is not constant neither for all the stops nor throughout the day, leading to bus bunching. These differences are not at all negligible, since the actual times can be equal to four times the planned ones.

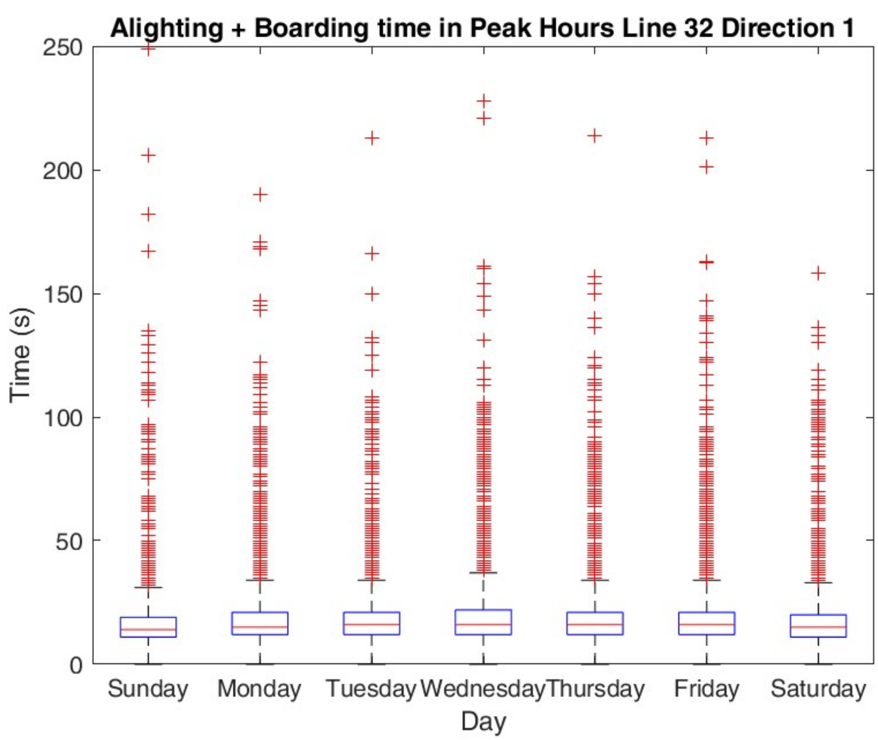

Figure 3.14: Boarding & Alighting times per day, Peak Hours, Line 32, Direction 1

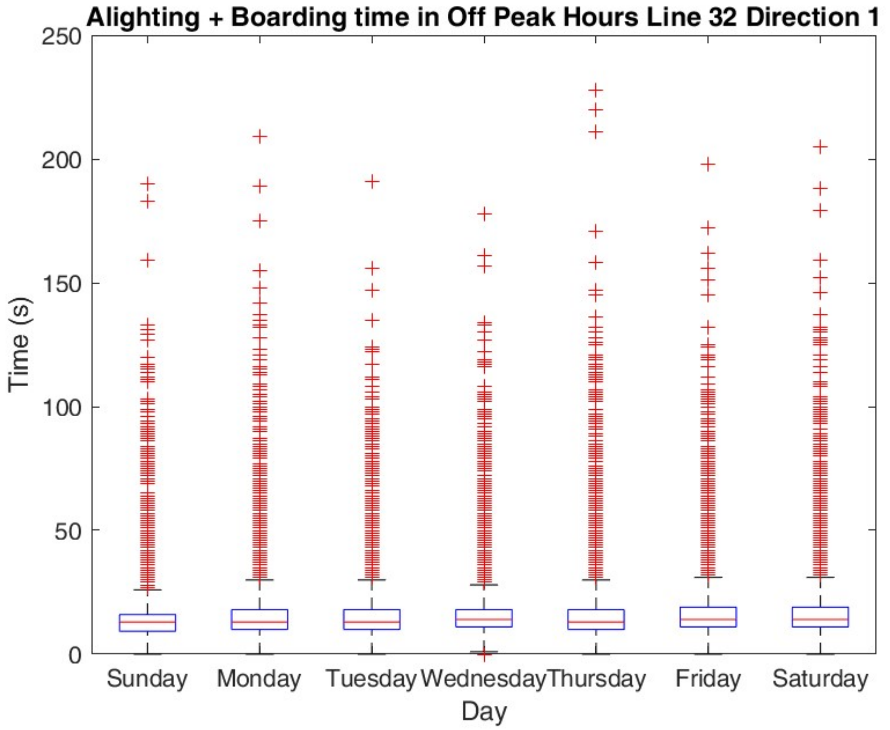

Figure 3.15: Boarding & Alighting times per day, Off Peak Hours, Line 32, Direction 1

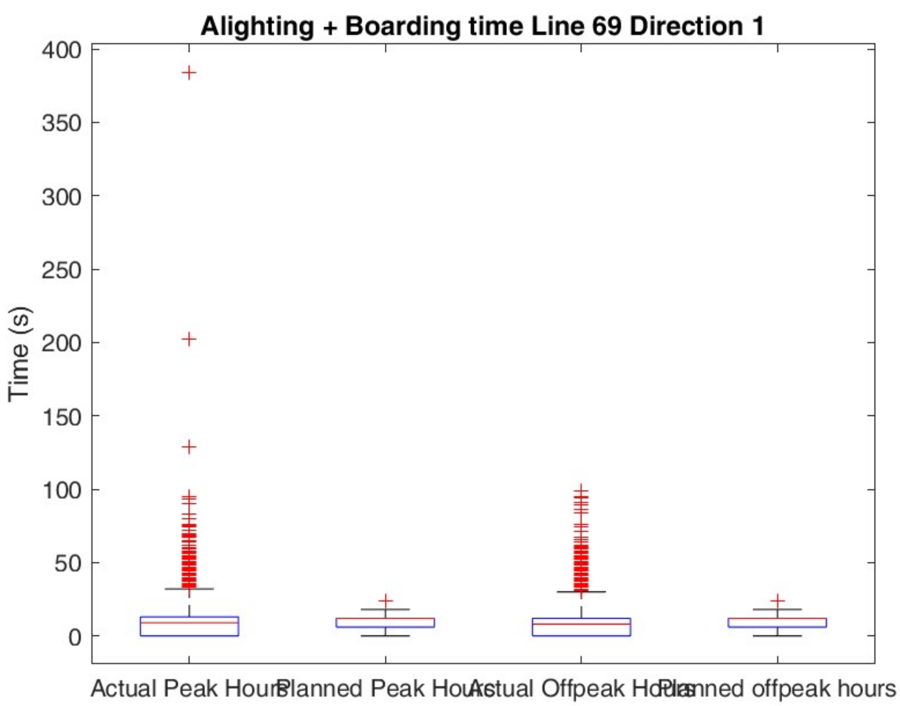

Figure 3.16: Comparison Peak & Off Peak hours Boarding & Alighting times, Line 69

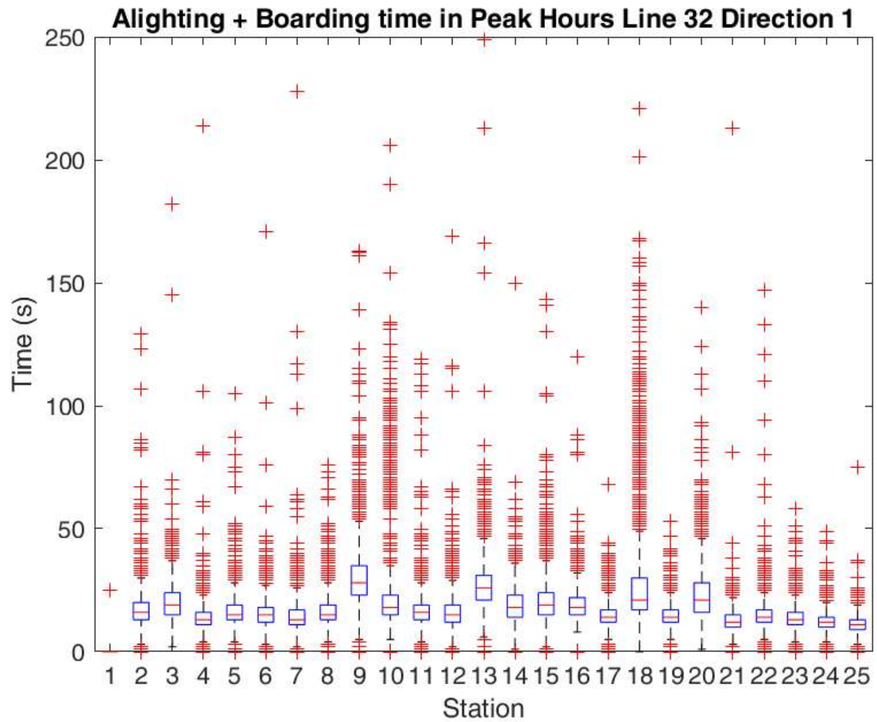

Figure 3.17: Boarding & Alighting times per station, Peak Hours, Line 32, Direction 1

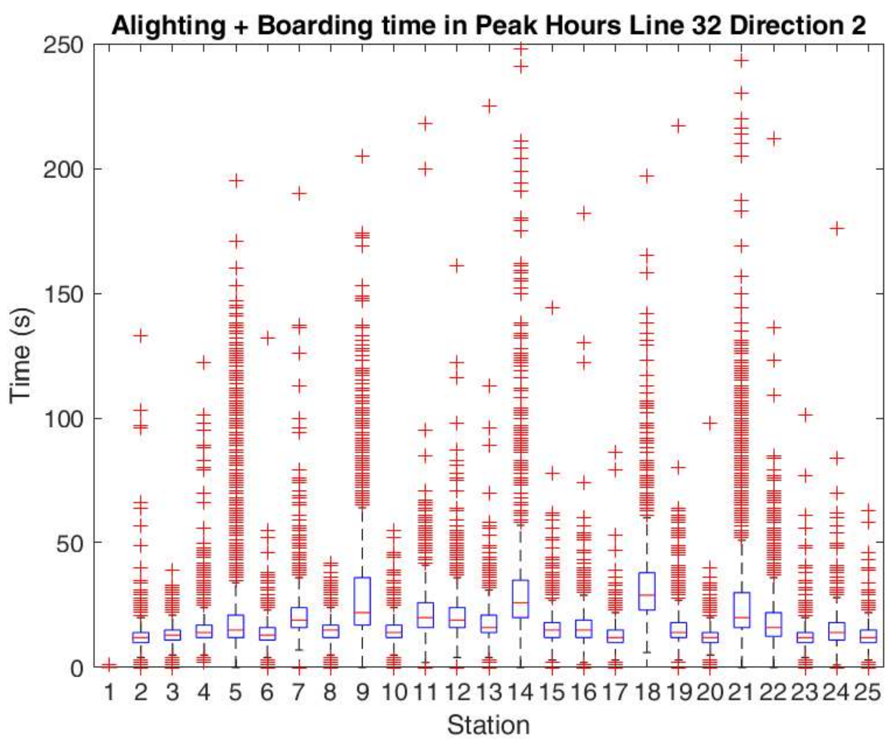

Figure 3.18: Boarding & Alighting times per station, Peak Hours, Line 32, Direction 2

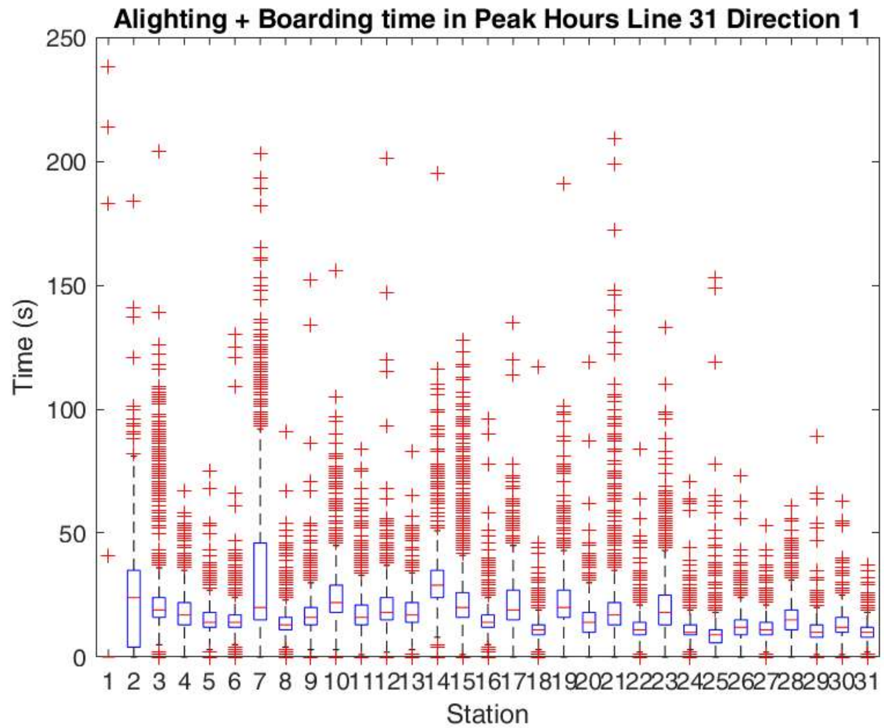

Figure 3.19: Boarding & Alighting times per station, Peak Hours, Line 31, Direction 1

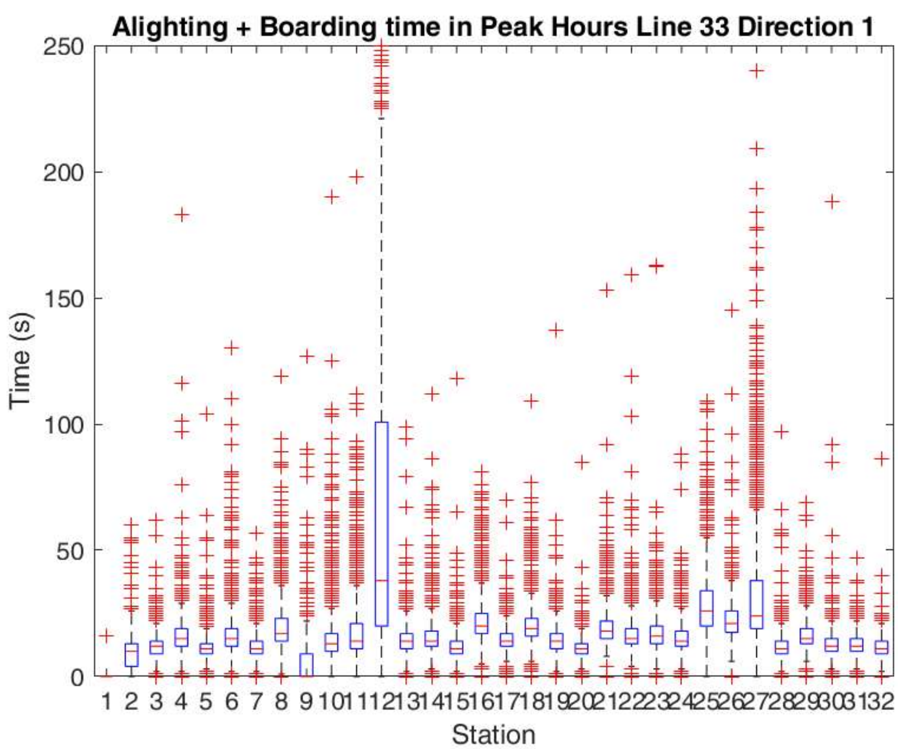

Figure 3.20: Boarding & Alighting times per station, Peak Hours, Line 33, Direction 1

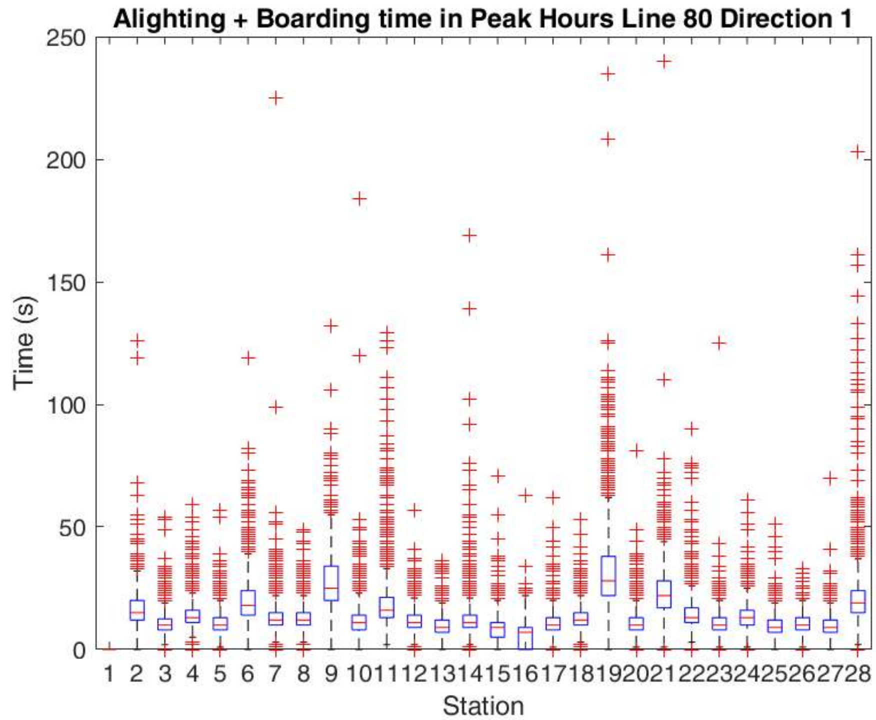

Figure 3.21: Boarding & Alighting times per station, Peak Hours, Line 80, Direction 1

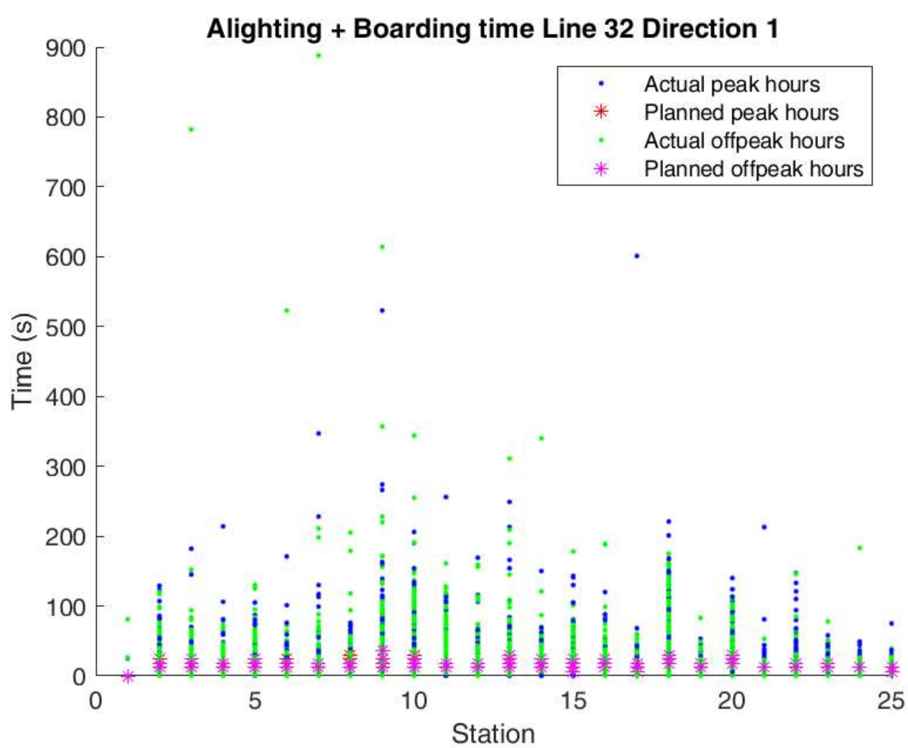

Figure 3.22: Actual & Planned for peak & off peak hours Boarding & Alighting times, Line 32

4 Conclusions

The most remarkable conclusions of the current project are described in the following paragraphs. Long lines are, as expected, more susceptible to bus bunching (Figure 2.33 ÷ Figure 2.37). The reason for this is that delays are accumulated along the bus route. However, there are cases where a time buffer is foreseen at some stations and this can contribute efficiently to facing the problem. Moreover, quite susceptible to bus bunching are also lines crossing the city center and tangential lines passing from crucial points of the city. However, lines leading to decentralize hubs do not suffer at all from bus bunching, which is anticipated considering that these lines usually neither run on congested roads nor cross central stations with high demand (Figure 2.1 ÷ Figure 2.8).

Moreover, the project shows a variation during the year, which can be attributed to the characteristics of each month, namely the weather conditions and the demand variation due to open or closed universities and businesses. This however does not imply that no bunching at all happens at the whole network, but lines serving specific spots show increased punctuality, e.g. line 69 serving ETH Hönggerberg. Although the bus bunching instances show a fluctuation for the different months, the spots remain mostly the same (Figure 2.9 ÷ Figure 2.20).

Another important fact is that for each line there is a direction suffering more from bus bunching than the other. This can be attributed to the fact that the stations of a line are not placed exactly on the same point for both directions, for example one stop can be placed before and one after an intersection. Moreover the demand for each direction can also vary (Figure 2.9 ÷ Figure 2.20).

It is highly possible that delays and bus bunching instances increase along the line, as the delays are accumulated. However, sometimes, the delays can be constant after a specific point or even decrease. This is attributed to a buffer time foreseen at some stations or to decreasing demand along the bus route resulting in lower boarding and alighting times. When less bunching instances are detected at later stations, lines running only on a part of the route can be the cause (Figure 2.21 ÷ Figure 2.24 and Figure 2.33 ÷ Figure 2.37).

A differentiation must also be made between the different days of the week. Of course delays and bus bunching phenomena are more severe during weekdays than during weekends. However, they are not at all negligible during weekends and especially Saturday. Differences can also be noticed between different working days for some lines with Tuesday showing for example more delays for line 32 (Figure 3.1 ÷ Figure 3.4 and Figure 3.9 ÷ Figure 3.10).

Finally, concerning the boarding and alighting times, a fluctuation can be observed along the line owed to the demand variation with particularly high values at nodal points (Figure 3.14 ÷ Figure 3.22). It should be mentioned however that even if there is high demand on some stops, it doesn't necessarily translate to higher delays at that point, provided that enough space for the people and the vehicles is foreseen, e.g. Bucheggplatz. Fluctuation is also observed during the day with of course higher values during the peak hours. The differences between the stations lead to a deviation from the planned boarding and alighting time, which combined with the fluctuation during the day implies bus bunching.

5 Summary & Future Work

To sum up the current project, bus bunching is indeed an existing problem for the city of Zurich. However, it is remarkable that it only concerns a few lines and more specifically lines 31, 32, 33, 46, 69, 72 and 80. These are the lines crossing the city or running on a corridor tangent to the city center. For these lines the total bus bunching instances at each station range mostly every month between 10 and 20% of the total station arrivals. The maximum bus bunching instances detected at a station for a month constitute 30% of the total arrivals at this station. Finally, it should be underlined that these values vary for these seven lines with the most severe problems occurring for lines 31, 32 and 33 running through the city center.

The bus bunching phenomenon can be a crucial issue for the public transport system of a city and thus requires deep investigation. For the city of Zurich a further investigation of the causes is required before trying to solve the problem. The congestion on different roads should be linked to the lines showing increased bus bunching instances. Moreover, the Verkehrsbetrieb Zürich offers data for the alighting and boarding passengers at each station, which can be used to extract definite conclusions for the impacts of demand variation on delays. An analysis of how lines sharing the same corridor affect each other. Furthermore, a more extended months' investigation is required, including all 12 months of the year and studying the instances fluctuation. Finally, measures can be proposed to mitigate the problem taking into consideration the needs and characteristics of the transport system

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A Appendix: Line 32

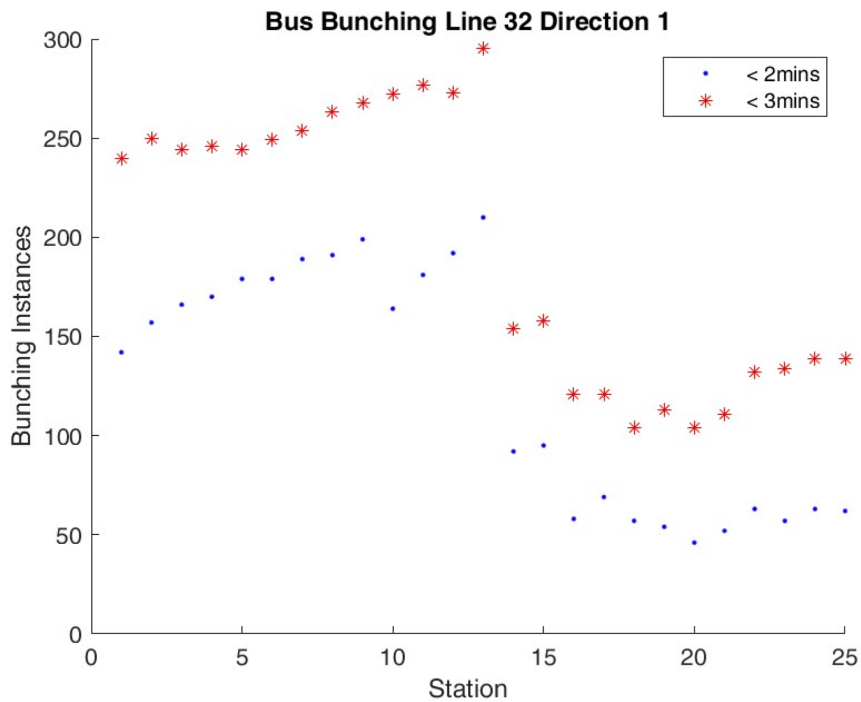

Figure A.1: Bus Bunching Instances, January, Line 32, Direction 1

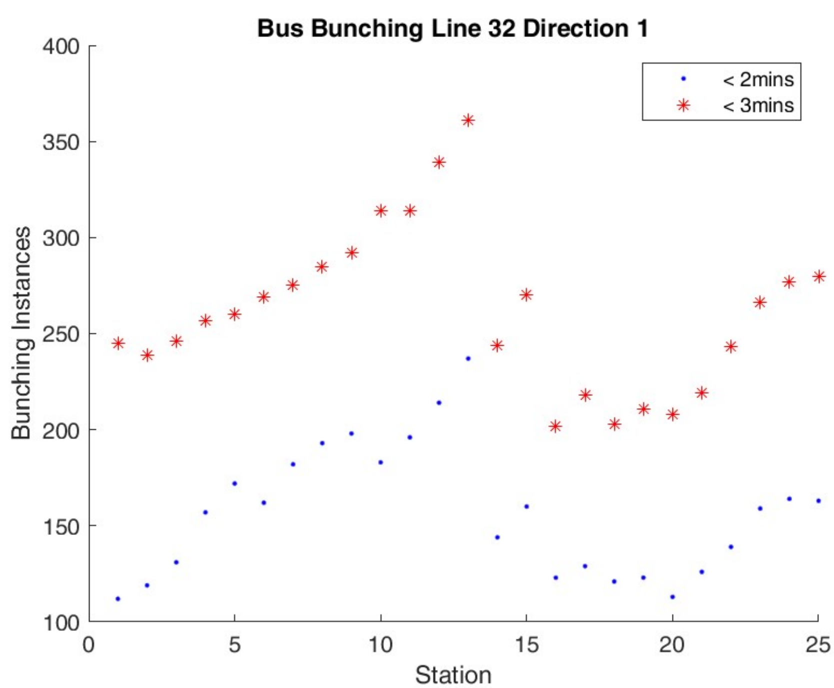

Figure A.2: Bus Bunching Instances, November, Line 32, Direction 1

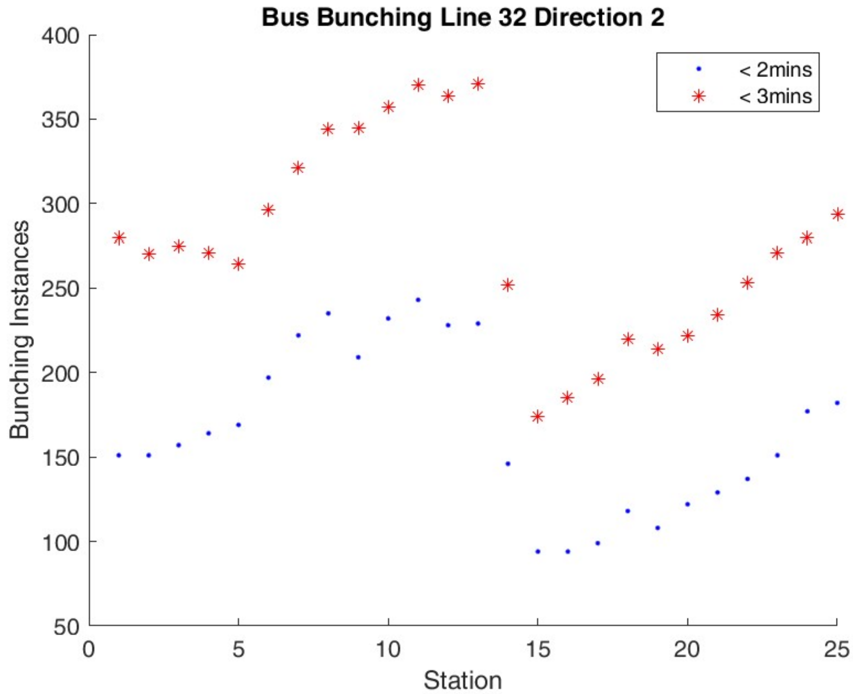

Figure A.3: Bus Bunching Instances, November, Line 32, Direction 2

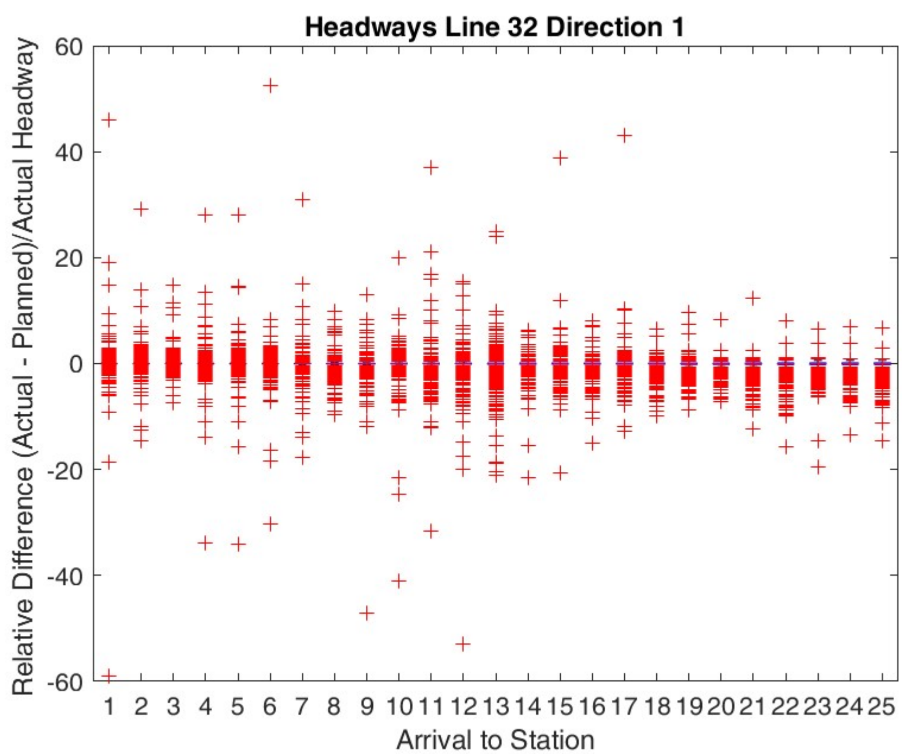

Figure A.4: Relative Differences Actual & Planned Headways, January Line 32, Direction 1

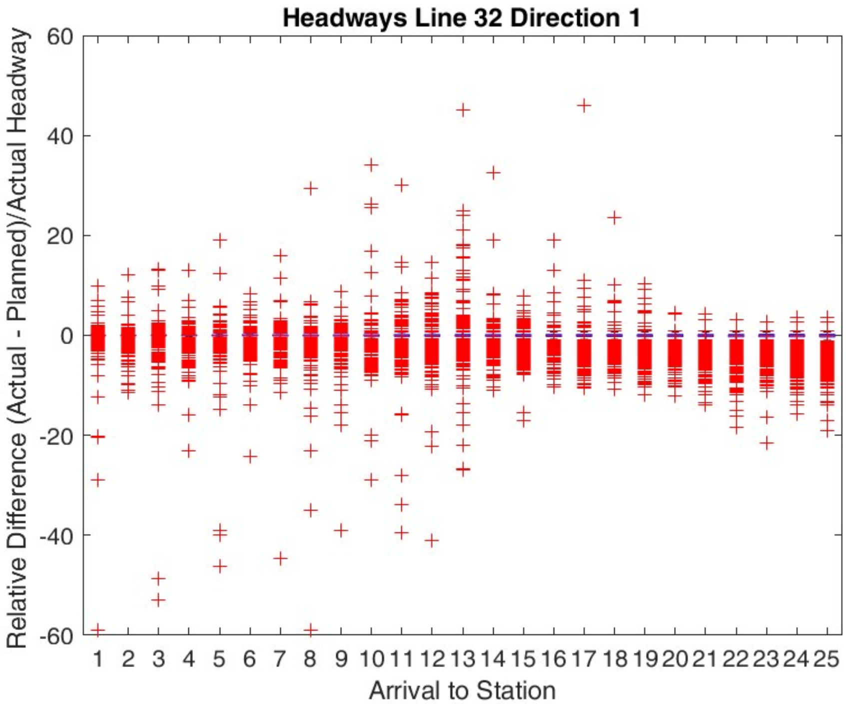

Figure A.5: Relative Differences Actual & Planned Headways, November Line 32, Direction 1

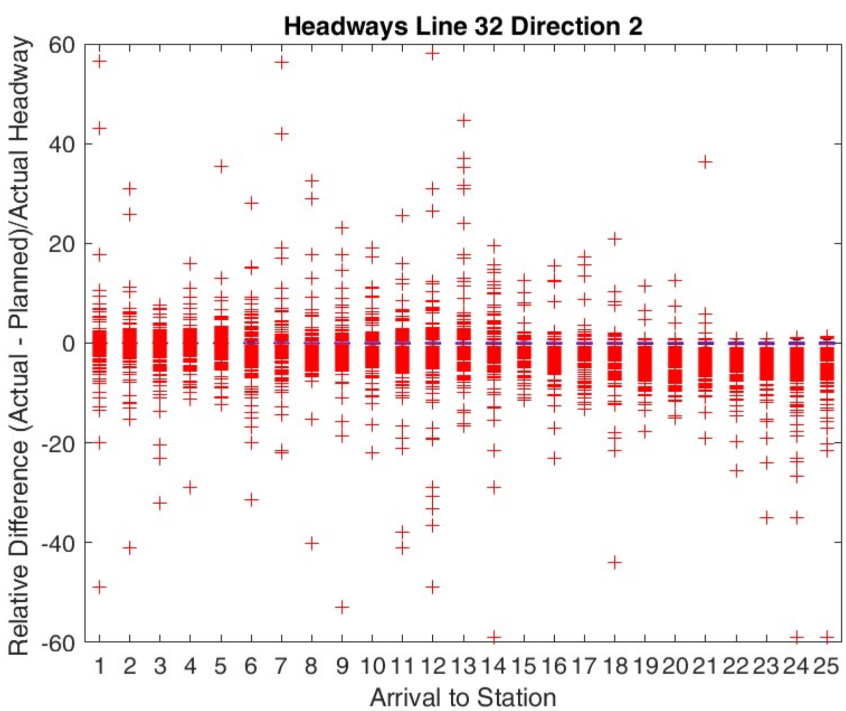

Figure A.6: Relative Differences Actual & Planned Headways, November Line 32, Direction 2

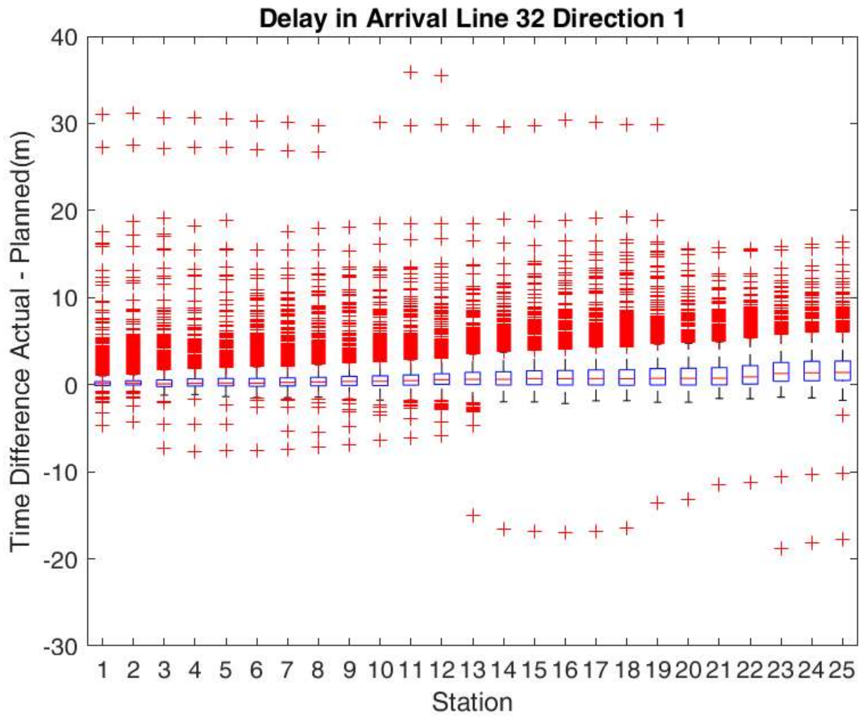

Figure A.7: Arrival Delays per station, January, Line 32, Direction 1

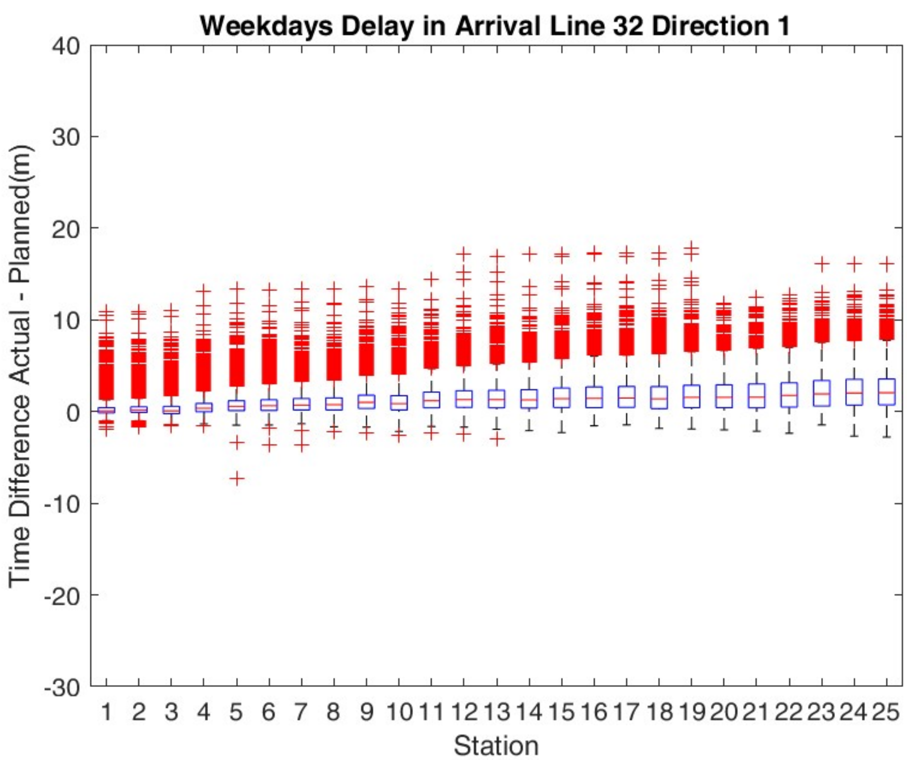

Figure A.8: Arrival Delays per station, November, Line 32, Direction 1

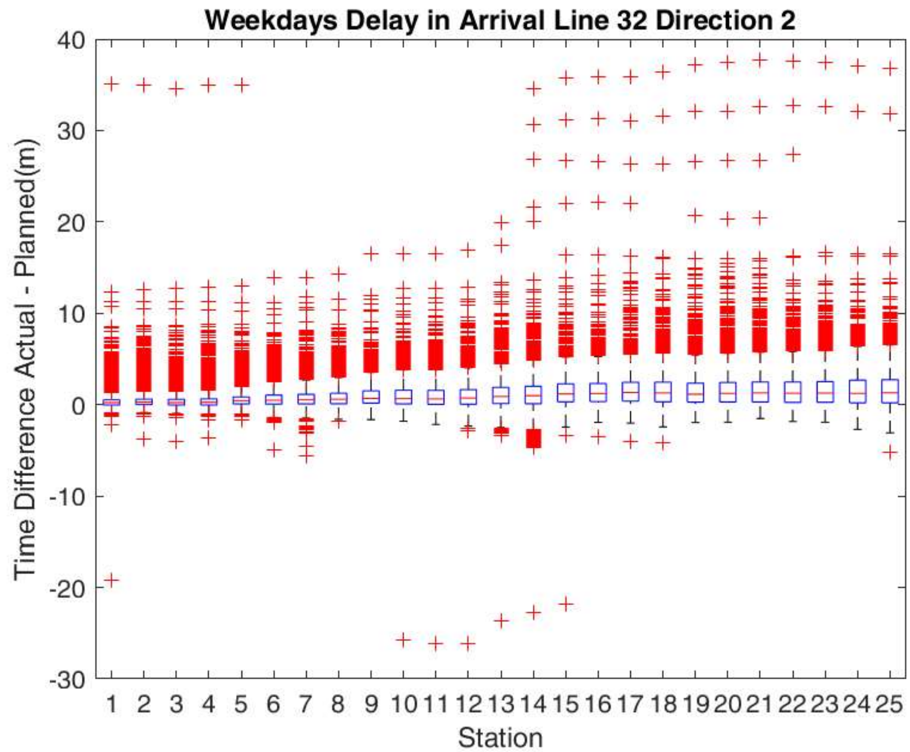

Figure A.9: Arrival Delays per station, November, Line 32, Direction 2

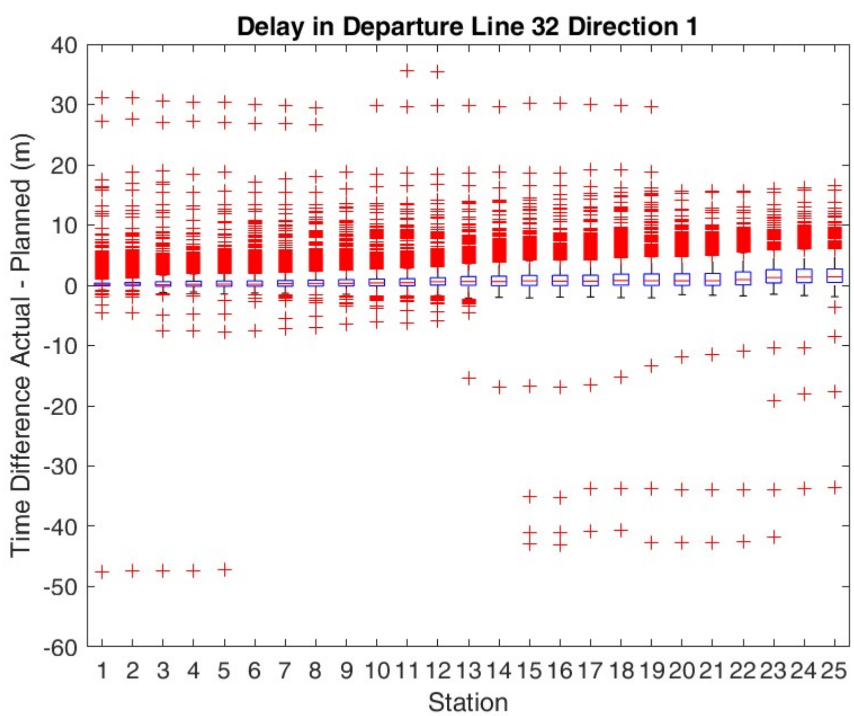

Figure A.10: Departure Delays per station, January, Line 32, Direction 1

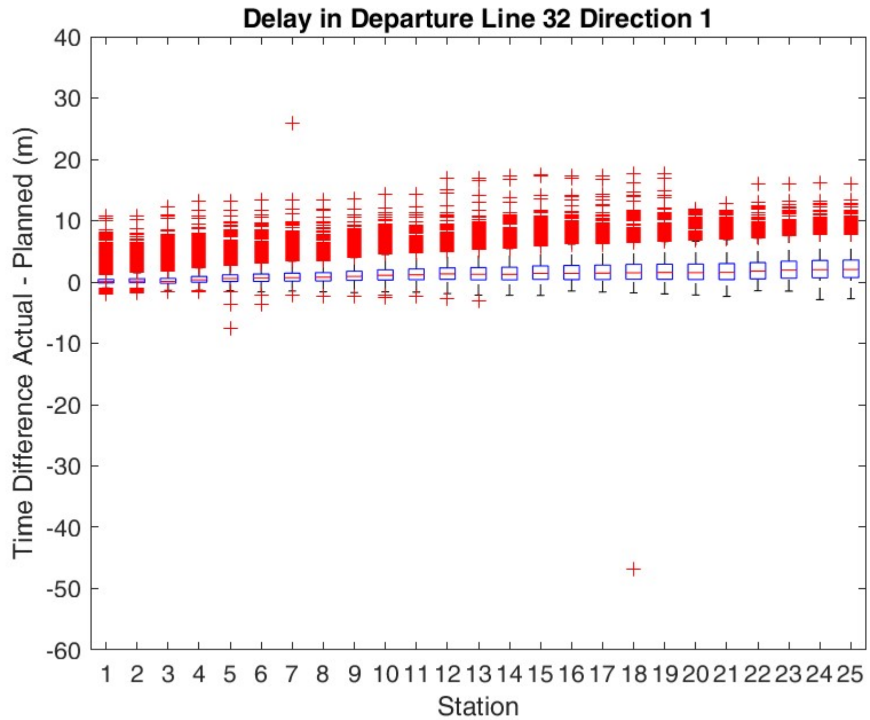

Figure A.11: Departure Delays per station, November, Line 32, Direction 1

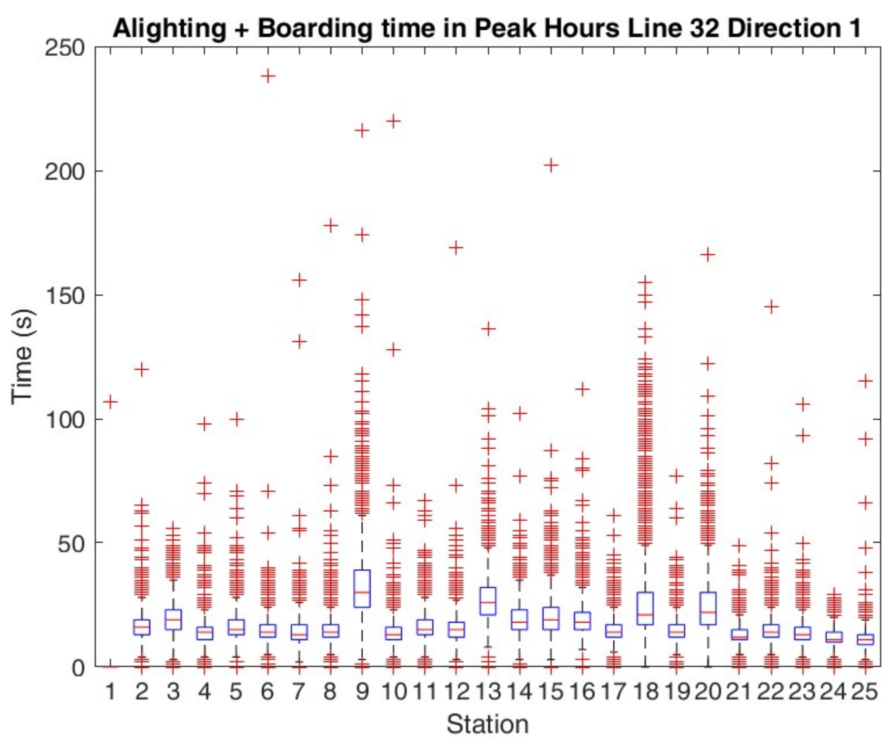

Figure A.12: Boarding & Alighting times per day, Peak Hours, January, Line 32, Direction 1

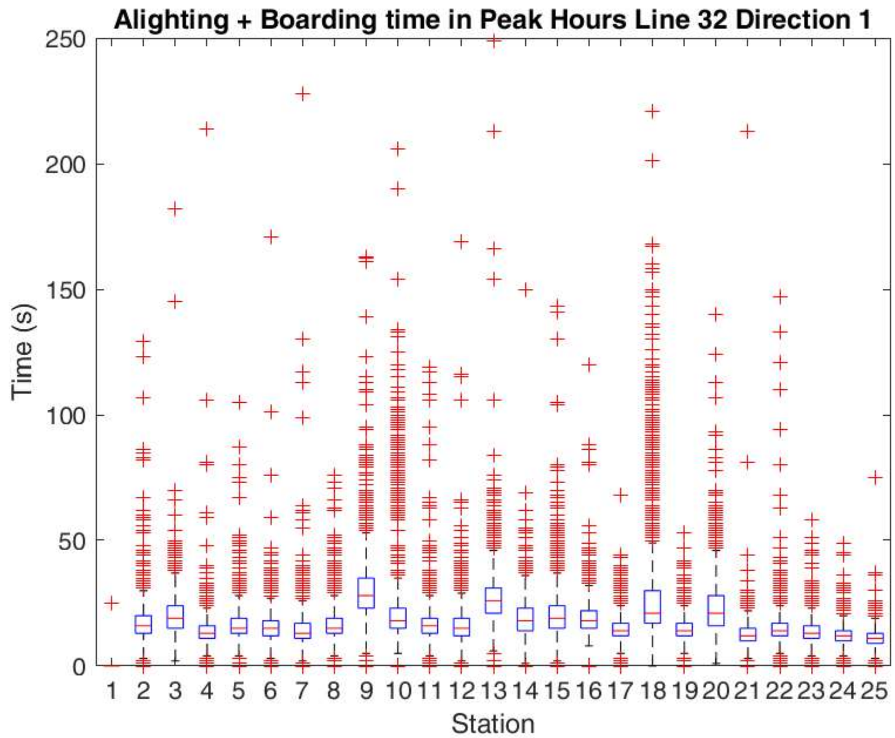

Figure A.13: Boarding & Alighting times per day, Peak Hours, November, Line 32, Direction 1

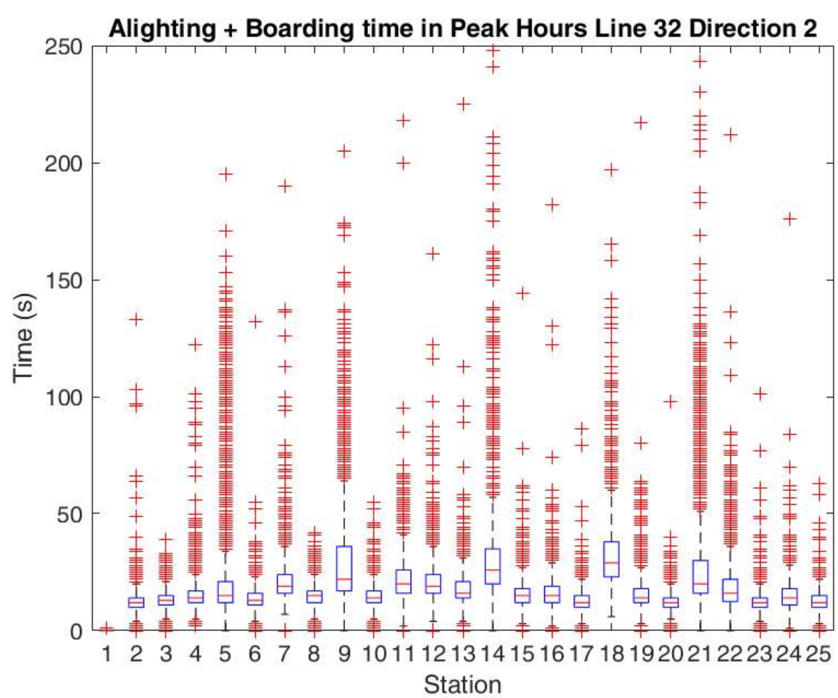

Figure A.14: Boarding & Alighting times per day, Peak Hours, November, Line 32, Direction 2

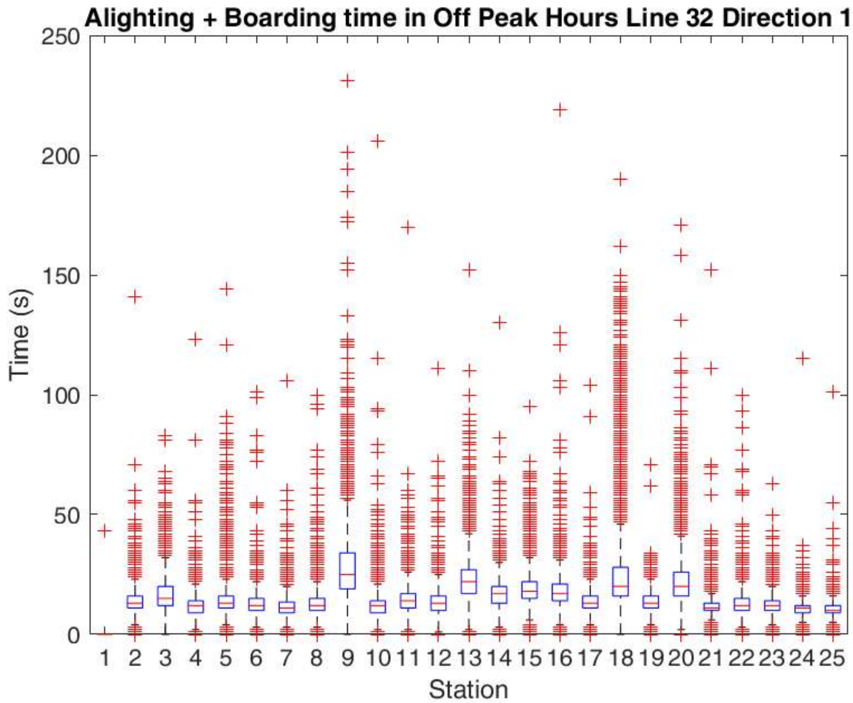

Figure A.15: Boarding & Alighting times per day, Off Peak Hours, January, Line 32, Direction 1

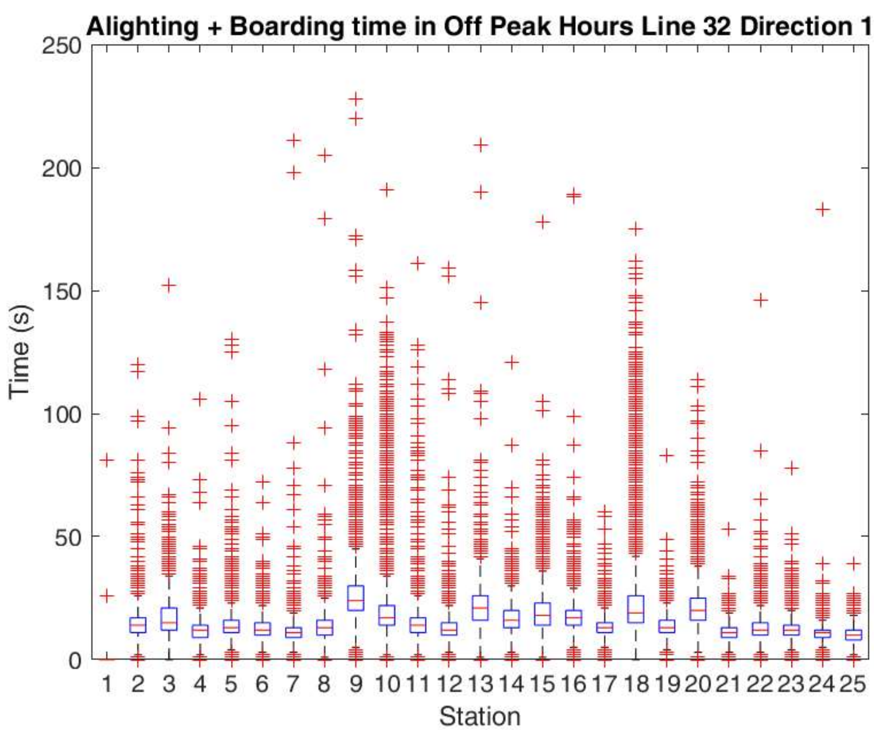

Figure A.16: Boarding & Alighting times per day, Off Peak Hours, November, Line 32, Direction 1

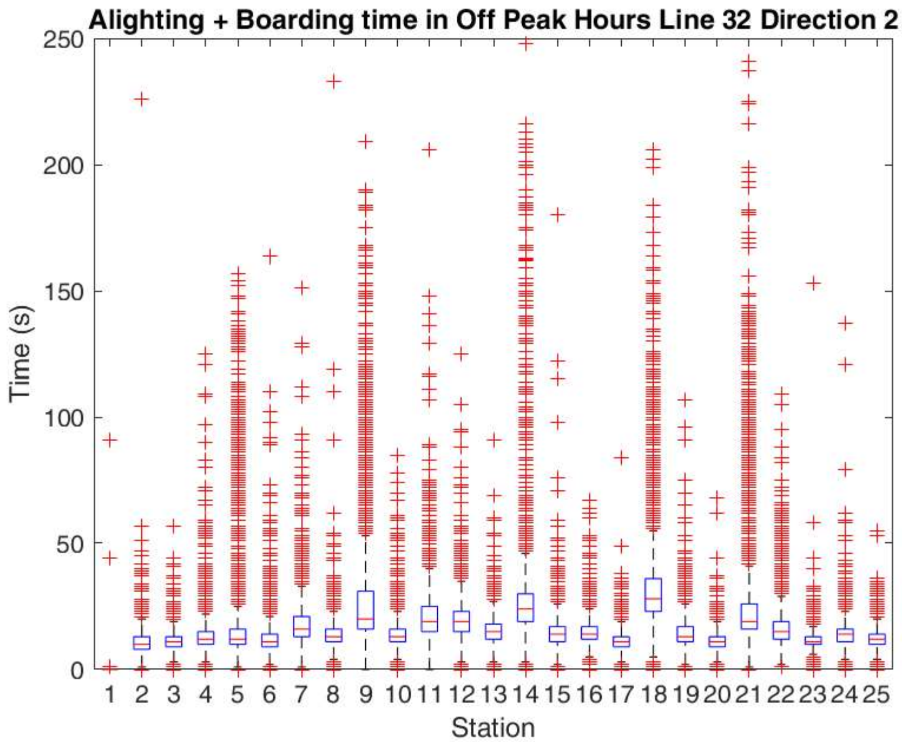

Figure A.17: Boarding & Alighting times per day, Off Peak Hours, November, Line 32, Direction 2

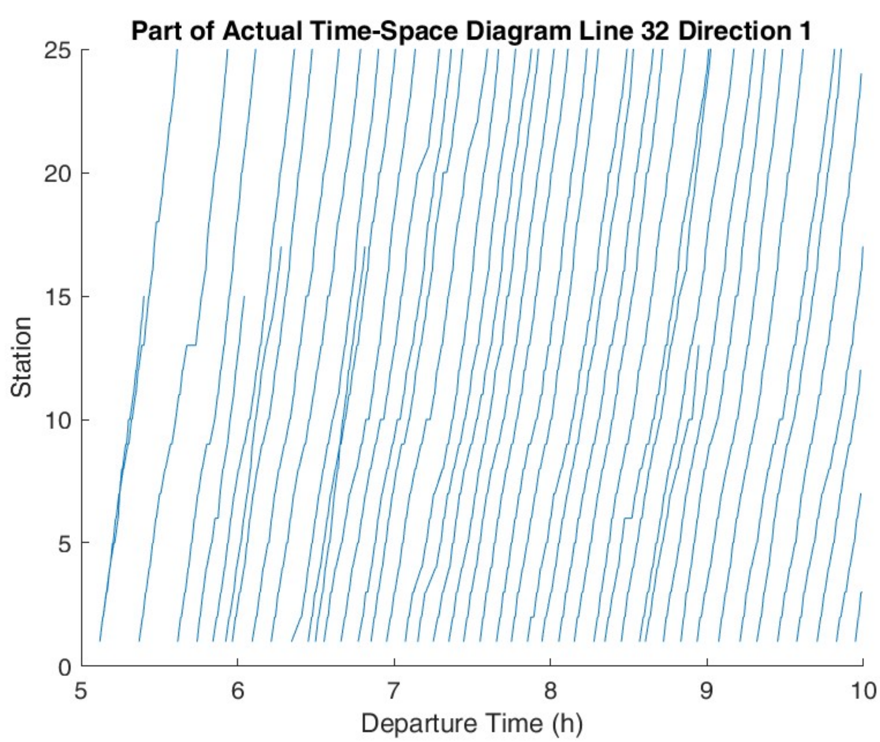

Figure A.18: Part of Actual Time-Space Diagram, Line 32, Direction 1, Monday 25.11.19

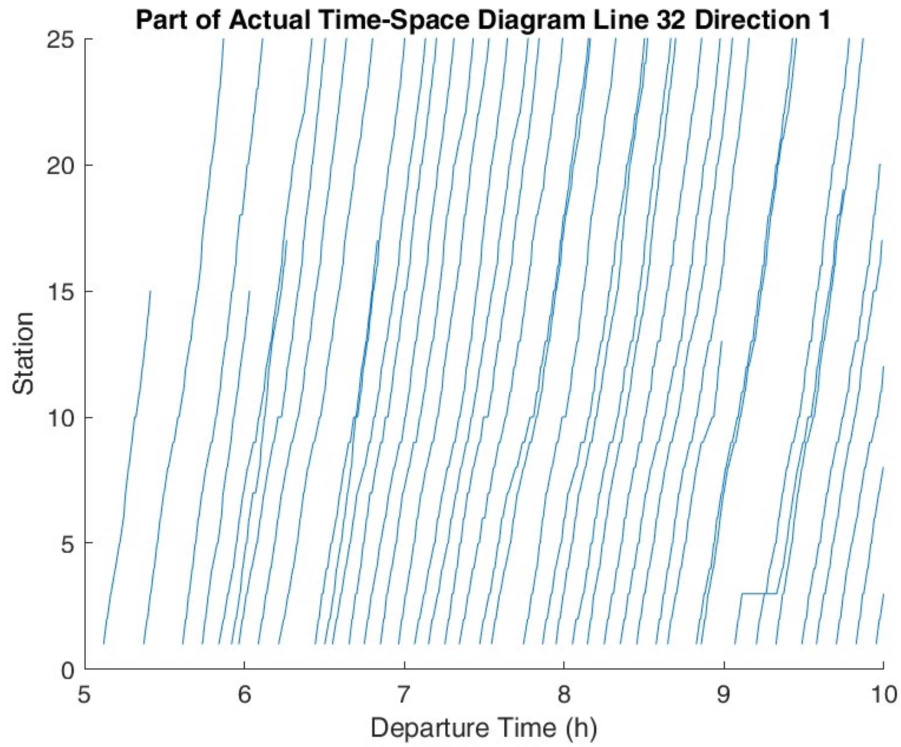

Figure A.19: Part of Actual Time-Space Diagram, Line 32, Direction 1, Tuesday 26.11.19

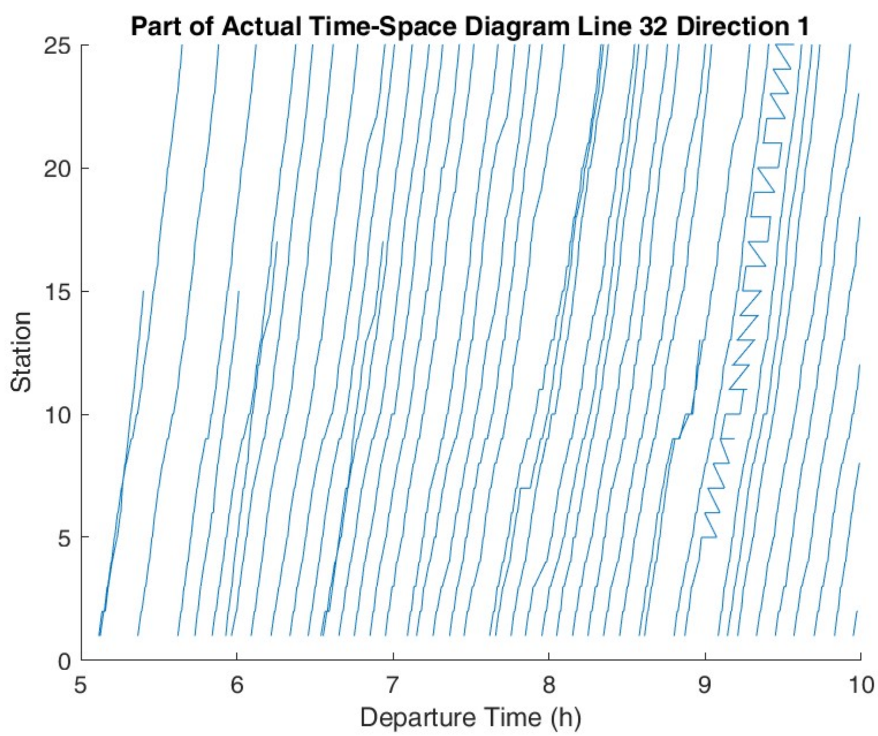

Figure A.20: Part of Actual Time-Space Diagram, Line 32, Direction 1, Wednesday 27.11.19

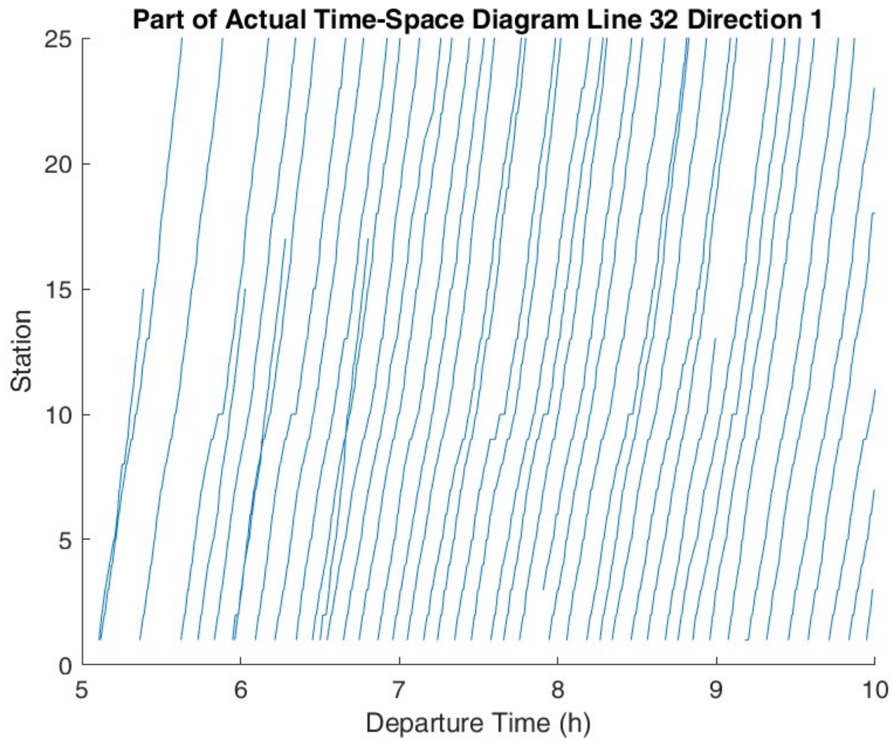

Figure A.21: Part of Actual Time-Space Diagram, Line 32, Direction 1, Thursday 28.11.19

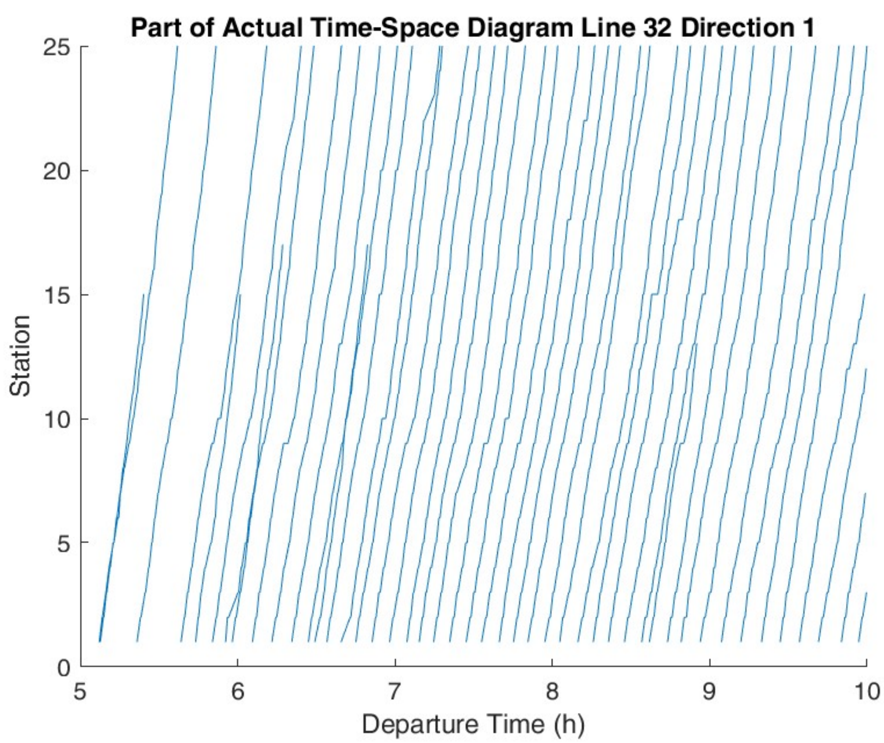

Figure A.22: Part of Actual Time-Space Diagram, Line 32, Direction 1, Friday 29.11.19

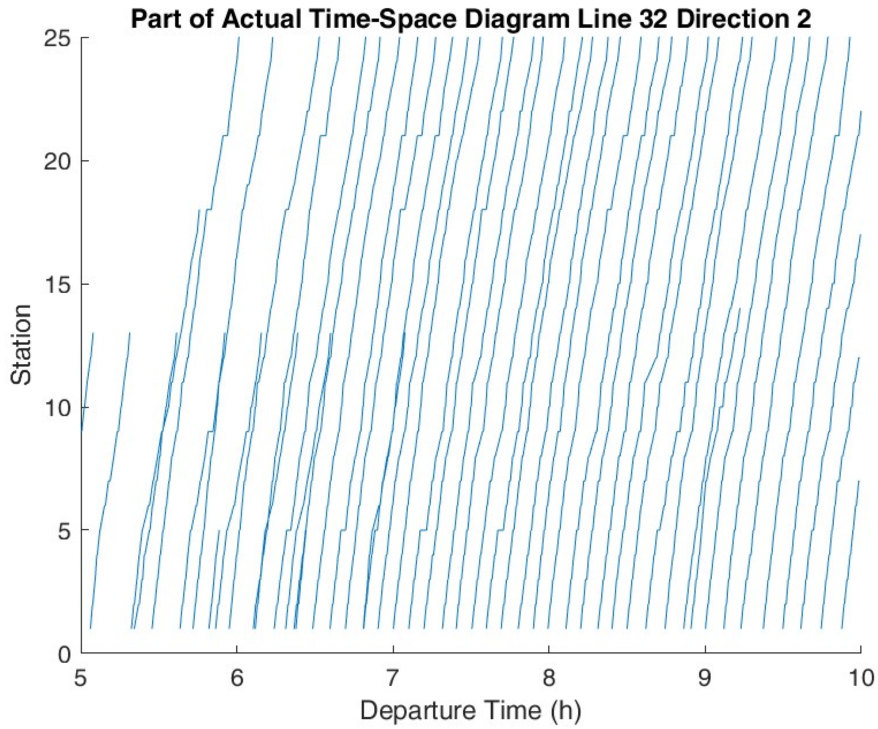

Figure A.23: Part of Actual Time-Space Diagram, Line 32, Direction 2, Friday 29.11.19