Raising frequencies on a high-frequency metro network and how new technologies can improve timetable reliability: a case study in Rotterdam

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Raising frequencies on a high-frequency metro network and how new technologies can improve timetable reliability: a case study in Rotterdam

by

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RET AARDIG ONDERWEG

Preface

As a boy who was – and still is – passionate for public transport, Rotterdam was an interesting city to grow up in. With a sizeable tram and metro network, many hours have been spent roaming the network, investigating every corner of the city and finding out where all these trams and metros actually go to when they leave the city. For everyone in my surroundings it was clear that an education and eventually a career in public transport was inevitable.

This thesis concludes my education at the TU Delft and is the last step in obtaining a master's degree in Transport & Planning. For me, this has been one important stop in my journey within the vast network that is public transport. Writing my master's thesis at Rotterdam's public transport operator RET has brought me back to my roots, where my passion for public transport began. It has provided me with a unique opportunity to experience the network I knew so well from a different perspective.

During the part months I have been supported by people, for which I am very grateful. Firstly I would like to thank Niels van Oort, my daily university supervisor. With his vast knowledge of and contacts within the public transport world, he as guided me though this process and has got me going again when I got stuck. Furthermore, I would like to thank professor Rob Goverde as the chair of my thesis committee, safeguarding the quality of my thesis. With his knowledge of OpenTrack he has provided me with critical and useful feedback, for which I am very happy. I also want to thank my external supervisor Wijnand Veeneman, who has provided me with insights from a different and interesting point-of view.

I have had a lot of help from people working at RET, helping me whilst doing their own job. I firstly want to thank my company supervisor Halmar Kranenburg for his support during my time at the RET, devoting a lot of time to helping me, discussing and giving feedback to freshly produced results. I will remember his patience with me and the endless – and sometimes time-consuming – talks we had, discussing the latest news in the interesting world of public transport. Furthermore, I would like to thank Wibout van Ede, for enabling me to graduate at RET and I would like to thank Richard Both, Harriët Joolink and Judith Mulder, who helped me with the OpenTrack model and provided me with data.

Lastly I would like to thank my family, friends and loved ones for their caring support, cups of tea and distractions in times when I needed it most.

Alexander Warmelink
Delft, October 2019

Summary

Mass rapid transit plays an important role in providing a sustainable form of transport in densely populated areas. According to World Health Organization (WHO) estimates, 54 per cent of the world's population lives in urbanised areas, and this number is increasing. Public transport operators worldwide are already experiencing ridership growth on their metro networks, and within 5 years, 5400km of new metro track will be built to accommodate that growth.

The Dutch city of Rotterdam and its public transport operator RET are facing similar challenges. Reports commissioned by Rotterdam city council predict that within Rotterdam's city limits alone, 50,000 new homes will be built within the next 20 years. Since the advent of the first metro line in Rotterdam, passenger numbers have been growing steadily. Given the growth rate of the city and the popularity of the metro network, it is predicted that within a few years, Rotterdam's metro network will reach its capacity limits. Therefore both RET and Rotterdam city council are interested in investigating measures to increase the network's capacity. Furthermore, as more and more metro networks around the world are building new automated lines or converting conventional lines into automated lines, Rotterdam's public transport operator is investigating the advantages and disadvantages of automation and is interested in the effects that automation has on the stability of its timetables.

Research outline

The goal of this thesis is to establish whether it is possible to maintain reliable services with frequencies of more than 24 trains per hour (i.e. intervals of 2.5 minutes) on the RET network. Two topics are covered. The first topic relates to the maximum service frequency that can reliably be achieved without altering the current infrastructure and signalling system. The second topic investigates the effects of automation, and aims to ascertain if a high-frequency schedule that would yield too unstable operations with the current signalling system would be feasible if a form of automation were implemented on Rotterdam's metro network.

To accomplish the research goal, the following main research question has been defined:

> *"In what way will the timetable performance of a metro network be affected when the existing service frequency is increased and what measures can be taken to increase capacity and reliability?"*

To examine the effects of increased frequencies, the microscopic simulation tool *OpenTrack* is used to simulate trains on the Rotterdam network following fictitious timetables. In order to ascertain the usefulness of OpenTrack, the model of the metro network is verified and validated, to determine the accuracy of the model. Following that, new scenarios are generated, for which timetables are constructed and implemented in OpenTrack. In each of the timetables, the frequencies on the network are increased, and by simulating them in OpenTrack, the performance of each of the scenarios can be analysed.

Assessment of alternatives

The scenarios are then assessed, consistent with the interests of the two main stakeholders: the public transport operator and the passenger. Reliable metro services are important for both the transport operator and the passenger. For the operator, delayed trains can lead to overtime for personnel, less time for maintenance or a higher strain on trains, infrastructure and personnel. Furthermore, many public transport operators are paid by transport authorities according to their punctuality performance. The passenger's objective is to minimise total travel time. Train delays can increase the travel time for a passenger. If a journey consists of more than one trip, train delays can lead to passengers missing their transfers, increasing their total delay even more. For a passenger, a timetable is reliable when they can rely on the trains to make connections and arrive at their destination on time.

Regular services are of interest to the operator and passenger as well. Services are regular when headways between trains are as planned and are consistent. Headways are related to passenger waiting times and therefore, regular services can contribute to a passenger's trip time and customer satisfaction. With regular services, passengers are distributed evenly over all trains, reducing the risk of overcrowding. This is important for the operator as well, not only as because of customer satisfaction, but regular services furthermore ensures that the available capacity is used efficiently.

Therefore, this research assesses timetable reliability based on the two measures mentioned above: punctuality and regularity. Both measures are quantified using two indicators. Regularity is represented by the *Percentage Regularity Deviation Mean (PRDM)*, which is the average rate at which the actual headway differs from the planned headway:

$$PRDM_j = \frac{\sum_i \left| \frac{H_{i,j} - H'_{i,j}}{H_{i,j}} \right|}{n_j}$$

Here, $H_{i,j}$ denotes the scheduled headway for train i at station j, $H'_{i,j}$ the actual headway and n_j the number of trains stopping at station j. A measure of *irregularity*, a PRDM of 0% indicates that the actual headways are exactly the same as the planned headways, indicating that services are fully regular. A PRDM of 100% indicates that the actual headway is twice as long (or zero) as the planned headway, indicating that bunching occurs.

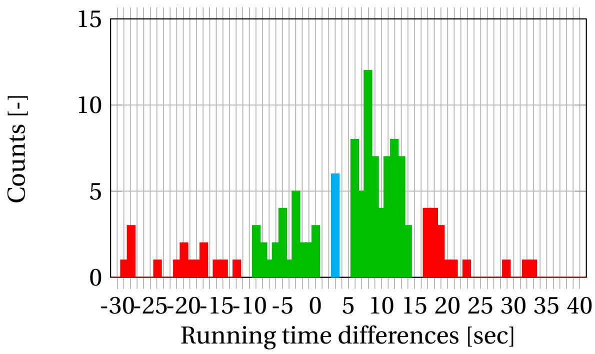
The indicator for punctuality is *dis-punctuality*, or the average amount of time that a departure from a station deviates from the scheduled departure. This can either be a departure too early or a departure too late.

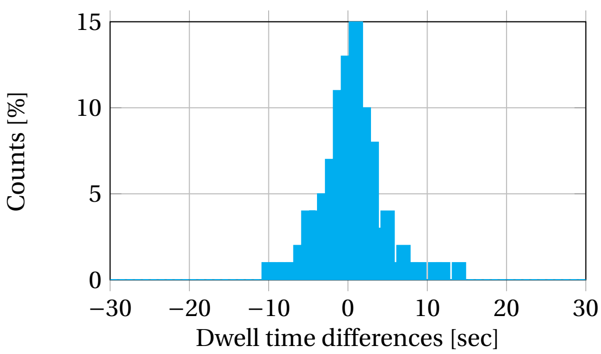
$$\bar{p}_j = \frac{\sum_i \left| t_{i,j}^{real} - t_{i,j}^{planned} \right|}{n_i}$$

Here, $t_{i,j}^{real}$ denotes the actual departure time for train i at station j, $t_{i,j}^{planned}$ the planned departure time, and n_i the number of trains. Measured in seconds, a dis-punctuality of 0 seconds indicates that all departures are perfectly on time. A dis-punctuality of, for example, 60 seconds indicates that a train has departed from a station with a departure time that deviates 60 seconds from the planned departure time.

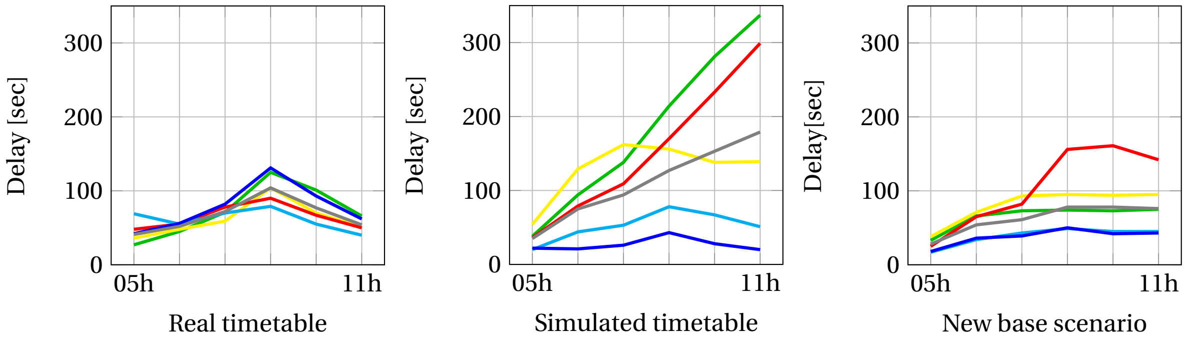
Modelling the metro network

The model of the Rotterdam metro network has been verified and validated. Stochasticity has been implemented in OpenTrack by adding variations to station dwell times, using a *Delay distribution* function at every station. This allows OpenTrack to pick a random number for the dwell time at a station following the implemented delay distribution. The running and dwell times have been compared with real-life data, extracted from the train detection system, a part of the signalling system. The two figures below show the number of sections (left figure) or stations (right figure), whose simulated running or dwell time differs from the real data. The running times show larger differences. However, the running times in OpenTrack are deterministic and therefore, larger differences are to be expected.





The model has been validated by comparing the performance of the real network with the OpenTrack network. A clear distinction can be found in performance between the east-west axis and the north-south axis. The east-west axis performs significantly worse in OpenTrack than in real life, while the north-south axis performs significantly better than in real life. The three figures below shows that the light-blue line D performs similarly in the simulations as in the real timetable, while the dark blue line E performs better than in the real timetable, due to the lack of trams on the *RandstadRail section* in the simulation. Lines A, B and C show escalating results in the simulated timetable, with delays increasing radically as time progresses. The cause for this is the lack of dispatching in OpenTrack and the inflexibility at the troublesome terminal stations *Pernis* and *Schiedam*. This hypothesis is tested by creating a new timetable, with the same pattern and frequencies, but with the trains not reversing at those stations. The right figure now shows that, apart from line C, the performances are realistic, showing similar levels of delay as in the real timetable. The high values of line C in the simulated base scenario are due to the shortage of running time supplements in the timetable. The right figure demonstrates that OpenTrack is able to provide realistic results, though its limitations have to be kept in mind.



Scenarios and results

To investigate which frequencies can still lead to reliable services on the RET metro network, four growth scenarios have been created, and for each scenario a new timetable has been written. In each scenario, the trunk section intervals are decreased. By simulating all scenarios, the performances of each timetable can be assessed. Furthermore, four operational variants have been created in which two different infrastructural upgrades are featured: moving block signalling and driverless trains. By applying those variants to the growth scenarios which yield unreliable services, the effectiveness of the infrastructural upgrades can be assessed. Different combinations of growth scenario and operational variants have been made, leading to the ten different scenarios that have been investigated:

No.	Growth scenario	Operational variant
1	Base scenario 2021	FB-GoA1
2	Scenario 150	FB-GoA1
3	Scenario 120	FB-GoA1
4		FB-GoA3/4
5		MB-GoA1
6		MB-GoA3/4
7	Scenario 100	FB-GoA1
8		FB-GoA3/4
9		MB-GoA1
10		MB-GoA3/4

The performances of the simulated growth scenarios are presented in the table below. A threshold level has been determined, stating that a timetable is too unreliable if the average overall dis-punctuality is higher than 120 seconds. In general, the lower the intervals on the trunk section, the higher the average dis-punctuality. Based on the threshold level mentioned earlier, the dis-punctuality of Scenarios 120 and 100 is too high to accept as reliable services. Scenario 150 performs remarkable well. Even though the intervals on the trunk sections are significantly lower, the average dis-punctuality is only 9 seconds lower than the base scenario.

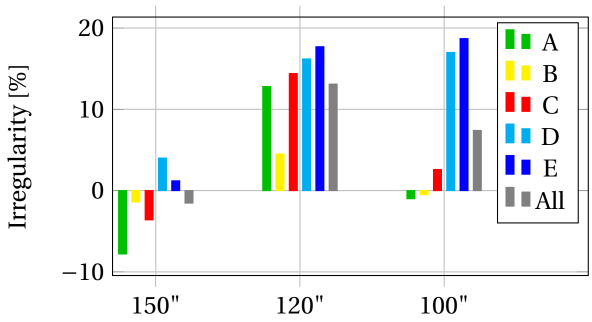
The overall rate of irregularity does not follow the same trend as dis-punctuality in the way that the lower the intervals, the higher the dis-punctuality. It can be seen that services are more regular in Scenario 150 and Scenario 100 than in the base scenario and Scenario 120 respectively, although the former two scenarios have lower trunk section intervals than the latter two scenarios. The reason for this phenomenon is the spread of trains on the branch lines. With an even number of train services on the trunk sections, it is easier to ensure an even spread on the branch lines. With an uneven number of train services on the trunk sections, this cannot be achieved.

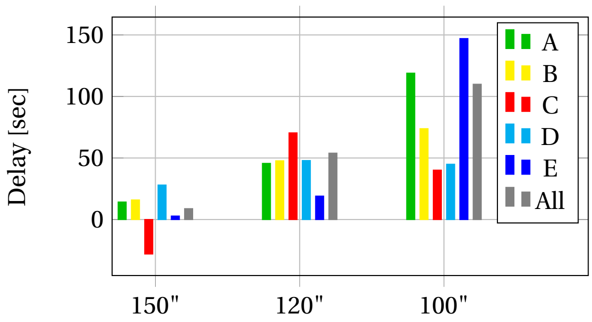
Scenario	Irregularity [%]	Diff. to base [%]	Dis-punctuality [sec]	Diff. to base [%]
Base 2021	17.9	–	70	–
Scenario 150	17.0	- 5	79	+ 13
Scenario 120	30.8	+ 72	124	+ 77
Scenario 100	26.4	+ 55	180	+ 157

The figures below show the differences in performance of Scenarios 150, 120 and 100 in respect to the base scenario, differentiated per line. A clear distinction can be found between lines A, B and C on the east-west axis and lines D and E on the north-south axis. Lines A, B and C follow the general trend that they are more regular in scenarios with an even number of services on the trunk sections than in scenarios with an uneven number. For lines D and E the case is different. Both lines are only 4 and 1 percentage point more irregular in Scenario 150 than in the Base scenario, even though the intervals in Scenario 150 are 25% lower than in the base scenario. While irregularity improves dramatically for lines A, B and C in Scenario 100 compared to Scenario 120 and even reach irregularity levels similar to the base scenario, for lines D and E irregularity remains just as high in Scenario 100 as in Scenario 120.

The reason for the poorer performance of lines A, B and C is the small amount of running time supplements for the lines on the east-west axis. The evenly spread trains for the "even" scenarios (150 and 100) provide each train on that axis with the same amount of running times supplements, while in the "uneven" scenarios (Base and 120) the availability of supplements depends on the pattern of the trains on the branch lines. When running time supplements are scarce, this will negatively affect performance.

The reason why line E performs poorly in Scenario 100 is due to the *safe haven* procedure on the section of track between *Rotterdam Centraal* and *Melanchthonweg*, preventing trains from leaving a station while the next station is still occupied. In Scenario 100, the projected intervals in the timetable are lower than the minimum intervals defined by the distance between *Blijdorp* and *Melanchthonweg*, causing delays.





Analysis of the performances per section has revealed that a sections with regularly planned headways perform better in regularity than sections with irregularly planned headways. For the case of dis-punctuality, the number of train and therefore the length of the headway is important. Sections with fewer services are more punctual than sections with more services.

Analysis of the growth Scenarios 120 and 100 with variant *FB-GoA1* has shown unreliable services and are therefore not preferable to be applied in practice. To improve the performance of these scenarios, this research has investigated two upgrades to the network that can improve reliability: moving block signalling and train automation to improve turnaround times at terminal stations. The table below shows the results of implementing either one or both of these measures to Scenario 120. All upgrade variants show improvements compared with the unaltered scenario. The removal of the human factor yields an irregularity of 27% – an improvement of 12% compared to variant *FB-GoA1* – and a dis-punctuality of 95 seconds, which is an improvement of 23% compared to variant *FB-GoA1*. The introduction of moving block technology has more drastic improvements. Variant MB-GoA3/4, featuring both the new signalling system and the new operational regime, performs with an irregularity of 16.6% and a dis-punctuality of 54 seconds even better than the base scenario with the current infrastructure, although the gains compared with moving block signalling only (variant *MB-GoA1*), especially for dis-punctuality, are low.

Scenario	Variant	Irregularity [%]	Diff. to base [%]	unpunctuality [sec]	Diff. to base [%]
Base	FB-GoA1	17.9	–	70	–
120	FB-GoA1	30.8	+ 72	124	+ 77
	FB-GoA3/4	27.2	+ 52	95	+ 36
	MB-GoA1	18.5	+ 3	57	- 19
	MB-GoA3/4	16.6	- 7	54	- 23

The table below shows the overall performance of the four operational variants applied to growth Scenario 100. With an irregularity of 26.4 % and an unpunctuality of 180 seconds, it is clear that the current infrastructure is not equipped for Scenario 100. Like Scenario 120, the both moving block signalling as automated trains result in an improved punctuality. Both measures together are able to reduce punctuality rates similar to those of the base scenario. The implementation of only automated trains while maintaining fixed block signalling is able to reduce punctuality by 45 seconds to 135, which is still too high. Moving block signalling only is able to improve punctuality more, bringing it down to an acceptable 81 seconds. Adding train automation as upgrade in combination with moving block signalling seems not to have a great effect, reducing dis-punctuality by only two seconds.

Therefore, based on punctuality only, introducing moving block signalling only seems to be sufficient. However, the situation is different for irregularity. Transitioning from fixed block to moving block while maintaining the current state of operation seems to have an adverse effect and only increases irregularity. Moreover, the implementation of automated trains only rather than both measures is the most beneficial to regularity, as this variant leads to the lowest irregularity rate of 19.6%.

Scenario	Variant	Irregularity [%]	Diff. to base [%]	Dis-punctuality [sec]	Diff. to base [%]
Base	FB-GoA1	17.9	–	70	–
100	FB-GoA1	26.4	+ 47	180	+ 157
	FB-GoA3/4	19.6	+ 9	135	+ 93
	MB-GoA1	30.0	+ 68	81	+ 16
	MB-GoA3/4	24.0	+ 34	79	+ 13

The findings in Table 6.4 lead to the suspicion that for the case of Scenario 100, the fixed block signalling system serves an alternative purpose. By forcing the trains to keep a distance from each other using fixed blocks, the signalling system contributes to maintaining regularity. By introducing moving block signalling and therefore enabling trains to run closer to each other, irregularity increases rather than decreases.

Table 6.4 shows that the increase of buffer times at terminal stations plays a more dominant role in improving regularity, as it is able to reduce irregularity by 20 - 26%. The lowest irregularity rates can be found in variant *FB-GoA3/4*, which feature automated reversing only and still maintains fixed block signalling.

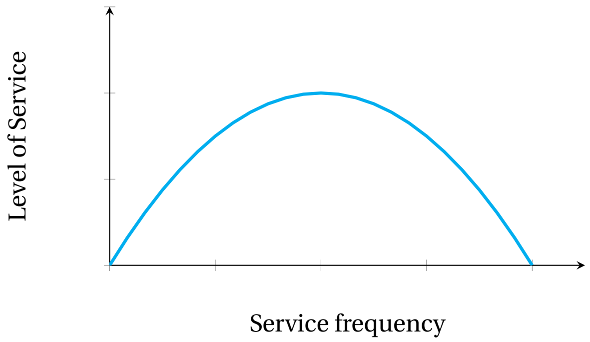
Conclusions

This research has applied a quantitative approach to assess the performance of an executed timetable. It has developed two indicators that provide a quantitative assessment from two different points of view. It has furthermore determined which factors affect the stability of timetables, and has shown in a case study how these factors play a role in timetable reliability.

Based on the two indicators used throughout this research, is has been observed that the overall performance of a timetable decreases if the intervals on the busiest section of a given network are decreased, under the condition that the infrastructure remains unaltered. The average delay on the network exceeds 120 seconds when intervals on the trunk sections of the network are 120 seconds and lower.

This research has found that for the Rotterdam metro network, a timetable with structural trunk section intervals of 150 seconds will still lead to reliable operations. With an irregularity rate of 17% and unpunctuality of 79 seconds, this scenario performs around 40% comparable to the simulated base scenario, even with a capacity increase of 33% on the trunk sections. Reliability down to these intervals mainly depends on the construction of the timetable. By allocating a sufficient amount of buffer time and running time supplements, incurred delays can be contained and reduced to a minimum. Furthermore, by ensuring that all trains are spread as evenly as possible in time, the available capacity can be used as efficiently as possible, distributing the available time supplements evenly over all trains. With intervals lower than 150 seconds, the Level of Service starts deteriorating, with average delays exceeding 120 seconds.

For the current Rotterdam metro network, an service pattern optimum has been found: a timetable with trunk section frequencies of 24 Trains per Hour (tph) (intervals of 150 seconds) will yield the highest Level of Service. With lower frequencies, reliability is higher, yet the Level of Service is lower due to a lower service pattern being offered. Frequencies higher than 24 tph will result in unreliable services, resulting in a lower Level of Service as well. Therefore, a relationship exists between service frequency and level of service. An example of how frequency and level of service can be related is shown in the Figure below:



To achieve reliable services with intervals of 120 seconds or less, RET has to invest in more radical changes to its network. The benefits of moving block signalling and automated reversing operations are clearly observable. Whereas with the current infrastructure, services start deteriorating when intervals are lower than 150 seconds, automated trains, and in particular moving block signalling, are able to provide reliable operations for these intervals. Although both measures are able to improve dis-punctuality, it is moving block signalling that produces the the highest reductions and cut dis-punctuality by 48%. Furthermore, with moving block installed, the added measure of automated trains does not provide any additional gains in terms of dis-punctuality.

However, with very low trunk section intervals of 100 seconds, regularity is more and more important. This is when both upgrade measures start showing different results. Whereas automated trains reduces irregularity, moving block signalling increases irregularity. While fixed blocks served an additional purpose of maintaining headways, moving block signalling removes that barrier, allowing trains to achieve far less headways. It is at this point where transport operators and authorities have to face a choice: to either strive for punctual services or for regular services. In a tree-like network, this decision is not straightforward: striving for punctual services may result in irregular services on the densely operated trunk sections, while striving for regular services on the trunk sections may lead to a poor Level of Service on the branch lines.

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List of Abbreviations

ATP Automatic Train Protection. 19, 23

CBTC Communication-Based Train Control. 21, 85

GoA Grade of Automation. 22–26, 62, 63, 77

HTM Haagsche Tramweg Maatschappij. 31, 84

LoS Level of Service. x, xvi, 10, 25, 55, 73, 77, 81, 88, 89

MRDH Metropoolregio Rotterdam Den Haag. 73

PRDM Percentage Regularity Deviation Mean. vi, 9, 10

PSD Platform Screen Doors. 25

RATP Régie Autonome des Transports Parisiens – the public transport operator in Paris. 25

RET Rotterdamse Electrische Tram. v, vii, x, xv, xvii, 3, 13, 28–31, 35–40, 46, 48, 53, 55–57, 60, 63–65, 73, 84, 85, 89, 90

SPAD Signal Passed at Danger. 25

tph Trains per Hour. x, 17, 84, 85, 87–89

UITP International Association of Public Transport. 1, 22

WHO World Health Organization. v, 1

1
Introduction

1.1. Background

Mass rapid transit plays an important role in providing a sustainable form of transport in densely populated areas. According to the World Health Organization (WHO), 54% of the world's population lives in urbanised areas and each year this number will increase with around 1.6% per year (WHO, 2018). The United Nations predict that by 2050, 68% of the world population will be living in urban areas (United Nations, 2018). With cities expanding, sustainable urban transport should grow alongside the cities to guarantee mobility in large metropolises.

Public transport operators worldwide are already experiencing ridership growth on their metro networks. The International Association of Public Transport (UITP) reports that in the past six years, global metro ridership has increased by 20% (UITP, 2018a), which is shown in Figure 1.1.

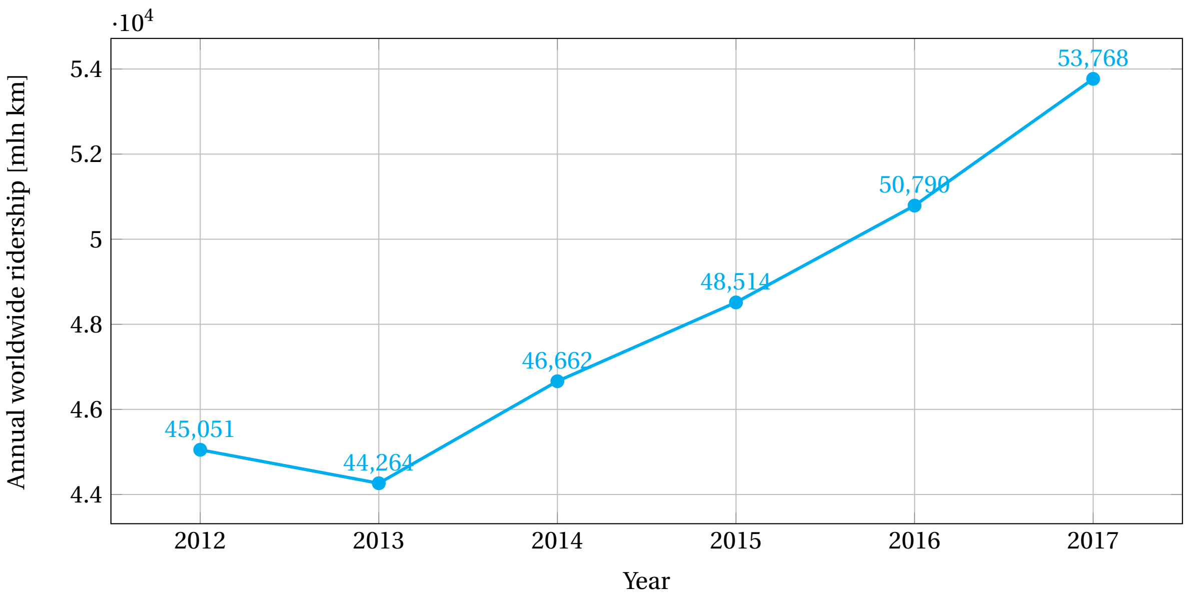


Figure 1.1: Global ridership evolution over the past six years in millions of passengers (UITP, 2018a)

The UITP predicts that ridership figures will continue to grow. Within the next 5 years, 5400km of new metro track will be built, shown in Figure 1.2.

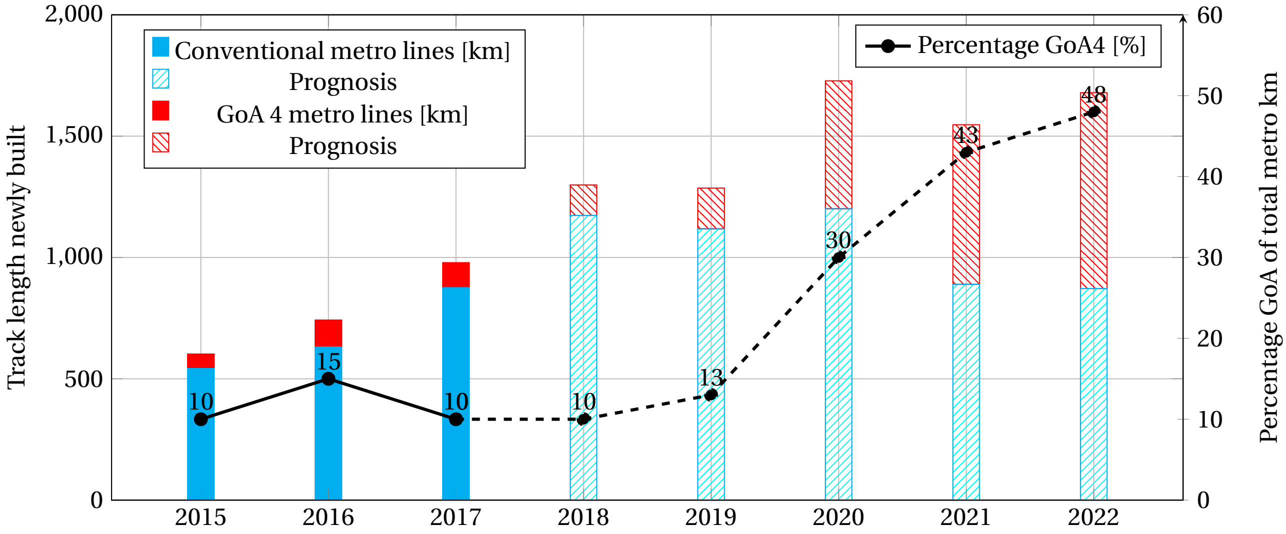


Figure 1.2: The global total track length of metro lines being built in the coming years (UITP, 2018a).

With limited space and funding available in dense urban areas, upgrading existing infrastructure rather than building new metro lines can provide good opportunities to guarantee mobility in urban areas. However, elongating or widening trains to increase capacity are often not preferred solutions, as expanding existing infrastructure in dense urban areas can be very costly or even impossible. Increasing service frequencies on the other hand, can be more easily achieved, as this requires no spatial expansion of existing infrastructure.

Multiple cities around the world achieve and maintain reliable metro services while operating with very high frequencies of more than 24 trains per hour. The metro system in Copenhagen, Denmark achieves a frequency of 30 trains per hour during rush hour periods (Københavns Metro, 2019). The operator of Paris Metro Line 1 achieves intervals of 85 seconds during rush hours (RATP, 2018).

Both examples above are fully automated metro lines and have no interaction with other traffic. Automated metros are becoming increasingly popular among metro operators around the world. Several public transport operators indicate that automation can enable very high frequencies up to 42 trains per hour and can reduce dwell times, operating costs and turnaround times (Cohen et al., 2015). The Paris and Copenhagen examples show that automation can lead to high service frequencies and high reliability rates. The owner of the Copenhagen Metro – Metroselskabet I/S – reports that their punctuality rate reached 98.5% in 2017 (Metroselskabet, 2017). As of 2016, 55 automated lines were operated in 37 cities around the world, amounting to a total length of around 800 km of automated lines (UITP, 2016). By 2025, this number will increase to around 2300 km. Automated metros, proponents say, will increase efficiency and enable higher frequencies than conventionally driven metros.

However, as many existing metro lines are relatively old and conventionally driven, it is often very costly to convert them to automated metros. It is therefore very interesting to see what the lowest interval technically achievable is, while still being conventionally driven. For example, the public transport operator in the Dutch city of Rotterdam RET currently maintains intervals of 200 seconds on the trunk section of its metro network. They claim that intervals of 90 seconds are technically possible on their metro system.

However, maintaining a reliable service might prove problematic. On paper, very high frequencies could seem feasible, yet in practice all sorts of effects could influence operations negatively. Variations in running and dwell time occur naturally and are perfectly normal. However, the problem is that by introducing more trains on the network, there will be less spare time to cope with perturbations. Variations in running and dwelling times could more easily percolate through the network and more easily lead to more serious disruptions. The risk therefore exists that the effort to increase the level of service by increasing the service frequency will lead to a lower rather than a higher level of service.

In the literature, two main topics are heavily investigated. The first is robustness in railway timetables. Different definitions are given for robustness, but from different perspectives. Andersson et al. (2013), Salido et al. (2008), Takeuchi et al. (2007) and Schöbel and Kratz (2009) define robustness from a passenger perspective, defining a timetable as robust when travel time for passengers is minimised and when delays do not cause passengers to miss connections during their trip. Solinen et al. (2017), Bešinović et al. (2016), Carey (1998) and Lee et al. (2017) look at robustness from a more technical point of view, calling a timetable robust when initial delays do not influence other trains. Goverde (2007) defines a timetable as robust when a delay does not impact on the next time period of a periodic timetable. From either perspective, both groups of authors define a timetable as robust when a delay can be contained, eliminating the effects of that delay by the end of the day or trip.

Other authors on robustness and timetable stability discuss measures to recover from substantial delays, aiming to return to the initial, undisturbed, situation. They mainly focus on measures at operational level, to minimise the effects, once a disruption has actually occurred. Carrel et al. (2010) for example, discuss a case on the London Underground, but their paper is mostly explanatory, showing why certain control tactics have been applied to that specific case. On the topic of metro systems, Durand et al. (2018) focus on disruption management from a passenger perspective. Other studies of reliability of scheduled services are mainly limited to surface systems, such as high-frequency bus lines (Werff et al., 2018; Imran, 2018) or urban tram lines (Roelofsen D. et al., 2018).

Though there is an abundant amount of literature available on robustness definitions and disruption management, limited information is available on what measures are needed to enable frequencies of more than 24 trains per hour. More insights are needed in how a stable high-frequency schedule can be implemented and maintained.

Maintaining high frequencies on metro lines faces different challenges. Surface systems have to navigate through traffic, and therefore maintaining a reliable service with varying running times is difficult. Although metro systems are closed systems and interaction with other traffic is not an issue, they are technically more complex. Infrastructure constraints and vehicle characteristics play a more important role in defining minimum intervals. There is not much literature available on infrastructural requirements to enable very high frequencies. Van Oort and Van Nes (2010) discuss rail terminal design and the effect this has on transit service reliability, but they limit their research to frequencies up to 24 trains per hour. Wang et al. (2017) has investigated different types of terminal stations an has found a minimum headway of 113 that can be achieved at terminal stations.

The Dutch city of Rotterdam and its public transport operator *Rotterdamse Electrische Tram (RET)* are facing similar challenges. They predict that they will face capacity problems on the metro network in the near future. RET is investigating options to increase capacity on the network. They are interested in finding out whether the current infrastructure is capable of providing reliable high-frequency services to increase capacity.

1.2. Scope and goals

The main goal of this thesis is to investigate whether it is possible to maintain a reliable service with frequencies of more than 24 trains per hour. This research covers two main topics. The first is to investigate the service performance with the highest frequency that is technically possible, with little or no infrastructural changes. The second is to investigate what measures need to be taken to increase the maximum capacity or improve reliability of operations. An important part of this topic is to ascertain which technical measures can improve the reliability of very high frequency services (24 trains per hour or more), or even enable those services.

Maintaining regular services is relevant for both the operator and the passenger. The objective for the metro network operator is to maximise capacity on a line with minimal resources. Irregular services have a negative effect on capacity. With short intervals, there is little opportunity to recover from (small) delays. This is especially important at bottlenecks, for example terminal stations or stations where trains merge or diverge.

The passenger also benefits from highly regular services. With increased frequencies, the volume of passengers is spread over more trains, resulting in a higher level of service, resulting in a lower occupancy rate for each train. Higher frequencies also mean that the waiting time for the passenger reduces, shortening their total travel time. Regularity ensures that all passengers are evenly spread over subsequent trains and keeps waiting times minimal.

1.2.1. Research questions

The main research question has been defined as follows:

> *"In what way will the timetable performance of a metro network be affected when the existing service frequency is increased and what measures can be taken to increase capacity and reliability?"*

To answer the main research question, the following sub-questions have been defined:

1. What is the state-of-the-art regarding high-frequency metro operations?
2. How can the reliability of metro networks be assessed?
3. In what way can the use of microscopic simulation tools create opportunities to investigate the implementation of high-frequency operations?
4. Which factors affect the reliability of a timetable?
5. Given the current existing infrastructure, up until which service frequency are reliable operations still feasible?
6. In what way can automation help to increase capacity and reliability?

1.2.2. Contributions

This research will provide insights into the feasibility of metro services with frequencies of more than 24 trains per hour. As mentioned in Section 1.1, the literature presents plentiful solutions on operational level to minimise the consequences of delays, but there is less to be found on strategic and tactical level. Also on the topic of the advantages of automation in respect to timetable stability, there is little scientific material to be found, other than the remark that automation might enable higher frequencies.

For this research, a clear and simple methodology is developed to analyse the execution of a timetable. It enables the operations to be scrutinised at network level, but also the performance on different sections, at different stations and during different time periods. Using two different indicators, the interests of the two most important stakeholders are represented and a quantitative analysis of the quality of the performance of a given timetable is provided.

The assessment will not be limited to real-life train services. An important part of this research is the use of microscopic simulation tools. With this model, timetables that have not yet been implemented can be scrutinised without having to test them in practice. This research will also shed light on the practicality of using these types of tools to investigate capacity increase and stability of metro lines.

1.3. Limitations

The following considerations have not been included in this research:

- The track layout has not been altered: switches, number of platforms at stations and number of reversing tracks at terminal stations remain the same,
- The characteristics of the trains remain the same
- The running times of each individual track segment remain the same as in the current timetable
- Only one timetable is created for each scenario. There are many timetables that can be created for every scenario and timetable with the highest performance within the scenario can be determined, however this has not been done for this research

- Scenarios with trunk section intervals of lower than 100 seconds have not been scrutinised

An important effect that has not been taken into account in this research in *bunching*. Bunching occurs in high-frequency transport links and is caused by a (small) delay of a train or vehicle. As due to this delay, headway with its predecessor has increased, the number of passengers accumulated on the platform before the delayed trains arrives is higher than normal. As a result, the dwelling process occupies more time, increasing its delay even more. At the next station, the effect of the delay is stronger than at the previous station, and as the route progresses, the delay of the train increases. Meanwhile, the train *behind* the delayed train experiences a headway *shorter* than normal, and therefore encounters fewer passengers than normal at the stations. As a result, the dwelling process is quicker, causes this train to fall ahead of schedule. The more stations that are passed, the initially delayed train will fall more and more behind schedule, while the train behind it, fill travel more and more ahead of schedule and eventually they will meet, effectively cutting the intended frequency in half.

This effect requires an interactive relationship between headway and dwell time. The longer the headway between two vehicles, the longer the dwell times, and vice versa. This feedback loop has not been implemented in this research and the OpenTrack model, and therefore, the effects of delayed trains are not a strong as would be, were this effect taken into account.

1.4. Report Outline

Chapter 1 gives the context of this research. It sheds light on the challenges that are faced in the presented case study. Furthermore, the objective of this thesis is given and the research questions are posed.

The methodology that is developed to answer the research questions is presented in Chapter 2. It explains the operation of the microscopic simulation tool OpenTrack, used for this research, and the two main indicators used are discussed.

Chapter 3 discusses the different factors that affect the stability of timetables and show what elements influence the stability in which way.

In Chapter 4, the case study is presented, and the OpenTrack model representing the network of the case study is verified and validated.

Following the case study, multiple scenarios have been generated to overcome the challenges that the public transport operator in the case study faces. The characteristics of the different scenarios are presented in Chapter 5 and the performances of each scenario in OpenTrack are presented in Chapter 6.

Lastly, conclusions and recommendations are given in Chapter 7.

2

Methodology

This chapter will discuss various tools and methods that will be used to generate and assess alternatives to enable reliable metro operations with frequencies of more than 24 trains per hour. These alternatives propose changes to the existing metro network in order to solve the problems that arise when more trains are added to the existing schedule. An overview of these different factors that affect the reliability of timetables will be given in Chapter 3.

The tools and methods described in this chapter are part of a research framework, which forms a step-wise approach to answer the research questions posed in Section 1.2.1. The different steps and the input required are presented in the framework given in Section 2.1. The relationship the different steps have with each other are shown graphically in Figure 2.1.

Next, the different steps in the research framework will be discussed in more detail. Firstly, the two indicators are discussed in Section 2.2. These indicators – regularity and punctuality – are widely used throughout this research and their principles and relevance to the different stakeholders are explained. Secondly, the use of the microscopic simulation tool *OpenTrack* will be explained in Section 2.3, which discusses the main concepts and features of the programme. Lastly, the different modelling steps are explained in Section 2.4.

2.1. Research framework

The main feature of this research project is the use of microscopic tool *OpenTrack* to assess different solutions to enable higher frequencies on the existing metro network used as a case study. Firstly however, the model will have to be verified and validated in order to ascertain that the model has been built correctly and is able to produce realistic results. For the verification and validation, real-life data is required as well as quantitative measures to compare the simulated results with the real-life data. These measures are the indicators mentioned earlier on.

To answer the research questions from Section 1.2.1, several potential solutions will be constructed, in which measures are proposed to enable higher frequencies on the case study metro network. The feasibility of each potential solution will be assessed using the validated OpenTrack model, using the same indicators as for the validation of the model itself.

A schematic overview of this framework is given in Figure 2.1.

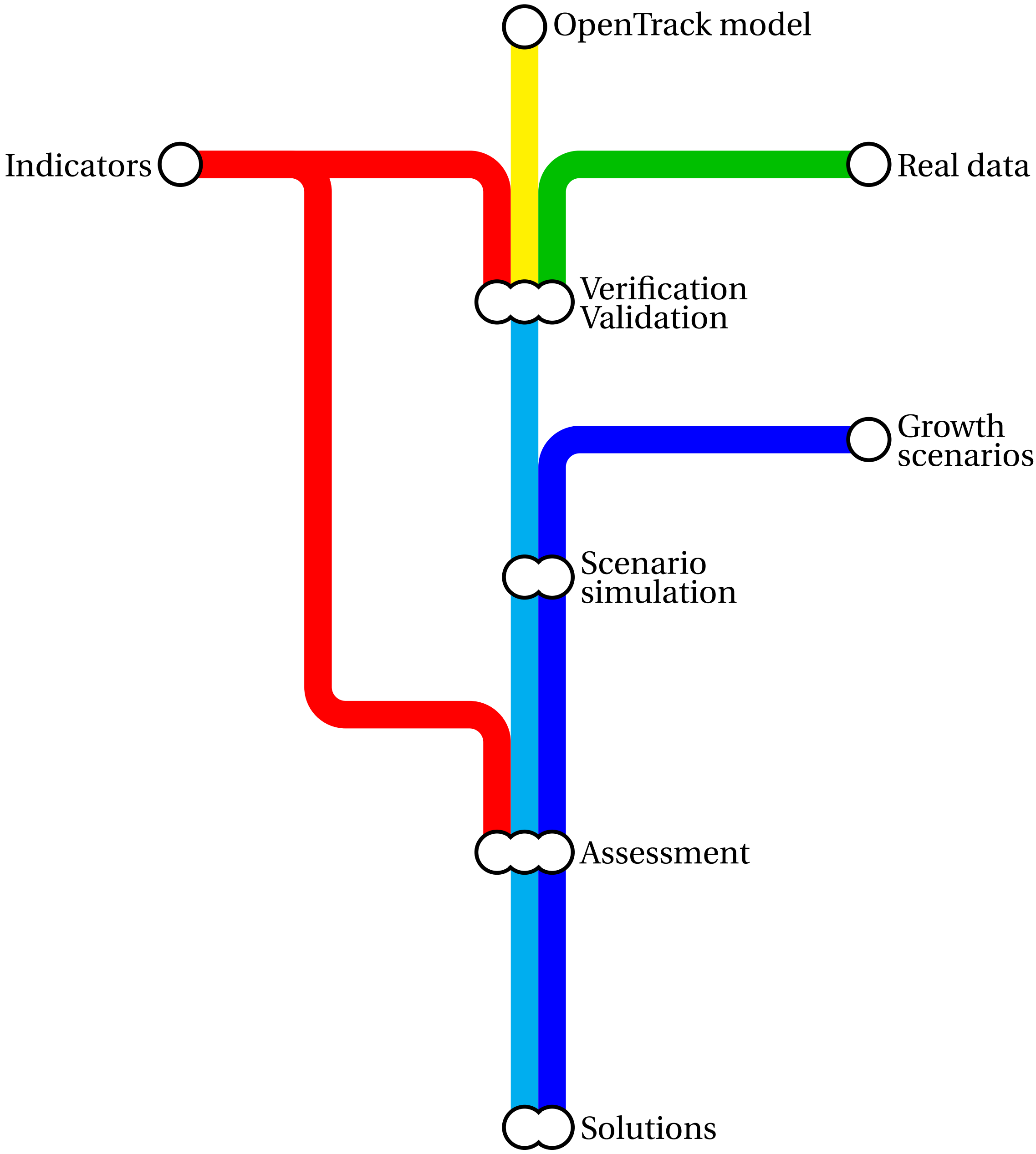


Figure 2.1: Research framework for this thesis

2.2. Indicators to assess timetable performance

This section discusses the two indicators that are used throughout this research. These indicators will be used for two steps of this research: the validation of the microscopic simulation model and the assessment of the alternative solutions. Two indicators will be used, covering the interests of the two main stakeholders involved in high-frequency metro networks.

2.2.1. Introduction

Firstly, a definition of reliable train operations has to be given. Train operations are reliable when users of a transport system know what to expect from a transport system. Bates et al. (2001) mention train lateness, the chance of obtaining a seat in a train or the expectation of the duration of activities such as waiting times as factors that define reliability. Furthermore, Chakrabarti and Giuliano (2015) add trip time variability as a factor that affects public transport reliability. If trip time variations are high, travellers – and also public transport operators – need to reserve more time for the trip, to account for variances occurring during the trip.

Reliable metro services are important for both the transport operator and the passenger. Both actors benefit from train services that are as punctual as possible and can remain as punctual as possible under all circumstances. For the operator, delayed trains can lead to overtime for personnel, less time for maintenance or a higher strain on trains, infrastructure and personnel. Furthermore, many public transport operators are paid by transport authorities according to their punctuality performance. This acts as a major incentive for transport operators to operate punctual services, as train delays can cost significant income.

The passenger's objective is to minimise total travel time. Train delays can increase the travel time for a passenger. If a journey consists of more than one trip, train delays can lead to passengers missing their transfers, increasing their total delay even more. From passengers' point of view, a timetable is reliable when they can rely on the trains to run without delays, or at least such that their transfers are not jeopardised (Schöbel and Kratz, 2009).

Regular services are of interest to the operator and passenger as well. Services are regular when headways between trains are as planned and are consistent. Headways are related to passenger waiting times and therefore, regular services can contribute to a passengers trip time and customer satisfaction. For the operator, regularity is important as well, and regular services ensure that passengers are distributed evenly over all trains, maximising capacity and reducing the risk of overcrowded trains.

Therefore, this research assesses timetable reliability based on the two measures mentioned above: punctuality and regularity. Both measures are quantified using two indicators: *regularity* and *punctuality*. Regularity and punctuality indicate the rate at which a certain executed timetable differs from the planned timetable. They relate to reliability as they indicate how well trains can adhere to the planned schedule. As running and dwell times vary, regularity and punctuality indicators can show how susceptible a timetable is to these variations in the network.

The indicators can not only be used to analyse an existing timetable, they can also be used to evaluate measures aimed at improving timetables. Using a microscopic simulation tool, these measures can be tested before actually implementing them in real life, and the indicators can give an quantitative analysis of the effectiveness of the proposed methods.

Both indicators are closely related to each other, yet indicate different concepts. Furthermore, a unidirectional relationship exists between the two measures. Services can be perfectly regular, meaning that the actual headways are exactly as planned, but all trains are delayed by the same rate. However, irregular service automatically indicate that some trains are delayed.

2.2.2. Regularity

Regularity is a relative measure that indicates the consistency of the intervals between the trains. Highly regular service means that the intervals between all trains are exactly as intended. As the measure compares the actual headway with the planned headway, it is assumed that the timetable is planned with trains running at regular intervals. This is important, since the number of passengers that boards and alights a train, and therefore the dwell time, depends on the interval between that train and the previous one.

Van Oort and Van Nes (2009b) describe a measure that expresses the rate at which observed headways deviate from scheduled headways; this can be regarded as an indicator to express *irregularity*. This indicator is called *Percentage Regularity Deviation Mean* and is shown in Equation (2.1):

$$PRDM_j = \frac{\sum_i \left| \frac{H_{i,j} - H'_{i,j}}{H_{i,j}} \right|}{n_j} \tag{2.1}$$

where:

$PRDM_j$ the relative regularity for stop j,
$H_{i,j}$ the scheduled headway for vehicle i with its predecessor at stop j,
$H'_{i,j}$ the actual headway for vehicle i at stop j, and

n_j the number of vehicles serving stop j.

The PRDM denotes the average headway deviation of a number of trains serving a certain stop. A PRDM of 0% means that all actual headways are the same as the scheduled headways and that therefore, regularity is perfect. A nonzero PRDM indicates that the actual headway differs from the planned headway by the indicated percentage.

In high-frequency train operations it can be assumed that passengers arrive at stations randomly and that therefore the average waiting time is half the headway between two trains. Therefore, the longer the headway between two trains, the more passengers will have accumulated on the platform and the more passengers that want to take the next train.

If train services are irregular, the actual headway might differ from the planned headway. For passengers, this can mean two things. Firstly, since more passengers have accumulated on the platform, the train they wish to travel in will be busier than planned and the passenger will likely experience this as an added level of discomfort. Secondly, passengers will experience a longer waiting time, as the train they were waiting for arrives later than scheduled. The definition of PRDM (Equation (2.1)) can be used to express a value for the *perceived* waiting time (Van Oort and Van Nes, 2009b):

$$E(W_j) \approx \frac{1}{2} \cdot H_j \cdot (1 + PRDM_j^2) \tag{2.2}$$

where:

$E(W_j)$ the expectation of waiting time at stop j,
H_j the scheduled headway to leading train at stop j
$PRDM_j$ the Percentage Regularity Deviation Mean (see Equation (2.1))

As train headway is inversely related to frequency, an expression for the *perceived* frequency can be found:

$$F_{p,j} = \frac{60}{H_{p,j}} \tag{2.3}$$

$$H_{p,j} = 2 \cdot E(W_j) \tag{2.4}$$

$$F_{p,j} = \frac{60}{H_{p,j}} = \frac{60}{H_j(1 + PRDM_j^2)} = \frac{F_j}{(1 + PRDM_j^2)} \tag{2.5}$$

where:
F_j = the scheduled frequency at stop j,
$F_{p,j}$ = the perceived frequency at stop j, and
$H_{p,j}$ = the perceived headway at stop j.

The above equations show that there is a difference between the *offered* frequency and the *perceived* frequency. If a train service runs irregularly, passengers might experience a lower frequency as they have to wait longer for their train. Being inversely related to frequency (Equation (2.3)), this directly translates into a lower perceived frequency. At the same time, other passengers might experience a shorter waiting time, as they might be able to catch an earlier, delayed train. Nevertheless, this delayed train is then more crowded, having the same crowding levels as the trains would have, were they operating under a lower frequency.

Irregularity is a useful indicator to assess a timetable from a passenger's perspective, as it directly relates to a passenger's experienced Level of Service. Equations (2.2) through (2.5) demonstrate that irregularity has a negative effect on the perceived frequency. Figure 2.2 is a graphical representation of Equation (2.5), using three different service frequencies as an example. When the train service is fully regular (i.e. PRDM = 0%), the perceived frequency is the same as the offered frequency. On the other hand, when the train service is fully irregular (PRDM = 100%), bunching occurs, and therefore the perceived frequency is half the offered frequency.

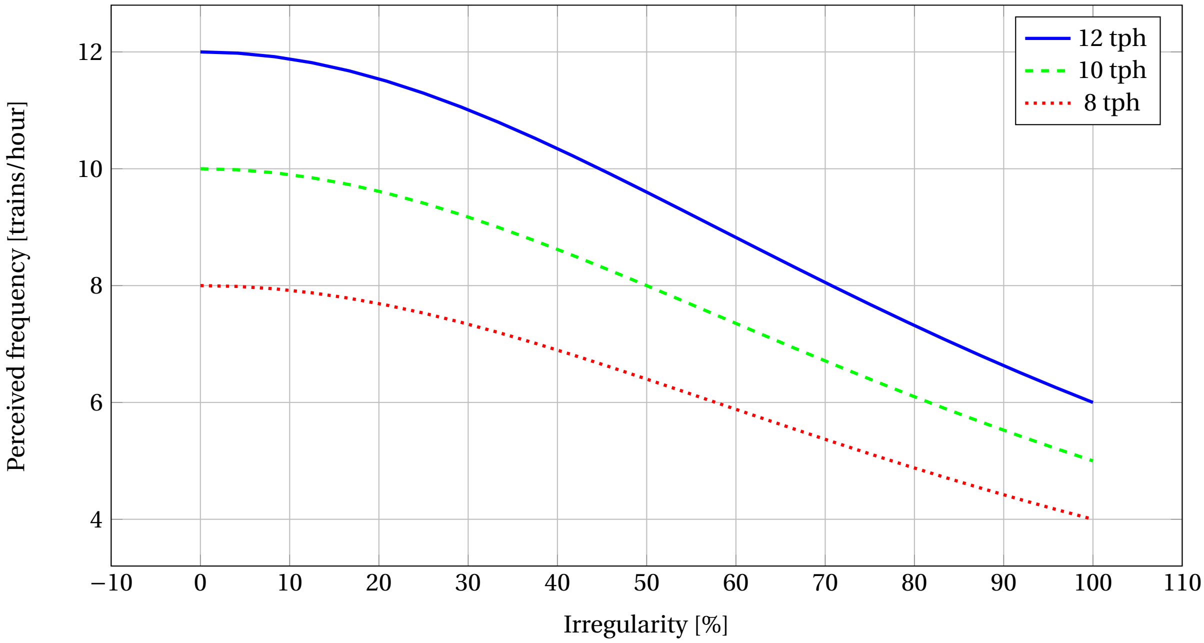


Figure 2.2: The relationship between irregularity and perceived frequency (adapted from Van Oort and Van Nes (2009b))

2.2.3. Punctuality

Punctuality is a measure to relate the actual departure time to the planned departure. It shows close resemblance to regularity, but is not the same. For example, if every train is exactly 2 minutes late, the punctuality for the whole service is low, as every train is late. However, since all trains still maintain their original headway, albeit 2 minutes later than planned, the service still is highly regular.

The reason to differentiate between the two indicators is because they each assess the timetable differently, putting the emphasis on one of the recurring perspectives mentioned throughout this research: regularity assesses the timetable mainly from a passenger's perspective, whereas punctuality assesses the timetable mainly from an operator's perspective.

Operators strive to be as punctual as possible, not only because punctual services are regular (note the one-way relationship between regularity and punctuality) and therefore result in a high passenger satisfaction, but also because punctual services are beneficial to their own operations. For example, late trains do not only cause passengers to miss connections, but train drivers also risk missing a connection, thus being unable to leave with a different train or course on time, or risk working for a longer period than personnel regulations allow. Furthermore, many transit authorities assess the operations based on punctuality and pay (or fine) them accordingly. Therefore, lateness also has substantial financial risks for the operator.

Van Oort and Van Nes (2009a) define punctuality as the average schedule deviation (being either a late or an early departure) at a certain station j:

$$\bar{p}_j = \frac{\sum_i \left| t_{i,j}^{real} - t_{i,j}^{planned} \right|}{n_i} \tag{2.6}$$

where:

$\bar{p}_j$	the average punctuality at stop j,
$t_{i,j}^{real}$	the real departure time of train i at stop j,
$t_{i,j}^{planned}$	the planned departure time of train i at stop j,
n_i	the number of trains,
j	the stop index, and
i	the train index.

Following Equation (2.6), a punctuality rate of 0 means that all trains are exactly on time. Any rate higher than zero indicates the average deviation from the schedule per train. This can either be one train that is severely delayed or several trains with a smaller delay.

2.3. OpenTrack: A microscopic simulation tool

When dealing with very high frequencies, static timetables and blocking time diagrams to assess the feasibility of a timetable are not sufficient. For example, they use predefined values for dwell times and running times, and assume that they remain more or less constant. In mass rapid transit, dwell times are relatively short (less than a minute) and vary strongly depending on passenger demand. In cases where intervals between subsequent trains are long , small variations in dwell times are not a problem, as there is enough slack in the timetable to alleviate the effects of the variation.

However, when intervals between trains are very short, small variations in dwell time have a significantly greater effect on the reliability of the timetable. Trains are less able to recover from a delay and those already behind schedule are affected by delays more easily. Static timetables cannot demonstrate the consequences, as they cannot show the dynamic interaction between trains and between train and infrastructure, and the effect that uncertainties has on the stability of train operations. These interactions are especially important when dealing with very high frequencies, as the smallest change of events can have severe consequences for the total operations.

Microscopic simulation tools are useful and appropriate means to investigate the consequences of subjecting metro lines to high-frequency services. In these tools, a railway line is modelled to the smallest relevant detail. Individual points, signals and stations are incorporated, as their behaviour strongly influences daily operations. Each individual train is also modelled, each having its own unique driving characteristics. Microscopic simulation tools can take dynamic events into account and can demonstrate how severe the consequences of deviations actually are.

A second main advantage of using a simulation is that the effect of newly proposed solutions can be investigated *beforehand*, without the need to test in practice. A new timetable, for example, can be tested using the simulation tool and its effects can be shown. Thus, the simulation tool can be used to test and assess multiple solutions, and based on the results of the simulations, the most effective solutions can be chosen and adapted in practice.

The microscopic simulation tool used in this research is *OpenTrack* (OpenTrack, 2018). In OpenTrack, all infrastructure features are modelled individually, and vehicle characteristics and working signalling systems are also included, to ensure that the model is as realistic as possible. Figure 2.3 shows an example of a simulation in OpenTrack. Several trains can be seen, as well as the status of every track section (unoccupied (grey), occupied (red) and reserved (green)).

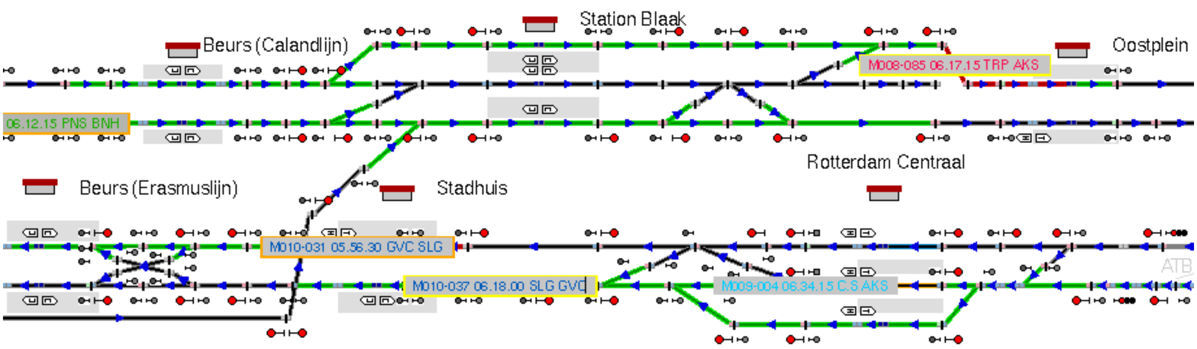


Figure 2.3: Example of a section of metro line during a simulation in OpenTrack

2.3.1. Infrastructure hierarchy

OpenTrack utilises a hierarchical structure to model infrastructure and enable trains to interact with infrastructure elements. This structure is shown in Figure 2.4. The lowest level is each individual infrastructure element, called a *Vertex*. A vertex describes the location of a signal, speed change sign or grade change for example. In a graph, a vertex is also called a *node*. Vertices are connected with each other using *edges*, which in OpenTrack represent sections of track.

A *route* is a section of track comprising at least two vertices, and always starts and ends at a main signal. A single signal can be the start of multiple routes, if, for example, this signal is located before a diverging point. Multiple routes form a *path* and multiple paths form an *itinerary*. Usually, itineraries describe a line as a whole, for example RET Line E. For a train to be able to travel on the modelled network, at least one itinerary has to be assigned. To offer a train alternatives, for example when a track at a terminal station is occupied, alternative itineraries can be assigned to the train as well. Using a preference ranking, the priority of the itinerary can be defined, assigning a default arrival track to a train.

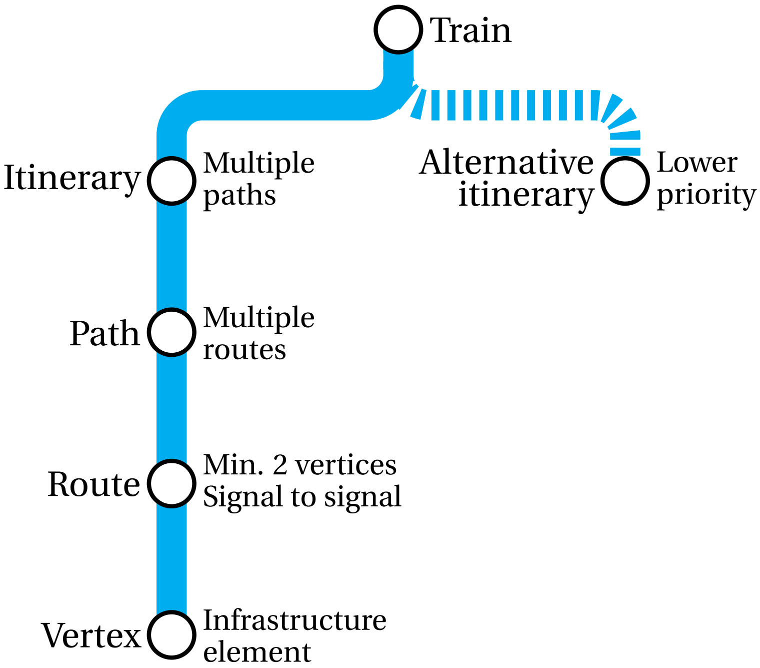


Figure 2.4: Infrastructure hierarchy in OpenTrack

2.4. Modelling the network in OpenTrack

This chapter discusses a vital step in the process of using simulation tools. To answer the research questions posed in Section 1.2.1, microscopic simulation tool *OpenTrack* is used to assess the feasibility of very high frequencies on the Rotterdam metro network (OpenTrack, 2018). RET has recently started using OpenTrack to investigate the effects of introducing new timetables to their network and have already created a working model of its network. An important step not only for RET but also for this research, is to assess whether or not OpenTrack can provide realistic output and to configure OpenTrack in such as way that the produced output can be considered "correct". A model that is able to produce realistic results can provide insights into the performance of modifications not yet proven in practice. This allows for future concepts to be tested using the model without having to actually execute the concept in real life. With a well-built model it can be rightfully assumed that, if the same circumstances are applied in practice as in the model, the model can provide useful insights into the performance of that concept in real life.

2.4.1. Approach to assess the applicability of the model

To investigate the usefulness of the OpenTrack model, two important steps are carried out: verification and validation. Law and Kelton (2000) define model *verification* as a method to ascertain whether the selected model has been built correctly, that it functions without errors during all simulations, and that it is able to provide the required data in the required format. In short, verification ensures that the *input* can be considered "correct".

Validation on the other hand assesses whether the *output* can be considered "correct". Law and Kelton (2000) define model validation as a method to assess whether the built model (and not the actual programming itself) can provide an accurate representation of the real-life situation that is to be scrutinised. Although results might differ from real-life situations, which is often the case when stochastic elements are involved, the results of a well-built model ought to be as expected and can be considered to be realistic. The verification and validation of the OpenTrack model are presented in Chapter 4.

2.4.2. Assessment of growth scenarios

The next step in this research is to investigate up to which frequencies the network in the case study can still provide reliable services. Therefore, four *growth scenarios* have been created. A new timetable has been written for each scenario, in which the frequencies on the trunk section are increased for every scenario. Furthermore, four different operational variants have been constructed, in which different infrastructural feature are upgraded. By applying those to the growth scenarios, the effectiveness of these upgrades can be assessed. The growth scenarios and variants are explained in more detail in Chapter 5.

The growth scenarios are simulated with the use of OpenTrack and the outcome of the simulations is assessed by again using the indicators defined in Section 2.2. The results of the simulations of each growth scenario are referenced against the simulations of a base scenario, in which the timetable is different than the current timetable, but does maintain the same service pattern and frequencies.

3

Factors that affect reliability of timetables

Public transport operators strive to find the optimal service schedule, in which trains are as punctual as possible and delays are reduced to a minimum. There are various factors that have an effect on the stability of a timetable. By changing these factors, train operators are able to optimise their train schedule and adapt their infrastructure to ensure that the planned timetable can be operated without problems and is robust enough to account for the most frequently occurring disturbances. This chapter discusses these factors and explains how these factors can be used – and changed – to optimise the schedule and ensure as stable operations as possible.

During this research, several scenarios in which the service frequencies are increased will be investigated and assessed based on their performance. Where the indicators mentioned in Chapter 2 will be used to quantify the performance of a timetable, the factors mentioned in this chapter will be used to explain why certain parts of the network perform better or worse than other parts. Furthermore, the factors will be used as building blocks to improve the scenarios under scrutiny and increase their performance.

Van Oort (2011) has researched factors that affect the variability – and therefore the reliability – of timetables in urban public transport systems. He has determined several factors, both internal and external, and the elements of a public transport service they affect. This is shown in Figure 3.1.

Van Oort (2011) has distinguished between two types of factors: internal and external. The external factors include weather, other traffic, irregular (passenger) loads and passenger behaviour. As this research investigates the reliability of a metro network, other traffic is not a factor that affects timetable operation. Although the metro network under study in Chapter 4 does feature crossings at-grade with road traffic, it is assumed that the signals at level crossings enforcing priority for metro vehicles function normally and that road traffic participants adhere to these signals, not hindering metro operations. The effects of passenger behaviour are included in the simulations (see Section 4.4.5), but are given as fixed input, and these effects are not changed during this research. Furthermore, normal daily operations are assumed for this research, neglecting the effects of (extreme) weather conditions. Also the changes in passenger demand due to (bad) weather are not taken into account.

This research is more interested in the *internal* effects that affect service variability, as these can be directly altered by the operator or other stakeholders involved in high-frequency metro operations. The effects of five of the eight internal factors are mentioned in this research. The other three – vehicle design, other public transport and vehicle availability – are not investigated in this research and are considered to remain unaltered in the different scenarios that are investigated later on in this research. It is for example assumed that the same type of train equipment is used in future scenarios as is currently operated to ensure fleet uniformity. Furthermore, it is assumed that the fleet is and will be large enough to accommodate the timetable of the future scenarios that are investigated later on in this research.

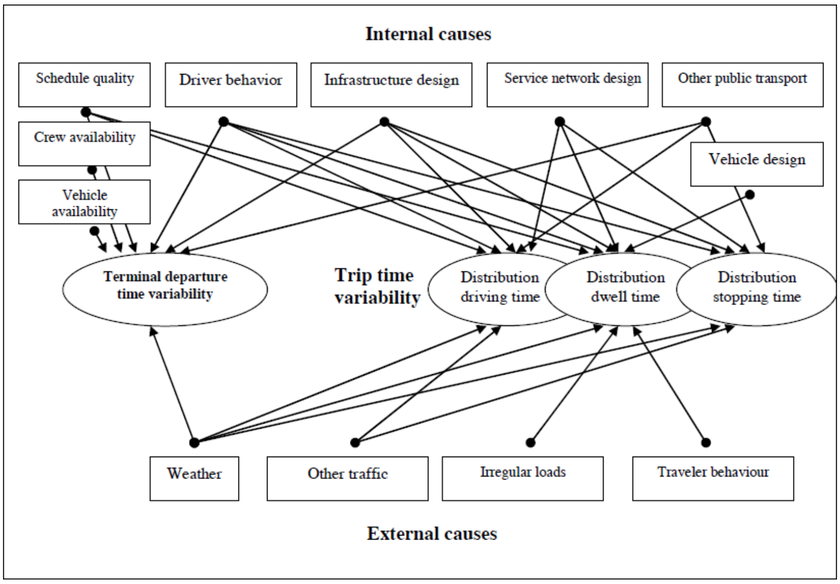


Figure 3.1: Causes of variability in public transport services (Van Oort, 2011)

3.1. Overview of timetable design

It is almost impossible to guarantee that every train uses exactly the same amount of time to perform the same activity. External effects mentioned by Van Oort (2011), such as varying weather conditions or varying passenger demand, but also internal effects such as driver behaviour and changes in passenger demand, cause variations in train travel times (see Figure 3.1). As these stochastic occurrences apply to each and every train on a metro system, train delays are unavoidable (Lee et al., 2017). Even though measures as on-time departures and driver information can reduce the risk of trains departing too late, delays can still be incurred during the trip.

3.1.1. Time supplements

A well-constructed timetable is able to account for these variances by adding extra time, or time supplements, to trip and dwell times (Van Oort and Van Nes, 2009a). At terminal stations, extra time is added to the minimum required reversing time, to account for the delays incurred on the previous trip and thus ensure that these delays do not affect the return trip. Furthermore, extra time is added to running times, to account for differences in driving behaviour and difference in station dwell times.

Allocating more time in a timetable will surely increase punctuality rates. However, this comes at a cost. Firstly, adding time supplements to running will increase the total trip time, effectively slowing down a train adhering to the schedule. Secondly, running time supplements and buffer times at terminal stations will lengthen the total cycle time of a train. This may result in the operator having to operate more trains.

This is where a trade-off has to be made between minimising total travel time and punctuality. Minimising travel time is beneficial to both the operator and the traveller, since trip times are minimised and the operator is able to use the minimum amount of rolling stock. At the same time, both actors wish to experience punctual services, which means allocating sufficient buffer and supplement times to account for the most common schedule deviations.

Carey (1998) mentions that adding more time to the minimum required time it takes to perform an activity may cause unaccounted behavioural effects to occur. By allocating more time to perform an activity, the activity will tend to take more time. This diminishes the effects of adding buffer and supplement times, as these times will be taken to perform the actual activity, rather than account for delays that it was intended to. From own observations, some drivers make a habit of deliberately departing late, in order to avoid the risk of having to slow down for danger signals and to avoid being held up at stations for being too early, things they experience as being a nuisance. Therefore, Carey (1998) cautions to be slightly conservative when adding buffer and supplement times.

3.1.2. Service pattern design

The second factor concerning timetable design is the determination of the desired service frequency and service pattern. Frequency, interval and capacity are very closely related to each other. In fact, all three measures indicate the same, though expressed in different units: the volume of a certain measure that passes within a certain time frame.

In passenger transport, operators are mainly interested in the volume of passengers a transport link can process, generally expressed in passengers per hour. Dividing by the number of passengers that fit in one train, one can obtain the required train frequency, or Trains per Hour (tph), for the number of trains to operate on the scrutinised transport link. The inverse of this is *headway*, or the amount of time that elapses between to successive trains.

The capacity of a transport link is the maximum number of passengers per unit of time that a transport link is able to carry safely. In order to increase capacity, two options are possible: increase the capacity of the trains, or increase the frequency. The former is very costly on underground tunnel sections, whereas the latter can be achieved more easily. With increasing frequencies, the headway between two vehicles drops. Dicembre and Ricci (2011) has investigated the influence of block lengths and dwell times on capacity. Although they have found that theoretical frequencies for urban railway systems (i.e. metro) of over 40 Trains per Hour (tph) are achievable, they have found that the practical capacity is lower, calculating a maximum practical capacity of 24 tph with a fixed dwell time of 20 seconds. No research has been found concerning network capacity incorporating stochastic elements and varying running and dwell times.

3.1.3. Relationship with dwell times

At the same time, train headway and station dwell times influence each other. In high-frequency metro operations, stops at stations are the main cause of variations in trip times. Dwell times, defined as the time between the moment the doors of a train open and the moment they close, depend on two main factors:

- the number of passengers wishing to board and alight at a station;
- and the number of doors through which these passengers board and alight the train.

Given the assumption that train compositions remain the same for every following train, passenger numbers are the main factor contributing to dwell time variation. The more passengers wishing to board and alight from a train, the longer the dwell time. The number of passengers wanting to board an individual train itself depends on two factors:

- the actual passenger demand;
- and the interval between two subsequent trains.

If headways are short enough, passengers start arriving randomly at station, without consulting the service timetable before arriving at the station. Many studies have investigated the threshold level at which passengers start arriving randomly at stations. In bus travel, randomness starts emerging at headways shorter than ten minutes, while a multi-modal study has revealed that the threshold level lies at between five and ten minutes (Ingvardson et al., 2018). Furthermore, studies conducted by Bowman and Turnquist (1981) and Frumin and Zhao (2012) revealed that the level of random arrivals increases when headways are short or when transit links are known to have poor reliability. Therefore, they argue that waiting times can be minimised when services are frequent enough or when reliability is high.

In high-frequency metro operations, where *scheduled* intervals are low enough to expect passengers to arrive at the station randomly, the headway between two vehicles determines the number of passengers that has accumulated on the platform. To ensure that passengers are distributed over all scheduled trains as evenly as possible, it is important to homogenise the headways of all trains as best as possible. Evenly spread trains enable the same number of passengers to accumulate at the platform for each train. Delayed trains cause the headway between that train and its predecessor to increase and this results in the delayed train having to pick up more passengers, thus increasing its delay even more. This initiates a downwards spiral where a delayed train becomes even more delayed and its successor, having to pick up fewer passengers because the delayed train in front is closer than it should be, will run ahead of schedule, eventually meeting each other.

Therefore, it is in the operator's utmost interest to ensure regular train operations, as it directly influences passenger experience. A feedback loop exists between headway and dwell time, which becomes a problem when the observed headways deviate from the scheduled headways. While this research takes variability of station dwell times into account, the aforementioned feedback loop is not taken into account and bases its dwell time distributions on observed, revealed distributions per station.

3.2. Overview of infrastructural effects

Is it easy to understand that the infrastructure plays an important role in defining the capacity of a rail-bound transport link. The capacity on single-tracked railway lines is determined by the time it takes to travel between two stations where trains can pass each other. On double-tracked lines, this is not the case and trains are able to follow previous trains at the smallest distance technically and operationally possible. Here, the minimum intervals are determined by the maximum speed allowed, signal block length, dwelling times at stations and homogeneity of train services. Terminal stations and junctions also play an important role in defining minimum interval, as these are locations where trains might conflict each other. This section will discuss the theory behind the method of identifying bottlenecks on railway lines. The calculation of minimum headway times will be discussed in Chapter 4, as OpenTrack will be used to determine the minimum headway.

3.2.1. Station complexity

Stations can prove to be bottlenecks and can therefore limit the capacity on the line. Terminal stations and junctions have a great influence on not only the maximum frequency on a line, but also on the stability of the timetable during (small) disturbances. They are locations where trains could have conflicting paths, where trains have to switch tracks or where trains merge onto a main line. Furthermore, passenger demand has an effect on the dwell time at stations, which in turn has an effect on the minimum interval.

Therefore, the layout of a station is important to determine the minimum interval and the robustness of the network, because the number of routes that conflict each other determines how dependent trains are on other trains. Generally, the more route conflicts exist at a station, the more vulnerable the station is to disturbances, and the more likely this station will cause troubles in maintaining stability of the timetable or in facilitating an increase in service frequency. A measure to indicate the vulnerability of a station is the *complexity index* (Jensen et al., 2014). The complexity index is the ratio between the number of conflicting route combinations divided by the total number of route combinations, as a means to assess the robustness of a station:

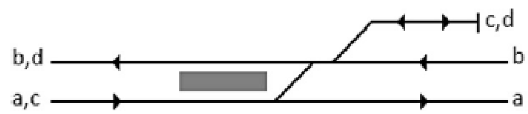
$$\phi_n = \frac{n_k - n_\lambda}{n_\Sigma - n_\lambda} \tag{3.1}$$

with:

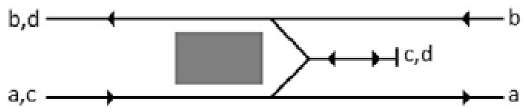
ϕ_n the complexity index of station n,
n_k the number of conflicting route combinations,
n_λ the number of routes that cannot be set consecutively (for example: a second route to a dead-end cannot be set after the first train has left the dead-end), and
n_Σ the total number of route combinations.

The higher the ratio, the more complex the station is, and thus the more risk there is that an initial delay will lead to secondary delays. Figure 3.2 is an example of this method, retrieved from Landex and Jensen (2013):

In Figure 3.2, two different layouts are shown for an intermediate station that also has a the ability to reverse trains. Both layouts contain a reversing track, but with different locations for this track. Every route is marked with a lowercase letter. In Table 3.1, all possible route combinations are shown, together with an indicator,



(a) Station A



(b) Station B

Figure 3.2: Two different layouts for a station where trains can be reversed, from Landex and Jensen (2013)

showing the type conflict two routes have with each other:

-: no conflict. These two routes *can* be set simultaneously,
O: Overlapping routes, these routes cannot be set simultaneously, yet can be set sequentially
D: Divergence of 2 routes,
C: Convergence of 2 routes,
X: Intersection of 2 routes,
Ø: Overlapping routes that cannot be set sequentially, as these are routes to or from a reversing track. If route *c* has been set, route *c* cannot be set after route *d* has been set to clear the reversing track.

Table 3.1: Table with the different route combinations

(a) Station A

$1^{st}\backslash 2^{nd}$	a	b	c	d
a	O	-	D	-
b	-	O	X	C
c	D	X	Ø	X
d	-	C	X	Ø

(b) Station B

$1^{st}\backslash 2^{nd}$	a	b	c	d
a	O	-	D	-
b	-	O	-	C
c	D	-	Ø	X
d	-	C	X	Ø

Table 3.1a shows that there are 16 combinations, so $n_\Sigma = 16$. Twelve of the routes have a conflict with each other ($n_k = 12$) and two routes cannot be set consecutively ($n_\lambda = 2$). This means that for Station A:

$$\phi_A = \frac{12-2}{16-2} = 0.71 \tag{3.2}$$

Station B (Figure 3.1b), which has 10 conflicting route combinations, yields:

$$\phi_B = \frac{10-2}{16-2} = 0.57 \tag{3.3}$$

As Station B has a lower value for ϕ_n, this station is less complex than Station A and has therefore a lower risk of incurring delays.

The complexity index can hence easily indicate stations where the risk of incurring delays at bottlenecks is highest. It can show the potential a station can have for setting a limit to a line's capacity. However, more factors are involved in determining capacity, such as the speed of a train travelling through the stations and the duration of route occupance.

3.2.2. Overview of effect of signalling system

Rail-bound mass rapid transit and heavy-rail transport use signalling systems to keep trains at a safe distance from each other. In classic signalling systems railway lines are divided into fixed blocks, and signals ensure that only one train can be in a block at any given time. The signals, together with an Automatic Train Protection (ATP) system, warn the driver of an occupied section and make sure the drivers adhere to these instructions. The lengths of the blocks determine the minimum spacing that trains are allowed to travel behind each other and therefore they are a factor in determining the capacity of a railway line.

The spatial distance that trains travel behind each other is defined as the product of headway and speed, provided that the speed remain constant:

$$s = h * v \tag{3.4}$$

where:

s = spacing [m],
h = headway [sec], and
v = constant speed [m/s].

When designing a new signalling system for a new or existing railway line, the lengths of the blocks must be such that the required spacing between two trains can be achieved. Inversely, on existing lines with a signalling system already installed, the minimum headway on a railway line depends on the largest minimum spacing than can be achieved anywhere on the line:

$$h_{min} = \frac{s_{max}}{v} \tag{3.5}$$

where:

h_{min} = the minimum headway [sec],
s_{max} = the minimum spacing between to trains determined by the longest block [m],
v = constant speed [m/s].

This means that the largest minimum spacing on a line therefore depends on the longest block length anywhere along that line. A key element in railway signalling is that a danger (i.e. red) signal always has to be preceded by a caution (i.e. amber) signal to inform the driver that the next signal is red and that he/she therefore has to start slowing down. To ensure an optimal throughput and the highest average speed, the train driver must encounter as many green signals as possible, lest he/she slows down in anticipation of a danger signal. In a classic three-aspect signalling system, signals can either show "danger" (red), "caution" (amber) or "proceed" (green). This means that trains must have at least two unoccupied blocks ahead, in order for the train driver to only encounter green signals. Furthermore, to prevent the driver from seeing a caution signal (and therefore starting braking), the signal must turn green before at least the sighting distance of the signal. If the headway between two trains is defined from the head of the leading train to the head of the following train, the length of the train has to be added to the minimum spacing as well. Therefore, the minimum spacing on an existing railway line with a three-aspect signalling system can be defined as follows (Dapré, 2012):

$$s_{max} = l_{sight} + 2 * l_{block,max} + l_{train} + l_{setup} + l_{release} \tag{3.6}$$

where:

s_{max} = the minimum spacing between to trains determined by the longest block [m],
l_{sight} = the sighting distance of the first caution-showing signal,
$l_{block,max}$ = the longest block length on the railway line,
l_{train} = the length of the train, and
l_{setup} = the length a train moves forward while the points and signals are being set,
$l_{release}$ = the length a train moves while the block is released.

Equations (3.5) and (3.6) imply that in order to increase capacity (and therefore decrease the minimum headway), two measures can be taken:

- shortening the block lengths
- increasing the operational speed

However, train drivers need to be informed well in advance of a danger signal in order to be able to stop safely in front of the signal. This means that the higher the speed, the longer the distance is required for a train to stop safely, and therefore the earlier a train driver has to be informed of a danger signal. Equation (3.6) assumes that the braking distance is no longer than the length of the blocks. If the braking distance does exceed block length, the train driver needs to be warned more blocks in advance. In conclusion, one of the two aforementioned measures cannot be changed without considering the other measure.

Rather than increasing maximum speed, capacity on a line can be increased by *slowing down* (Gonzalez et al., 2010). As the braking distance relates to the *square* of speed, braking distance and therefore the distance between amber and red signal diminishes in the case of slower operational speeds. In a classic, three-aspect signalling system, maintaining slower operational speeds can enable shorter block lengths. An added advantage of decreasing operational speeds is that is can positively affect reliability because this can add more time supplement to the running time, but a disadvantage of driving slower is that it negatively affects travel time.

Capacity can be further increased by considering the way track occupation information is transmitted from the signal control systems to the driver. Discrete train protection systems transmit data to the driver at every signal. If the signal in front of them clears, they will only know of this upon arrival at the signal. Continuous train protection systems transmit data to the train continuously and drivers will be instantly informed of the signal clearing ahead. This way they can clear the block they are in more quickly, allowing the train following them to enter the block earlier, thus decreasing headway.

The next step in continuously providing information to the train is to provide information of the exact *location* of the preceding train rather than the status of the block in front of it. Consequently, this renders the need for fixed blocks obsolete. Provided drivers know the exact location of the tail of the train in front of them, they can receive a movement authority to that location, rather than waiting for the whole of the block to clear. This concept is called *moving block* technology, where a train is allowed to proceed to a defined safety distance away of the rear end of the preceding train.

Moving block technology requires an accurate location of the position of a train. This can be obtained with two measures:

- Using blocks with a very short length. The tail of the train can be estimated to be within the length of that block. The smaller the block length, the more accurate the location of the tail of the train can be determined.

- Using non-track-bound communication methods (e.g. GSM) for trains to communicate with each other and report their accurate locations. This principle is called *Communication-Based Train Control (CBTC)*.

3.3. Human factors

In urban passenger transport systems, humans have an great effect on the process of operations. The number of passenger at a station waiting for a train has an effect on the dwell time of trains stopping at that station. Running times of conventionally driven trains are influenced by the driving behaviour of the train driver. While the former human factor is classified by Van Oort (2011) as an external effect as is regarded in this research as an unchangeable given factor, the availability and driving behaviour of train driving personnel is an internal factor which can be changed by the operator.

The availability of personnel affects the departure time variability of a timetable (Van Oort, 2011). A shortage of driving personnel could result in trains not being able to depart from the depot or a station. Though this is an extreme case, the availability of drivers also affects the flexibility of train operations. For example, adding trains to operations to accommodate an unexpected passenger demand, swapping trains due for technical or operational reasons all depend on the availability of spare drivers or depot personnel. Operational decisions need to be taken some time in advance, to allow for driving personnel to reach the correct locations.

During the trip, each driver behaves differently and this has an effect on the variability of both running and dwell times. Although the implications of differing driving styles may seem relatively small, they can have an effect on punctuality and regularity rates a timetable. A late departure from the first station can affect other trains waiting to enter that station. Furthermore, due to trains running late, the headway with the previous train increases, leading to more passengers waiting at the next station (see Section 3.2) and can eventually lead to bunching (see Section 1.3).

3.4. Automation

Whereas automation in the automotive industry is a relatively new concept, the first automated metro line was in operations in the sixties (Wang et al., 2016). During the past decade, metro automation is increasing in popularity rapidly. UITP reports that in the coming years, the share of automated metro systems as opposed to conventionally driven metro systems will increase rapidly (UITP, 2016). Currently, Asia is the leading continent in automated metros, with a share of 50% of the total global length of automated metro lines being situated in Pacific-Asia (UITP, 2018b). With the opening of the first fully automated line in China in 2017, many Chinese cities have ambitious plans for automation, expecting to have 19 automated networks consisting a total of 40 lines, 1200 km and 861 stations by 2023 (UITP, 2018b). Figure 3.3 shows the total current and a 10-year projection of the length of automated metro lines in operation (UITP, 2018b).

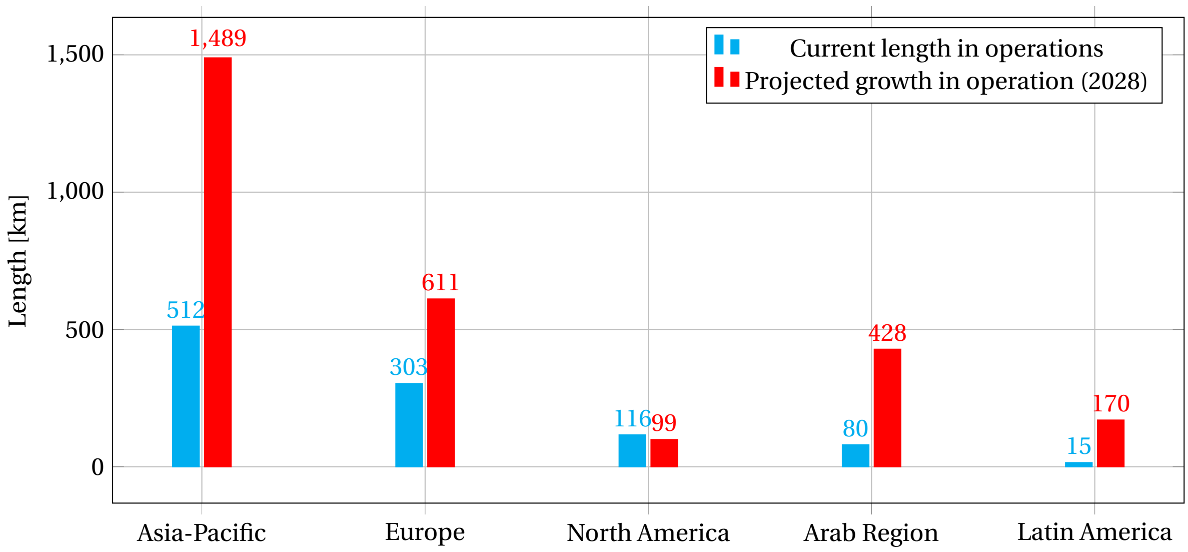


Figure 3.3: Current and projected length of automated metro lines (UITP, 2018b)

The majority of automated metro lines that have be opened in the past decade have been automated from the beginning (UITP, 2016). However, in an increasing amount of cities, mainly in Europe, conventionally driven metro are being converted to automated lines. UITP reports that, following successful conversions in Neuremberg and Paris, seven cities reported to plan conversion projects on (parts of) their network: Brussels (2 lines), Glasgow (one line), London (Docklands Light Rail), Lyon (2 lines), Marseille (2 lines), Paris (Line 4) and Vienna (2 lines) (UITP, 2018b).

3.4.1. Automation levels

A common misconception when speaking about train automation is that one assumes that an "automated metro" always means that no personnel is present to oversee operations. Following a questionnaire conducted among the public by Fraszczyk et al. (2015), this raises concerns regarding communication with passengers and safety. A study by Karvonen et al. (2011) demonstrates the value of a train driver, showing that he/she has much more tasks than simply driving the train from station to station. Karvonen et al. (2011) argue that only when these additional tasks are accounted for in an automated system, can a fully automated metro service be implemented.

In the railway industry, there is no unique thing as an "automated metro". Generally, "automation" entails one or more functions, normally executed by a human, being taken over by a computer. As humans perform many duties during metro operations, there are many forms of automation. To distinguish the different forms of automation, a grade system is introduced, varying from no functions automated to a fully automated metro system (UITP, 2016). The higher the level of automation, the more functions are taken over by a computer. These levels are called *Grade of Automation (GoA)*:

- **GoA 0**: In this level no driving functions are taken over by a computer, including no automatic train protection. The drivers are responsible for driving the train and operating the doors. They are also responsible for ensuring that the maximum speed it not exceeded and that railway vehicles do not collide. Even though there can be wayside signals to keep following trains at a safe distance from each other, there is no system in place to intervene when these signals are ignored. This generally is the case for trams on street level.

- **GoA 1**: In this level all driving functions are carried out by the train driver, except that Automatic Train Protection (ATP) is present, ensuring that the maximum speed allowed is not exceeded, and that trains adhere to the signal aspects. This level is mainly present in conventionally driven metro systems and heavy-rail lines. Furthermore tram lines travelling through tunnelled sections (e.g. several *Stadtbahn* systems in Germany) have a form of automatic protection and therefore these sections can be regarded as GoA 1.

- **GoA 2**: In this level, setting the train in motion, driving and stopping the train is taken over by a computer. The computer also ensures the train adheres to the maximum speed limit, and stops the train if the track in front of it is occupied. The system can roughly be compared with "Adaptive Cruise Control" systems applied in the automotive industry. The driver is still responsible for door operations and is still present in the cabin. Once the doors are closed, the driver presses a button, allowing the computer to take over driving operations. In case of calamities, the driver is able to take over and drive the train manually. Many high-capacity metro lines, such as the Victoria line in London or the the more recent North-South line in Amsterdam are equipped with GoA 2 signalling systems.

- **GoA 3**: In this level, no train driver is present in the front of the train. Instead, a train attendant is present in the train, interacting with passengers and operating the doors at stations, in the same way a train conductor would do in heavy-rail systems. There is still a human being present to oversee the dwelling process, which eliminates the need of expensive and complex systems such as platform screen doors. In case of calamities, the attendant is able to drive the train manually. The Docklands Light Railway in east-London is a good example of a GoA 3 network.

- **GoA 4**: Compared with GoA level 3, no personnel needed for driving operations is present in the vehicles at all. All functions – driving, stopping and door operations – are performed by computers. Also in the case of calamities, trains are still operated automatically. This does not mean there is completely no human interference in metro operations. The central control room staff is able to short-turn automatic trains from a distance, or call on extra trains in the case of higher passenger demand.

Table 3.2 summarises the above list, indicating which functions are carried out by whom, being either a driver/attendant or a computer.

Table 3.2: The different levels of automation in railways

Grade of Automation	Type of Train Operation	Setting train in motion	Stopping train	Door control	Operation during Disruptions
GoA 0	No ATP	Driver	Driver	Driver	Driver
GoA 1	ATP with Driver	Driver	Driver	Driver	Driver
GoA 2	ATP and ATO	Automatic	Automatic	Driver	Driver
GoA 3	Driverless	Automatic	Automatic	Attendant	Attendant
GoA 4	Unattended	Automatic	Automatic	Automatic	Automatic

3.4.2. Effects of automation on timetable reliability

Section 3.4.1 has given a general overview on the different grades of automation. This section discusses the which effects mentioned at the beginning of this chapter are affected by the conversion of a metro network to an automated network. However, Cohen et al. (2015) states that their is little scientific data available on the exact effects of automated operations and therefore, quantifying the effects of automated operations is difficult.

Research conducted by Janmaat (2019) on the effects on automating buses has indicated factors, initially mentioned by Van Oort (2011), that are directly affected by automation. Although this research studies the

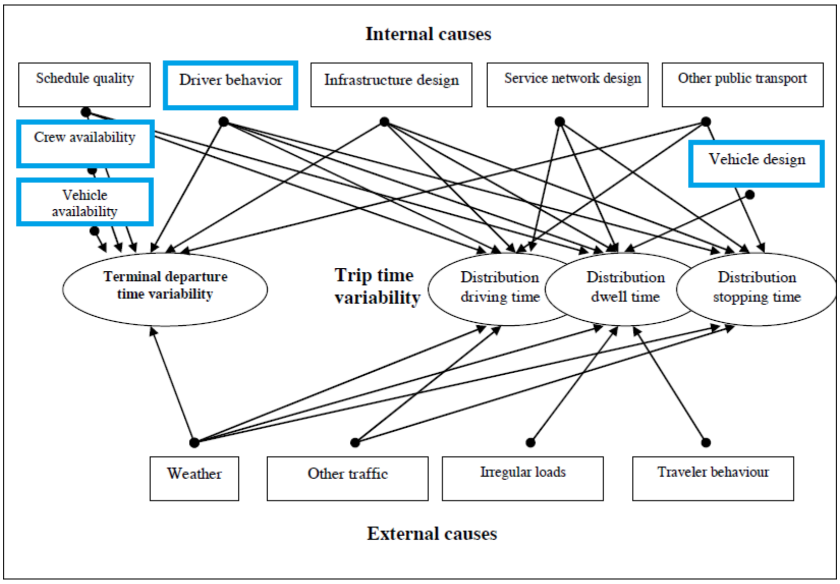


Figure 3.4: Factors of timetable variability that are affected by automation (Janmaat, 2019))

effects on metro lines rather than on bus lines, the same effects apply for metro networks. These factors are marked blue in Figure 3.4:

Crew availability
The role of the staff on automatically driven metro lines is significantly different compared to conventionally driven metro lines. While, depending on the Grade of Automation, no personnel is required to physically drive the train, this does not mean that no staff are needed at all. However, their role may be different. With GoA Level 2, the driver still is present in the front of the train, overseeing safe boarding and alighting operations. Under Level 3, instead of a driver sitting in front, an attendant roams around, answering questions from passengers and operating the doors at stations. Stations may still be staffed to oversee safety on the platforms and to ensure smooth boarding and alighting. Depending on the staffing model and the choice to staff trains and stations, automation could lead to a reduction in the number of staff required (Cohen et al., 2015). Keolis, a company operating numerous automated metro network around the world has reported a reduction of 10% in operational costs due to staff reductions (Wang et al., 2016).

The greatest effect of automation is that service operations are less dependent on the availability of staff, depending on the Grade of Automation. Efficiency and flexibility can be increased dramatically. Reversing times can be reduced to a matter of seconds, depending only on the time it takes for the route to clear and for the points and signal to be set correctly for the reverse direction. No driver is present at the front of the train, who has to walk to the other end to resume operations in the opposite direction. Under GoA 4, where no staff are present at all in the vehicle, flexibility is highest. Any change in service such as the addition or subtraction of rolling to to accommodate changes in passenger demand, can be realised in a matter of minutes, without the need of spare personnel for driving or shunting operations. In case of disturbances, trains can be short-turned more quickly and more easily and supplementary delays caused by staff being at the wrong location at the wrong time can be reduced or eliminated.

Vehicle design
Under GoA Levels 3 and 4, no driver is present in the front of the train. Therefore, no cabins have to be constructed to provide the driver with a distraction-free workplace. This free space can be used by passengers, and therefore can capacity on metro lines be increased without altering the size of the trains. Capacity can thus be increased on sections such as underground section where elongating or widening trains is deemed too costly.

Driver behaviour
Automatically driven trains (GoA Levels 2, 3 and 4) eliminate the human factor in the driving of the trains and this has a positice effect on the variability of running times. While running times can still vary due to external factors and the state of maintenance of the trains, it reduces as the driver's driving behaviour is the biggest factor in running time variability. With a reduced variance, actual running times can be predicted more accurately, which can lead to a higher regularity and reliability of train services. Melo et al. (2011) reports that 33% of 5-minute delays can be reduced due to the transition from GoA Level 1 to Level 2. Furthermore, as the human factor is eliminated from driving the train, safety margins can be smaller, allowing for trains to drive more closely behind each other. Together with more precise running times – and therefore the less need for running time supplements – this can lead to an increase in capacity.

Vehicle availability
With the use of automated trains, the number of trains needed for operations can be reduced. Janmaat (2019) has stated that although availability is not necessarily impacted due to automation, the availability can be increased because the downtime of vehicles can be optimised due to different maintenance schedules. However, as has been stated in the section on driver behaviour, the use of time supplements in the timetable can be reduced, which effectively reduces running times. This can reduce the total cycle time of a train, which can result is the need of less rolling stock. Furthermore, without a driver in front, reversing times can be reduced, which has a positive effect on cycle times as well. Paris metro operator RATP reports that due to automation of Paris metro Line 1, the same service pattern can be operated with fewer rolling stock compared with Line 1 before automation (Cohen et al., 2015).

3.4.3. Other effects of automation

Safety
Automation can improve the safety of metro networks, and reduce the number of incidents. Wang et al. (2016) states that 50-60% of incident in urban rail traffic are caused by human error. Automation could reduce this number significantly or even eradicate human error incidents. Depending on the level of safety of the original signalling system, automation eliminates the human factor in regards to adherence to signal aspects and prevents Signal Passed at Danger situations.

However, the train driver performs more tasks than just driving the train and he/she is a key factor in ensuring the safety of passengers and ensuring smooth train operations (Karvonen et al., 2011). Well-trained drivers are able to spot anomalies during the trip and can identify abnormal objects along the track or suspicious behaviour of passengers when entering stations (Karvonen et al., 2011). In case of (minor) defects such as a defective door, a driver can actively interfere and play a prominent role in getting the train moving again as fast as possible. In case of emergencies, the driver can play an important role in aiding passengers or coordinating with emergency services.

In an automated system, all these abnormal events need to be accounted for, and complex systems and protocols have to be in place to deal with these situations. The absence of a driver in front of the train requires the need for technological solutions to enhance and ensure the safety along the track, such as collision/obstacle warning sensors or Platform Screen Doors (PSD). This is especially an issue on metro networks that feature sections outside or even have level crossings with road traffic. As the track can be accessed relatively easily, and thus where the chance of colliding with objects is far greater than on underground sections, automation can be a problem on these section. When a train is unattended (GoA Level 4), a defect can cause the whole automatic system to stop operations as a safety measure, while awaiting the arrival of maintenance crews and thus causing delays. The physical absence or distance of staff during unexpected halts, disruptions or emergencies can cause discomfort to passengers. The presence of staff is a contributing factor in the Level of Service that passengers experience.

Costs
Although automated systems are technically complex, which certainly is the case when existing metro lines are automated, construction or conversion costs can be very high compared to conventionally driven trains. However, due to less staff needed, more efficient operations, operational costs can be reduced (Wang et al.,

2016). The Paris metro has reported a reduction of 30% in operational costs when transitioning to GoA Level 3 or 4 (Ossent, 2010). The Copenhagen metro (GoA 4) reports that when the service pattern is increased, no additional labour costs apart from costs for office staff to implement the plan is required (Wang et al., 2016).

Energy efficiency
Being energy efficient is an important goal for an operator, not only to reduce operational costs, but also to help its public image. Due to optimised acceleration, traction and braking, the total energy consumption of automated trains can be reduced as compared to conventionally driven trains. As tractive energy accounts for 40-50% of the total energy consumption of urban rail systems (Wang et al., 2016), automation could lead to significant energy savings. A case study of the Valencia metro concluded that a reduction of 19% of the total energy consumption can be achieved (Sanchis and Zuriaga, 2016).

3.4.4. Conclusions automation

Automating metro networks can provide several opportunities, beneficial to both the passenger and the operator. This section has listed the vary factors on trip time variability as well as other factors that automation affects. As every metro system is different, automation can have different benefits, differing per situation. As automated networks, especially networks that are converted from conventionally driven to automatically driven, are relatively new, sufficient data on the exact benefits is scarce (Cohen et al., 2015). It is therefore difficult to determine that automation always is beneficial for all actors involved, however results are promising. Various metro operators around the world report saving is either operational costs, fleet size or energy consumption.

4

Increasing frequencies on the Rotterdam metro: a case study

4.1. Rotterdam metro case study

The research questions posed in Section 1.2.1 are applied to a case study of the metro network in the Dutch city of Rotterdam. The case study will be used to quantify the effects that increasing the frequencies has on timetable stability.

4.1.1. History of the network

In the early sixties, only two river crossings for inner-city traffic existed in Rotterdam: the Willemsbrug and the Maastunnel. Two other crossings were under construction, being part of the current ring-road around the city. At that time, many trams had to cross the narrow and crowded Willemsbrug, and were often hindered by frequent bridge openings. A plan was then made to re-route the trams to the south of the city through a new to be built tunnel. This plan was later changed into a new metro line, connecting the central station located north of the river Maas with the neighbourhoods located south of the river. This plan was put into reality and in 1968 the first Dutch metro line was opened together with a major re-organisation of the existing tram network. Since the opening of the six kilometre line the metro network has expanded steadily and nowadays the Rotterdam metro network consists of five lines extending far beyond the city limits, forming the backbone of Rotterdam's public transport network.

4.1.2. Current network

The current network consists of five lines on two main axes. The core of the network consists of two underground tunnels, one in east-west direction and one in north-south direction. Both tunnels intersect right in the city centre at the station of *Beurs*. Each of the five lines uses one of these tunnel sections, making *Beurs* the busiest and most important station, as all lines on the network pass that station.

Each of the five lines shares their trackage on the underground trunk sections with other lines and then diverges into the different neighbourhoods and municipalities surrounding Rotterdam. The east-west trunk section between *Schiedam Centrum* and *Capelsebrug* carries lines A, B and C, while the north-south trunk section between *Rotterdam Centraal* and *Slinge* carries lines D and E. There are two depots for the maintenance and storage of trains, each located on one of the axes: *Remise Waalhaven* between the stations of *Slinge* and *Rhoon*, and *Remise 's-Gravenweg* between the stations of *Capelsebrug* and *Kralingse Zoom*. Figure 4.1 shows the layout of the current network.

Table 4.1 shows the intervals per line that are currently maintained on the metro network. During the day, each line operates with a 10-minute interval, achieving an interval of 3.3 minutes (or 200 seconds) on the trunk sections during peak hours. Additionally, three additional trips are operated on line E between Slinge and Pijnacker Zuid (for a larger map of the network see Figure A.1) during rush hour periods. In the off-peak period, the interval is brought back to five minutes on the north-south trunk line. In the evening, the intervals are brought back again to a train every 7.5 minutes on the trunk sections. As a result, intervals of around

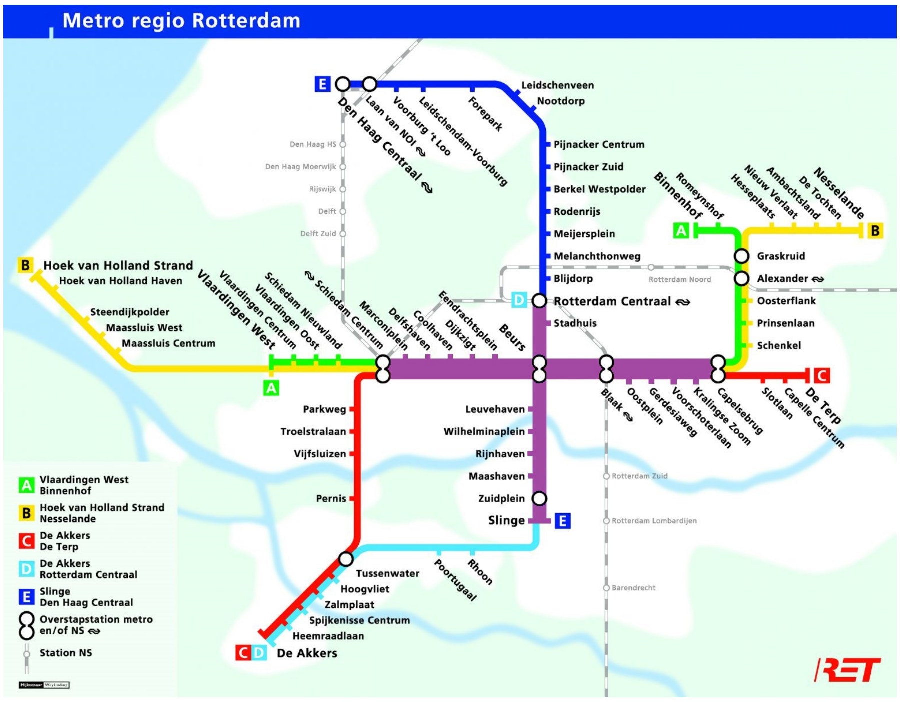


Figure 4.1: The two trunk sections of the Rotterdam metro, indicated in purple. Source original picture: RET

200 seconds are achieved during rush hour periods on these shared sections. According to RET, the metro network's current signalling system can deal with a minimum interval of around 90 seconds. Therefore *theoretically* the current network *should* be able to handle frequencies twice of what is currently achieved.

Table 4.1: Overview of intervals on the different sections of the network currently operated (RET, 2018)

Line	Route	Morning Peak	Off-Peak	Afternoon Peak	Evening
A	Vlaardingen West - Binnenhof	10'	10'	10'	–
A	Kralingse Zoom - Binnenhof	–	–	–	15'
B	Hoek van Holland - Nesselande	10'	10'	10'	15'
C	De Akkers - De Terp	10'	10'	10'	15'
D	De Akkers - Rotterdam Centraal	10'	10'	10'	15'
D	De Akkers - Rotterdam Centraal	10'	–	10'	–
E	Slinge - Den Haag Centraal*	10'	10'	10'	15'
Trunk sections:					
ABC	Schiedam Centrum - Capelsebrug	3.3'	3.3'	3.3'	7.5'
DE	Slinge - Rotterdam Centraal*	3.3'	5'	3.3'	7.5'

*In rush hours, 3 extra train trips are operated on Slinge - Pijnacker Zuid

4.1.3. Challenges for RET

Along with the growth of the network, passenger numbers have grown as well. Being a fast and frequent means to travel through the metropolitan area, the metro network is so successful that a new problem is arising: overcrowding. To relieve pressure on the now overcrowded trains, RET is currently operating a few extra trains during rush hour periods on line E (RET, 2018).

However, the extra trains on line E during the rush hours are not sufficient to handle future growth. The municipality of Rotterdam predicts that by 2040, 200,000 new homes will be built in the southern Randstad area, 50,000 of which within the city limits of Rotterdam alone (Gemeente Rotterdam, 2017). According to calculations done by the Dutch Ministry of Infrastructure and the Environment and RET, the busiest sections of the metro network under the city centre will soon reach their capacity limits and no longer be able to facilitate the future growth of the city (Gemeente Rotterdam, 2017; Ministerie van Infrastructuur en Milieu, 2017). The first sections of the network due to arrive at capacity limits are the trunk sections of the network running underneath the city centre. Structural measures in addition to the three extra trains during the rush hour periods are therefore necessary to accommodate the increased passenger volumes.

Recognising the steady growth in passenger numbers on the network and the challenges this will generate for the future, RET is interested in finding reliable solutions to increase capacity on its existing network. Not only are they interested in discovering what is achievable with their current network and infrastructure, they are also currently starting a preliminary study to investigate the advantages and disadvantages of automating parts of their metro network. Based on findings from other metro systems worldwide, automation might increase reliability of the metro network and hence enable the implementation of higher frequencies. They are interested in determining the bottlenecks on the network that hinder the increase of frequency and the measures that they can take to enable higher frequencies.

4.2. Data used for the verification and validation of the model

Verification and validation requires data. Firstly to provide input such as dwell times with the correct values and secondly, to assess whether the input has been modelled correctly (verification) and whether the model can provide accurate and usable results (validation).

In this research, two different types of data are mentioned. RET has conducted their own verification of their model, which is described in the first part of Section 4.4.4. They have conducted nightly test runs on 8 sections of track, resulting in 18 observations. Using data retrieved from the black box of the train used during the test runs, RET has compared the speed profiles from OpenTrack with the speed profiles extracted from the black box data.

Using the model provided by RET as a basis, alterations have been made to the model to include stochasticity in dwell times. Therefore the model has to be verified again during this research. For this, different, more extensive, data has been collected and utilised. Rather than using a very small sample size of 18 observations, the new data collected contains all stations halts of all trains travelling on the network during 10 working days. This data has been used to re-verify the trains' performance (Section 4.4.4), to construct and verify dwell time distributions (Section 4.4.5), and to validate the model (Section 4.5), using the two indicators described in Section 2.2.

The data required has to be able to show how well trains in operation perform in respect to their planned timetable. On individual train level, the arrival and departure times at each station are registered, together with the planned arrival and departure times at each stop. With this data, the running times of the trains can be analysed, as well as dwell times and punctuality rates, satisfying the input requirements for the indicators mentioned in Section 2.2.

Table 4.2 shows the format in which OpenTrack produces the output and in which the real-life data is presented. The first four columns relate to the identification of an individual train: the day of operation (when multiple days are analysed), the train service number, and the first and last station on the route of the train. The last five columns relate to a single scheduled stop at a station, showing the station in question, and the planned and actual arrival and departure times. With this information it it possible to determine the planned and actual headway between two trains, the punctuality of a train, and the dwell time of a train at a station.

Table 4.2: General format of the data required (the presented data is fictitious)

Date	Course ID	First Station	Last Station	Current Station	Planned Arrival	Actual Arrival	Planned Departure	Actual Departure
01-01-2019	M001-001	C.S	AKS	LHV	10:00:00	10:00:30	10:00:15	10:00:45
01-01-2019	M002-002	C.S	AKS	LHV	10:10:00	10:10:30	10:10:00	10:01:00
01-01-2019	M002-052	NSL	SDM	OPL	09:45:00	09:45:30	09:44:45	09:45:30
02-01-2019	M001-001	C.S	AKS	LHV	10:00:00	10:00:30	10:01:15	10:01:45

The accuracy of the real-life data plays a major role in determining how well the simulated running times coincide with the real ones. This data has been provided by RET. During the collection period for this research, the operator did not have a system installed on its metro trains that keeps track of the exact location of the train and registers when doors are opened and closed. A system like this has already been installed on RET's buses and trams for a number of years. Instead, performance data is extracted from the traffic control centre. That system controls the signals along the track and train positions are obtained through the train detection systems, which are part of the signalling system. The train detection system only provides the signalling system and the traffic control dispatcher with information on the occupation of a block in the network. A train could be anywhere in a block, and yet the same information is provided to the dispatcher. The only moment that a train's location can be exactly determined is when it crosses from one block into another and when the rear of the train releases the previous block.

The moment that happens is used to determine when a train halts at a station. On the Rotterdam metro network with the older signalling system installed (everywhere apart from line E north of *Rotterdam Centraal*, the majority of the station blocks have roughly the same length as the length of the platform. Dwell times are measured from the moment the station block is occupied to the moment it is released again. However, as trains are not stationary the moment they enter and exit the station block, these times have to be corrected, as some time elapses between the moment a train has entered the station block, comes to a halt and opens it doors.

The correction factors depend on several variables:

- the distance between the signalling block separation and the start of the platform,
- the length of the platform,
- the stopping location along the platform,
- the length of the train, and
- the acceleration and braking rate of the trains

These variables differ per station, and also differ per train. RET conducted research to determine this data and has measured the time that elapses between the moment that a train enters into the station block and the moment that the train comes to a stop, and has measured the time that elapses between the moment that a train is set in moment and the moment that the train traverses into the block directly after the station. RET has furthermore concluded that during the day, all trains have the same length, solving the issue of differing train lengths. Moreover, on the majority of the network, all platforms have the same length and all stations blocks are the same length, being the exact length of the platform.

Therefore, RET has applied one correction factor for the arrival time, correcting for the fact that a train opens its doors on average 11 seconds *after* entering the station block section, and has applied one correction factor for the departure time, correcting for the fact that a train closes its doors on average 5 seconds *before* its head has left the station block section. However, there are some stations on the network where block or platform lengths are significantly different from the rest for which the applied correction factors are not representative. For those stations, RET has applied different correction factors specific to those stations.

RET and this research both realise that this method is not fully accurate and that differences of a few seconds can exist between the dwell times (and therefore running times) presented in the data and the real dwell times. The data that has been obtained for this research is the most accurate data available of the execution of full-day timetable. Due to no systems present to register the exact moment of doors opening and doors closing of each train, the dwell times extracted from the train detection data will always be an approximation of the real dwell times and can therefore differ by a few seconds.

4.3. Modelling choices

When building a model, one strives to represent the real world as accurately as possible. However, an exact representation is impossible and one always has to make assumptions and modelling choices that simplify the real-life situation. It is inevitable that differences exist between the real-life situation and the model.

This research has used an existing model that has already been built and has been provided by RET. In the model, the network as was in operation in the spring of 2019 has been modelled. This includes lines A and B (green and yellow lines) east of *Schiedam Centrum* – the western section of these lines (called the *Hoekse Lijn*) was still under construction during this thesis – and all parts of lines C, D and E (red, cyan and blue lines).

4.3.1. Trams on the RandstadRail section

A special property of the *RandstadRail* line is that metro vehicles on line E share trackage with The Hague's tram lines 3 and 4 between the stations *Leidschenveen* and *Laan van NOI*. The trams, operated by The Hague's public transport operator HTM, operate on that section very frequently and therefore affect performance of RET's trains. However, the trams have not been incorporated in RET's model. No data of the trams' performance, neither for the driving characteristics, nor for the timetable performance, has been made available for both RET and for this research. Therefore the behaviour of the trams cannot be modelled accurately. Delays encountered elsewhere on the trams' network cannot be incorporated in the OpenTrack model of the metro network.

Therefore it has been chosen to leave the trams out of the model entirely. To correct for the trains' behaviour on the RandstadRail section, it has been assumed that due to the presence trams, the trains do not leave the stations along the line early, which is possible under the current signalling system. For the comparison between the performance of the current timetable in real life and the current timetable in OpenTrack, the *Timing station* functionality has been switched on for trains on the RandstadRail, to compensate for the absence of the trams.

However, this measure does not account for delays incurred by RET's trains due to the high occupation on the shared sections of track. This is an important limitation of this model. An option is to omit the shared section of track from the model. A disadvantage of this is that this impairs the quality of the representation of trains on line E even further. The reversing of line E trains is then not taken into account, which is a key element in the reliability of a timetable and can therefore shed insights in the effects of buffer times at terminal station.

These arguments have led to the decision to include the whole of the *RandstadRail* section in the OpenTrack model, but to not include the trams in the timetable. Therefore, when assessing the performance in future scenarios, one has to take into account that the presence of trams on the *RandstadRail* section have a negative effect on the performance of trains on line E and that therefore the performance of line E trains is too optimistic in the OpenTrack model.

4.3.2. Time-frame of collected data and sample size

To compare the OpenTrack performance with real-life, the same timetable that is currently in operation on the Rotterdam metro network has been imported into OpenTrack. To include stochastic effects properly in OpenTrack, multiple simulations have to be run. OpenTrack provides for the option whether or not to include stochasticity in the simulations. If this functionality is enabled and the correct data is implemented in the programme, OpenTrack picks a random number for the dwell time based on the user-defined dwell time distributions. The choice of random number is controlled by the *Delay scenario* functionality, which contains 200 pre-defined scenarios. In each scenario, different random numbers are chosen, which will result in a different outcome for each run. Moreover, even within a scenario itself, the dwell times are different each time a train stops, and therefore each individual stop within a simulation run contributes to the sample size.

It has been chosen to limit the simulation data and the real-life data to the time-frame in which the network is the most under stress: the morning rush-hour. In Rotterdam, the busiest is between 07:00 and 09:00 in the morning. Therefore, it is chosen to run simulations between 04:00 and 11:00 in the morning, to include not only the rush hour period, but also some hours before and after, to include the effects of the timetable frequency increase and decrease just before and after the peak moment.

Within the time-frame of 04:00 to 11:00, roughly 7,000 stops are made on the whole of the network. It has therefore been chosen to run *ten* different simulations, which brings the total number of stops – and therefore the sample size – to 70,000. The corresponding real-life data of ten working days during which the same timetable has been operated as the timetable that has been simulated, has been collected to match the number of simulated stops.

4.4. Verification

4.4.1. Introduction

As has been mentioned in Section 2.4, verification assesses the quality of the model; whether or not it has been built correctly. Therefore verification relates to the "input" side of the model, determining whether all the elements that need to be implemented in the model are there, contain no errors and interact with other elements the way they should.

Four main elements are implemented in the OpenTrack model and therefore require verification:

- Verification of infrastructure;
- Verification of train characteristics;
- Verification of dwell behaviour;
- Verification of timetable implementation

All four elements mentioned above define how trains behave, how they interact with each other and how they are capable of adhering to a schedule. Verification of the infrastructure entails that all infrastructure elements of the network under study have been modelled correctly in OpenTrack. The train characteristics are verified, to ensure that trains react to the infrastructure or other train as they would do in reality. Acceleration and braking rates have to be modelled correctly, as they are elements of train travel times.

Another element of travel time is dwell times, the time that trains are stationary at stations and during which passengers board and alight. The length of dwell times is determined by the passengers and is an important cause of trip time variability (Van Oort, 2011). The length of the dwell times are of a stochastic nature. The way that that stochasticity is implemented in OpenTrack is a key element in ensuring the correct behaviour at stations.

The last important element is the implementation of the timetable. This is mainly of importance during the validation phase of the assessment of the model and for the assessment of future scenarios. During both phases, the execution of the timetable in the simulations is compared with the planned timetable. Therefore, the timetable implemented in OpenTrack has to match the timetable as operated in the real world, as in both cases, in order to ensure that the realised operations are the same in the simulations as in the real world.

4.4.2. Verification of infrastructure

OpenTrack allows for a detailed representation of rail-bound infrastructure. The details of the infrastructure hierarchy have been discussed in Section 2.3.1. This allows for exact locations of infrastructure elements such as signals and electrical track insulators to be defined by assigning a value to the *Kilometre point* property at each vertex. OpenTrack then calculates the length of each edge between two vertices. This way the exact length of the network has been implemented up to an accuracy of one metre. Station stop locations, being either at the beginning, centre of end of the platform, have also been modelled according to the real-life situation.

The model that was provided for this research did not yet included stochasticity in the dwell times and instead used a fixed dwell time of 20 seconds for every train at each station. Early tests of this deterministic model showed that a full timetable was able to be executed within a time period of a full day. However, when stochasticity in station dwell times was added, major traffic jams started occurring at terminal stations where trains reverse, indicating that trains block each other. Figure 4.2 shows these blockages on a space-time diagram.

The space-time diagram shows the trajectories of different trains graphically as they progress through time and space. With the stations on the vertical axis and the progress through time on the horizontal axis, the coloured lines represent lines A through E and their corresponding colours. Figure 4.2 shows the east-west axis from *De Akkers* to *Nesselande*. From around 08:30 traffic jams start to occur at the stations *De Akkers* and *Schiedam Centrum*, both terminal stations for lines C and D and line B respectively. This can be deduced from Figure 4.2 as horizontal lines indicate that a train does not move in space as time progresses.

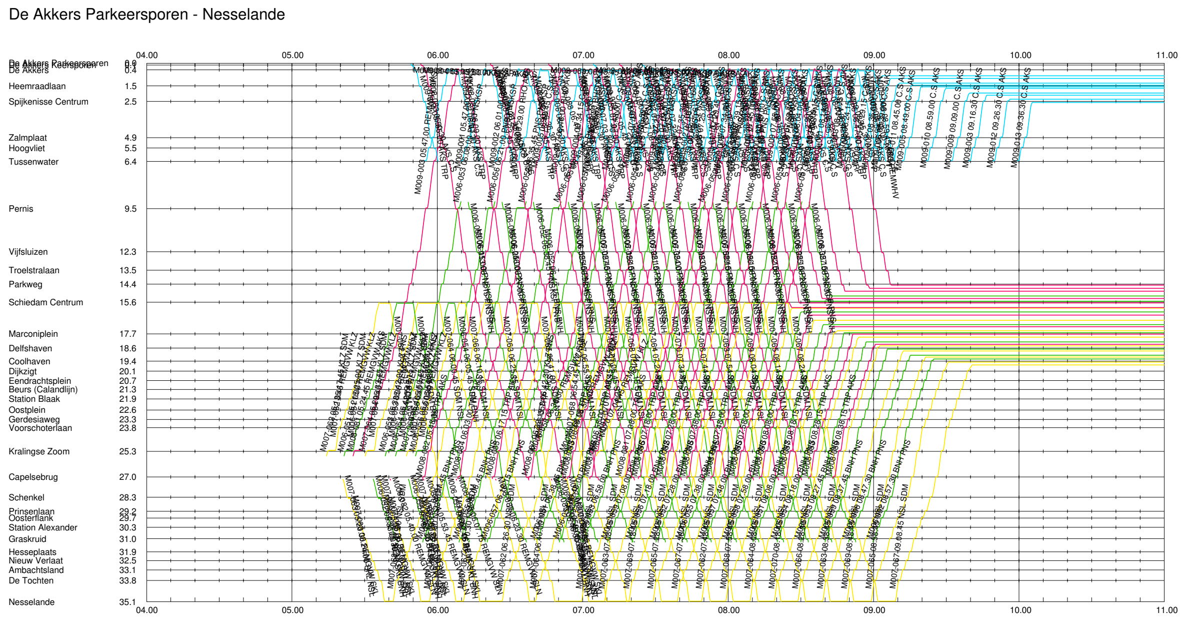


Figure 4.2: Space-time diagram demonstrating blockages at terminal station (horizontal lines represent stationary trains)

Flaws in signalling system representation

Although all signals were implemented at their correct locations, the interaction between different infrastructure elements and between trains apparently still contained errors, else no blockages would have occurred. This phenomenon occurred in more tests and at more locations, but only at terminal stations. This indicated that the traffic jams occurred due to a "deadlock" situation, where a train that is about to leave the station is blocked by a train entering the station that has to wait for the first train to leave the station. Figure 4.3, a screenshot of OpenTrack, shows the cause of the traffic jam. In OpenTrack, reserved tracks are indicated green, occupied track sections red, and reversing trains orange. Figure 4.3 shows that both platform tracks at *De Akkers* are occupied by reversing tracks when a third train approaches. Rather than waiting in front of the entry signal (indicated in red in the OpenTrack model), the third train travels on to the cross-over switches and waits in front of the signal just before the platform, thus creating a deadlock and preventing both reversing trains from leaving the station.

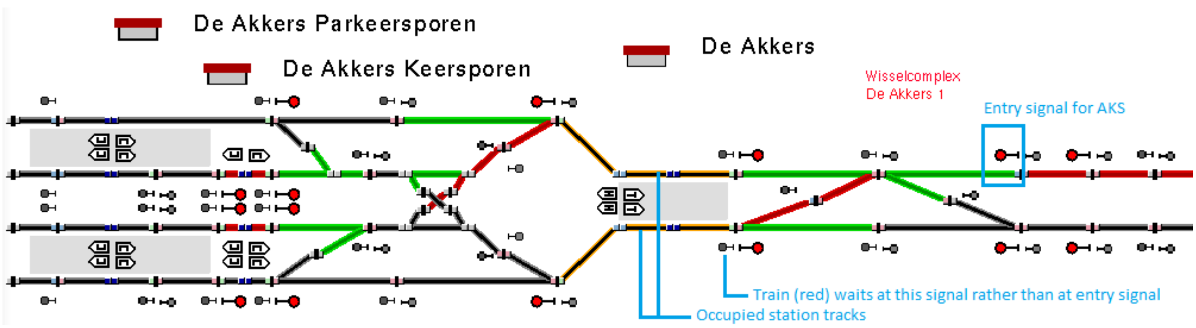
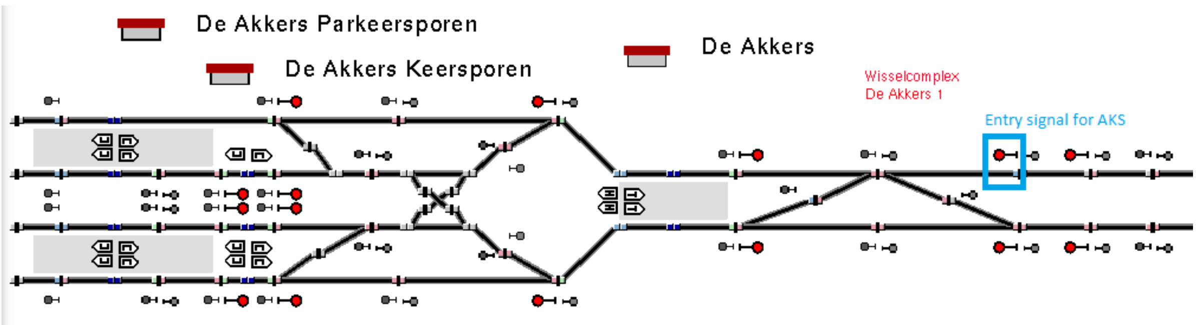


Figure 4.3: The traffic jam at *De Akkers*, caused by an entering train wanting to enter an occupied track

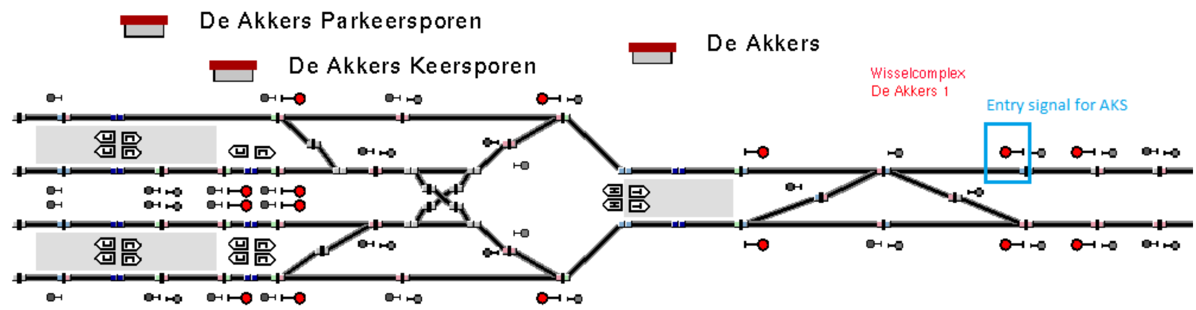
OpenTrack has a functionality to prevent deadlocks called *Reserve with previous Route*; this parameter can be applied to a route (for the infrastructure hierarchy, see Section 2.3.1). If this functionality is enabled for a route, the route preceding that route it not reserved for an incoming train if the first route in question is occupied by a train having a different direction than the incoming train. Separate routes can be chained, ensuring that a deadlock cannot occur on a set of points or a section of bi-directional track.

This functionality can work at terminal stations if the headway between two trains is large enough. However, when trains follow each other very closely, the first train does not have enough time to reverse direction before the second train starts to reserve incoming routes, still causing a deadlock. This occurred during some simulations at one or more terminal stations.

The choice has been made to alter the infrastructure in the model in order to eliminate the possibility of deadlocks. This meant removing a couple of signals. This has an effect on the degree of realism at those locations, as the signals – albeit virtual as most of the Rotterdam metro does not contain wayside signals – tell the driver what speed is allowed in the upcoming section. Removing a signals results in a slower aspect being shown a signal earlier than in real life, meaning that a train will slow down earlier in the model than in real life. This obviously has an effect on the running times of the trains, but this (small) loss of realism is accepted in favour of avoiding traffic jams in one or more of the simulations.



(a) Signalling situation *De Akkers* in the original layout



(b) Signalling situation of *De Akkers* after some signals are removed

Figure 4.4: Situation at *De Akkers* before and after removal of a couple of signals

Figure 4.4 shows that four signals east of the platform of *De Akkers* have been removed. Trains entering the station from the east will now wait at the signal coloured red in Figure 4.4 just east of the cross-over switches, rather than wait just before the platform and occupying the cross-over switches, as is shown in Figure 4.3. This practice has been applied to all terminal stations where this risk of deadlocks existed. As a result, no more traffic jams occurred, which is shown in Figure 4.5.

This section has demonstrated the difficulties of modelling a signalling system. Each signalling system used in rail transport is unique and implementing this into a simulation tool, designed to be used for as much rail-bound systems as possible, proves to be a challenge. This section proves that in some occasions the level of realism has to give way for the practicality of the model.

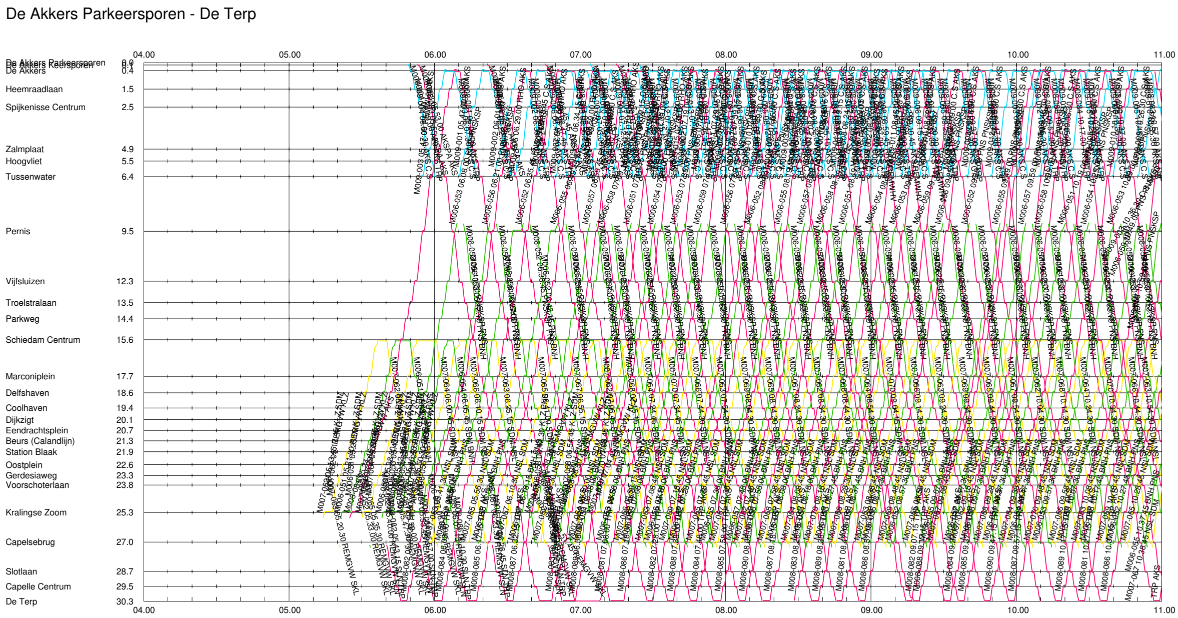


Figure 4.5: Space-time diagram demonstrating stable operations with stochastic dwell time variations included

4.4.3. Verification of the timetable

To assess the adherence to a timetable in OpenTrack, the timetable itself and the response of trains to that timetable have to be modelled correctly. This is governed in OpenTrack by a *course*. A course is one train travelling on the network, with equipment (defining the train's driving characteristics), itinerary and the departure time of the first station assigned to the course. Therefore, a course in OpenTrack defines *one* trip of a train, starting at one end of a line and ending at the other end of the line. A timetable is loaded into OpenTrack, by exporting a timetable from the software used by RET to construct their timetables, converted into the format that is readable by OpenTrack and then loaded into the simulation tool. This way, a timetable of a full day can be easily imported into OpenTrack.

If no additional parameters are defined in OpenTrack, a train arriving at the last station of its itinerary in OpenTrack simply disappears. In real-life, trains at terminal stations obviously do not disappear, but rather reverse direction, await their departure time and then depart for the return trip.

An important element of terminal station dwelling is the inclusion of buffer time. Buffer time makes up for delays encountered on the inbound trip and prevents them from affecting the return trip. The use of buffer time at terminal stations is an important measure to reduce the effects of delays and is therefore of importance in timetable reliability. However, not all time spent at terminal stations can be regarded as buffer time; a minimum time has to be allocated to reverse the train. This time does not count as buffer time, as this time always has to and will be used for reversal procedures. As a result, station halts at terminal stations do not depend on passenger demand, but rather on the time required to reverse the train and the amount of allocated buffer time.

Rotterdam metro operator RET has defined a minimum reversing time of two minutes to grant the train driver enough time to walk to the other end of the train and set the train up for the return trip. RET has constructed its timetables so that at least two minutes is available at terminal stations, on the condition that trains are punctual. In most cases, more than two minutes reversing time is allocated, to incorporate buffer times into the timetable and to grant the train driver more time.

In OpenTrack, dwell behaviour at terminal stations is modelled differently from the behaviour at intermediate stations. Given the less-stochastic nature of terminal dwell times, no delay distributions are utilised at terminal stations. As reversing operations and the allocation of buffer times play a key role in timetable punctuality, OpenTrack has to be able to accommodate this feature.

In OpenTrack, each train on the network is defined as a *course*, following an itinerary and being assigned a train, to have the correct driving characteristics modelled. Train fleets do not exist, so generally speaking, courses are independent of each other. This becomes an issue at terminal stations, as OpenTrack does not necessarily assume that two courses are operated by the same physical train. This is important, because trains can start their course with a delay if the delay on the previous trip was greater than the available buffer time at the terminal station.

The method to solve this is to instruct OpenTrack that a certain course cannot depart from the terminal station before another course has arrived at the same station. Both courses are in reality the same train, but in OpenTrack there are no physical trains. OpenTrack does have a *connections* functionality, with which trains (courses) can be instructed to wait for another course to arrive at a certain station before departing. Additionally the minimum and maximum time it is allowed to wait after the arrival of the other connecting train can be specified. Figure 4.6 shows the connection window in OpenTrack, where the connecting course and minimum waiting time can be specified.

Course ID	Station	Type	Min. Wait	Max. Wait	Join	Split	
M006-051 05.25.	SDM	Arr./Pass.	00:02:00	HH:MM:SS			

Figure 4.6: Example of a connection assigned to course *M006-051 05.49.45 SDM BNH* at SDM to wait for the train's previous trip to arrive

This feature can be used to model a reversing train, by instructing the departing train that it is allowed to depart at least two minutes after its connection (which would be the same train's previous course in real life) has arrived. By assigning a minimum connection time of two minutes, the minimum reversing time required for a train to turn around can be modelled.

For the connection functionality to model a reversing train correctly, both the arriving course and the succeeding departing course have to be assigned a "connection". The arriving train has to be "split" into a train of "zero" length which will disappear, and the departing train with exactly the same length as the arriving train. This way, the track will remain physically occupied during the connecting period of two minutes, The newly "split" departing train will have to have a connection assigned to it as well, to ensure that it will depart two minutes after its predecessor has arrived. Were the "split" not applied, then the departing train will still depart at least two minutes after the arriving train, but in the meantime the track would be unoccupied. This is because trains at the end of their course will just disappear without waiting the minimum two minutes, unless for example a "split" is assigned to it.

The connection time is the minimum time that a train will wait. If the two minutes have expired but the scheduled departure time has not been met, the connecting train will wait until the scheduled departure time, under the condition of course that the *Timing station* functionality has been enabled for that station. This way, the reality has been modelled accurately in OpenTrack, because potential (substantial) delays on the inbound trip are able to affect the return trip due to this connection.

4.4.4. Verification of running times

Train running times are defined by train characteristics, track length and track speeds. The latter two measures are defined in the infrastructure model in OpenTrack, while the first factor is determined by acceleration and braking rates of the trains, train lengths and train weight. RET operates two classes of Electric Multiple Units on its network:

- Class SG2/1: 30 metres in length, carried by three bogies, operated on lines A, B, C and D;
- Class SG3: 45 metres in length, carried by four bogies, operated on all lines.

During the day (and therefore during the observation period in this research) the two types are coupled in pairs of class SG3 or triples of Class SG2/1 to form trains of 90 metres in length. Both types of trains have similar driving characteristics, yet are slightly different due to differences in weight and number of axles. The two different classes are implemented in OpenTrack to model these differences. In the simulations, each class is assigned to the line on which it is planned to operate. However, as both classes are able to operate on multiple lines, RET is granted a level of flexibility to re-assign train sets to other lines, depending on the availability of operable units. Therefore the possibility exists that in the simulation a different class can be operated on a line or individual course than in real-life for a specific day, however these difference are expected to be minimal.

Verification of train characteristics
The running times have been verified twice by two different parties: once by RET before the start of this research and once during this research, both using a different source of data. As has been mentioned in this research, the basis of the model has been built by RET, who provided a deterministic model that could operate stably. They have verified the train characteristics by comparing the speed profiles of the simulated trains with speed profiles, obtained from "black box" data from real trains. This data was retrieved during tests carried out at night, during which no other traffic was present on the network. Thus the train under scrutiny would not be hindered by other traffic. Furthermore, the nighttime period provided opportunities to test unusual train movements, such as travelling over crossover points and other movements that cannot not be tested during daytime operations without hindering trains in revenue service.

The train driver was asked to travel over a section of line twice: once in the way he/she would normally do with a train full of passengers, and once using the full potential of the train's capabilities. The average of the two observations was taken and compared with the results of the same trip in OpenTrack. To fully capture the train's behaviour, at least three different sections of track were observed, achieving at least three different types of movement:

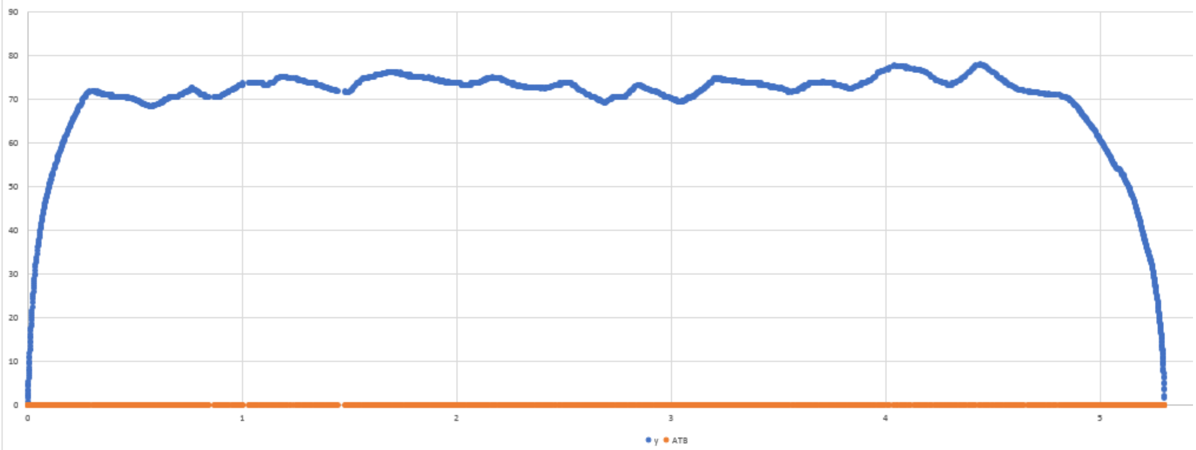
- Travelling at maximum speed on a section of track without limitations imposed by signals or points
- Departing from a terminal stations with a speed limit during departure
- Crossing over to the neighbouring tracks using points with a low speed limit

The results of these observations are presented in Table 4.3. Furthermore, Figures 4.7, 4.8 and 4.9 show the speed profiles of real trains and trains computed in OpenTrack of three of the sections presented in Table 4.3, each with different speed characteristics (free speed, speed restriction and crossover). The speed profiles of the real trains have been extracted from the black box data from the trains.

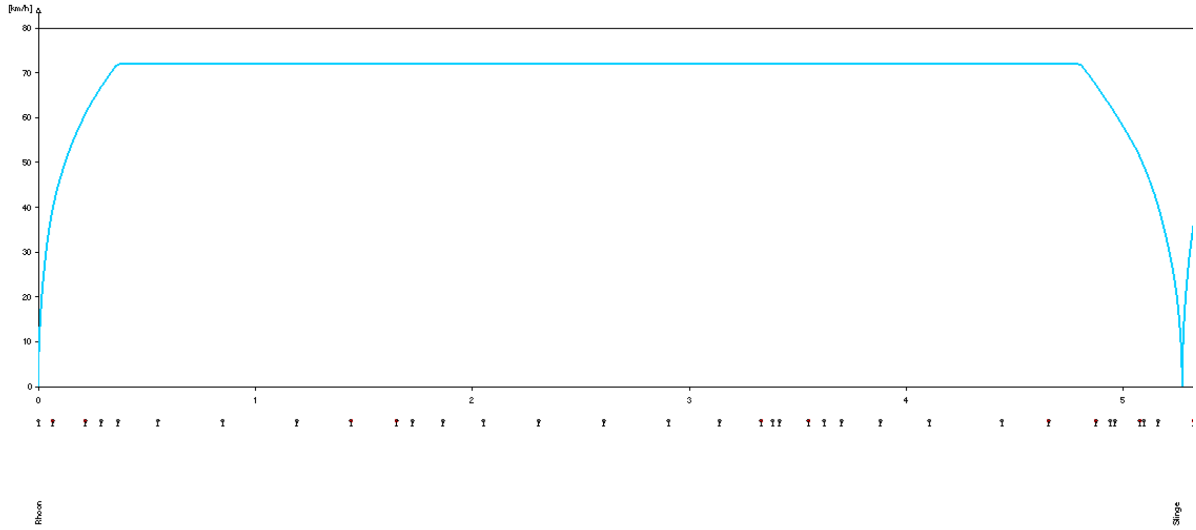
Table 4.3: Results of the verification (Data courtesy of RET)

Track section	Real observations [sec]	OpenTrack [sec]	Differences [sec]
RHO1 - SLG1	288	295	7
MHV1 - RHV1	63, 69, 72	69	[-3,+6]
RHV1 - WHP1	69	67	-2
SLG3 - ZPL1	111, 126	119	[-7,+8]
RHV1 - WHP2	78, 80	76	[-4,-2]
SHS2 - BRE2	48, 52, 55	51	[-4,+3]
WHP2 - RHV2	61, 65, 66	66	[0,+5]
ZPL2 - SLG3	118, 126, 136	123	[-13,5]

Figure 4.7 shows the speed profile of both a real train and a simulated train between *Rhoon* and *Slinge*, a segment of open track with a maximum speed of 80 km/h. Figure 4.7a shows the speed profile of a real train, while Figure 4.7b shows the speed profile of a train simulated in OpenTrack. The first element that is observable is the difference in driving style between the driver and the simulation while cruising at maximum speed. While the train simulated in OpenTrack cruises at a constant speed of 72 km/h, the driver seemingly has more difficulty keeping the train at a constant speed. The segment between *Rhoon* and *Slinge* contains various changes in gradient, which explains the more varying cruising speed of the driver. The simulations are more able to keep trains at a constant speed and therefore the variance of running times in OpenTrack are lower than in real-life.



(a) Speed profile of a real train between *Rhoon* and *Slinge* (Graph courtesy of RET)



(b) Speed profile of a simulated train between *Rhoon* and *Slinge* (Graph courtesy of RET)

Figure 4.7: Graphs comparing a real-life and a simulated train between *Rhoon* and *Slinge*

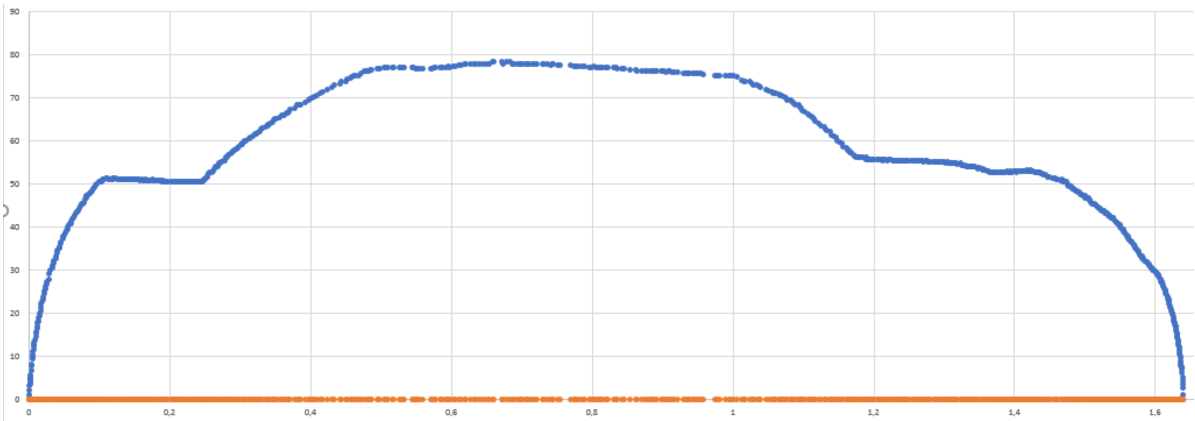
Figure 4.8 shows two speed profiles that are more alike. Here the driver maintains a more constant speed while cruising and while adhering to the maximum speeds of 50 and 80 km/h respectively.

Figure 4.9 shows a situation which does not occur in everyday practice: using cross-over switch to transfer to the other track and continue in wrong-line operation. Figure 4.9b shows that the simulated train shows the correct behaviour by slowing down after passing the signal showing the speed restriction for the switches, maintaining the restricted speed well ahead of the speed restriction itself (the black line in Figure 4.9b shows the maximum speed allowed). The behaviour of the driver is different. In this case the driver is aware that the speed restriction will follow and, after departing *Rijnhaven*, does not accelerate to the maximum speed then allowed (50 km/h), but maintains a speed close to the speed restriction ahead.

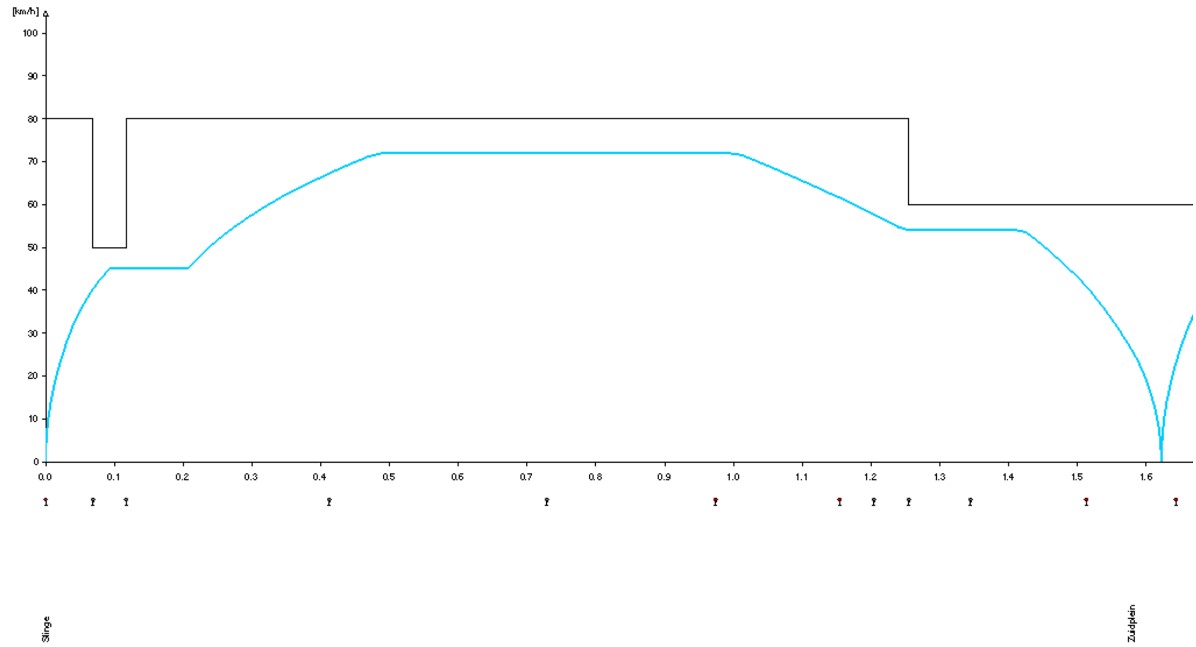
Figures 4.7, 4.8 and 4.9 show that the simulated train behave as they should, adhering to the maximum speed, and showing acceleration and braking rates that match the real-life acceleration and braking rates. Figure 4.9b confirms that the trains react to the signalling system as they would in real-life, by indicating that trains immediately start slowing down when passing a signal showing a speed restriction.

Calibration of performance parameter

However, Figures 4.7b, 4.8b and 4.9b also show that the simulated trains never reach the maximum permitted



(a) Speed profile of a real train between *Slinge* and *Zuidplein* (Graph courtesy of RET)



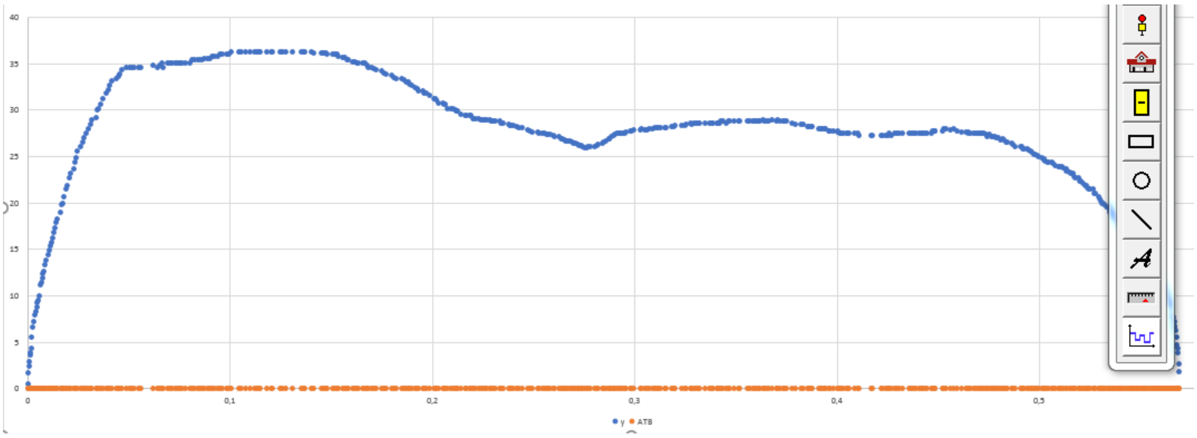
(b) Speed profile of a simulated train between *Slinge* and *Zuidplein* (Graph courtesy of RET)

Figure 4.8: Graphs comparing a real-life and a simulated train between *Slinge* and *Zuidplein*

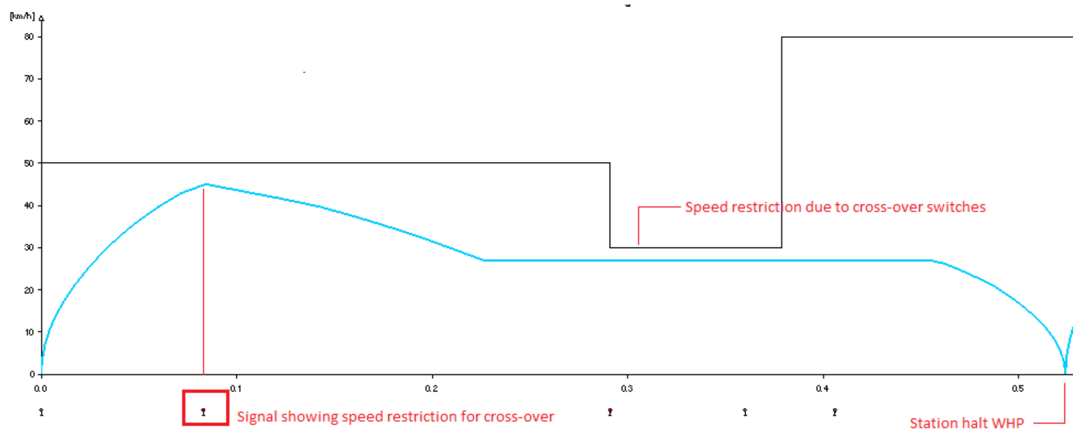
speed, but always stay below. This is caused by the *performance parameter*. The performance parameter – a percentage – restricts the driving performance of the trains, effectively slowing it down. A performance parameter of 50% indicates that a train will accelerate, brake, and cruise with 50% of its maximum acceleration rate, braking rate or maximum (permitted) speed.

RET has performed their verification with the performance parameter set to 90%. This is reflected in Figure 4.7b, where with a maximum speed of 80 km/h, the train travels with a speed of 72 km/h, which is exactly 90% of the maximum permitted speed. With this performance parameter setting RET has ensured that the running times between two stations in OpenTrack are the average of the observations from the nightly tests shown in Table 4.3. Furthermore, they claim that there is little variation in running times on their network, and that the drivers show constant driving behaviour, regardless of punctuality of their train.

However, the nightly tests conducted by RET have shown that two types of driving behaviour do actually exist: driving calmly and driving at the train's full potential. Own observations by accompanying drivers during their work have shown that variations in driving behaviour do indeed exist and do depend on the punctuality



(a) Speed profile of a real train between *Rijnhaven* and *Wilhelminaplein*, using switch-over points (Graph courtesy of RET)



(b) Speed profile of a simulated train between *Rijnhaven* and *Wilhelminaplein* using switch-over points (Graph courtesy of RET)

Figure 4.9: Graphs comparing a real-life and a simulated train between *Rijnhaven* and *Wilhelminaplein*

of the train. This research has therefore concluded that the performance parameter set at 90% is not accurate enough.

OpenTrack contains a functionality that enables different performance parameters to be set, depending on the lateness of the trains. Therefore the following values are a more accurate representation of the real world:

- Performance parameter at 90% when early
- Performance parameter at 100% when late

However, the signalling system installed on the Rotterdam metro prohibits trains from departing early. As this functionality is present in OpenTrack as well, a performance parameter set to 100% leads to a more accurate representation of the real-life driving behaviour.

Verification of running times
With the performance parameter now set to 100%, this research has conducted another verification by comparing the running times between stations between the simulations and the real-life data. To accomplish this, the "pure" running times of trains have been examined, both in OpenTrack and in real life. The "pure" running time is measured as the time that elapses between the arrival at a station and the departure of the previous station, thus eliminating the effects of station dwell time (and its possible delays). As dwell times are subjected to variations caused by passenger behaviour, including them in the running times will give a

distorted view of a train's performance.

The Rotterdam metro network comprises 124 segments, each covering one section of line between two stations. This includes different directions (e.g. *KLZ > VSL* and *VSL > KLZ* are counted separately) and diversions (e.g. *CPB > SLN* and *CPB > SKL*). The running time on a segment is defined as the time that elapses between doors closed at the first stations and doors open at the second station. This includes train acceleration and braking due to station stops, which are the main factors that determine the accuracy of the implemented train characteristics.

The running times on each segment are calculated for both the simulation and the real-life data. Next, the differences between the average running times are computed. Figure 4.10 is a histogram which shows the number of segments on the vertical axis that have a certain difference (on the horizontal axis) between the simulated average running time and the real average running time. The average difference in running time and the standard deviation of the difference are computed as well. The blue bar on Figure 4.10 is the average difference in the average running times, being + 3 seconds. The green bars are all differences that fall withing the standard deviation of 10 seconds, and the red bars are all differences that fall outside the standard deviation.

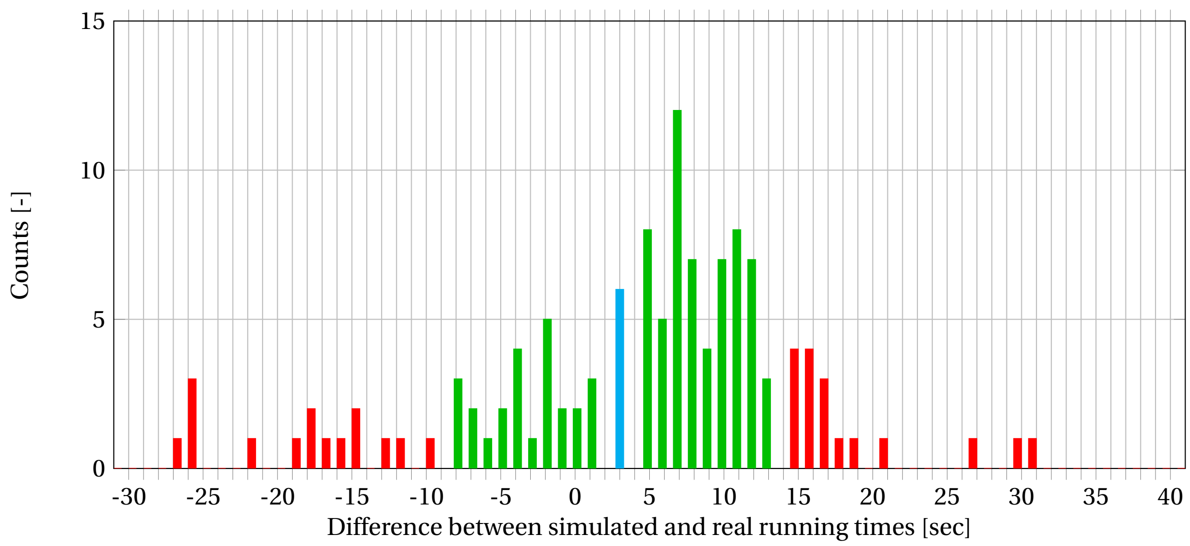


Figure 4.10: Histogram of differences between simulated and real running times

4.4.5. Verification of Dwell times

Implementation of dwell times in OpenTrack
In OpenTrack, the user is offered four different options to model a train's dwelling behaviour at stations. The first is the way OpenTrack deals with adherence to the schedule in case of early trains. Each station contains the attribute *Timing point*. If a station has this attribute enabled, then each train stopping at that station will wait until the scheduled departure time – if it arrived early – or depart after dwelling for at least the specified minimum dwell time – if it arrived late. If the *Timing point* attribute is not enabled, each train will dwell for at least the minimum dwell time, will add time to that based on the type of delay distribution used and then depart regardless of the schedule.

The second functionality is *Minimum dwell time*. If a value is specified at a certain station for a certain train, then that train will wait for *at least* the specified amount of time before departing. The train can wait longer, either because the scheduled departure time has not yet been reached (see previous paragraph on timing points) or because extra delay is added to the dwell time.

Furthermore, there are two different methods of including randomness to dwell times in the simulation. The first is by adding a mean delay to the dwell time. OpenTrack then selects a random number from an exponential function and adds that time to the minimum dwell time. This process is pseudo-random, meaning that the computations can be reproduced, but if multiple simulations are run sequentially, different results can be obtained per simulation run. The exponential distribution from which OpenTrack picks random numbers is the default setting. If the user wishes to use a different distribution, OpenTrack allows for the user to enter a user-defined, piece-wise linear distribution from which OpenTrack picks its random numbers.

Table 4.4: Overview of different tools to model dwelling behaviour in OpenTrack

Function	Description
Timing station	All early trains at selected station wait until scheduled departure time
Minimum dwell time	Includes a minimum waiting time for a train at a specified stop
Mean delay	Stochasticity included using default distribution (exponential)
Delay distribution	Stochasticity included via user-defined (piece-wise linear) delay distribution

To re-create the behaviour of the trains on the network in OpenTrack, the tools listed in Table 4.4 have be used as follows:

- **Timing station** The original signalling system of the Rotterdam metro, used on all lines except the Randstadrail line north of *Rotterdam Centraal*, has a signalling aspect at stations that prevents trains from leaving the station early. The Randstadrail line uses a different signalling system which does not include that functionality. Up until 2019, train drivers on the whole of the network were not aware of the departure times at all intermediate stations, but only the departure and arrival time of the first and last station of their course. This did not matter, for the signalling system prevented early departures anyway. This practice was not changed, even though the new signalling system on the Randstadrail line did not carry that feature. This behaviour has been re-created in OpenTrack by switching the timing station functionality on for all stations with this system, and off for all stations north of *Rotterdam Centraal*.
- **Minimum dwell time** Is not used, as the dwell times are determined by the user-defined distribution function, and may be able to include very short dwell times, depending on the distribution used.
- **Mean delay** Is not used either, as the dwell times are determined by user-defined distribution functions and not by the standard exponential distribution.
- **Delay distribution function** OpenTrack allows for events that have a stochastic nature, such as duration of signal failures, train breakdown or dwell delays to have the user input a user-defined distribution, using the *Distribution Window* functionality. To re-create the real dwell behaviour in OpenTrack, dwell time histograms have been extracted from real-life data and turned into delay distributions for each individual station. Based on the defined distribution, OpenTrack picks a random number to calculate the dwell time.

Dwell time distributions are constructed by extracting dwell time histograms from the real-life data and implementing them as a piece-wise linear distribution in OpenTrack. Figure 4.11 shows the histogram in which all station stops for all trains for all stations are included. Analysis of the dwell times yields the following values:

Average:	(μ)	31	seconds
Standard deviation:	(σ)	14	seconds
Sample size:	(n)	70,222	observations

However, using one aggregated distribution for all stations will not yield realistic results, as no distinction is made between stations with higher and lower dwell times. Figure 4.12 demonstrates why this is done by showing the histograms for *Beurs* – a very busy station – and *Forepark* – a very quiet station – and the aggregate distribution in which all stations are included. Figure 4.12 shows that the aggregate distribution is shifted to the right compared with *Forepark*, but shifted to the left compared with *Beurs*. Were the aggregate distribution used for all stations, then the dwell times for *Forepark* would be too high, and for *Beurs* too low.

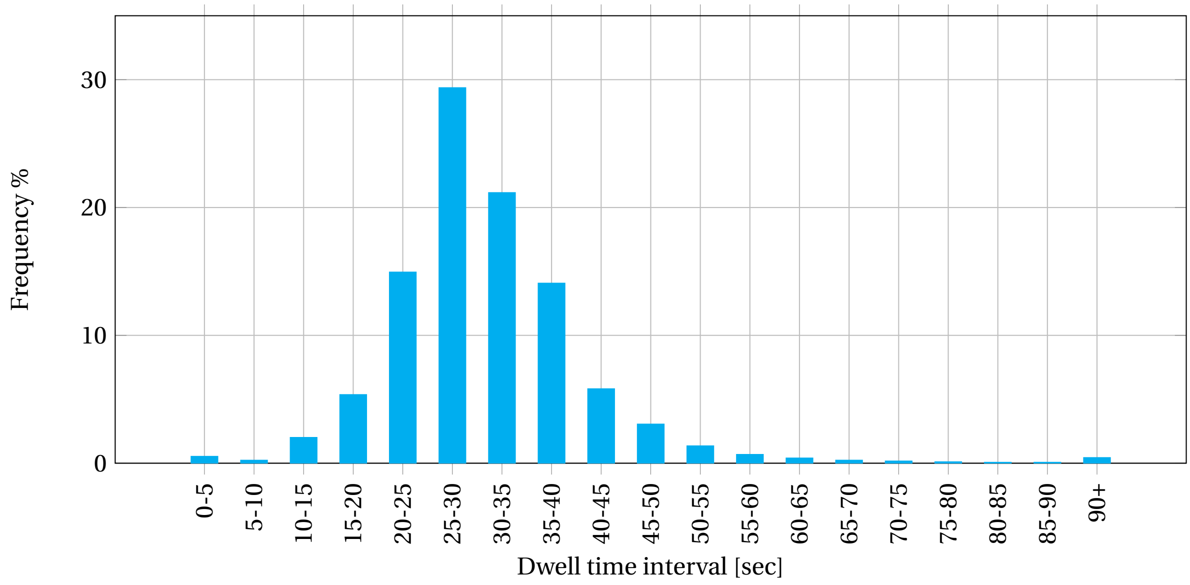


Figure 4.11: Dwell time histogram based on actual data with all stations included

In general this means that quiet stations will have their dwell times overestimated, while busy stations have their dwell times underestimated.

To solve this and simulate more accurate behaviour at stations, a distinction has to be made between different stations. Figure 4.12 shows that there are significant differences in dwell behaviour at different stations, so different delay distributions have to be constructed that distinguish between different levels of passenger demand. It has been chosen to assign each station its own delay distribution, which resulted in 58 different delay distributions that had to be implemented. For simplicity, only one delay distribution has been constructed for each station, not distinguishing between time of day or train type and length.

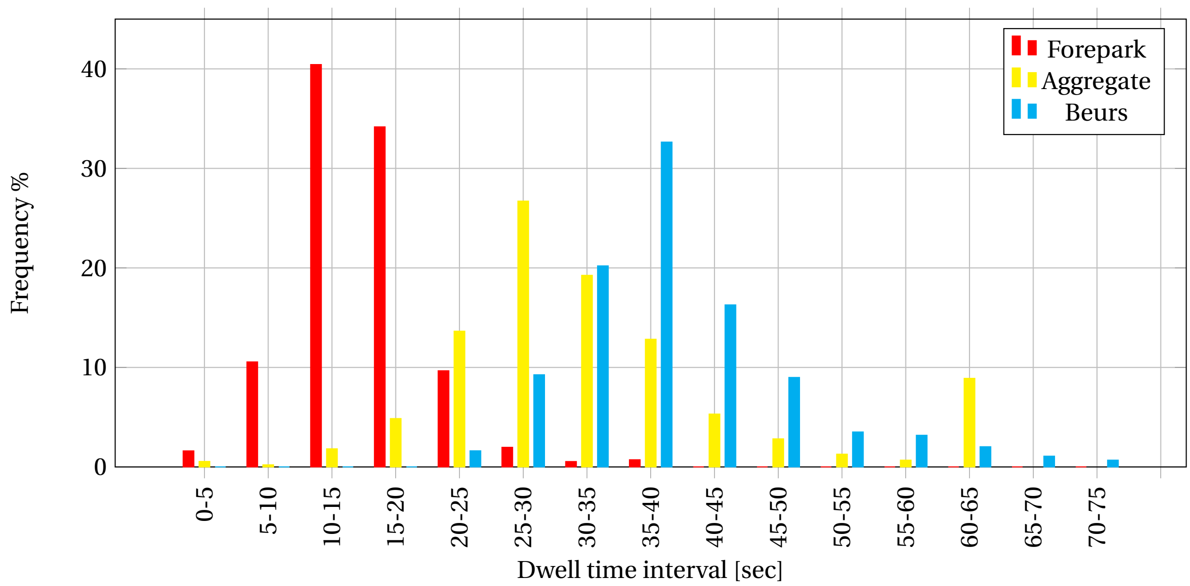


Figure 4.12: Comparison of dwell time behaviour between two stations

Verification of dwell times

Figure 4.13 compares the dwell times from reality with the dwell times from the simulations. It can be seen

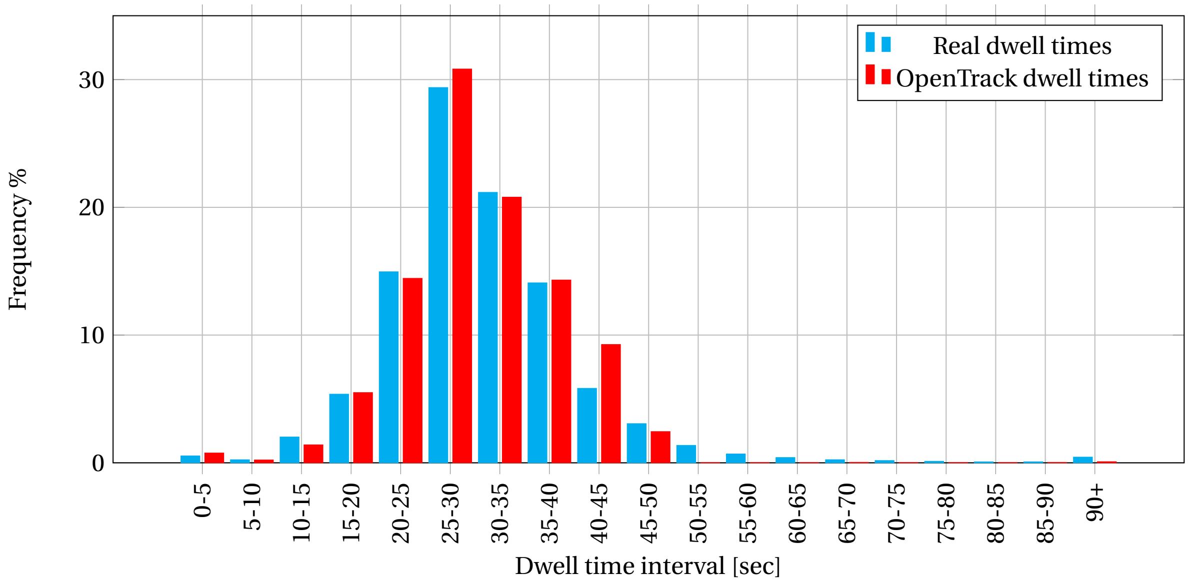


Figure 4.13: The dwell time distribution of the OpenTrack simulations compared with the dwell distribution of the actual timetable

that the two histograms match reasonably well. However, some differences do exist at some intervals, with the highest difference of three percentage points at the interval range [40,45].

The overview that 4.13 provides is not detailed enough to give a well-founded assessment of the quality of the computed dwell times. Further statistical analysis has been performed to provide more insights into how well the computed dwell times actually match. A statistical t-test has been performed to assess whether the simulated dwell times are picked from the same distribution as the real dwell time distribution. As the average value and standard deviation are different for both samples, the *Welch's t-test* is used:

$$t = \frac{\bar{X_1} - \bar{X_2}}{\sqrt{\frac{s_1^2}{N_1} + \frac{s_2^2}{N_2}}} \tag{4.1}$$

where:
t the t-statistic,
$\bar{X_1}$ the first sample's average value,
$\bar{X_2}$ the second sample's average value,
s_1^2 the first sample's variance,
s_2^2 the second sample's variance,
N_1 the first sample size, and
N_2 the second sample size.

With a confidence interval of 95%, the null hypothesis H_0, stating that both samples do originate from the same distribution, is rejected when the absolute value of t is greater than 1.96, which is the critical t-value for the given confidence level. If this is not the case and H_0 can be accepted, then can confidently be assumed that both samples do originate from the same distribution.

Table 4.5 presents the average value, standard deviation and sample size for both the real dwell time distribution as from the simulations. Furthermore, the t-statistic is calculated used the Welch's t-test, and is calculated to be **10.72**. Given that 10.72 is greater than 1.96, the null hypothesis H_0 is rejected. As a result, one can conclude that both distributions do not originate from the same distribution.
Though the t-test presented in Table 4.5 has revealed that both samples do not originate from the same distribution, the difference in average dwell time is 3 per cent. Secondly, given the fact that the standard deviations from the simulated dwell times is significantly lower than the standard deviation from the real dwell times, one can confidently say that the length of the dwell times is slightly *underestimated* in the simulation. The fact that the simulated running times are a slight overestimation of the real running times has a mitigating

Table 4.5: Statistical analysis for total dwell times

Parameter	Real	Simulations
Average (μ)	31	30
St. deviation (σ)	14	9
Sample size (n)	70,222	69,104
Welch's t-test	10.72	

effect on the consequences of the underestimation in general.

An important difference between the simulated and the real dwell times is the fact that the simulated dwell times are randomly chosen within the given distribution. In reality dwell times are far from random and depend on passenger demand, train punctuality and train headways. In OpenTrack, the only feedback loop that exists between running and dwell times is in the case when a train departs from a station on time. Arriving ahead of schedule at the next station, the train awaits its scheduled departure time, both in reality and in OpenTrack. As the time it has to wait depends on the earliness of the train, for the case of OpenTrack this means that the dwell time no longer depends entirely on the implemented train delay distribution. As the running times are slightly overestimated in OpenTrack, this means that the dwell time will be slightly shorter than in real life. Differences in dwell times are then likely to occur. The general lack of interdependency between running and dwell time in OpenTrack is an important limitation of this study.

Table 4.5 shows the difference between real and simulated dwell times broadly. Local differences might be greater, which could be cancelled out in the overall picture. Therefore, more detailed analysis of the dwell times has been performed. As only one delay distribution is constructed for each station, no distinctions are made between direction or time period.

Therefore, the average dwell times have been analysed for both the real and the simulated data, in which distinctions are made between station, direction and time period, leading to 780 different average values. Figure 4.14 presents the number of observations where the computed average dwell time has a certain difference with the real average dwell time. It shows an average difference of +1 second and a standard deviation of 5 seconds.

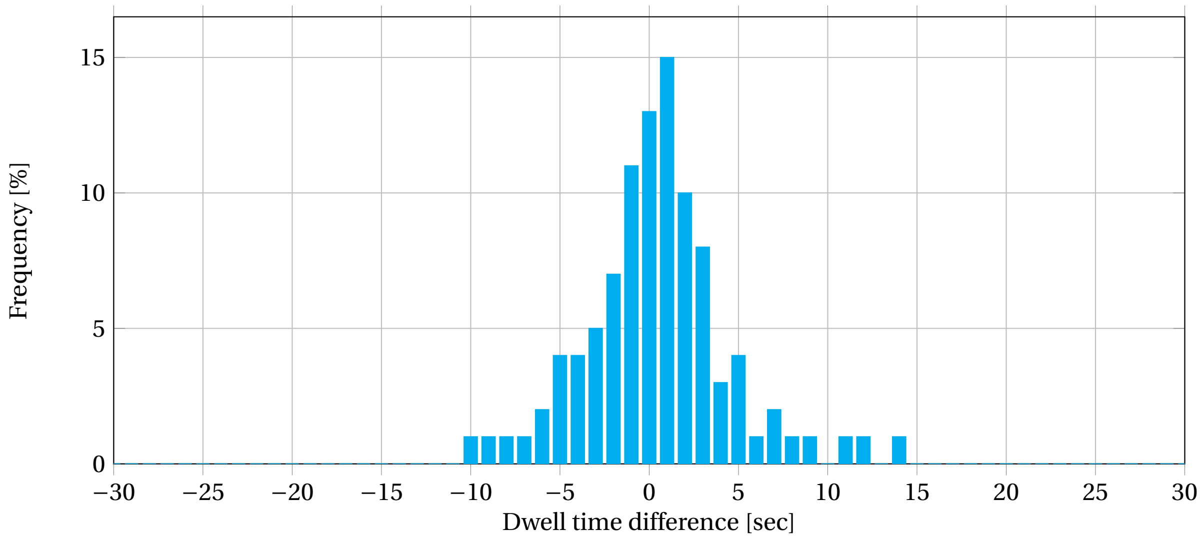


Figure 4.14: Number of observations that have a certain difference in seconds between real and simulated data

Figure 4.15 investigates the differences per station to pinpoint potential modelling differences. One of the things that can be immediately seen is that almost all stations that have a positive difference in average dwell times are stations along the RandstadRail line. This has to do with the modelling choice described in Section

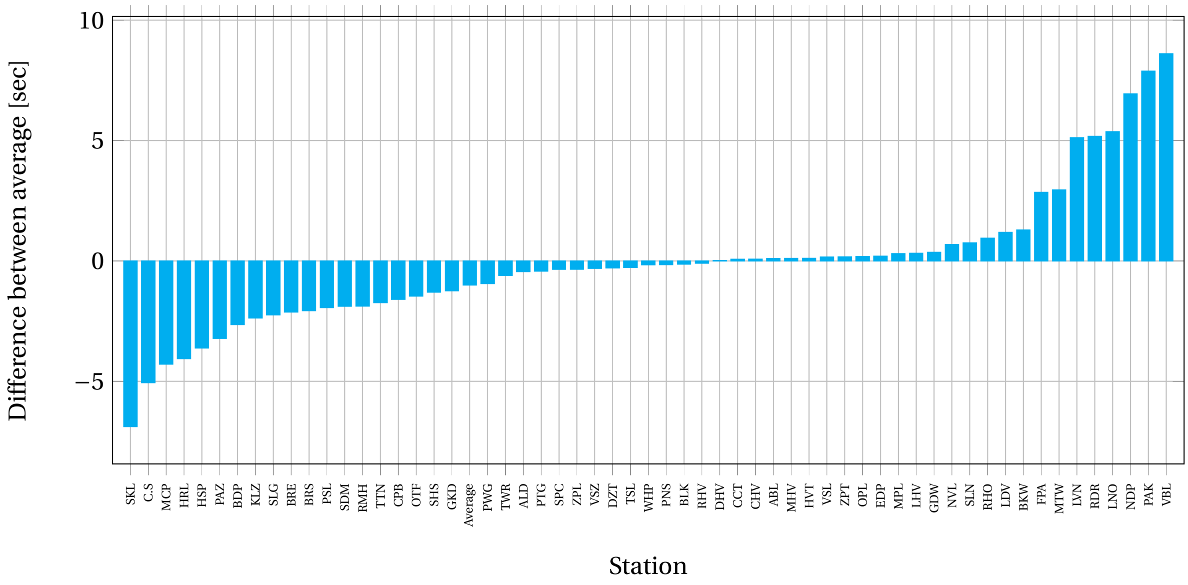


Figure 4.15: Differences in average dwell time differentiated by station

4.3. Keeping the *Timing station* enabled, a train on the Randstadrail line will await its scheduled departure time, as this leads to longer dwell times than in real life, as trains on the RandstadRail line do not await the scheduled departure time in real life.

4.4.6. Conclusions verification

Verification has shown that the infrastructure and the timetable have been modelled correctly in OpenTrack. Furthermore, the verification of running and dwell times have shown differences. It is impossible to model phenomena that are subject to variation perfectly. However, this verification has shown that the average differences in running and dwell times are small, differing with a few seconds. How this influences the results of the simulations in shown in the validation of the model, presented in Section 4.5.

4.5. Validation

4.5.1. Introduction

Where verification assesses whether the model has been built correctly by analysing all components that comprise the "input" side of the model, *validation* assesses the practicality and usability of the outcome of the model, or the "output" side. Furthermore, the output is compared with real-life data to assess the quality and accuracy of the model. In other words, validation assesses whether the model is the correct tool to serve the intended purpose and how the model is to be applied and interpreted.

The data that is extracted from the OpenTrack model follows the same format as described in Section 4.2. The performance of the executed timetable from OpenTrack is compared with the planned timetable, using the indicators mentioned in Section 2.2. The same is done with the train detection data from the real timetable, the same data that is used to verify the model. Thus, both the real executed timetable and the simulated executed timetable can be compared with each other to assess the quality of the output of the simulation.

4.5.2. Current timetable

The comparison is executed with use of the timetable that is currently operated on the Rotterdam metro network. This section discusses the details of this scenario. The network that is presented in Section 4.1.2 includes the extension on the former railway line to Hoek van Holland, which is due to open in the autumn of 2019. However, at the time of this research, the construction works along the new route had not yet been finalised. RET has adapted their timetable to accommodate the construction works west of *Schiedam Centrum*. As a result, line A continues towards *Pernis* as a temporary measure, while line B continues to reverse at *Schiedam Centrum*. The service pattern is shown in Figure 4.16.

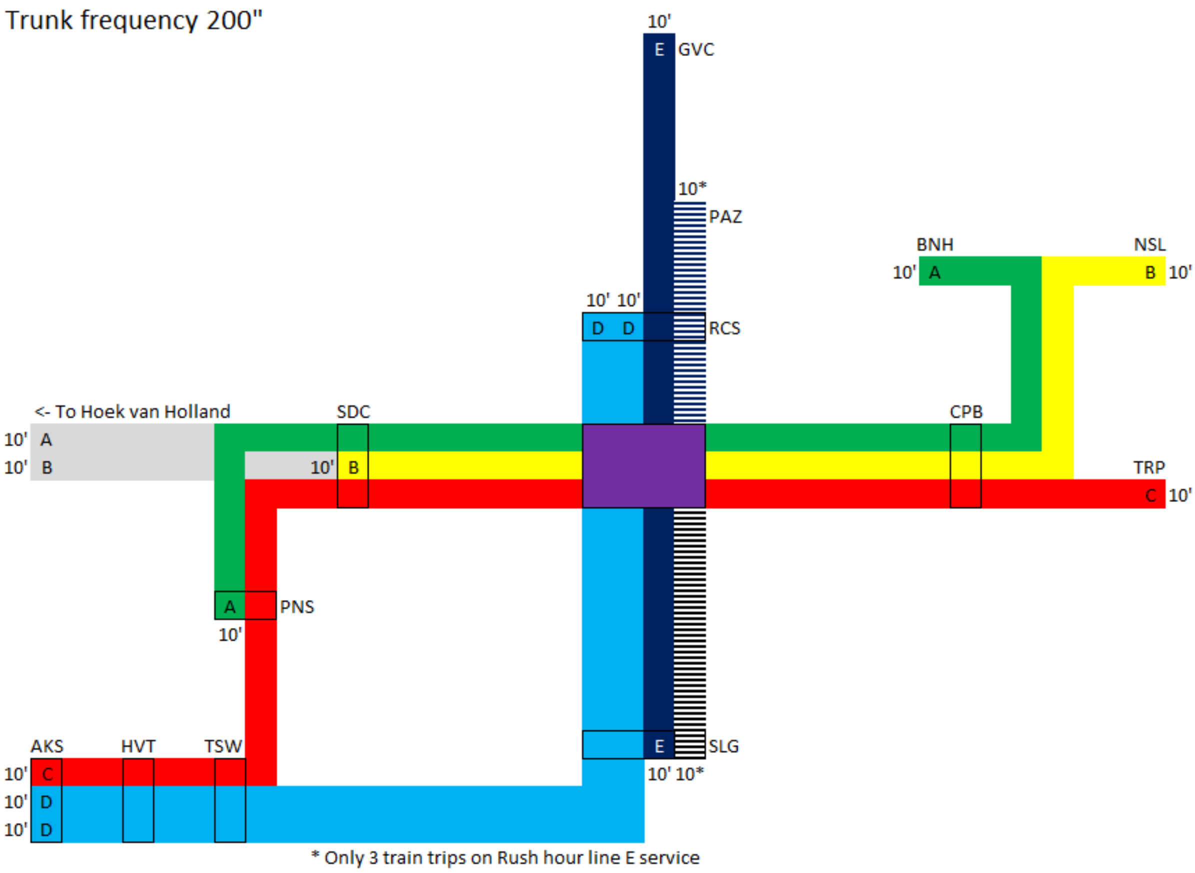


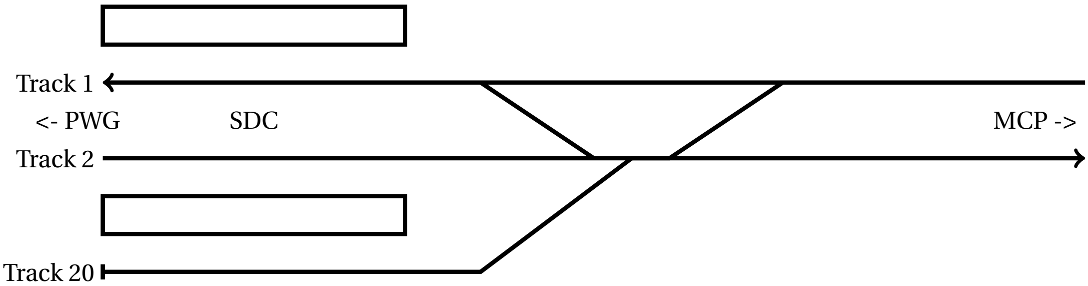
Figure 4.16: Schematic overview of the lines and frequencies operated in the current timetable

All services operate in a 10-minute interval, resulting in a 3.3-minute interval on the trunk sections. However, this is not entirely true for the north-south trunk section, where, during rush hour periods, 3 trains travel up and down to *Pijnacker Zuid* once. As a result, the intervals are even lower than 3.3-minutes for a brief moment of time.

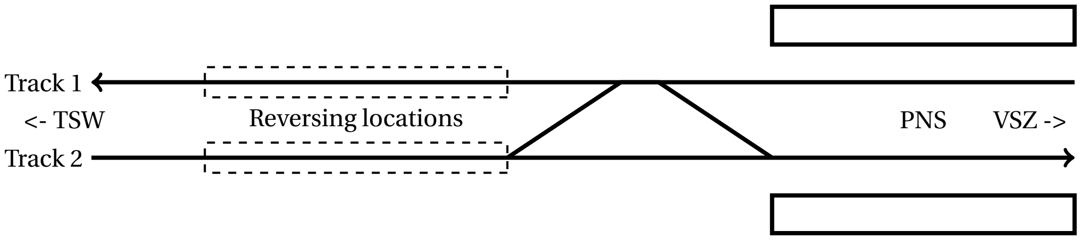
Reversing operations at Pernis *and* Schiedam Centrum

The reason why line A reverses temporarily at *Pernis* is twofold. Firstly, the regular reversing tracks behind *Schiedam Centrum* station are not available for regular traffic during the construction and testing phase of the Hoekse Lijn. This means that reversing has to be done alongside the platform on track 20 (see Figure 4.17a). As a result, there is only enough capacity available at *Schiedam Centrum* for one 10-minute service, while ensuring as stable operations as possible. The second reason is the higher passenger demand at *Vijfsluizen*, three stops west op *Schiedam Centrum*. Due to the construction works on the Hoekse Lijn, the role of *Vijfsluizen* has become more important. This is not only due to its vicinity to parts of Schiedam and Vlaardingen, but also because it provides connections to several bus services, which also have become more important in keeping Schiedam and Vlaardingen connected during the construction works.

Figure 4.17 shows the schematic track layouts for both *Schiedam Centrum* and *Pernis*. For the case of *Schiedam Centrum* (Figure 4.17a), a line B train coming from *Marconiplein* station (MCP), travelling on Track 1, reverses along the southern platform on Track 20. Therefore, it has to cross Track 2, used by line A and C trains travelling eastbound from *Parkweg (PWG)* to *Marconiplein (MCP)*. In the timetable, this cross-over is planned such that no conflicts between trains exist. However, in the case of delays on either of the three lines, trains might have to wait for the delayed train to clear the points. Not only do these trains incur delays, they also block main line tracks for other trains. If the delays are long enough, a delay incurred by one train will affect more trains, and might cause delays throughout the whole of the network.



(a) Track layout of the station of *Schiedam Centrum (SDC)*



(b) Track layout of the station of *Pernis (PNS)*

Figure 4.17: Track layouts of the stations *Schiedam Centrum* and *Pernis*

The case is worse for *Pernis*. A Line A train coming from *Vijfsluizen* and reversing at *Pernis* reverses on one of the two main line tracks west of *Pernis* (the reversing locations are marked with dashed boxes on Figure 4.17b). Not only does a reversing train have to cross the other main line track, it also reverses *on* the main line track it used. During the whole of the reversing period, it blocks that track for other traffic.

The reversing procedures at both stations are recognised by RET as major disturbing factors in ensuring a stable timetable. Meant as temporary measures to last for only five months, the reconstruction of the Hoekse Lijn has suffered major delays and these temporary measures have been in effect for two years now. OpenTrack also has difficulties dealing with these temporary measure, as is demonstrated in Section 4.5.3.

4.5.3. Performance current timetable in OpenTrack

Table 4.6 shows the performance of the actual timetable from both the real world and the simulations in OpenTrack. Both timetables are assessed using the indicators for irregularity and punctuality. Apart from the actual value, the relative difference is also given, indicating how much the simulations differ from the real data. With an irregularity of 28.2%, this is 16% higher than the real data. However, the difference is average delay is even greater, with the value for the simulations being 70% higher than the real data. On average, average delays are higher by little less than one minute.

Table 4.6: Overall network performance comparison between real and simulations

Performances	Irregularity [%]	Average delay [sec]
Real	24.3	73
OpenTrack	28.2	124
Difference [%]	+ 16	+ 70

Table 4.6 presents the values for the indicators for the complete investigation period between 04:00 and 11:00. However, as passenger demand on the network is highest in the rush hour period between 07:00 and 09:00, it is more relevant to observe this busiest time period only than the whole time period, under the assumption that due to the higher passenger demand during this period, performance is the worst during that time of day. Furthermore, with only one dwell time distribution modelled per station, not distinguishing between time periods, the time period after the rush hour period is less accurately represented in the model and is therefore less relevant to observe.

Table 4.7 compares the same scenarios with use of the same parameters, but then for the two busiest hours of the morning: between 07:00 and 08:00 and between 08:00 and 09:00. During those two hours, the differences are much smaller The simulated timetable now is only 5 per cent more irregular, while the average delay is 25% higher. Within the time period, average delays in the simulations are on average 23 seconds higher than the real data, while irregularity is 1.5 percentage point higher.

Table 4.7: General network performance of the current timetable during rush hour periods

Performances	Irregularity [%]			Average delay [sec]		
	07:00-08:00	08:00-09:00	**07:00-09:00**	07:00-08:00	08:00-09:00	**07:00-09:00**
Real	24.6	32.1	**28.4**	72	104	**88**
OpenTrack	27.4	32.3	**29.9**	94	127	**101**
Difference [%]	+ 12	+ 1	**+ 5**	+ 30	+ 22	**+ 25**

Tables 4.6 and 4.7 present the average performances for the whole network in total in general. However, on a more detailed level, the differences between real and simulated data might be different. However, Tables 4.6 and 4.7 do not show local performances of different lines or different track sections separately. Analysing the performances more in detail can shed more light on the origins of the differences and is furthermore necessary to assess the usability of the model and its results. The data behind Figures 4.18 and 4.19 can be found in Tables D.2 and D.3.

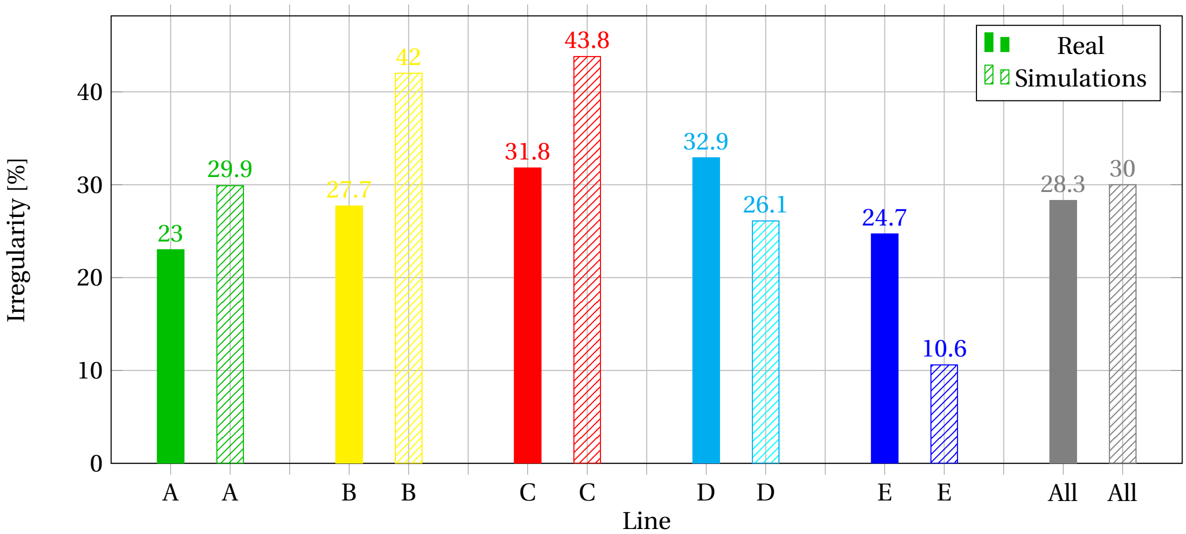


Figure 4.18: Regularity per line for both real and simulated data

To provide a more detailed analysis of both scenarios' performance, the performance of each line individually is determined. Figures 4.18 presents the irregularity of lines A through E, both for the current timetable, and for the same timetable reproduced in OpenTrack. The same format is applied to Figure 4.19, but now with the average delay shown for each line.

For both indicators, lines A, B and C perform worse in the simulations than in the real life. On the other hand, lines D and E perform better than in real life. The differences in punctuality are largest for lines A and E. Delays on line A are 80 per cent *higher*, while delays on line E are nearly 70 per cent *lower*. Both figures present a different picture than Tables 4.6 and 4.7. Furthermore, a clear distinction can be seen in performance between the two different axes of the network. The lines travelling on the east-west axis (A, B and C) perform worse in the simulations than their real-life counterparts, while the lines travelling on the north-south axis, D and E, perform better in the simulations.

Analysing the network's performance per section rather than per line produces the same observations. The network has been divided into different sections, distinguished from each other by having different characteristics and/or service frequencies. An overview of the different sections and the stations they contain can

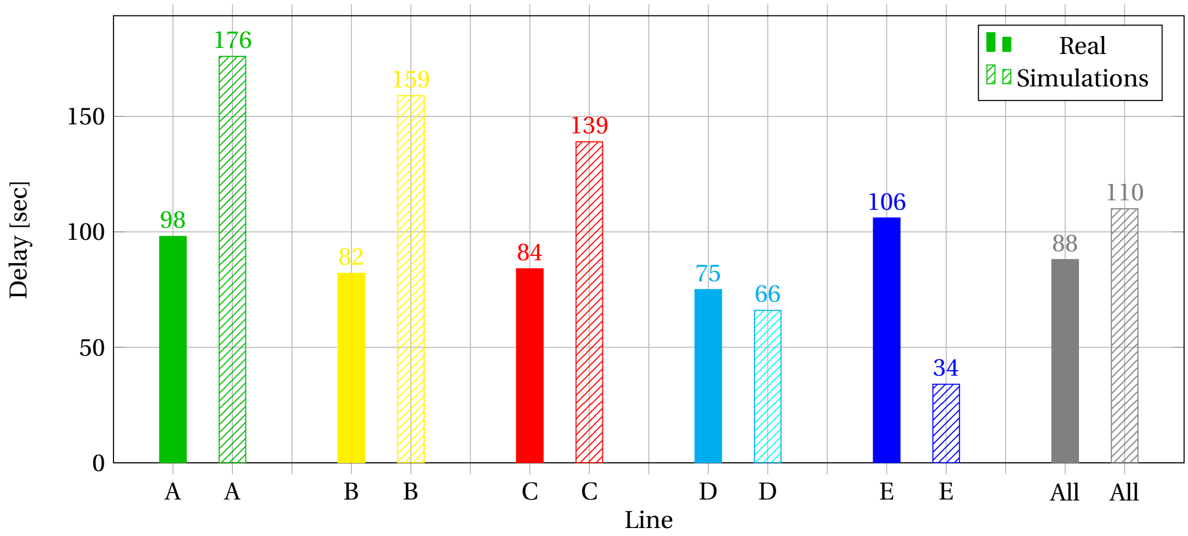


Figure 4.19: Average delay per line for both real and simulated data

be found in Table D.1 in Appendix D.1. The results are presented in Figures 4.20 and 4.21. Again, the east-west axis performs worse in the simulations, while the north-south axis performs better. Furthermore, the more train services that travel on a section, the worse the section performs in OpenTrack in terms of irregularity. However, the same does not apply to average delays, as the average delay on all sections of the east-west axis are consistently 60 seconds higher than in real life.

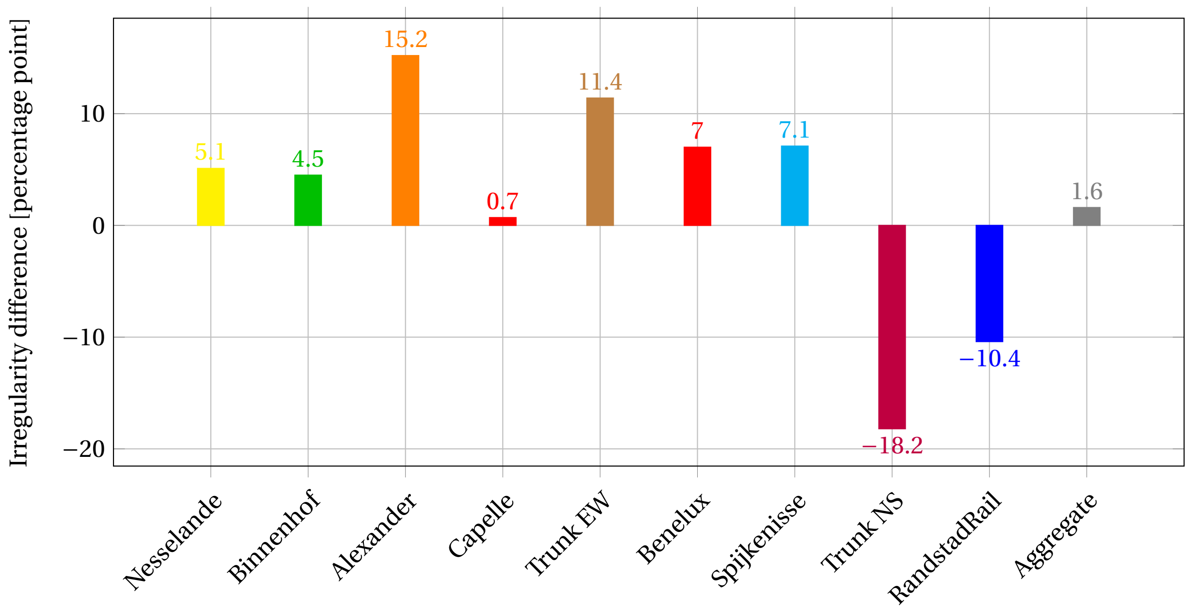


Figure 4.20: Difference (in percentage point) per section in terms of irregularity in performance of simulations compared with real data

4.5.4. Differences in performance between simulated and real data

Section 4.5.3 has shown that, although verification has revealed that running and dwell times differ by a couple of seconds, the differences in performance in terms of the indicators are large. Especially the performance measured in average delay is much worse in the simulations than in the real data, leading up to a 50-second delay difference between the simulations and the real data, measured over the full time period. Section 4.5.3 has also listed two observations:

- The performance of the simulated timetable during the rush hour period is less worse than the overall

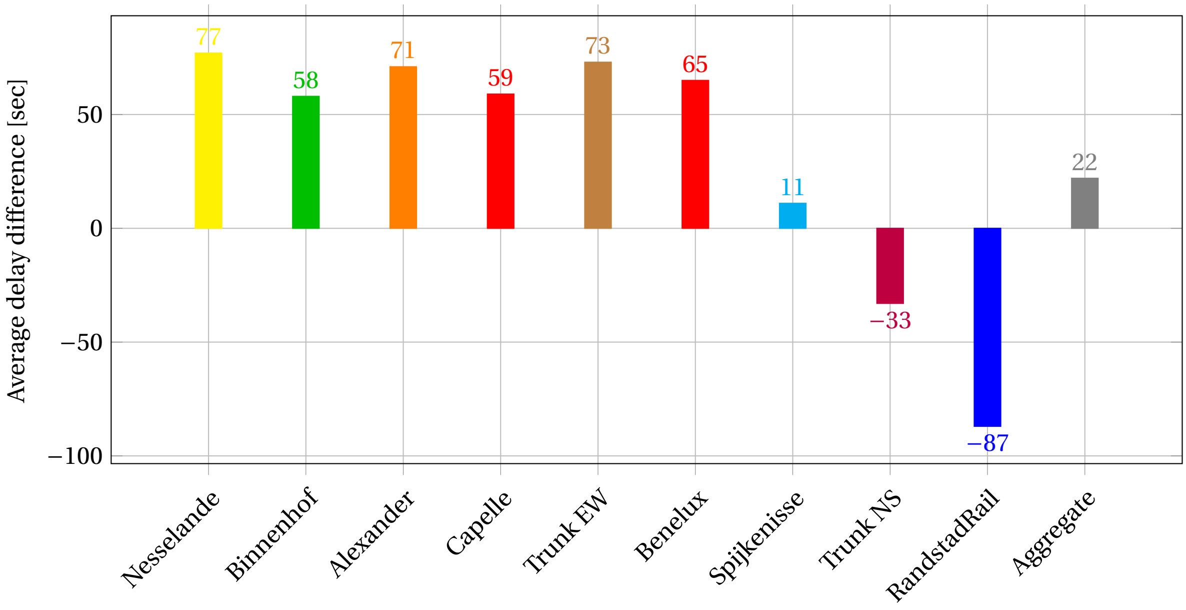


Figure 4.21: Difference (in seconds) per section in terms of average delay of performance of simulations compared with real data

performance during the full observation period;

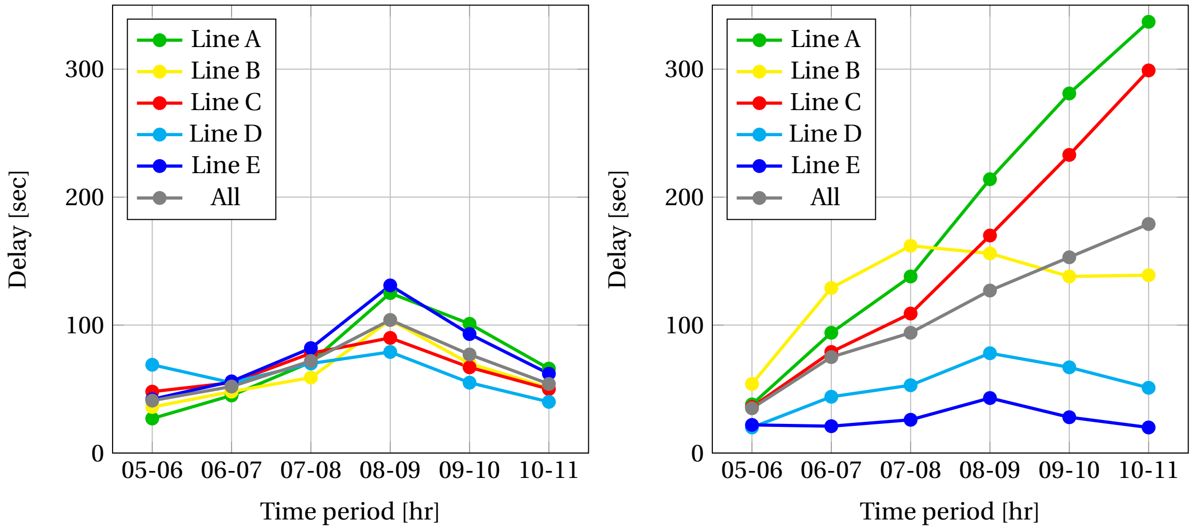
- The lines on the east-west axis perform significantly worse in simulation than in real-life, while lines on north-south axis perform equally or better in simulation than in real life.

The first observation leads to the hypothesis that simulated delays propagate in time as the simulation progresses and that these delays increase over time as well. The delays seem not to recover as they would do in real-life practice. This is demonstrated in Figure 4.22, which shows the progress of average delays per time period for both the real data (Figure 4.22a) and the simulations Figure 4.22b). In the real timetable, all lines follow roughly the same pattern. The delays are highest during the busiest time of day: between 08:00 and 09:00. In the two hours after 09:00 the delays all all lines diminish.

Figure 4.22b shows the development of delays for the simulations of the current timetable. While line D and E follow the same pattern in the simulations as in the real data, lines A, B and C show deteriorating behaviour as time progresses. As lines A, B and C travel on the east-west axis of the network and lines D and E on the north-south axis, a clear distinction of behaviour on both axis can be observed, which is the second observation listed above.

This raises the question why the east-west axis performs so much worse in OpenTrack, while the north-south axis performs equally for line D and better for line D than the real data. It seems that the east-west axis in OpenTrack is more vulnerable to variances in dwell times than the north-south axis.

The main contributing factor is the presence of major bottlenecks on the east-west axis, of which the reversing stations of *Pernis* and *Schiedam Centrum*, discussed in Section 4.5.2, is the most important. The reason why these bottlenecks cause that much trouble in OpenTrack is the inflexibility of the simulation tool. In real-life, a train dispatcher monitors the situation of the operations on the network, and is able to intervene when something out of the ordinary occurs. A train dispatcher is able to anticipate if the delay of one track is likely to cause conflicts, and can therefore re-route a train to a different (reversing) track. At *Pernis* for example, reversing A trains can use both main line tracks, but use the northbound track by default. If the reversing train or the northbound C train is delayed, this may cause a conflict and the train dispatcher can choose to reverse the A train on the southbound track, provided that the headway behind the reversing train is high enough to not cause an additional conflict. This confirms the very reason why train dispatchers exist in the first place. As it is their job to strive for as smooth operations as possible, OpenTrack is not able to spot potential conflicts and make operational decisions accordingly.



(a) Train detection data

(b) OpenTrack simulations

Figure 4.22: Overview of average delay per line per time period, for the real train detection data and OpenTrack simulations

To investigate whether *Pernis* and *Schiedam Centrum* are indeed major contributing factors, a timetable is written in which both stations are not used to reverse trains. This scenario will form the basis for later investigation in the effects of increasing service frequencies and is discussed in further detail in Section 5.3.1. In this base scenario, the same frequencies are maintained as in the currently operated timetable. Furthermore, the buffer times at the terminal stations and running times remain the same, to eliminate the influence of these factors.

Figure 4.23 shows the propagation of delays over time for this base scenario. It shows that without the two bottlenecks in play, the delays do not deteriorate as much as they did in the simulations of the current scenario. As all other factors remain the same, this research therefore concludes that the deteriorating delays are caused by the inflexibility of OpenTrack at the terminal stations.

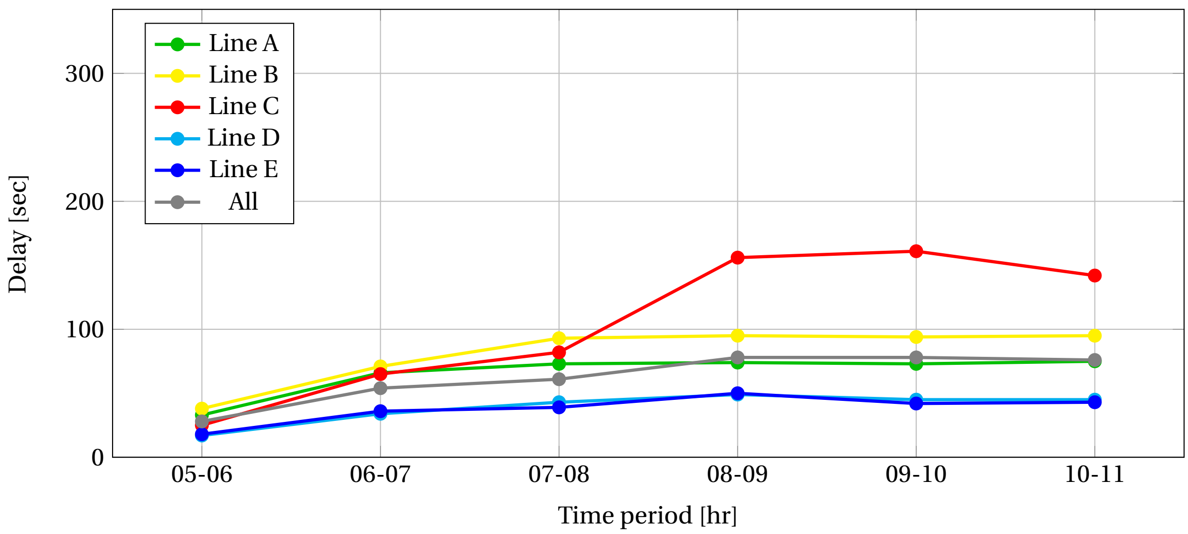


Figure 4.23: Overview of average delay per line per time period, for the base scenario (see Section 5.3.1)

Figure 4.23 also shows that for lines A, B, D and E delays remain more or less constant after 07:00, with levels that are representative for the 08:00 to 09:00 time period of the real timetable performance shown in Figure 4.22a. However, this is not the case for line C, which still features higher delays than the other lines. The reason for this is the amount of time supplements implemented in the planned timetable. RET has indicated that while there are enough running time supplements in the timetable on the north-south axis, there are little time supplements on lines on the east-west axis. Moreover, RET has also admitted that the running times for line C are too short in the planned timetable. Train drivers are currently complaining that they have difficulty adhering to the schedule while travelling on line C, and especially on the "Beneluxlijn" section between *Tussenwater* and *Schiedam Centrum*. This is reflected in Figure 4.23, showing that line C has significantly higher delays than lines A and B.

This shows that OpenTrack is more vulnerable to cope with deviations when few time supplements are available. A reason for this is the independence of dwell times in relation to running times and punctuality. The dwell time distributions that are extracted from the real timetable data and are implemented in OpenTrack, are an aggregate. Included in this one distribution are all time periods in which passenger demand differs, but also the dwell behaviour of both late trains (with shorter dwell times) and early trains (with longer dwell times waiting to depart on time). In OpenTrack, there is no interaction between dwell time length and punctuality of a train. Whereas a driver in real life can attempt to reduce its delay by adopting a stricter station dwell policy, OpenTrack picks a random dwell time from the defined distribution, regardless of the train's punctuality. Therefore it is less likely that with few time supplements available in the timetable, delays will be alleviated in OpenTrack as they would in real life, as OpenTrack will not deliberately select a shorter dwell time in case of a delayed train.

As for line E, Figure 4.22b shows that line E performs significantly better than in the real data (Figure 4.22a). The cause for this is the lack of trams in the simulated model, as has been explained in Section 4.3.1. While this is a deliberate modelling choice, the performances of Line E in every simulated scenario will be too optimistic as the presence of trams is deemed to be negative factor on the performance of trains on line E. This is a factor that has to be taken into account when assessing the scenarios later on in this research.

4.5.5. Conclusions Validation

The validation that this research has conducted, has revealed factors that influence the outcome and the accuracy of the model. It has identified the (in)ability of OpenTrack to deal with flexibility at (complex) reversing stations as the main factor of the difference between the real-life data and the model outcome. Without these factors in play, OpenTrack is able to provide stable simulations with an outcome that is representative for normal stable daily operations of a metro network.

It is impossible for a model to provide an exact representation of a real-life situation, and therefore always differences will exist between the real world and its simulated counterpart. It is important to gain insights in these differences, in order for the model outcome to be usable in the assessment of future scenarios.

5 Scenarios

Chapter 4 discussed the case study of the Rotterdam metro network and the model that is utilised to represent the network in the simulation tool. Furthermore, the various features of the model have been validated to assess the quality of representation in the model. Validating OpenTrack is the first of two main goals of this thesis project and one of the wishes of RET.

The next step is to use the validated model to assess future proposals. As it can be assumed that the model is an accurate representation of the real-life infrastructure, future proposals for the improvement of the current timetable can be assessed without having to test them in practice. An accurate assessment of the effects can thus be made *ex-ante*.

Due to the growth of the city of Rotterdam (see Section 4.1.3), the Rotterdam metro network will face capacity problems if the network continues to be operated in the current form. Public transport operator RET recognises that the signalling systems that are currently installed on the majority of the network are able to facilitate services with intervals down to 90 seconds, but realises that this might not be achievable due to bottlenecks and limitations of various elements in the network. The operator is therefore interested in increasing the frequencies on the network and would like to investigate up to which frequencies the current network can still maintain stable timetables.

Therefore, a step-wise approach is applied in which multiple scenarios are assessed with the use of OpenTrack. Reference points are the frequencies on the trunk section of the network, between *Schiedam Centrum* and *Capelsebrug* and between *Rotterdam Centraal* and *Slinge*. In each of the constructed scenarios, the frequencies on the trunk sections are increased. This does not necessarily mean that the frequencies on branch lines will be increased as well. As a result, four *growth scenarios* have been constructed:

- Reference Scenario 2021: Trunk section intervals of 200 seconds, Hoekse Lijn and tail track *PAZ* operational
- Scenario 150: Trunk section intervals of 150 seconds
- Scenario 120: Trunk section intervals of 120 seconds
- Scenario 100: Trunk section intervals of 100 seconds

Each growth scenario represents a different incremental step in frequency. By assessing each growth scenario, the minimum intervals under which stable operations can still be maintained can be determined. Furthermore, four different *operational variants* have been developed and can be applied to each growth scenario. In each variant, one or more of the internal factors that effect timetable variability, discussed in Chapter 3, are altered as compared to the current situation.

Not all variants are assessed for each growth scenario, but also scenarios that yield a too unreliable Level of Service. Of the four variants, the first retains the current infrastructure as is currently in operation, while the others abandon this assumption, to assess which upgrades can improve reliability for the otherwise unreliable scenarios.

This results in a two-step procedure. The first step is to assess the maximum frequency under which stable operations can be maintained without alterations to the current network, by applying the first variant to the four different growth scenarios. This is important for RET, as the operator can then determine what service increase is feasible in the short term, as infrastructure changes are very time-consuming. The second step follows the first, after determining which growth scenario(s) will yield too unreliable operations. Then, the three other variants are applied, by allowing upgrades to the current network to be implemented. The second step is designed to ascertain which measures are helpful in enabling reliable operations for scenarios which, without infrastructural changes, would be too unreliable.

In this chapter firstly the general methodology is explained how the new timetable have been constructed. In Section 5.2 the different variants are discussed. In Section 5.3 the four different growth scenarios are discussed and the chapter is concluded by Section 5.4 which provides a summary for this chapter.

5.1. Timetable construction

The timetables that have been written for the scenarios discussed in this chapter are fictitious and have been constructed with the use of Excel. Mathematical expressions have been defined, governing the relationships between departure, arrival, running and buffer times of the various trains, stations and line sections. These expressions, that are discussed in this section, have been implemented in an Excel spreadsheet, enabling a graphical and clear representation of the departure time of the whole of network. This way, a timetable can be quickly optimised. In a quick a simple way can the basic service pattern be determined and the relation between different lines can be shown. By changing the departure time of a line at its first station, the departure time at each node is changed automatically for that line. Furthermore, the reversing times can be easily determined.

Let i be a train travelling on line $l \in [A, B, C, D, E]$, with stations $j \in [1, \dots, n]$. The time of arrival A at station $j+1$ is defined as the departure time D at previous station j added with the running time R between stations j and $j+1$, which is shown in Equation (5.1):

$$A_{i,j+1}^{l,d} = D_{i,j}^{l,d} + R_{j,j+1} \tag{5.1}$$

with:

$A_{i,j+1}^{l,d}$ = Arrival time of train i running on line l travelling in direction d at station $j+1$,
$D_{i,j}^{l,d}$ = Departure time of train i running on line l travelling in direction d at station j,
$R_{j,j+1}$ = Running time from station j to station $j+1$,
l = line $l \in [A, B, C, D, E]$,
i = a train travelling on line l,
j = a station along line l,
d = direction, either outbound ($d = 0$) or inbound ($d = 1$).

RET does not distinguish between arrival and departure times at stations in their timetable and instead uses one value between the departure at two consecutive stations. The dwell time at stations has been included in the running time. Therefore, with $D_{i,j}^{l} = A_{i,j}^{l}$, this leads to Equation (5.2):

$$D_{i,j+1}^{l,d} = D_{i,j}^{l,d} + R_{j,j+1} \tag{5.2}$$

with:

$D_{i,j+1}^{l,d}$ = Departure time of train i running on line l at station $j+1$,
$D_{i,j}^{l,d}$ = Departure time of train i running on line l at station j,

$R_{j,j+1}$ = Running time from station j to station $j+1$.

Thus, if a line l contains stations $j \in [1,...,n]$, then the total trip time from first ($j = 1$) to last ($j = n$) station is defined in Equation (5.3):

$$A_{i,n}^{l,d} = D_{i,j=1}^{l,d} + \sum_{j=1}^{n-1} R_{j,j+1} \tag{5.3}$$

with:

$A_{i,n}^{l,d}$ = The arrival time of train i running on line l at terminal station n,
$D_{i,j=1}^{l,d}$ = The departure time of train i running on line l at the first station,
$\sum_{j=1}^{n-1} R_{j,j+1}$ = The sum of all running times on line l.

Depending on the infrastructure, layout of signals, points, etc, can the running times differ per direction. Therefore, a distinction has to be made between the running times in different directions: $R_{j,j+1}$ can be, but not necessarily has to be the same as $R_{j+1,j}$.

Trains change direction at terminal stations. The time between the arrival of a train and the departure time of the same train is the total reversing time, which is the time required for reversing added with buffer times. This is shown in Equation (5.4):

$$D_{i,j=n}^{l,d\pm1} = A_{i,j=n}^{l,d} + B_{j=n}^{l} \tag{5.4}$$

with:

$D_{i,j=n}^{l,d}$ = The departure time of train i running on line l at terminal station n,
$A_{i,j=n}^{l,d}$ = The arrival time of train i running on line l at terminal station n,
$B_{i,j=n}^{l}$ = The total reversing time of train i running on line l at terminal station n.

As the total reversing time at terminal stations must be *at least* the minimum required reversing time, this sets a lower boundary to the reversing time. For the case of RET, this is set to be 2 minutes. Furthermore, to minimise the amount of rolling stock needed, an upper boundary can be defined as well. If the reversing time of a train is higher than the line's interval, the train's successor will arrive at the terminal station, requiring a second track at the terminal station. If the reversing time is higher than the line´s interval *plus* the minimum reversing time, then even the second arriving train would be able to depart on time for the first train. Therefore, to minimise the amount of rolling stock required, the total reversing time is governed by Equation (5.5):

$$2 \leq B_j^l \leq (H^l + 2) \tag{5.5}$$

The superscript l in the expression for reversing time B_j^l indicates that the reversing times are line-dependent. If multiple lines terminate at the same terminal stations, their reversing times may be different depending on the projected service pattern. Furthermore, the reversing times at the terminal stations on both ends of the line cannot be chosen freely. In order to maintain periodicity, Equation (5.6) governs a constant headway between subsequent trains travelling on the same line:

$$D_{i+1,j}^{l,d} - D_{i,j}^{l,d} = H^l \tag{5.6}$$

with:

$D^{l,d}_{i,j}$ = the departure of a train i on line l,
$D^{l,d}_{i+1,j}$ = the departure of the next train $i+1$ on line l,
H^l = the scheduled headway for line l.

This affects the reversing times, as the departure at a terminal stations depends on the departure of the previous train. This depends on the *cycle time* of a line, which is defined as the time between two consecutive departures from the same train *at the same station.* To maintain a regular and periodic timetable, the cycle time must be a multiple of the line's headway. Equation (5.7) governs the cycle time for line l:

$$\sum_{j=1}^{n-1} R_{j,j+1} + \sum_{j=1}^{n-1} R_{j+1,j} + B^l_{j=1} + B^l_{j=n} = n * H^l \tag{5.7}$$

with:

$\sum_{j=1}^{n-1} R_{j,j+1}$ = the total running time in outbound direction,
$\sum_{j=1}^{n-1} R_{j+1,j}$ = the total running time in inbound direction,
$B^l_{j=1}$ = the reversing time for line l at station $j = 1$,
$B^l_{j=n}$ = the reversing time for line l at station $j = n$,
H^l = the headway for line l,
$n \in \mathbb{N}$.

Figure 5.1 is a graphical representation of a train i, circulating on line l with stations $j \in [1, n]$. By implementing the graph of Figure 5.1 into Excel and constructing a graph for each line, a clear overview can be created of the whole network. By altering departure times or reversing times at terminals stations, one can easily learn what effect a longer reversing time ro

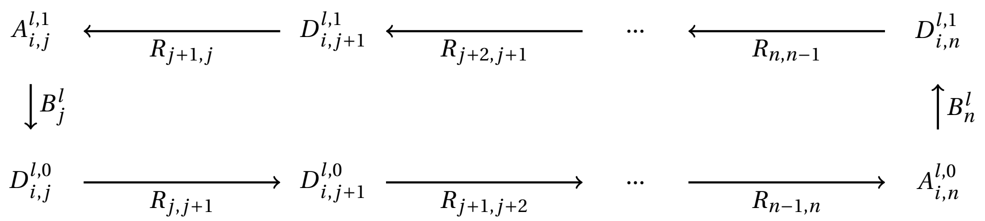


Figure 5.1: Graphical representation of departure times, arrival times, running times and reversing times along line l

Figure 5.2 shows how the mathematical expressions of Equations (5.1) through (5.7) are implemented in Excel. The spreadsheet is simplified to important transfer and junction stations, rather than showing all stations along the line, as these stations are important in determining how different lines interact with each other. The colours except light green in Figure 5.2 represent the departure times of each line in minutes and seconds (mm:ss) and the light green cells show the available reversing time at each terminal station. By changing the departure time of a line at the terminal stations, all departure times along the line change accordingly, adhering to the cyle presented in Figure 5.1.

Although fleet sizes are not taken into account, efforts are made in each scenario to utilise least amount of trains as possible. One of the methods to achieve this is called *interlining.* If two lines share the same terminal station, reversing times can be reduced by "connecting" two lines with each other. This means that an arriving train departs from the station as another line arrives. Interlining has three major advantages:

- Reversing times are minimised and thus the total time that trains are not in revenue service
- The number of trains can be reduced
- Capacity can be used more efficiently, as reversing tracks are occupied for a shorter period of time. In some cases interlining can be the only way that a planned timetable fits in the available infrastructure

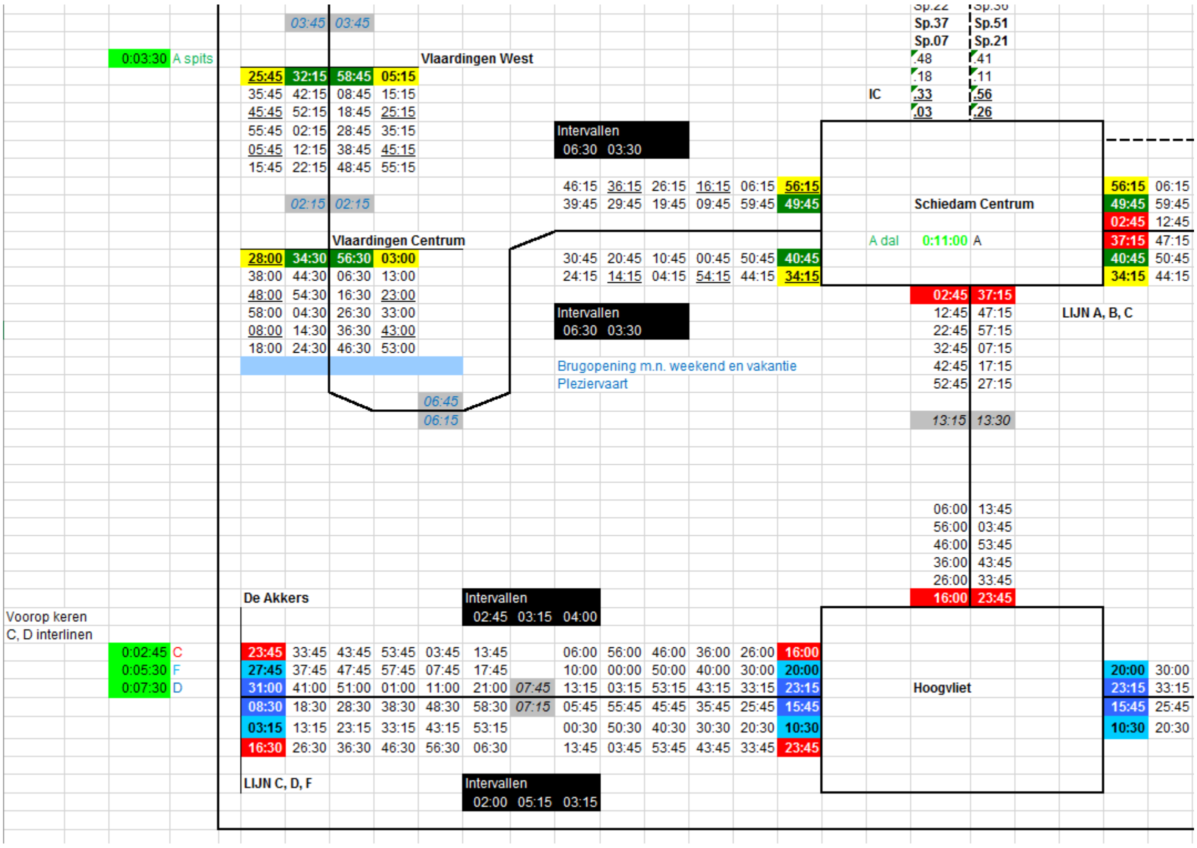


Figure 5.2: screenshot of part of the connection plan used to construct timetables

However, a major disadvantage is that delays incurred on one line can spread more easily onto another line, as the same trains are used for both lines. This can be a reason not to interline two lines together, especially with lines that are known to incur serious delays. Another reason not to interline is that a mixed fleet is required that is able to operate on both lines.

The Rotterdam metro has several examples where interlining is not applied, even though it could increase efficiency. For example, interlining lines C and D at *De Akkers* could be beneficial. Is it not done in practice, in order to keep the lines running on the east-west axis operationally separate from the lines running on the north-south axis. Furthermore, line E is operationally isolated, as this is a line where the risk of delays is higher.

In the growth scenarios, the same considerations are taken into account. As as result, most of the lines are not interlined. In some cases, the services travelling on a shorter sections of the line are interlined with the services travelling the full length. As they share most of the same tracks anyway, interlining them is considered to be less vulnerable than when two completely different lines are interlined.

5.2. Operational variants

Chapter 3 has discussed eight internal factors determined by Van Oort (2011) that influence the reliability of public transport operations. These are:

- Other public transport
- Vehicle design
- Vehicle availability
- Network design

- Timetable quality
- Infrastructure design
- Crew availability
- Driver behaviour

In this section the four variants will be discussed based on these eight factors. As has been mentioned in the introduction, in the first variant the current infrastructure and driving operations remains unaltered. In the other three, two upgrades measures are proposed. In the following sections, these two categories will be discussed.

5.2.1. Variant 1: No infrastructure alterations

As has been mentioned in the introduction of this chapter, an important step in investigating measures to facilitate growth on a metro network is by first determining what measures can be taken using the *current* state of infrastructure and following the current planning procedures. As infrastructure investments are usually very costly, measures that can be taken without altering infrastructure allow for short-term and relatively low-cost solutions.

This has resulted in the first of the four variants. Under the assumption that the current state of infrastructure and operations remain unaltered, the following internal factors remain unchanged:

- Apart from the construction of the tail track at *Pijnacker Zuid*, no infrastructure has been altered and the track layout of the network remains as the current situation. This means that no switches, signals and station tracks are added, moved or removed, and that the same signalling system remains.
- The availability of staff is determined and planned as is currently practised. The current operational constraints that are present at RET are still applied to the new scenarios. This means that each course has a minimum reversing time of two minutes at any terminal station.
- The behaviour of drivers remains the same. Furthermore, the level of automation is remains unchanged, and the same running times and dwell time distributions are applied for all scenarios.
- The design of the vehicles remains unchanged. In order to achieve maximum flexibility, rolling stock ordered to accommodate the service increase will be compatible with the current rolling stock as the letter is still in operation when the new stock arrives.
- The availability of rolling stock is assumed to be sufficient to be able to operate the future timetables. The timetables are constructed such that the operation hours allow for the same amount of time available for maintenance as is currently the case in the current timetable. This means that the first trains leave the depots at around 05:30 (earlier for services whose terminal is far away from the depot), to ensure that each station on the network has its first trains passing no later than 06:00.
- The influence of other public transport has not been investigates and its influence of metro service variability is assumed to be minimal.

This leaves two internal factors remaining: network design and timetable quality. In the future scenarios, the following considerations and assumptions have been taken into account:

- *Network design*:
  On the current network, five lines are in operation, serving all branches of the Rotterdam network. All lines are *transversal*: meaning that they all start in a suburb or neighbouring municipality, and then travel through the city centre to a neighbourhood on the other side of the city. As a result, every line on the network passes the station of *Beurs*, the intersect station for both axes. This means that every line travels on at least one branch line and one trunk section. For the new scenarios this is not different, albeit that some lines may be extended or services added that travel on a reduced section of the line, in order to achieve the required intervals on the trunk section.

This operational pattern is maintained in the future scenarios. This means that *Beurs* can still be directly reached from all branches and that every station on the network can be reached with a maximum of one transfer at *Beurs*. Furthermore, each service – running either the full length of a line or only a section of line – operates with a 10-minute interval. By multiplying the number of services through the trunk sections, the intervals there are decreased. Therefore, the timetable is periodic with a periodicity of ten minutes.

- *Timetable quality*:
  All new timetables used for this research are constructed such that the service pattern is optimised for the trunk sections. All services are planned such that the spread of trains is even on both directions on the trunk sections. This does not necessarily mean that the spread of trains is even on the branch lines. For example, in Scenario 2021, two line D services and one line E service travel on the north-south trunk section. Line E terminates at *Slinge*. On the remaining line to *De Akkers*, two line D services remain. Being both 10-minute services, the interval pattern between *Slinge* and *De Akkers* is 6.6'-3.3' rather than 5'-5'.

5.2.2. Variants 2-4: Infrastructure alterations

For these variants, the assumption that the current infrastructure and operational procedures remain unchanged, has been let go. Because of this, three of the factors mentioned by Van Oort (2011) can now be altered:

- Infrastructure design
- Crew availability
- Driver behaviour

Of the above factors, crew availability and driver behaviour can be combined into one factors: human behaviour. By changing either the infrastructure, or the influence of human behaviour, or both, three more variants are created. How each of the above two factors are implemented in OpenTrack is discussed in this section.

Infrastructure design
For simplicity reasons, it is assumed that the layout of the tracks, stations, junctions and the switches will not be altered. However, this does leave a part of the infrastructure that can be investigated: the signalling system.

The current signalling system follow the principle of *fixed block signalling*, the principles of which have been discussed in Section 3.2.2. In a fixed block system, a train has to wait for the whole block to be cleared before it is allowed to enter the block. In a classic three-aspect signalling system, for a train to not encounter a signal showing anything other than "proceed", the train to be separated by at least the distance defined by Equation 3.6. Depending on the length of the longest block along the line, the spacing can be quite substantial, which limits the capacity of a section of track significantly.

Section 3.2.2 has also mentioned *moving block signalling* as a measure to increase capacity. Therefore, the implementation of moving block technology is one of the proposed measures to increase reliability that is featured in these variants.

Moving block in OpenTrack
OpenTrack has a feature to model and study the effects of moving block, and can thus investigate the effects of moving block compared to the conventional fixed block technology. OpenTrack features two different moving block settings:

- "Pure" moving block, and
- Moving block with communication

The difference between both settings is the formula that OpenTrack applies to calculate the minimum spacing between two trains . For the pure moving block system, the minimum spacing is defined by Equation 5.8 (Huerlimann and Nash, 2017):

$$l(v) = l_b + l_s \tag{5.8}$$

with:

$l(v)$ = the minimum separation distance as a function of the speed of the following train,
l_b = the braking distance of the following train as a function of speed,
l_s = a specified safety distance between two trains.

The minimum spacing for moving block with communication is governed by Equation 5.9 (Huerlimann and Nash, 2017):

$$l(v) = l_b + l_s + r_{res} + l_{rel} + (t_r * v) \tag{5.9}$$

with:

$l(v)$ = the minimum separation distance as a function of the speed of the following train,
l_b = the braking distance of the following train as a function of speed,
l_s = a specified safety distance between two trains,
l_{res} = the Reservation Distance, an attribute assigned to routes in OpenTrack,
l_{rel} = the Release Distance, an attribute assigned to routes in OpenTrack,
t_r = the Reaction Time, an attribute assigned to routes in OpenTrack,
v = the speed of the following train.

Equation 5.9 shows similarities to Equation 3.6, as both formulae include terms as "reservation" or "setup" time and "release time". In the Rotterdam metro model in OpenTrack, the terms such as "Reservation distance" are used to model the distance at which a train reserves an block ahead. Including this in the function for minimum spacing will not yield the intended behaviour of moving block technology, as the minimum separation will be far more than the intended distance right behind the tail of the leading train.

Therefore, it has been chosen to use the "pure" moving block setting to model the intended behaviour of moving block technology in OpenTrack. Trains are now allowed to proceed to the tail of the previous train, regardless of location.

However, this setting – again – presents problems at terminal stations. There, a following train will pull up right behind its predecessor, which is stationary alongside the terminal platform. This will create a deadlock situation like the one shown in Section 4.4.2. To solve this, all incoming routes into a terminal station should have the feature *Discrete for moving block* enabled. This setting ensures that trains following the moving block regime regard that block as fixed, and will therefore wait at the signal guarding that block in case it is occupied.

Human behaviour in OpenTrack
A key element of automation is that the influence of human behaviour on metro operations is reduced, by replacing one or more function otherwise carried out by a human by a computer. Generally, the influence of humans is visible at three moments of timetable operation:

- Before the trip: Trains operating with Grade of Automation Level 1, 2 or 3 need crew present on the trains. If they are not present, the train cannot leave for service. Only trains with GoA Level 4 do not need crew at all and can leave for service regardless of the availability of personnel.

- During the trip: Each human behaves differently and therefore, each driver drives its train slightly differently, causing variations in running times. With a computer driver the train (GoA Levels 2, 3 and 4), running time variations are reduced significantly.

- At terminal station: With a driver present in a cabin in the front of the train (GoA Level 1 and 2), a train requires time to reverse, during which a driver walks to the other end of the train and sets the train up for the return trip. Without a driver in front (GoA Levels 3 and 4), reversing operations can be sped up, depending only on the time required to set up the route for the return trip and for the passengers to board and alight.

The first point will not be investigated by OpenTrack and it is assumed that enough staff is available to carry out all operations. Not being dependent on personnel increases flexibility, allowing for service pattern changes to be effectuated on a much shorter notice. For this research, normal pre-planned services will be investigated and therefore, the availability of staff will not be taken into account.

The second point involves running time variances. A key feature of automation is that due to automation, running time variances are reduced, reducing the need of running time supplements. Modelling this difference in OpenTrack is problematic, as running times are calculated on train characteristics only. Therefore, they are already deterministic and contain no variances. As a result, the simulations in OpenTrack can already be regarded as Grade of Automation Level 2.

This leaves the third point remaining regarding driver behaviour. The main differences between GoA Levels 1 and 2 and Levels 3 and 4 is the presence of a driver in front. With no driver in front can the minimum required reversing time be reduced. This is modelled in OpenTrack by altering the connections at terminal stations (see Section 4.4.3). RET currently maintains a minimum reversing time of 2 minutes. The effects of GoA Levels 3 and 4 are modelled by reducing the minimum reversing time from 2 minutes to 30 seconds. If a train is on time, the train will dwell in the terminal station as long as is defined in the timetable. However, is a train is substantially late and arrives at the terminal station later than the planned departure time, the train will reverse as long as the minimum reversing time. As no dwell time distributions have been constructed and implemented for terminal stations, the 30 seconds reversing time is chosen to model a representative time to dwell, allowing for passengers to board and alight. By reducing the minimum required reversing time from 2 minutes to 30 seconds while keeping the timetable unchanged, 90 seconds of buffer time is gained at each terminal stations, which can then be useful to reduce the effects of incurred delays.

5.2.3. Summary of the four variants

Section 5.2.1 and 5.2.2 have shown that the difference between the four variants depends on the implementation of two important factors: the signalling system and human behaviour. The first variant, called *FB-GoA1* or *Fixed Block; no automation*, corresponds with the current situation, while the other three variants – *FB-GoA3/4*, *MB-GoA1* and *MB-GoA3/4* – are upgraded variants and are only applied to growth scenarios if their performance in variant *FB-GoA1* yield too unreliable services. Table 5.1 gives an overview of the four different variants and the implementation of the eight internal factors in each variant.

Table 5.1: Overview of the four variants and the implementation of the internal effects

Factor	**Variant**			
	FB-GoA1	**FB-GoA3/4**	**MB-GoA1**	**MB-GoA3/4**
Other public transport Vehicle design Vehicle availability	As current	As current	As current	As current
Network design Timetable quality	Optimised	Optimised	Optimised	Optimised
Signalling system	Fixed block		Moving block	
Crew availability Driver behaviour	Driver in front	No driver in front	Driver in front	No driver in front

5.3. Growth scenarios

The starting point of the construction of scenarios is a newly constructed Base Scenario, which has been briefly introduced in Section 4.5.4. In this scenario, two infrastructural changes that are projected in the (very) short term – the extension towards Hoek van Holland and the construction of a tail track at *Pijnacker*

Zuid – are implemented. A new timetable has been written for that scenario, in which the trunk frequencies are the same as in the current timetable, and in which running times, dwell times and reversing times remain the same as well. In each following scenario, the infrastructure remains unaltered, while new timetables are written, accommodating an increase of frequencies in each new scenario.

The following list shows the different scenarios that are analysed in this research. These are then discussed in the following sections.

- Reference Scenario 2021: Trunk section intervals of 200 seconds, Hoekse Lijn and tail track *PAZ* operational
- Scenario 150: Trunk section intervals of 150 seconds
- Scenario 120: Trunk section intervals of 120 seconds
- Scenario 100: Trunk section intervals of 100 seconds

5.3.1. Reference Scenario 2021: New infrastructure

In this scenario, two short-term expansions up to 2021 are included in the model and a new timetable is constructed to accommodate the new extensions. The expansions comprise the extension of lines A and B from *Schiedam Centrum* westwards to *Hoek van Holland*, and the construction of a reversing track at *Pijnacker Zuid*. Although the tracks of the former *Hoekse Lijn* railway line between *Schiedam Centrum* and *Hoek van Holland* are not actually modelled in OpenTrack, the timetable in the OpenTrack model and the routes of the trains are built such that the line is in fact in operation, though not "visible" in OpenTrack. At the location where the tracks to and from the Hoekse Lijn diverge, a so-called "cordon" is in place. Trains travelling to and from Hoek van Holland appear and disappear at this cordon, following the timetable as if the Hoekse Lijn were actually modelled.

An important limitation of using this cordon is that potential delays sustained on the Hoekse Lijn do not influence the rest of the network. This can be partly solved by adding a constraint, forcing a train that leaves the OpenTrack model at *Schiedam Centrum* to re-appear at least a defined time after it has disappeared. This has as result that the delays sustained on the westbound trip of a train service to Hoek van Holland persist during the eastbound trip. Slack times and buffers times at termini along the Hoekse Lijn are then not taken into account. It is therefore chosen to abandon this connection, ensuring that eastbound trains are not affected by delays sustained on the previous, westbound trip. Therefore, it is assumed that slack and buffer times on the Hoekse Lijn are high enough to eliminate all delays sustained on the westbound trip.

Figure 5.3 shows the operational model used in the base scenario. Six lines are operated, each line operating with 10-minute intervals, resulting in 3.3-minute intervals on the trunk sections between *Rotterdam Centraal* (RCS) and *Slinge* (SLG) and between *Schiedam Centrum* (SDC) and *Capelsebrug* (CPB). The picture shows the frequencies on the network during the peak moment in the rush hour period, which is roughly between 07:00 and 09:00.

Reversing track Pijnacker Zuid

In the current timetable, Lines D and E both operate with 10-minute interval, resulting in a 5-minute interval on the north-south trunk line (see Table 4.1) outside the rush hour periods. During the rush hours, another 10-minute service is added on line D, resulting in three 10-minute services on the north-south trunk section. Furthermore, three supplementary trains are run up and down once between Slinge and Pijnacker Zuid to alleviate overcrowding on line E during rush hours. This adds extra pressure on the trunk section, where an uneven spread of trains now exists. Furthermore, these extra trains reverse alongside the northbound platform at the station of Pijnacker Zuid, blocking the line for following trains wishing to continue to Den Haag Centraal. RET wants to solve this issue by extending the rush hour Line D services from Rotterdam Centraal to Pijnacker Zuid, eliminating the need for the irregular supplementary trains, while reversing the regular Line D services at Rotterdam Centraal. This way, extra capacity is offered on line E between Rotterdam Centraal and Pijnacker Zuid while maintaining an evenly spread pattern on the trunk section.

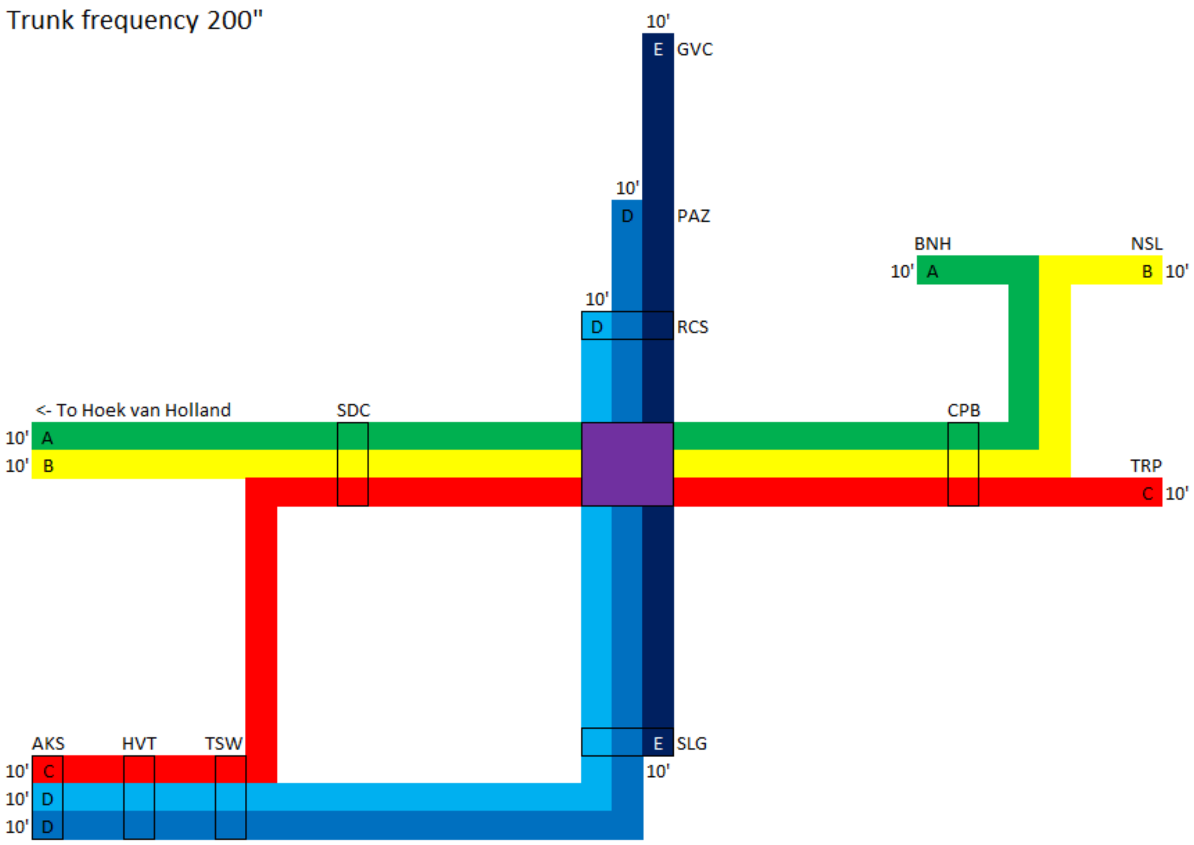


Figure 5.3: Schematic overview of lines and frequencies operated in the base scenario

However, the current station layout at Pijnacker Zuid is not equipped to facilitate reversing operations of the extended Line D rush hour services. RET is already struggling to maintain punctual services with the daily six extra trains. As the extra trains have to reverse on the main line track alongside the northbound platform, they only have three minutes to reverse before blocking a following train, which is not enough to cope with small delays. RET expects punctuality to deteriorate even more if a full 10-minute service reverses at Pijnacker Zuid.

Therefore, RET has decided to construct a separate reversing track at Pijnacker Zuid, located beyond the station and in between the two main line tracks. This allows for trains to reverse while through-going trains can pass and continue towards The Hague. This also means that more buffer time can be allocated to the reversing trains, making overall train operations more stable, as the reversing trains have more time to account for delays incurred earlier on.

Figure 5.4 shows the different reversing procedures at Pijnacker Zuid. Figure 5.4a shows the current situation, while Figure 5.4b shows the situation with reversing track. The reversing track is realised by adding a third track east of the two main tracks. Trains terminating at Pijnacker Zuid reverse north of the station on the original northbound track. Through-going trains travelling northbound for The Hague can still use the original northbound track to travel to The Hague, but if this track is occupied by a reversing train, they can bypass the reversing train by using the new third track. Southbound trains can use the original southbound track, passing the reversing train unhindered.

To assess whether the proposed new layout for *Pijnacker Zuid* is effective, the theory on complexity indices presented in Section 3.2.1 is applied to both track layouts. If the complexity index for the new track layout is lower than in the old layout, this means that the station is less complex and therefore more robust.

In the old situation trains reverse alongside Platform 1 (see Figure 5.4a. Following the classification system explained in Section 3.2.1, the following routes are defined:

a) Northbound through route over Track 1

b) Southbound through route over Track 2

c) Northbound entry into Track 1

d) Southbound departure from Track 1

Table 5.2 shows the resulting complexity index table:

Table 5.2: Complexity index table for Pijnacker Zuid without reversing track

1^{st} \ 2^{nd}	a	b	c	d
a	O	-	O	X
b	-	O	-	C
c	Ø	-	Ø	X
d	X	C	X	Ø

Following Table 5.2 this results in the following parameters:

$n_\Sigma = 16$
$n_k = 12$
$n_\lambda = 3$

And from this follows:

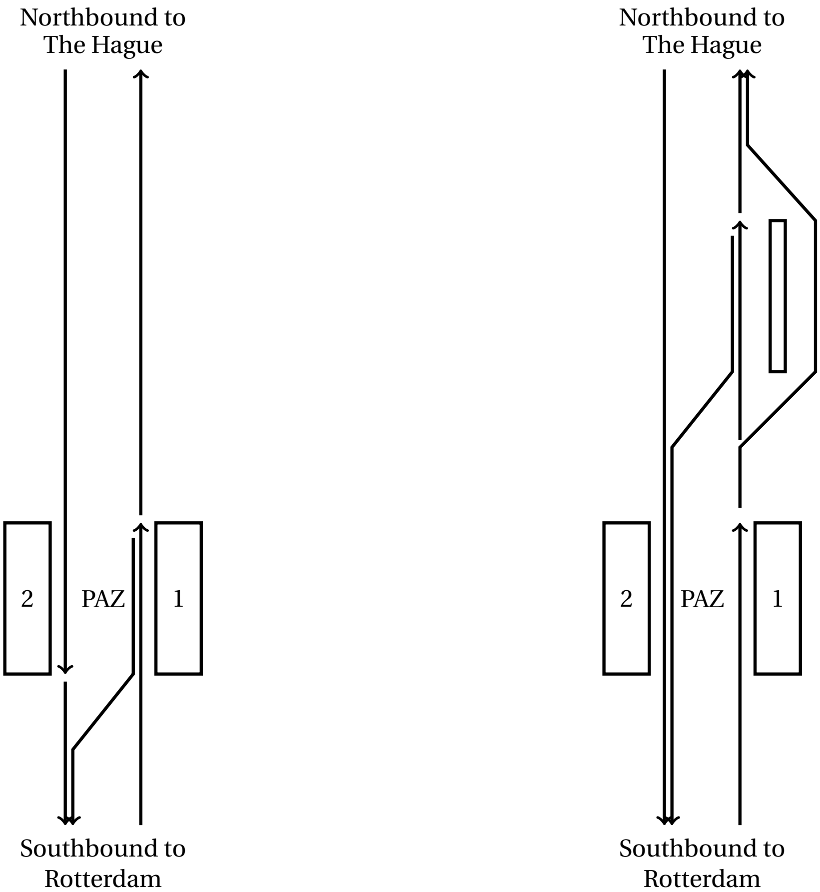
$$\phi_n = \frac{n_k - n_\lambda}{n_\Sigma - n_\lambda} = \frac{12-3}{16-3} = \frac{9}{13} = 0.69 \tag{5.10}$$

The new station layout, where reversing trains use the centre track and trough-going trains used the outer tracks, is the same as Figure 3.2b, shown as example in Section 3.2.1. From that example, it follows that the complexity index of the new station is $\phi_n = 0.57$. Therefore, the layout of the new station is more robust, meaning that the new situation will lead to smaller secondary delays, because reversing trains do not block through trains running further towards The Hague.

Timetable design
In Scenario 2021, roughly the same line network is used as in the current timetable, with the difference that lines A and B are extended westwards from *Schiedam Centrum* onto the Hoekse Lijn (which is not modelled in OpenTrack, but the service pattern is followed). The rush hour service on line D is extended northwards from *Rotterdam Centraal* to *Pijnacker Zuid*. This leads to the operating scheme shown in Figure 5.3 and shown in Table 5.3.

Table 5.3: Operating scheme in the base scenario

Line	**Route**	**Frequency**
A	Vlaardingen West - Binnenhof	10’
B	Hoek van Holland - Nesselande	10’
C	De Akkers - De Terp	10’
East-west Trunk:		
ABC	Schiedam Centrum - Capelsebrug	3.3’
D	De Akkers - Rotterdam Centraal	10’
D	De Akkers - Pijnacker Zuid	10’
E	Slinge - Den Haag Centraal	10’
North-south Trunk:		
DE	Slinge - Rotterdam Centraal	3.3’



(a) Reversing at Pijnacker Zuid without reversing track (b) Reversing at Pijnacker Zuid with new reversing track

Figure 5.4: Schematic layout of Pijnacker Zuid before and after construction of the reversing track

5.3.2. Scenario 150

While both previous scenarios had intervals of 200 seconds on the trunk section, this scenario is the first in which lower intervals are achieved than is currently in operation. For Scenario 150, the intervals on the trunk sections are lowered from 3.3 minutes (or 200 seconds) to 2.5 minutes (or 150 seconds). This is accomplished by operating four 10-minute services on the trunk sections. The advantage of having an even number of services is that when half of the services terminate at a certain intermediate station (for example *Slinge* on the north-south axis), the remaining two services are still evenly spread within the 10-minute time period, effectively achieving one combined 5-minute service.

Table 5.4 shows the overview of the service pattern on the whole network for Scenario 150, which is also shown graphically in Figure 5.5. Using Scenario 2021 as a basis, services on the east-west axis are extended by adding a short-turn service of line C, that travels between *De Terp* and *Hoogvliet*. The reason to not continue the fourth service to *De Akkers* as well is because of limited capacity at the latter station. As *De Akkers* also has to facilitate two D-train services, three 10-minute services (two D's and one C) is the maximum that the terminal station can manage. It is predicted that an extra service to *De Akkers* would cause too unreliable services.

On the north-south axis, the rush-hour service between *Pijnacker Zuid* and *De Akkers* (see Section 5.3) is cut back to *Rotterdam Centraal*, effectively creating an evenly spread 5-minute service between *Rotterdam Centraal* and *De Akkers*. The remaining service between *Slinge* and *Den Haag Centraal* is expanded by adding an extra service between *Slinge* and *Pijnacker Zuid*.

On all sections of track except between *Hoogvliet* and *De Akkers*, an even number of services operate. This means that on those sections the services are evenly spread, meaning that at any station in the network, either

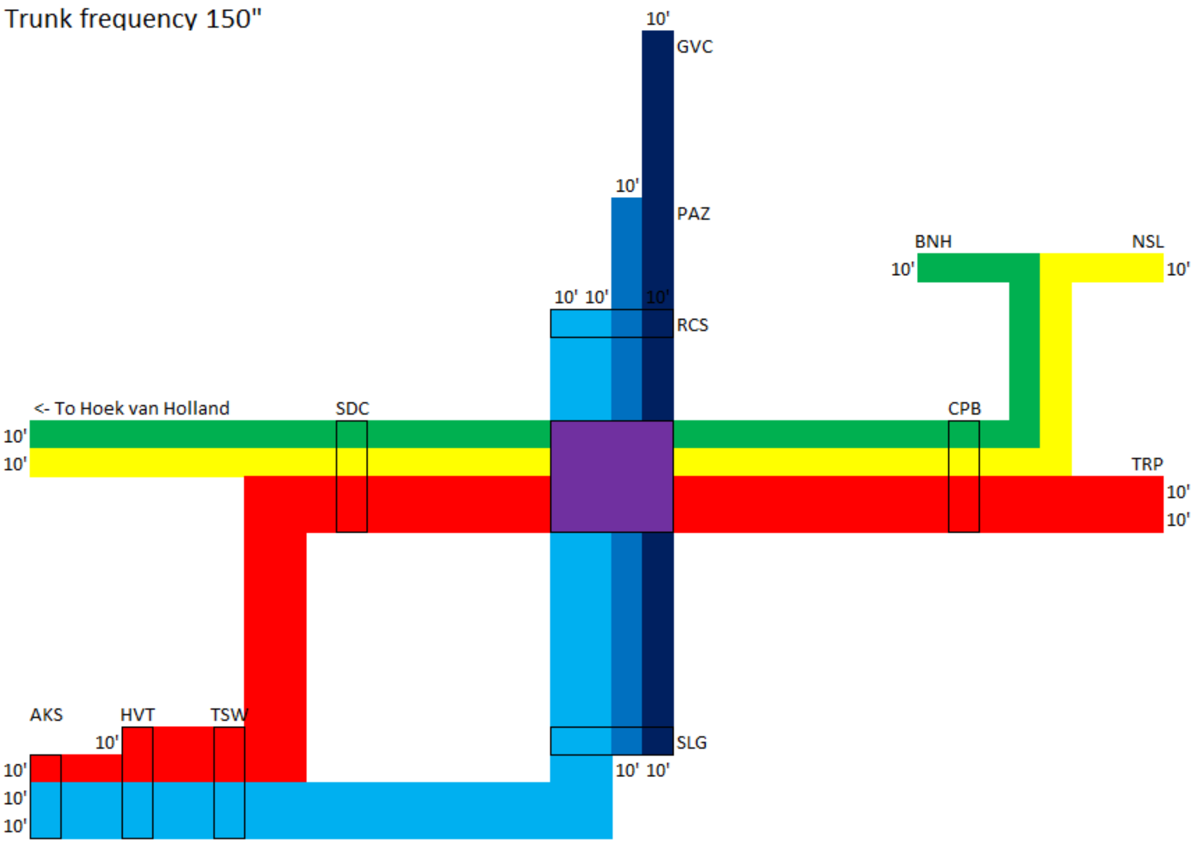


Figure 5.5: Schematic overview of lines and frequencies operated in Scenario 150

Table 5.4: Operating scheme in Scenario 150

Line	Route	Frequency
A	Vlaardingen West - Binnenhof	10'
B	Hoek van Holland - Nesselande	10'
C	De Akkers - De Terp	10'
C	Hoogvliet - De Terp	10'
East-west Trunk:		
ABC	Schiedam Centrum - Capelsebrug	2.5'
D	De Akkers - Rotterdam Centraal	10'
D	De Akkers - Rotterdam Centraal	10'
E	Slinge - Den Haag Centraal	10'
E	Slinge - Pijnacker Zuid	10'
North-south Trunk:		
DE	Slinge - Rotterdam Centraal	2.5'

a 10-minute, a 5-minute, or a 2.5-minute service pattern exists.

5.3.3. Scenario 120

In this scenario, the intervals on the trunk sections are decreased from 150 seconds to 120 seconds. This means operating five services on both axes. Compared to Scenario 150, an extra service is added on the north-south axis between *Den Haag Centraal* and *Slinge*. On the east-west axis, an extra service is added travelling only on the trunk section between *Capelsebrug* and *Schiedam Centrum*. With an odd number of of services on the trunk sections, services on the branch lines are not spread out evenly over time. For example, with three services terminating at *Slinge (SLG)*, two services remain between *Slinge* and *De Akkers*. Due to the evenly spread intervals on the trunk section, these two cyan-coloured services are spread in a 4'-6' pattern. It is expected that this has a negative effect on regularity rates for this scenario.

Table 5.5: Operating scheme in Scenario 120

Line	Route	Frequency
A	Vlaardingen West - Binnenhof	10’
B	Hoek van Holland - Nesselande	10’
C	De Akkers - De Terp	10’
C	Hoogvliet - De Terp	10’
C	Schiedam Centrum - Capelsebrug	10’
East-west Trunk:		
ABC	Schiedam Centrum - Capelsebrug	2.0’
D	De Akkers - Rotterdam Centraal	10’
D	De Akkers - Rotterdam Centraal	10’
E	Slinge - Den Haag Centraal	10’
E	Slinge - Den Haag Centraal	10’
E	Slinge - Pijnacker Zuid	10’
North-south Trunk:		
DE	Slinge - Rotterdam Centraal	2.0’

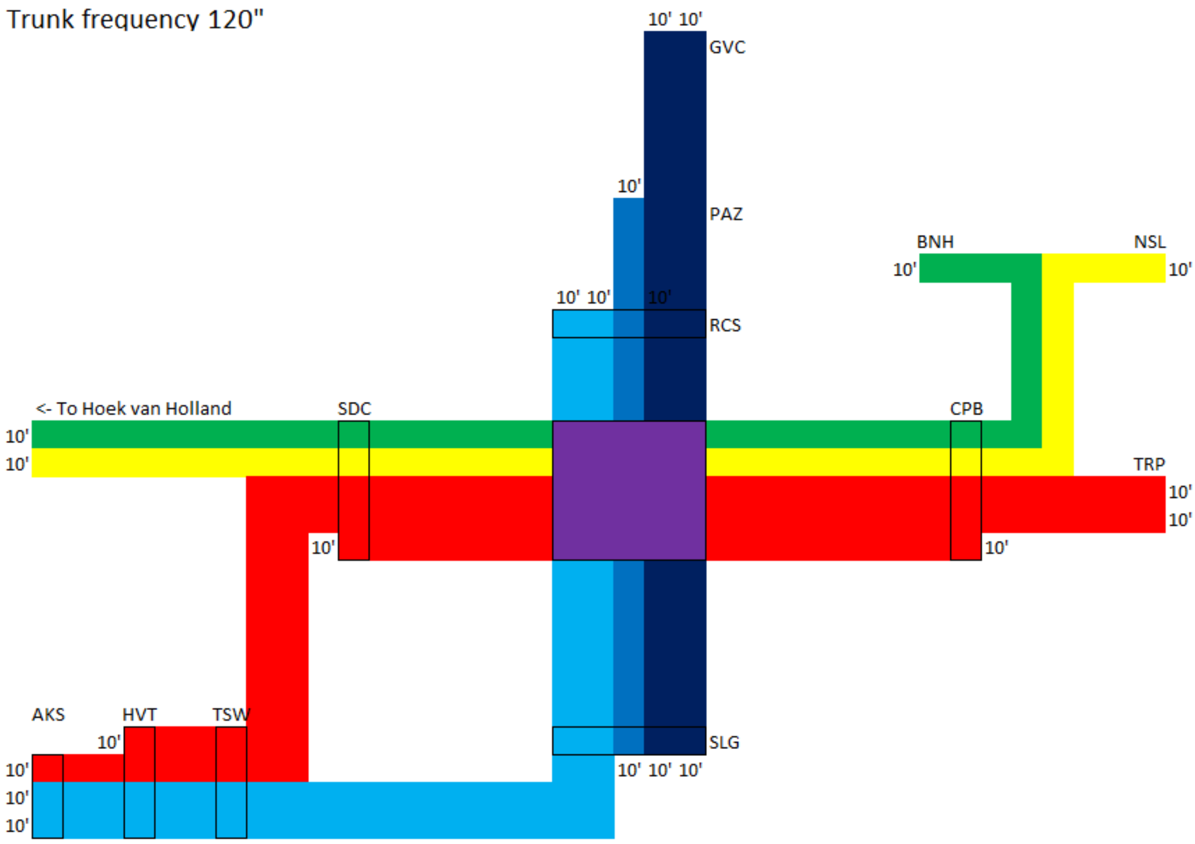


Figure 5.6: Schematic overview of lines and frequencies operated in Scenario 120

5.3.4. Scenario 100

In this scenario, the intervals on the trunk sections are decreased even further from 120 seconds to 100 seconds by operating six services on both axes. On the north-south axis, lines D and E both run at 5-minute intervals. The last two services consist of a new line F, running every five minutes between *Pijnacker Zuid* and *Slinge*, and every ten minutes to *Tussenwater*. On the east-west axis, the six services are achieved by adding an extra service to line B between *Nesselande* and *Hoek van Holland*.

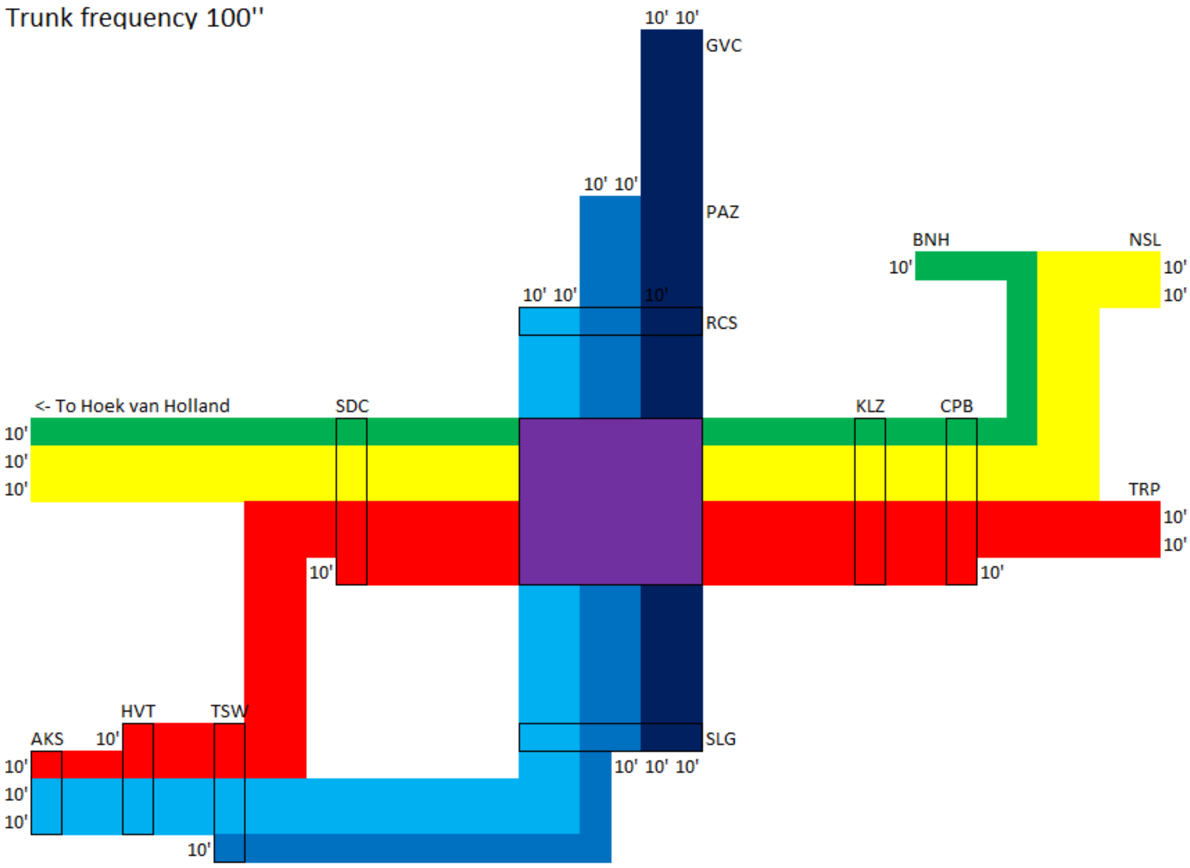


Figure 5.7: Schematic overview of lines and frequencies operated in Scenario 100

Table 5.6: Operating scheme in Scenario 100

Line	Route	Frequency
A	Vlaardingen West - Binnenhof	10'
B	Hoek van Holland - Nesselande	10'
B	Hoek van Holland - Nesselande	10'
C	De Akkers - De Terp	10'
C	Hoogvliet - De Terp	10'
C	Schiedam Centrum - Capelsebrug	10'
East-west Trunk:		
ABC	Schiedam Centrum - Capelsebrug	1'40"
D	De Akkers - Rotterdam Centraal	10'
D	De Akkers - Rotterdam Centraal	10'
E	Slinge - Den Haag Centraal	10'
E	Slinge - Den Haag Centraal	10'
F	Tussenwater - Pijnacker Zuid	10'
F	Slinge - Pijnacker Zuid	10'
North-south Trunk:		
DE	Slinge - Rotterdam Centraal	1'40"

A difference with Scenario 120 is that an *even* number of services is operated on the trunks section. This means that the services on the branch line are spread out evenly over time, with exception the sections between *Capelsebrug* and *Graskruid* and on the Hoekse Lijn west of *Schiedam Centrum*, where a 2'-3'-5' pattern exists.

5.4. Conclusions

This section has presented four different growth scenarios and four different operational variants. Different combinations of growth scenario and operational variants have been made, leading to the ten different scenarios that have been investigated:

Table 5.7: Overview of different scenarios investigated during this research

No.	Growth scenario	Operational variant
1	Base scenario 2021	FB-GoA1
2	Scenario 150	FB-GoA1
3	Scenario 120	FB-GoA1
4		FB-GoA3/4
5		MB-GoA1
6		MB-GoA3/4
7	Scenario 100	FB-GoA1
8		FB-GoA3/4
9		MB-GoA1
10		MB-GoA3/4

6 Results

Chapter 5 has discussed the four different growth scenarios and the four different operational variants. In this chapter, the scenarios shall be assessed using the model of the Rotterdam metro in OpenTrack. The simulated performances of the growth scenarios shall be assessed using the indicators described in Section 2.2. The indicators represent the interests of both the operator and the passenger: maintaining regular services and maintaining punctual services.

The growth scenarios will all feature the recent infrastructure upgrades of the *Hoekse Lijn* and the tail track at *Pijnacker Zuid* and do not feature the troublesome reversing operations at *Pernis* and *Schiedam Centrum*. As infrastructure changes have major consequences for the performance of a timetable, referencing the growth scenarios with the simulations of the current timetable would be a futile exercise, as comparing two scenarios that have different track layouts is like comparing apples with oranges. Therefore, a reference scenario, called "Base scenario 2021", is constructed, featuring the above mentioned infrastructural alterations as a benchmark for the assessment of the growth scenarios. Furthermore, a new timetable has been written, to included the new infrastructure in the simulated operations. However, the frequencies and terminal buffer times are the same as in the current timetable, in order for the base scenario to be a fair representation of the metro network in the short term.

Operator RET and the region's transport authority MRDH define a train's departure as "late" when a train departs more than 120 seconds after the scheduled departure time. Transport authority MRDH realises that it is impossible to demand that all trains depart on time and has therefore allowed a maximum percentage of all monthly departures to be "late". However, the exact agreement between RET and MRDH on the amount of allowed late departures and its consequences is considered to be sensitive information and is therefore not utilised in this research. Furthermore, apart from the classification that a train is late if its departs more than 120 seconds after the scheduled departure time, a train's lateness is not further quantified. Following this assessment, a train being 120 seconds late is statistically just as worse as a train that is 600 seconds late. However, the size of lateness is indeed important for both the operator and the passenger. Lateness can directly affect the (total) travel time of a passenger, the working hours for train staff, or the risk to miss connections to further trips for both passengers and staff.

Therefore, this research has chosen to define its own threshold level of what delay is acceptable. Rather than measuring the on-time performance of all monthly departures (which therefore includes evenings and weekends), this research regards an overall *average* delay of under 120 seconds during the rush hour periods as acceptable Level of Service.

6.1. Results growth scenarios

Table 6.1 shows the general performance of the simulated growth scenarios for the rush hour period and also shows the difference with respect to the base scenario. In general, the lower the intervals on the trunk section, the higher the average dis-punctuality. Given the threshold mentioned in the introduction of this chapter, the dis-punctuality of Scenarios 120 and 100 is too high to accept as reliable services. Scenario 150 performs remarkable well. Even though the intervals on the trunk sections are significantly lower, the average dis-punctuality is only 9 seconds lower than the base scenario.

The overall rate of irregularity does not follow the same trend as dis-punctuality in the way that the lower the intervals, the higher the dis-punctuality. It can be seen that services are more regular in Scenario 150 and Scenario 100 than in the base scenario and Scenario 120 respectively, although the former two scenarios have lower trunk section intervals than the latter two scenarios.

Table 6.1: Overall network performance between 07:00 and 09:00 of the four growth scenarios

Scenario	Irregularity [%]	Diff. to base [%]	Dis-punctuality [sec]	Diff. to base [%]
Base 2021	17.9	–	70	–
Scenario 150	17.0	- 5	79	+ 13
Scenario 120	30.8	+ 72	124	+ 77
Scenario 100	26.4	+ 55	180	+ 157

The reason for this phenomenon is the spread of trains on the branch lines. During the construction of the timetables, all trains on the trunk section have been spread evenly within the repeating time period of 10 minutes. How the passage of trains is divided on the branch lines depends on the amount of train services on the trunk section. With an even number of train services on the trunk sections, it is easier to ensure an even spread on the branch lines. With an uneven number of train services on the trunk sections, this cannot be achieved. The good performance of lines A, B and C in Scenario 100 can be related to this theory, as in this scenario an even interval pattern of 5'-5' is achieved both on the sections *Benelux* and *Alexander*. In Scenario 120, an uneven interval pattern of 4'-6' is achieved on the *Benelux* and *Alexander* sections. As the headway is different for the two train services, a delay will lead to a higher irregularity rate on the service with the lower headway than on the service with the higher headway.

However, this observation only holds in general. Figure 6.1 shows the differences in percentage point between Scenarios 150, 120 and 100, and the base scenario, but then differentiated per line. A clear distinction can be found between lines A, B and C on the east-west axis and lines D and E on the north-south axis. Lines A, B and C follow the general trend that they are more regular in scenarios with an even number of services on the trunk sections than in scenarios with an uneven number. For lines D and E the case is different. Both lines are only 4 and 1 percentage point more irregular in Scenario 150 than in the Base scenario, even though the intervals in Scenario 150 are 25% lower than in the base scenario. While irregularity improves dramatically for lines A, B and C in Scenario 100 compared to Scenario 120 and even reach irregularity levels similar to the base scenario, for lines D and E irregularity remains just as high in Scenario 100 as in Scenario 120.

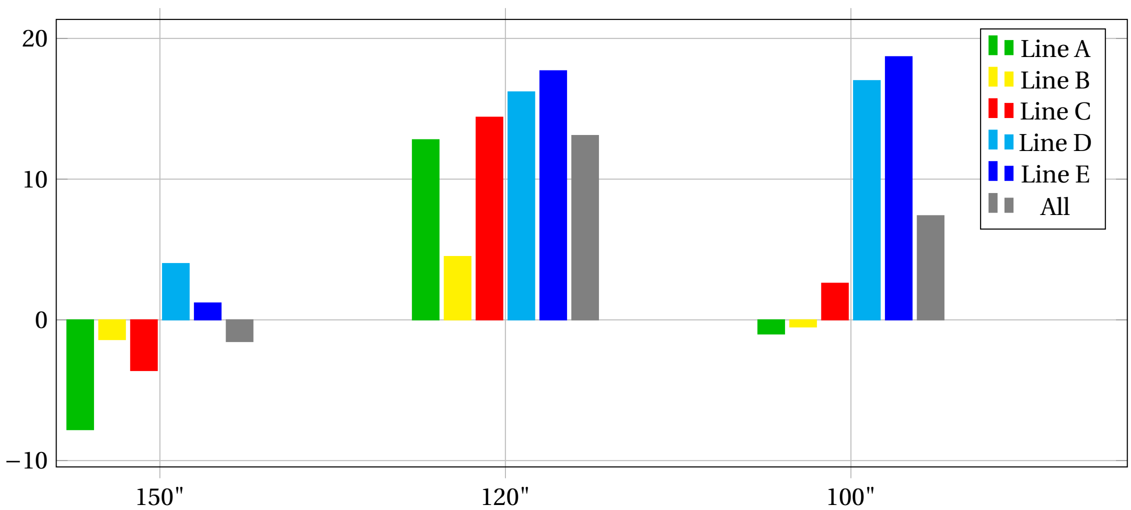


Figure 6.1: Difference in irregularity compared to Base Scenario 2021, differentiated per line

There are two main explanations for these observations. The first is the small amount of running time supplements for the lines on the east-west axis. The evenly spread trains for the "even" scenarios (150 and 100) provides each train on that axis with the same amount of running times supplements, while in the "uneven" scenarios (Base and 120) the availability of supplements depends on the pattern of the trains on the branch lines. In Scenario 120 this can be observed as lines A and C follow their predecessor more closely on branch lines than for example line B.

The second explanation relates to why lines D and E remain irregular in Scenario 100. This has to do with the presence of the *safe haven* principle on the section of track between *Rotterdam Centraal* and *Melanchthonweg*. This principle entails that a train travelling on that underground section is only allowed to depart from a station when the platform at the next station is free. This is a safety measure, to ensure that a train always has a safe location to go to in case of a calamity in that section of tunnel. Therefore, on that section capacity is defined by the longest distance between two stations. In Scenario 100, the projected intervals in the timetable are lower than the minimum intervals defined by the distance between *Blijdorp* and *Melanchthonweg*.

That this safe haven principle acts as a bottleneck is observed in Figure 6.2, which shows the difference in dis-punctuality between the growth scenarios and the base scenario. With an average dis-punctuality of 274 seconds, this is 134 seconds higher than the average dis-punctuality of line E in Scenario 100.

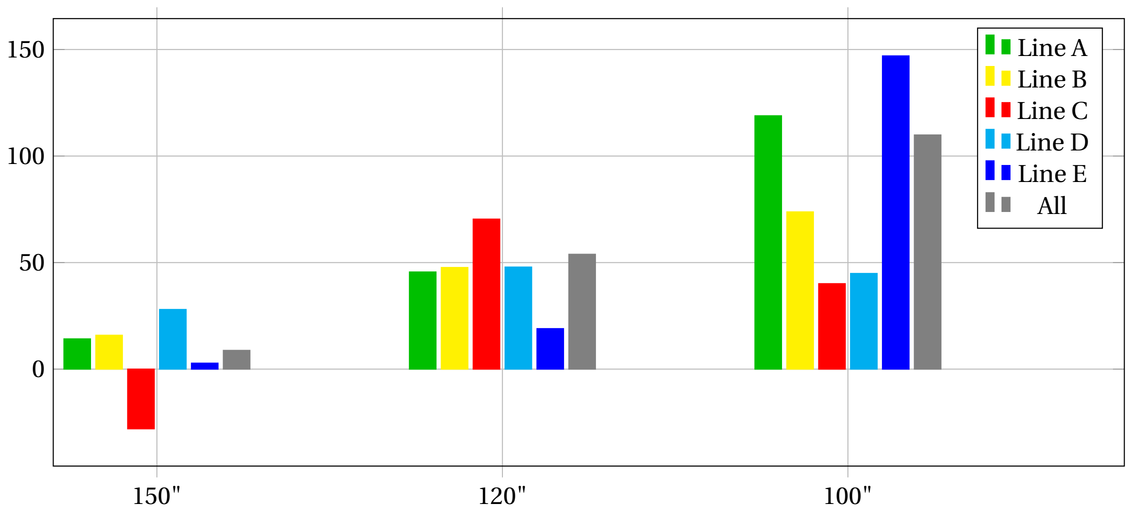


Figure 6.2: Difference in dis-punctuality compared to Base Scenario 2021, differentiated per line

Furthermore, Figure 6.2 shows that different patterns are visible, depending on the line observed. For example, dis-punctuality on lines A and B increases as trunk intervals decreases, while line C follows the same trend for dis-punctuality as for irregularity, showing lower delay rates in Scenarios 150 and 100 than in the Base scenario and Scenario 120 respectively. The performance of line C differs per direction. In northbound direction (*De Akkers* to *De Terp*, delays on line C are consistently lower for the "even" scenarios 150 and 100 than the "uneven" Base scenario and Scenario 120. In other direction, delays on line C increase as the number of services on the trunk section increases. While delays on the *Capelle* are low (15 seconds on average for lines C), delays start increasing drastically on the trunk section, where six 10-minutes services are operated. This is also the case for lines A and B, showing that the combination of the number of services and the merging at the start of the trunk section proves to be very vulnerable. The poor performance in respect to delays on the trunk section is not reflected by irregularity, which is ten percent lower in the "even" scenarios than it is on the "uneven" scenarios.

Figure 6.3 and Figure 6.4 show the differences in irregularity and dis-punctuality between the growth scenarios and the base scenarios, but now differentiated per section. Figure 6.3 shows that in Scenario 120, the *Capelle* and *Benelux* section perform poorly, showing nearly 40% higher irregularity rates than in the base scenario. Following *Capelle* and *Benelux* are *Spijkenisse* and *RandstadRail*, who all score more than 20% worse than in the base scenario. These section all feature irregularly headways in the *planned* timetable already. The same is valid for the *Spijkenisse* in Scenario 100, which also features irregularly *planned* headways.

This confirms the hypothesis mentioned earlier in this section, that regularly *planned* headways increase actual regularity. Outliers in this case are the *Nesselande*, *Binnenhof*, *Alexander* and *RandstadRail* sections in Scenario 100. The RandstadRail section is highly irregular due to the limitations posed by the safe haven principle mentioned earlier. Irregular services on the first three sections are caused by the junction at-grade in the north-east of the network, between the stations *Graskruid* and *Romeijnshof* and *Hesseplaats*. Although this junction is taken into account during the construction of the timetable, a delayed northbound train taking the junction in westward direction towards *Binnenhof*, might have to wait for a southbound train from *Nesselande*.

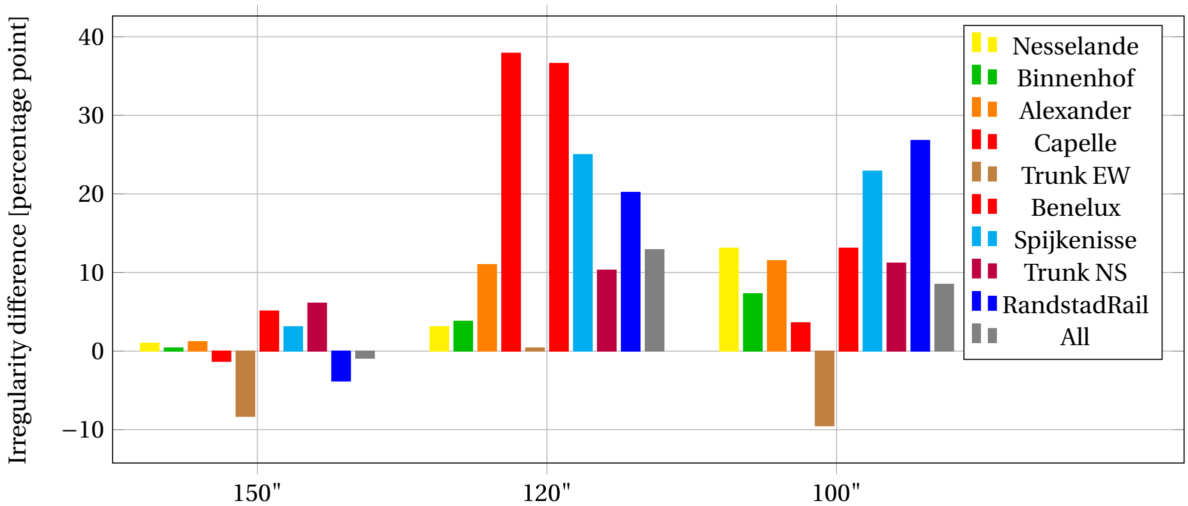


Figure 6.3: Difference in irregularity compared to Base Scenario 2021, differentiated per section

Figure 6.4 shows that this even spread of trains in the planned timetable is less important for dis-punctuality. Here, the number of trains travelling on a section is important for punctuality, especially for the very low intervals in Scenario 100. The both trunk sections are particularly poorly scoring sections, with dis-punctuality more than 100 seconds higher than in the base scenario. Again the *RandstadRail* section is scoring very poorly in Scenario 100, with a 200-second increase compared to the base scenario. Again, this is due to the limitations of the safe haven principle, which, according to Figures 6.1 through 6.4, starts the be troublesome in Scenario 100.

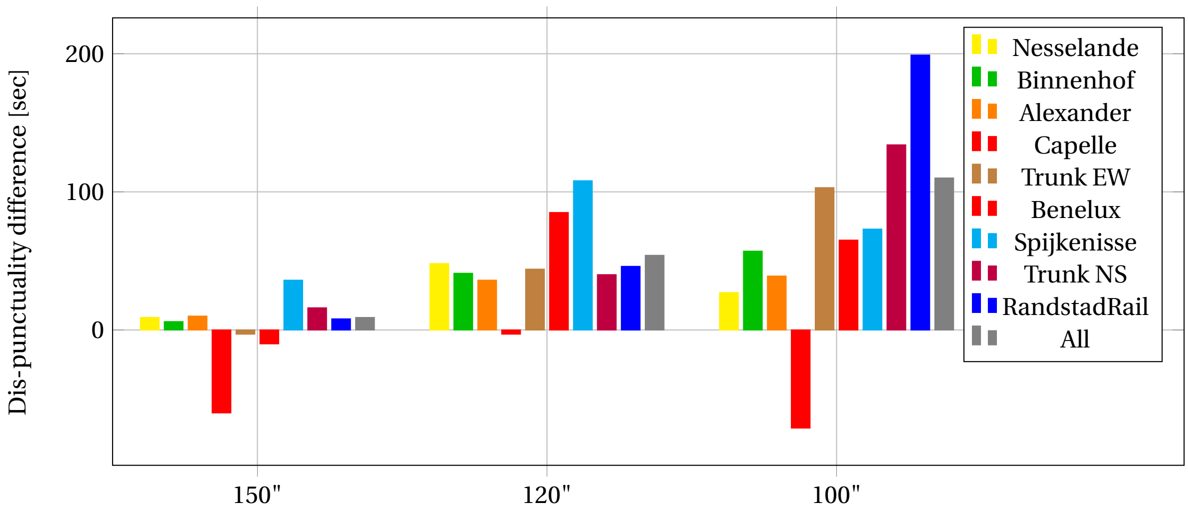


Figure 6.4: Difference in dis-punctuality compared to Base Scenario 2021, differentiated per section

6.1.1. Conclusions results growth scenarios

Section 6.1 has shown that a clear distinction is observable in the performances of both axes, caused by the availability of running time supplements and infrastructural constraints. Furthermore, the two indicators grade the different growth scenarios differently. For example, while in Scenario 100 the delays in southbound direction are over 5 minutes, irregularity rates rates remain relatively low and even lower than the Base scenario. The impacts of the performance depends on the stakeholder and the origin and destination of the passenger. While high delays are generally disliked by both the operator and the passenger, the destination of the passenger is also a factor in the appreciation of the performance. A passenger travelling only on the trunk section can take the first train that arrives regardless of the train's destination and is therefore more interested in regular services, whereas a passenger travelling to one of the branches requires only one specific service and is therefore more interested in punctuality. For the first type of passenger, the performance of Scenario 100 is more acceptable than for the second type of passenger.

Nevertheless, this research has deemed the performances of Scenarios 120 and 100 too high, especially given that the average dis-punctuality of both scenarios exceeds 120 seconds. Although the overall irregularity rates are reasonable, local irregularity rates exceed 40 or even 50 percent. Therefore, based on Table 6.1 and Figures 6.1 and 6.2, this research concludes that a frequency increase to 150 seconds on the trunk sections does not result in a significantly lower reliability and decrease of Level of Service. With general irregularity rates of around 17 % and general dis-punctuality of well under two minutes, Scenario 150 performs as well as the base scenario, and is even slightly more regular. Apart from the need to procure supplementary rolling stock and sufficient space to stable the enlarged fleet, the decrease of trunk section intervals from 200 to 150 seconds can be achieved fairly easily and is an effective measure to increase capacity in a medium-term time frame.

6.2. Results growth scenarios with upgrades

Section 6.1 has assessed the growth scenarios with operations variant *FB-GoA1*: featuring the current signalling system (Fixed Block) and driving operations (GoA1). That section has shown that Scenario 150 still yields reliable services, comparable with the base scenario. Furthermore, Section 6.1 has concluded that Scenarios 120 and 100 yield too unreliable services with the current infrastructure. Therefore, the 3 upgraded operations variants discussed in Section 5.2 are applied to Scenario 120 and Scenario 100 to investigate the effects of the upgrades. As a result, for each of the two growth scenarios, four different variants have been investigated and are presented in this section:

Table 6.2: Overview of the four variants investigated for growth Scenarios 120 and 100

Variant	Signalling system	Automation	Remarks
FB-GoA1	Fixed block	GoA1	Investigated in Section 6.1
FB-GoA3/4	Fixed block	GoA3/4	
MB-GoA1	Moving block	GoA1	
MB-GoA3/4	Moving block	GoA3/4	

6.2.1. Results Scenario 120

Table 6.3 shows the performances of the four variants of Scenario 120 compared with the Base scenario. In terms of regularity, variant *FB-GoA* performs 72% worse than the Base scenario, as has been shown in 6.1 in Section 6.1. With a 77% increase compared to base, dis-punctuality is also significantly worse at 124 seconds, exceeding the threshold of an acceptable average overall delay of 120 seconds.

All upgrade variants show improvements compared with the unaltered scenario. The removal of the human factor yields an irregularity of 27% – an improvement of 12% compared to variant *FB-GoA1* – and a dis-punctuality of 95 seconds, which is an improvement of 23% compared to variant *FB-GoA1*. The introduction of moving block technology has more drastic improvements. Variant MB-GoA3/4, featuring both the new signalling system and the new operational regime, performs with an irregularity of 16.6% and a dis-punctuality of 54 seconds even better than the base scenario with the current infrastructure, although the gains compared with moving block signalling only (variant *MB-GoA1*), especially for dis-punctuality, are low.

Table 6.3: Overall network performance of all variants of Scenario 120 compared to base

Scenario	Variant	Irregularity [%]	Diff. to base [%]	unpunctuality [sec]	Diff. to base [%]
Base	FB-GoA1	17.9	–	70	–
120	FB-GoA1	30.8	+ 72	124	+ 77
	FB-GoA3/4	27.2	+ 52	95	+ 36
	MB-GoA1	18.5	+ 3	57	- 19
	MB-GoA3/4	16.6	- 7	54	- 23

Figure 6.5 shows the difference in irregularity between the different upgrades variants (*FB-GoA3/4*, *MB-GoA1* and *MB-GoA3/4*) compared with the current variant (*FB-GoA1*). All lines perform better with upgrades than without, except for line B, which performs slightly worse in variant *MB-GoA1* than in *FB-GoA1*, but better in *MB-GoA3/4* than *FB-GoA1*.

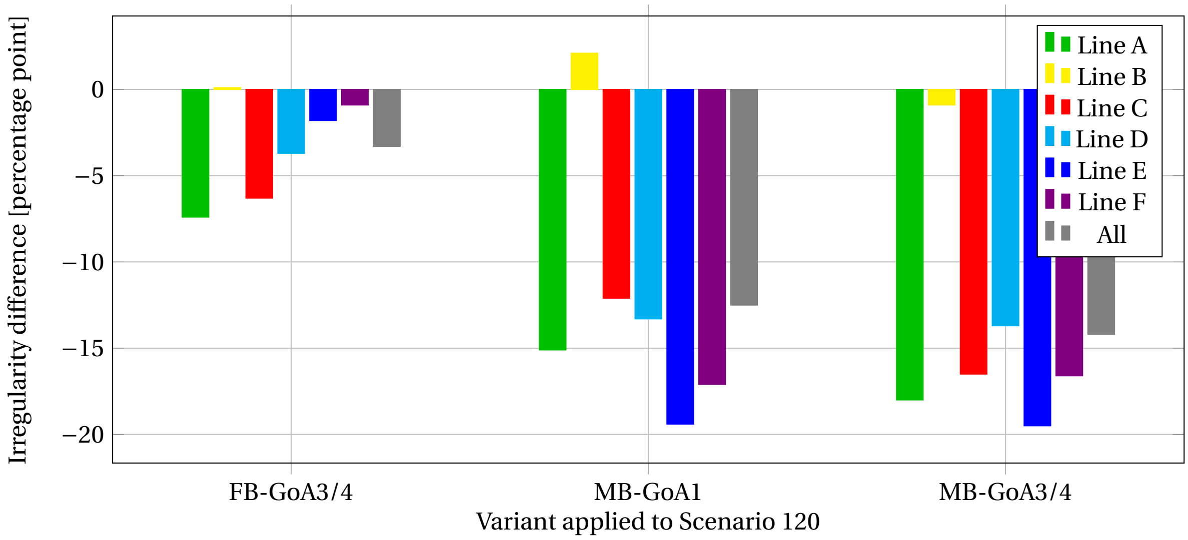


Figure 6.5: Difference in irregularity between upgrade variants and current variant for Scenario 120

Figure 6.6 shows the differences in dis-punctuality. Lines C and F seem to improve the most, realising over 100-second improvements in the variants with moving block. Line C is the most susceptible to delays, due to its running time supplements being too small. The implementation of a new signalling system appears to be most effective to line C, which experiences major improvements in punctuality, especially on its sections *Capelle* and *Benelux*, where dis-punctuality decreases by 84 and 106 seconds respectively. The new signalling also has effects on the *RandstadRail* section, as block lengths of the current signalling system are as long as the distance between two stations. Line F running to *Pijnacker Zuid* improves the most, as in the timetable follows a line E train at a short headway of two minutes. With the fixed block system, this interval proved to be too short, causing delays for lines F. With the new moving block system, line F is now able to follow significantly more closely, reducing its delays by more than 100 seconds.

6.2.2. Results Scenario 100

Table 6.4 shows the overall performance of the four operational variants applied to growth Scenario 100. With an irregularity of 26.4 % and an unpunctuality of 180 seconds, it is clear that the current infrastructure is not equipped for Scenario 100. Like Scenario 120, the both moving block signalling as automated trains result in an improved punctuality. Both measures together are able to reduce punctuality rates similar to those of the base scenario. The implementation of only automated trains while maintaining fixed block signalling is able to reduce punctuality by 45 seconds to 135, which is still too high. Moving block signalling only is able to improve punctuality more, bringing it down to an acceptable 81 seconds. Adding train automation as upgrade in combination with moving block signalling seems not to have a great effect, reducing dis-punctuality by only two seconds.

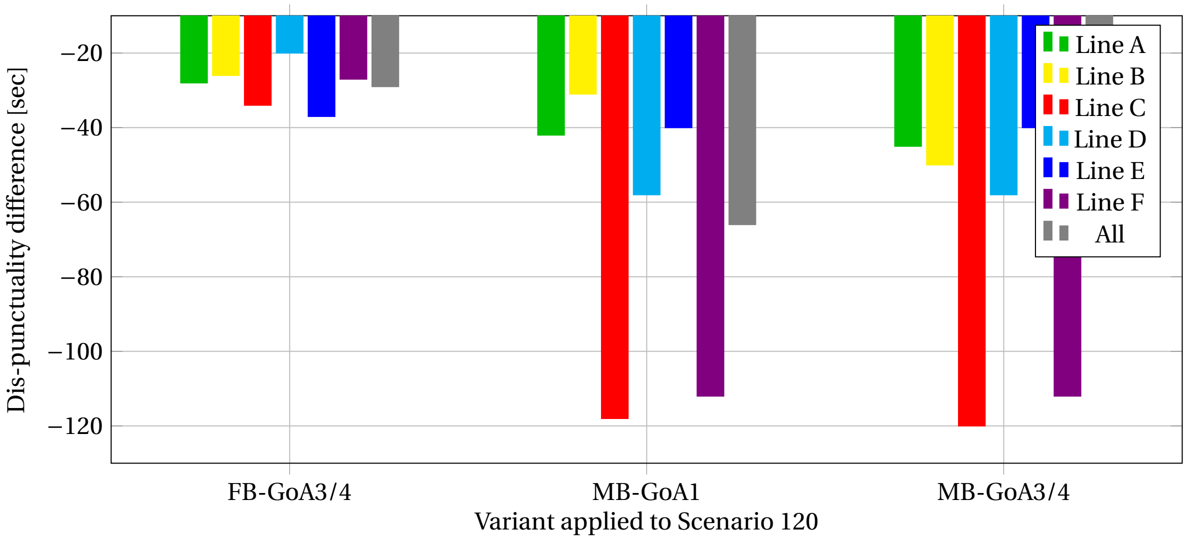


Figure 6.6: Difference in dis-punctuality between upgrade variants and current variant for Scenario 120

Therefore, based on punctuality only, introducing moving block signalling only seems to be sufficient. However, the situation is different for irregularity. Transitioning from fixed block to moving block while maintaining the current state of operation seems to have an adverse effect and only increases irregularity. Moreover, the implementation of automated trains only rather than both measures is the most beneficial to regularity, as this variant leads to the lowest irregularity rate of 19.6%.

Table 6.4: Overall network performance of all variants of Scenario 100 compared to base

Scenario	Variant	Irregularity [%]	Diff. to base [%]	Dis-punctuality [sec]	Diff. to base [%]
Base	FB-GoA1	17.9	–	70	–
100	FB-GoA1	26.4	+ 47	180	+ 157
	FB-GoA3/4	19.6	+ 9	135	+ 93
	MB-GoA1	30.0	+ 68	81	+ 16
	MB-GoA3/4	24.0	+ 34	79	+ 13

The findings in Table 6.4 lead to the suspicion that for the case of Scenario 100, the fixed block signalling system serves an alternative purpose. By forcing the trains to keep a distance from each other using fixed blocks, the signalling system contributes to maintaining regularity. By introducing moving block signalling and therefore enabling trains to run closer to each other, irregularity increases rather than decreases. It is the increase of buffers times at terminal stations that plays a more dominant role in improving regularity, as it is able to reduce irregularity by 20 - 26%. The lowest irregularity rates can be found in variant *FB-GoA3/4*, which feature automated reversing only and still maintains fixed block signalling.

Figure 6.7 compares the performance in irregularity for each line between the three upgrade variants and variant *FB-GoA1* without upgrades. It shows that the lines perform differently, depending on the upgrade. Automated metro only is beneficial for all lines, realising a 5 - 10 percentage point decrease in irregularity. Moving block only seems to have an adverse effect on regularity, increasing irregularity for lines A, B an D, while lines C, E and F remain more or less the same. Even the implementation of both measures results in different performances, as it increases irregularity for lines A and B, and decreases irregularity for the other lines.

Figure 6.8 shows the performance of all lines measured in dis-punctuality. The implementation of automated trains sees a great increase in punctuality on the lines travelling on the *RandstadRail*. In Scenario 100, reversing times are relatively short for lines E and F, being 03:50 and 02:10 respectively. Especially for line F, whose reversing time is only a little more than the minimum required reversing time for drivers. It is not straightforwards to increase reversing times, as reversing times depend on line headway and cycle time, as has been

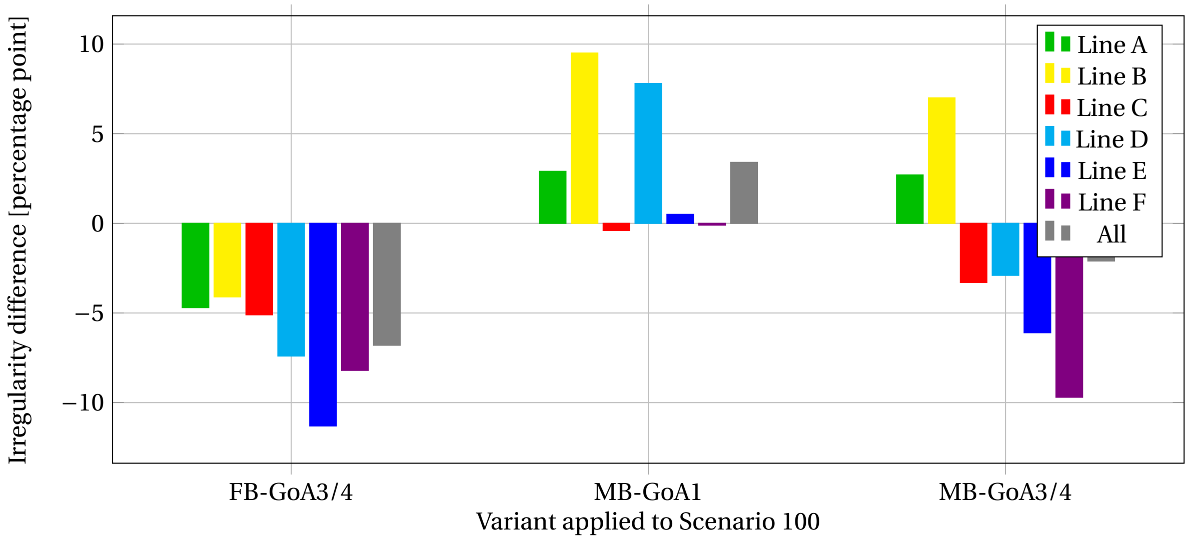


Figure 6.7: Difference in irregularity between upgrade variants and current variant *FB-GoA1* for Scenario 100

explained in Section 5.1. This is where the benefit of automated trains at terminal stations is visible. As reversing operations are sped up from 2 minutes to 30 seconds, this provides 1:30 more buffer times, which is beneficial to both punctuality and regularity.

Moving block benefits both axes. With more capacity available on the network, trains with small delays are less likely to affect other trains. Figure 6.8 shows that moving block signalling is able to alleviate most of the trains' delays caused by other trains. The delays that remain, are primary delays, caused by extended dwell times and not due to delays of other trains. This is proven by the fact that the addition of short reversing times above moving block signalling does not significantly improve punctuality and that most delays remain the same.

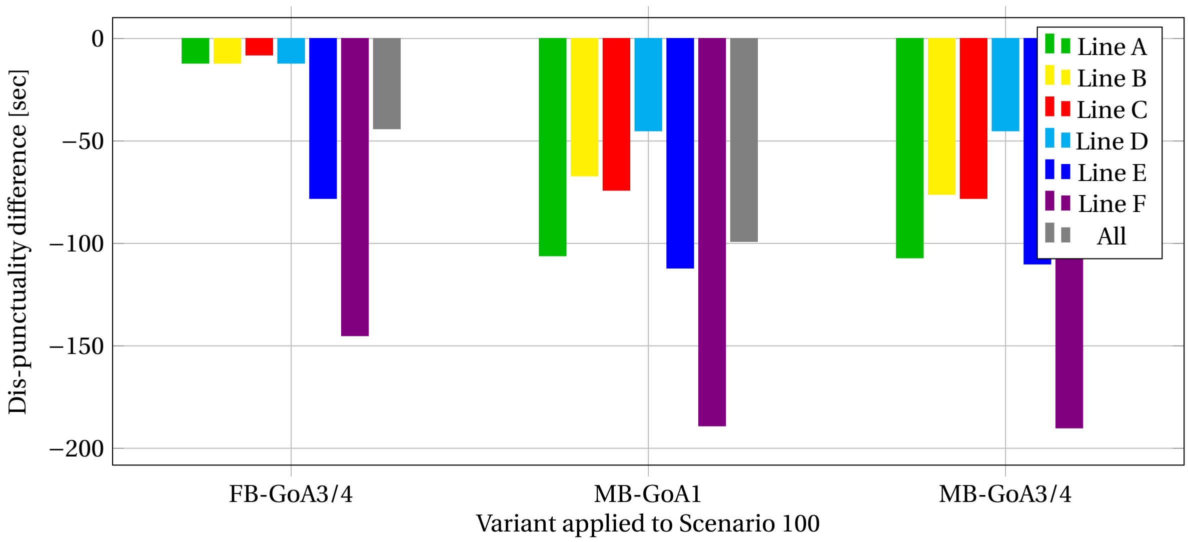
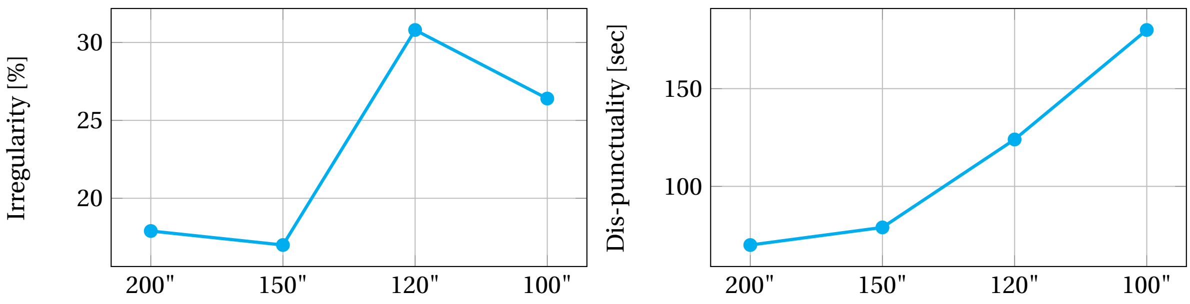


Figure 6.8: Difference in dis-punctuality between upgrade variants and current variant *FB-GoA1* for Scenario 100

With the introduction of upgrade measures to Scenario 100, a dilemma arises. The variant yielding the lowest delay does not yield the lowest irregularity rate, while the variant with the lowest irregularity rate feature high delays. This raises the question whether operators and transport authorities have to chose between striving for punctual delays or striving for regular delays. Not all passengers benefit from either of the choices. Passengers travelling to branch lines benefit more from punctual services, as frequencies on the branch lines are lower than on trunk section. A late train directly affects their travel and waiting time. Passengers travelling on the trunk sections only benefit mostly from regular services. As they can take any train that arrives, a late train is less of a nuisance to them. Here, waiting time is the most contributing factor of their total trip time and this is directly effected by regular headways.

6.3. Conclusions results

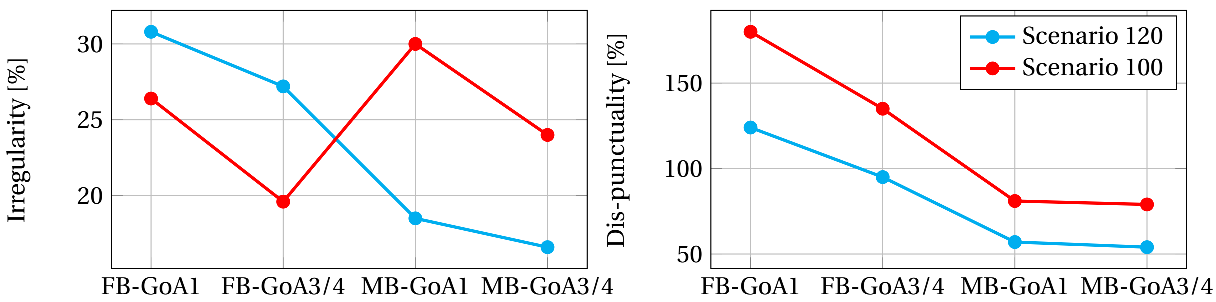
Analysis of the growth scenarios with the first operational variant has revealed that in general, the overall Level of Service decreases when the frequencies are increased. The more trains that circulate on the network, the less time supplements can be assigned to each train and the higher the chance that trains hinder each other in case of delays. The two indicators used throughout this research, regularity and punctuality, show different reactions to frequency increase. This is shown in Figure 6.9. As the intervals on the trunk sections are increased for every growth scenario, dis-punctuality rates increase (Figure 6.9b). As for irregularity, the decrease of intervals does not necessarily mean that irregularity is higher as well, as is shown in Figure 6.9a. Depending on the scenario, lower intervals can mean more regular services.



(a) Irregularity as function of trunk interval (b) Dis-punctuality as function of trunk interval

Figure 6.9: Average network irregularity and dis-punctuality per growth scenario

Figure 6.10 shows the effects of the different upgrade variants, applied to Scenario 120 and Scenario 100. It shows for both growth scenarios how regularity and dis-punctuality rates react to the two different elements in the upgrade variants. For both scenarios, dis-punctuality is improved with either one or both upgrade elements. Furthermore, Figure 6.10b shows that the dis-punctuality is reduced the most due to introduction of a moving block signalling. Once the new signalling system is installed, the absence the human factor at terminal station does not result in significant gains. However, different conclusions can be made regarding irregularity. The impact of either one of the upgrade elements depends on the trunk section intervals. For Scenario 120, the absence of a driver in front results in a 3 percentage point reduction of irregularity, while the introduction of moving block signalling results in a 12 percentage point reduction. However, for Scenario 100, the introduction of a new signalling system results in higher irregularity rates, while the absence of human factors at terminal stations results in more regular services. While for Scenario 120 both upgrade elements contribute to more punctual and more regular service, for Scenario 100, moving block signalling is the main contributor to the reduction of delays, while the gains in terminal buffer times due to the elimination of human factors at terminal stations is the main contributor to the increase in service regularity.



(a) Irregularity per operational variant (b) Dis-punctuality per operational variant

Figure 6.10: Average network irregularity and dis-punctuality per operational variant

7

Discussion and conclusions

In Chapter 5 different growth scenarios have been constructed and are assessed with the use of microscopic simulation tool OpenTrack. The performances of the simulated scenarios are presented in Chapter 6. In this chapter, firstly the results of the simulations are be discussed in Section 7.1. Furthermore, conclusions will be given in Section 7.2, answering the research questions posed in Section 1.2.1. Lastly, recommendations shall be given in Section 7.3, not only on the implementation of higher frequencies on a metro network, but also on future research that can function as a follow-up to this research.

7.1. Discussion of results

During this research, a microscopic simulation model has been applied to a case study of the Rotterdam metro network, investigating the effects that increasing frequencies has on the reliability of timetables for that specific case study. To accomplish that, four growth scenarios have been constructed and four operational variants have been developed and applied to the growth scenarios, depending on the performance of the scenario. As as result, a total of ten scenarios have been assessed. The first four are the growth scenarios without infrastructure alterations (the first operational variant). Furthermore, of two of the growth scenarios, three more variants have been investigated in which infrastructure elements have been altered, adding six more sub-scenarios to be investigated.

7.1.1. General analysis

The trend that delays increase when traffic on the network increases follows expectations. Dicembre and Ricci (2011) presented a trend that the higher the volume of traffic, the higher the average delays. Figure 6.9b shows similarities to the exponential relationship between traffic volume and delays presented in that graph. Furthermore, Dicembre and Ricci (2011) has presented a graph showing the relationship between line capacity and reliability, stating that the higher the capacity, the lower the reliability.

If reliability is based on punctuality only, Figure 6.9b seems to confirm this theory: the more trains that are scheduled on the network, the higher the dis-punctuality and therefore the lower the reliability. However, this research has concluded that regularity also contributes to the reliability of public transport operations. Figure 6.9a shows a different pattern than Figure 6.9b, showing that services are more regular, depending on the service pattern of the planned timetable. This does not follow early expectations, in the way that the lower the intervals, the lower the reliability.

Section 3.4 has mentioned various effects that automation has on driving operations, safety and costs. Furthermore, this research has indicated the limited abilities of OpenTrack to incorporate all effects of automation and has stated that, as running times in OpenTrack are deterministic, and can therefore be considered to represent automatic driver behaviour. This research has therefore chosen to model one effect of automation, which is the reduction of dependency on train staff. The results in Section 6.2 have shown that this measure can lead to a reduction of dis-punctuality by 23-25%, depending on the operated timetable. Irregularity improvements depend on the growth scenario. With trunk frequencies of 120 seconds, this measure results in a 10-12% regularity increase, while with trunk frequencies of 100 seconds, regularity improvements of 20-26%

have been achieved.

A second upgrade measure is the introduction of a new type of signalling system: moving block. Moving block eliminates the use of fixed blocks governed by signals, permitting a train to move up until the tail of the previous train. As minimum headway is not determined by block length anymore, this can result in a capacity increase and an increase in punctuality. The results of this research, presented in Section 6.2, follow this expectation, demonstrating that the introduction of moving block signalling can improve punctuality by around 48%. However, moving block signalling does not necessarily improve regularity as well, and the effects depend on the operated services frequencies. With trunk intervals of 120 seconds, moving block achieves a regularity increase of 40%, while with trunk intervals of 100 seconds, moving block signalling results in a regularity decrease, achieving a increase in irregularity of 13-22%.

7.1.2. Application of the simulation model

In general, this research has demonstrated that OpenTrack is able to provide realistic results and is able to assess the implications of implementing different timetables, but also the implications of implementing upgrades to existing infrastructure and operations. The quality of the model is an important factor in interpreting the outcome of the results. Verification in Section 4.4 has revealed that running and dwell times are realistic, though differences exist between real and simulated values. This is partly because the simulated running times are deterministic and have therefore a low variance, and secondly because the data used to verify and validate the model contains inaccuracies itself.

Nevertheless, validation has shown that, given the limitations of the model, OpenTrack is capable of producing realistic results. However, as models always are a simplification of the real world, the limitations of the model and the modelling assumptions have be taken into account when basing decisions on the modelling results. The following list mentions several limitations of the model that affect the simulated outcomes:

- A major cause for differences in performance, pointed out during validation, is the lack of dispatching and the inflexibility of OpenTrack. The validation in Section 4.5 has mentioned the two reversing stations of *Pernis* and *Schiedam Centrum* being major bottlenecks in ensuring stable operations. As demonstrated in Figure 4.22b, the lines that are affected by the bottlenecks show unstable performances, with delays increasing as time progresses. Validation has furthermore pointed out that if these bottlenecks are not included in the the timetable while maintaining the same service pattern and service intervals, stable operations can be achieved during the investigation period. This research does realise that the lack of dispatching in OpenTrack can affect other terminal stations and junctions, but has concluded that these effects are much smaller at those locations.

- The trams operated by HTM on part of the *RandstadRail* section have not been modelled and therefore the simulated performance of line E can be considered too optimistic. Validation has shown that the line E is 10 percentage point more regular and about a minute more punctual in the simulations than in the real timetable. Although a frequency increase on line E might affect irregularity and dis-punctuality more strongly, a assuming that line E will be 10 percentage point more irregular and a minute more delayed is a good approximation of how line E will perform in an implemented real-life scenario compared to a simulated scenario.

- The effects of bunching has not been taken into account. Bunching is the result of a reciprocal relationship between dwell times and headway. Irregular headways have an effect on dwell times. In the model used for this research, this reciprocal relation had not been incorporated. The exact effects that bunching has on timetable performance have not been investigated in this research, but it is expected that this effect will have a negative effect on delays on lines that are irregular. This increases the importance of regularity as an indicator, as the higher the irregularity, the stronger the bunching effect and therefore the worse the performance of the line or section will be in reality.

7.1.3. Implications for case study

By investigating different growth scenarios, this research has investigated if increasing frequencies is feasible on the Rotterdam metro and can provide a solution for operator RET to alleviate congestion and increase capacity on its network. This research has found that with the current infrastructure, reliable services can be maintained when the trunk section frequencies are increased from 18 Trains per Hour as is currently operated to 24 Trains per Hour. This satisfies their needs for the coming 10 to 15 years. Investments for RET comprise the procurement of new rolling stock, as the increase of service frequencies requires the current fleet size to be increased by 21%. This furthermore requires investments to expand the current stabling facilities, in order facilitate the parking and maintenance of the expanded fleet.

However, to satisfy the passenger demand for the long term of 15 years and further, more radical investments are required. This research has shown that timetables with trunk section intervals of less than 150 seconds result in unreliable services if the current infrastructure is maintained. This research has investigated to measure to upgrade the current infrastructure and operations, but they are very costly. Apart from investments to account for the increase in fleet size (for Scenario 120 52% more trains compared with today's fleet, and for Scenario 100 84% more trains), the new fleet has to be compatible with the new technology, increasing costs per train, and the complete network requires a retrofit to install the new technology. However, with these measures, reliable operations of timetables with trunk section intervals of 100 can be achieved.

7.2. Conclusions

In this section, the research questions posed in Section 1.2.1 are answered. Firstly, the sub-questions are answers in order of question in Section 7.2.1. Secondly, the answer to the main research question will be given in Section 7.2.2.

7.2.1. Answers to the sub-questions

In this section the sub-questions are answered:

What is the state-of-the-art regarding high-frequency metro operations?
The literature is scarce on the subject high-frequency metro operations. Several studies have investigated the role of terminal stations on the minimum headway that can be achieved (Van Oort and Van Nes, 2010; Wang et al., 2017; Jiang et al., 2015). Dicembre and Ricci (2011) has investigated the influence of block lengths and dwell times on capacity. Although they have found that theoretical frequencies for urban railway systems (i.e. metro) of over 40 Trains per Hour (tph) are achievable, they have found that the practical capacity is lower, calculating a maximum practical capacity of 24 tph with a fixed dwell time of 20 seconds. No research has been found concerning network capacity incorporating stochastic elements and varying running and dwell times.

Studies have reported that frequencies of more than 24 tph are achievable. Notable examples are the Copenhagen metro system and Line 1 of the Paris Métro. The former achieves intervals of 2 minutes and a punctuality rate of 98 per cent, while Line 1 achieves intervals of 85 seconds. A study conducted by Cohen et al. (2015) found that of the 156 lines studied, 27 achieved frequencies of 30 tph and higher. While 16 of these lines were automated, using a Communication-Based Train Control system with moving block signalling is the key of achieving very high frequencies. Although automated metro systems are globally increasingly popular, especially in Asia, there is little scientific data available on the exact effects of automation on operations (Cohen et al., 2015).

How can the reliability of metro networks be assessed?
There are two main stakeholders who benefit from reliable metro operations. The first is the public transport operator, operating the trains and maintaining the assets. The second is the passenger, who uses the metro network as a quick and reliable form of transportation in densely urbanised areas. Both stakeholders benefit from punctual services. Passengers rely on punctual trains to reach their destinations on time or to catch connections to other forms of transportation. Late trains might jeopardise these connections. Punctuality is important for the operator as well, for whom delayed trains affect personnel working hours, maintenance windows and public image. Currently, most transit authorities employ performance-based payment schemes for the operator, giving an operator financial motivations to maintain punctual services.

However, in high-frequency transport systems, the share of passengers consulting the timetable before arriving at the platform decreases when trains headways are lower than a threshold value of 5 - 10 minutes. As the timetable is not known to those passengers, a train's lateness is not their concern anymore, but rather their waiting time and crowding rates of trains, both of which are determined by the trains' headway. It is therefore in the interest of both the passenger and the operator to maintain regular services as well. Regular services ensure that all passengers are evenly spread over all trains, which adds to customer satisfaction and minimises the risk of trains bunching.

The interests of both stakeholders are quantitatively expressed using two indicators: irregularity and dis-punctuality. The first is a relative indicator, showing the percentage that the actual headway differs from the planned headway. The second measure is an absolute indicator, showing the amount of time that the actual departure from a train at a station differs from the planned departure.

In what way can the use of microscopic simulation tools create opportunities to investigate the implementation of high-frequency operations?
In high-frequency services, a few seconds difference can have a great effect on the performance of a timetable. The infrastructure, the interactions between the train and the infrastructure, and the interactions between trains all play an important role in the stability of a timetable. The behaviour of trains on a specific network that has its own unique characteristics can best be captured with a microscopic simulation model, in which all individual infrastructure elements are modelled.

During the construction of a timetable, the limitations that the infrastructure imposes on the timetable are all taken into account. However, when variations are added to the execution of certain activities, conflicts can arise that were not accounted for during the construction of the timetable. It is then that the layout of the available infrastructure has a considerable effect on how trains behave in respect to each other. Macroscopic simulations are not detailed enough to encapsulate the behaviour of trains at terminal stations, or the length of time that routes are reserved in advance.

Which factors affect the reliability of a timetable?
Van Oort (2011) has identified several factors that affect the variability and therefore reliability of urban public transport systems and has distinguished between internal and external factors, the former can be directly influenced by the transport operator. For urban railway systems, these factors can be classified into three main categories: *timetable design*, *human factors* and *signalling system*.

A well-designed timetable includes running time supplements and buffer times at terminal stations to mitigate the effects of delays incurred along the route of a train. Running time supplements can account for small delays incurred on different sections among the network. Running time supplements directly affect the size and existence of primary delays incurred during the trip. This research has leaned that the lines on the east-west axis (lines A, B and C) feature less fewer running time supplements in its running times than lines on the north-west axis (lines D and E). As a result, lines A, B and C consistently had higher delays in all scenarios than lines D and E, as is shown in Figure 7.1. The only exception is Line E in Scenario 100, which feature high delays due to the limitations of the *safe haven* principle between *Rotterdam Centraal* and *Melanchthonweg*.

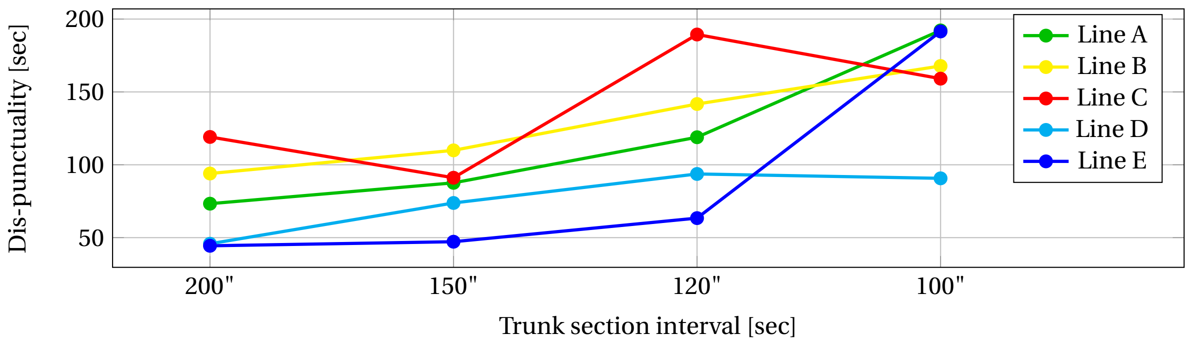


Figure 7.1: General performance of each line for each growth scenario

An even spread of trains over the time period, maximises the available buffer times between two subsequent trains. Section 6.1 has shown that regularity benefits mostly, showing that Scenarios 150 and 100, both with evenly spread trains on all sections of the network, result in more regular services than the base scenario and Scenario 120 respectively, which both feature lower frequencies. Even with lower trunk intervals, Scenarios

150 and 100 achieve an 8 and 16 percent regularity increase compared with the base scenario and Scenario 120 respectively.

The influence of buffers times has been shown in Section 6.2. Due to the elimination of the driver behaviour at terminal stations, 90 seconds of buffer time has been added to the reversing times. This has resulted in a reduction of the average dis-punctuality of 23-25%, and a reduction in irregularity, varying from 10 to 26%.

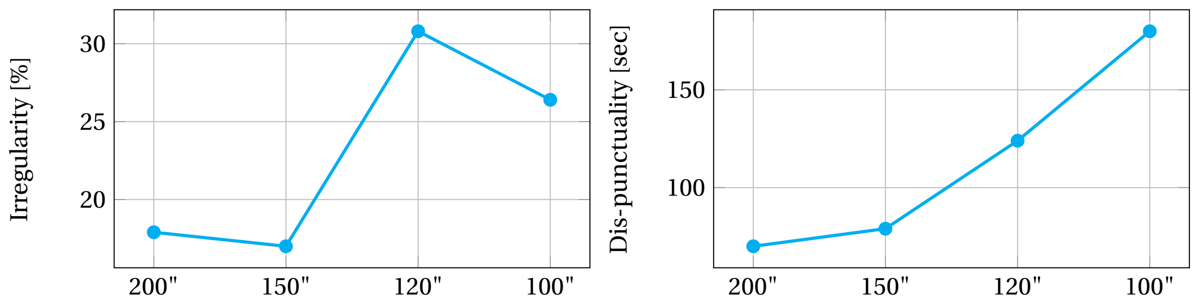
The influence of driver behaviour has been more difficult to demonstrate. This research has indicated that running times in OpenTrack are deterministic and do not incorporate variances caused by differing driver behaviour. The behaviour of drivers at terminal stations has been investigated, as is shown in the precious paragraph on buffer times. The behaviour of passengers has been incorporated in the OpenTrack model, by including stochastic behaviour in dwell times. However, these distributions have remained unaltered throughout this research and therefore, the effect of changes is passenger behaviour on timetable reliability has not been investigated.

Lastly, the role of the signalling system has been investigated. The introduction of moving block technology, in which the tail of the previous train determines the distance that the following train is allowed to travel, has seen an overall dis-punctuality improvement of 48% and irregularity improvement up to 40%, depending on the service timetable operated. This and the previous paragraph concluded that both factors affect timetable reliability greatly, and that introducing moving block signalling and eliminating the human factor at terminal stations can improve reliability such that very-high frequencies of more than 30 tph can be achieved.

Given the current existing infrastructure, up to which service frequency are reliable operations still feasible?
This research has investigated four growth scenarios with the following intervals on the trunk sections:

- Intervals of 200 seconds – the same as currently operated
- Intervals of 150 seconds
- Intervals of 120 seconds
- Intervals of 100 seconds

With the current infrastructure available (including the Hoekse Lijn and the reversing track at *Pijnacker Zuid*), a timetable with trunk section intervals of 150 seconds (i.e. 2.5 minutes) still leads to reliable operations. Moreover, due to a better spread of trains on the branch lines than in the base scenario, services are more regular than in the scenarios with a lower frequency. Figure 7.2 shows the overall regularity punctuality rate for each growth scenario, applied to the current infrastructure. The growth scenario with trunk section intervals of 150 seconds shows a similar performance to the base scenario, with an overall irregularity rate of 17% and overall dis-punctuality of 79 seconds.



(a) Irregularity as function of trunk interval (b) Dis-punctuality as function of trunk interval

Figure 7.2: Average network irregularity and dis-punctuality per growth scenario

The quality of service starts deteriorating when trunk section intervals are 2 minutes and lower. For both Scenario 120 and Scenario 100, the average dis-punctuality exceeds the threshold level of 120 seconds (this threshold is defined in the introduction of Chapter 6).

In what way can automation help to increase capacity and reliability?
Janmaat (2019) has determined four factors defined by Van Oort (2011) are affected by automation:

- Crew availability
- Driver behaviour
- Train availability
- Train design

Due to automation, no driver cabins are required in the trains, freeing space that can be used by passengers. Although this factor has not been investigated in this research, Paris metro has reported a 6-percent capacity increase due to the removal of the cabins (Wang et al., 2016). Train availability can be optimised with automation. Maintenance schedules can be optimised and lines can be operated with fewer trains (Cohen et al., 2015). Driver behaviour and crew availability have been investigated in this research, in the form of reducing the minimum required reversing time at terminal stations from 2 minutes to 30 seconds. The literature has mentioned that capacity can be increased due to shorter turnaround times of automated metro systems (Cohen et al., 2015; Wang et al., 2016), and this research has confirmed this hypothesis, showing a punctuality increase of 23 - 25 percent reduction of delays.

Moving block signalling is not by definition part of automation. Automated metros can, and do, exist with fixed block signalling, such as the Montreal Métro (Turcotte-Langevin). Furthermore, moving block signalling systems do not necessarily require automation train operations, such as ERTMS Level 3 (Furness et al., 2017). However, installing either moving block signalling or implementing automated trains can provide opportunities to install both systems simultaneous and in many projects around the world this is often the case.

7.2.2. Answer to the main research question

Lastly, the main research question is answered:

"In what way will the timetable performance of a metro network be affected when the existing service frequency is increased and what measures can be taken to increase capacity and reliability?"

This research has applied a quantitative approach to assess the performance of an executed timetable. It has developed two indicators that provide a quantitative assessment from two different points of view. It has furthermore determined which factors affect the stability of timetables, and has shown in a case study how these factors play a role in timetable reliability.

Based on the two indicators used throughout this research, is has been observed that the overall performance of a timetable decreases if the intervals on the busiest section of a given network are decreased, under the condition that the infrastructure remains unaltered. The average delay on the network exceeds 120 seconds when intervals on the trunk sections of the network are 120 seconds and lower.

Based on the results depicted in Chapter 6, this research has found that for the Rotterdam metro network, a timetable with structural trunk section intervals of 150 seconds will still lead to reliable operations. With an irregularity rate of 17% and unpunctuality of 79 seconds, this scenario performs around 40% comparable to the simulated base scenario, even with a capacity increase of 33% on the trunk sections. Reliability down to these intervals mainly depends on the construction of the timetable. By allocating a sufficient amount of buffer time and running time supplements, incurred delays can be contained and reduced to a minimum. Furthermore, by ensuring that all trains are spread as evenly as possible in time, the available capacity can be used as efficiently as possible, distributing the available time supplements evenly over all trains. With intervals lower than 150 seconds, the Level of Service starts deteriorating, with average delays exceeding 120 seconds.

For the current Rotterdam metro network, an service pattern optimum has been found: a timetable with trunk section frequencies of 24 Trains per Hour (tph) (intervals of 150 seconds) will yield the highest Level of

Service. With lower frequencies, reliability is higher, yet the Level of Service is lower due to a lower service pattern being offered. Frequencies higher than 24 tph will result in unreliable services, resulting in a lower Level of Service as well. Therefore, a relationship exists between service frequency and level of service. An example of how frequency and level of service can be related is shown in Figure 7.3.

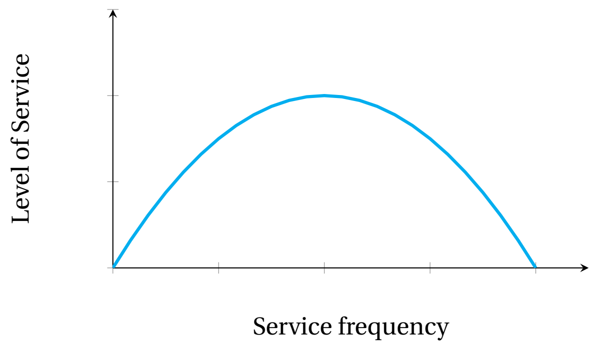


Figure 7.3: Example of how Level of Service relates to service frequency

To achieve reliable services with intervals of 120 seconds or less, RET has to invest in more radical changes to its network. The benefits of moving block signalling and automated reversing operations are clearly observable. Whereas with the current infrastructure, services start deteriorating when intervals are lower than 150 seconds, automated trains and moving block signalling are able to provide reliable operations for these intervals. Although both measures are able to improve dis-punctuality, it is moving block signalling that produces the the highest reductions and cut dis-punctuality by 48%. Furthermore, with moving block installed, the added measure of automated trains does not provide any additional gains in terms of dis-punctuality.

However, with very low trunk section intervals of 100 seconds, regularity is more and more important. This is when both upgrade measures start showing different results. Whereas automated trains reduces irregularity, moving block signalling increases irregularity. While fixed blocks served an additional purpose of maintaining headways, moving block signalling removes that barrier, allowing trains to achieve far less headways. It is at this point where transport operators and authorities have to face a choice: to either strive for punctual services or for regular services. In a tree-like network, this decision is not straightforward: striving for punctual services may result in irregular services on the densely operated trunk sections, while striving for regular services on the trunk sections may lead to a poor Level of Service on the branch lines.

7.3. Recommendations

Given the challenges that RET faces in the near future, increasing the frequencies is the most realistic option to increase capacity on its network for the medium term. This research has shown that the current network and the current infrastructure is sufficiently able to operate a timetable with intervals on the trunk sections of 150 seconds: an increase of 33% compared to the current timetable.

This research recognises that the current network and infrastructure have not reached their maximum potential yet and that room is available for the increase in capacity. To achieve this, this research recommends that RET implement a timetable in which intervals of 150 seconds are maintained on the trunk sections. It furthermore recommends that the timetable be constructed such that an even distribution of the trains is planned over time, to provide an equal share of time supplements over all trains. The current running time on the east-west axis of Rotterdam's metro network require re-calculation, as this research has shown that the tightly planned running times on the east-west axis are a cause for elevated delay and irregularity rates.

As making alterations to the current infrastructure, especially to underground infrastructure, is very costly, a transport operator should use the current infrastructure as efficiently as it can. As the increase of capacity necessitates an investment in the procurement of rolling stock anyway, this research recommends that RET pay special attention during the procurement procedures to the length of the train sets and to select them such that the train lengths can be maximised on all lines of the network.

This research has observed that the *safe haven* procedure between *Rotterdam Centraal* and *Melanchthonweg* is a limiting factor in providing reliable service for very low intervals of 100 seconds. This research does realise that this principle is a safety measure, but also realises that this procedure has been applied to one of the most modern and safest tunnels in existence. Furthermore, other metro systems around the world maintain lower intervals and do not feature the *safe haven* procedure. Therefore, this research recommends RET to investigate the need of the *safe haven* procedure on the long term and investigate other safety measure that can be implemented as an alternative to this principle.

During this research, only one of the potential benefits of automation has been investigated: the role of the driver at terminal stations. However, automated trains accomplish much more than a reliable timetable. Other potential benefits are, but not limited to:

- a higher energy-efficiency,
- a higher flexibility in respect to passengers demand,
- reduced operational costs, or
- a reduced fleet size.

All of the benefits mentioned above can be reasons for a transport operator to implement automated trains on its network. The benefits of these effects have not been included in this research. Therefore, this research recommends that if automated trains are considered to be implemented on Rotterdam's metro network, the factors mentioned above should also be taken into account and that the considerations that influence the decision whether or not to implement automation should no be limited to the effects automation has on the reliability of the timetable.

7.3.1. Future research

Little research has been carried out to quantify the exact effects of automation on urban railway networks. Although some transport operators who operated automated metro lines report reductions in operation costs, fleet size or delays, a large amount of data is not available to quantify effects and show the effects of unique elements of local metro networks. Furthermore, this research has not investigated all benefits of metro automation. Future research might incorporate more elements of automation, such as difference is driving variability and the effects of energy-efficient driving.

This research has incorporated stochastic elements in dwell time variation on a limited basis. No distinction has been made in varying passenger demands over time and the bunching effect has not been taken into account. For future research it is recommended to incorporate these elements in dwell time variation, to provide more accurate results.

This research has investigated the effects of increasing frequencies on a network with trunk and branch lines. For networks with stand-alone lines, different results might be found. This research looks forward to encounter similar studies with networks with a different service pattern. For this specific case study, the implementation of a different service pattern with no lines sharing the same trackage, could lead to interesting results.

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A
Map of Rotterdam metro network

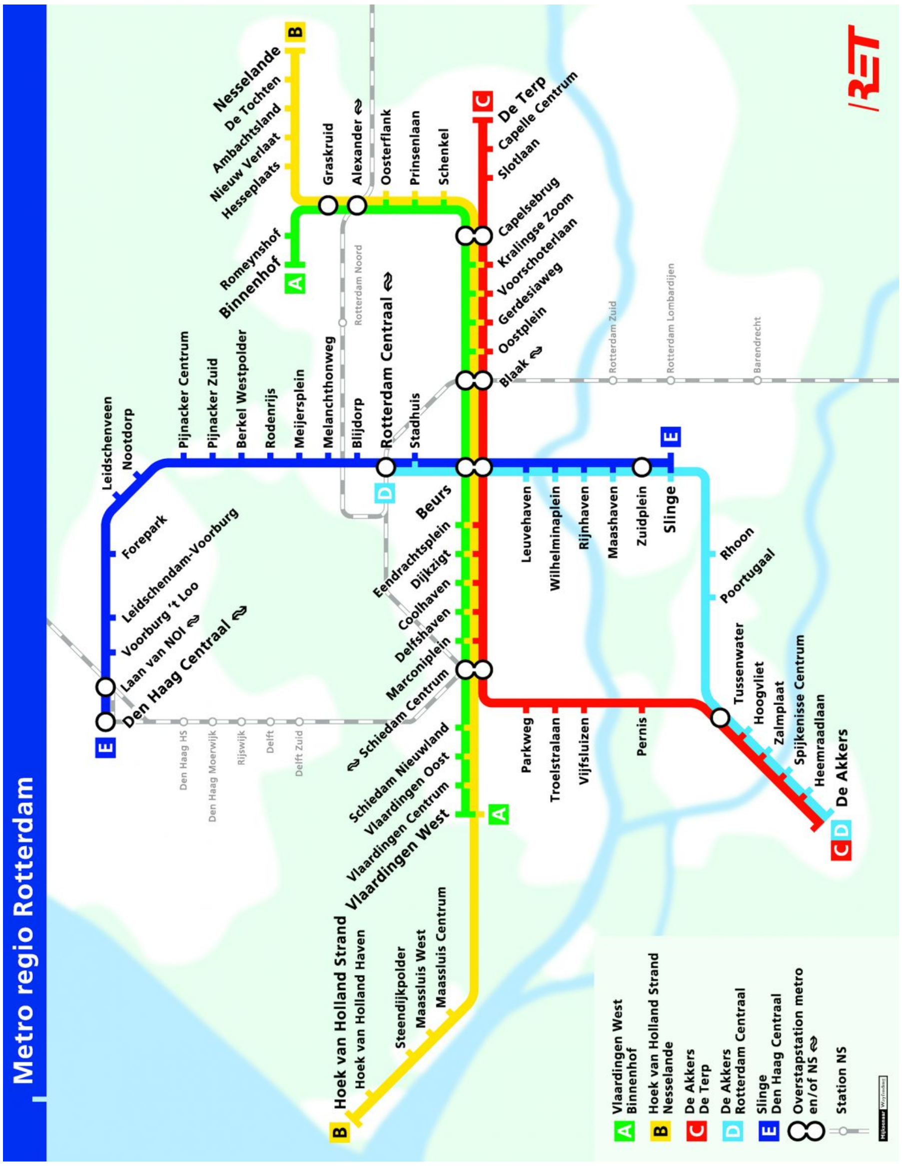

Figure A.1: Map of the Rotterdam metro network

B

List of Stations

North-south axis

Abbreviation	Station name
AKS	De Akkers
BDP	Blijdorp
BKW	Berkel Westpolder
BRE	Beurs (Erasmuslijn)
FPA	Forepark
GVC	Den Haag Centraal
HRL	Heemraadlaan
HVT	Hoogvliet
LAA	Laan van NOI
LDV	Leidschendam-Voorburg
LHV	Leuvehaven
LVN	Leidschenveen
MEP	Meijersplein
MTW	Melanchthonweg
NDP	Nootdorp
PAK	Pijnacker Centrum
PAZ	Pijnacker Zuid
PTG	Poortugaal
RCS	Rotterdam Centraal
RDR	Rodenrijs
RHO	Rhoon
RHV	Rijnhaven
SHS	Stadhuis
SLG	Slinge
SPC	Spijkenisse Centrum
TSW	Tussenwater
VBL	Voorburg 't Loo
WHP	Wilhelminaplein
ZPL	Zuidplein
ZPT	Zalmplaat

East-west axis

Abbreviation	Station name
ABL	Ambachtsland
ALD	Alexander
BLK	Blaak
BNH	Binnenhof
BRC	Beurs (Calandlijn)
CHV	Coolhaven
CPB	Capelsebrug
CPC	Capelle Centrum
DHV	Delfshaven
EDP	Eendrachtsplein
GDW	Gerdesiaweg
HSP	Hesseplaats
KLZ	Kralingse Zoom
MCP	Marconiplein
NSL	Nesselande
NVL	Nieuw Verlaat
OPL	Oostplein
OTF	Oosterflank
PNS	Pernis
PSL	Prinsenlaan
PWG	Parkweg
RMH	Romeijnshof
SDC	Schiedam Centrum
SKL	Schenkel
SLN	Slotlaan
TRP	De Terp
TSL	Troelstralaan
TTN	De Tochten
VSL	Voorschoterlaan
VSZ	Vijfsluizen

C
Station Complexity

Table C.1: The values for the station complexity, as described in Paragraph 3.2.1, for all stations on the network

(a) North-south line

Station (n)	n_k	n_λ	n_Σ	ϕ_n
Den Haag Centraal	14	4	16	0.83
Laan van NOI	10	0	16	0.63
Voorburg 't Loo	2	0	4	0.50
Leidschendam-Voorburg	2	0	4	0.50
Forepark	2	0	4	0.50
Leidschenveen	8	0	16	0.50
Nootdorp	2	0	4	0.50
Pijnacker Centrum	2	0	4	0.50
Pijnacker Zuid	2	0	4	0.50
Berkel Westpolder	2	0	4	0.50
Rodenrijs	2	0	4	0.50
Meijersplein	2	0	4	0.50
Melanchthonweg	2	0	4	0.50
Blijdorp	2	0	4	0.50
Rotterdam Centraal	50	4	64	0.77
Stadhuis	2	0	4	0.50
Beurs	2	0	4	0.50
Leuvehaven	2	0	4	0.50
Wilhelminaplein	2	0	4	0.50
Rijnhaven	2	0	4	0.50
Maashaven	2	0	4	0.50
Zuidplein	2	0	4	0.50
Slinge	44	6	64	0.66
Rhoon	2	0	4	0.50
Poortugaal	2	0	4	0.50
Tussenwater	8	0	16	0.50
Hoogvliet	10	2	16	0.57
Zalmplaat	2	0	4	0.50
Spijkenisse Centrum	2	0	4	0.50
Heemraadlaan	2	0	4	0.50
De Akkers	14	4	16	0.83

(b) East-west line

Station (n)	n_k	n_λ	n_Σ	ϕ_n
Nesselande	14	4	16	0.83
De Tochten	2	0	4	0.50
Ambachtsland	2	0	4	0.50
Nieuw Verlaat	2	0	4	0.50
Hesseplaats	2	0	4	0.50
Binnenhof	14	4	16	0.83
Romeijnshof	2	0	4	0.50
Graskruid	10	0	16	0.63
Alexander	2	0	4	0.50
Oosterflank	2	0	4	0.50
Prinsenlaan	2	0	4	0.50
Schenkel	2	0	4	0.50
De Terp	14	4	16	0.83
Capelle Centrum	2	0	4	0.50
Slotlaan	2	0	4	0.50
Capelsebrug	20	2	36	0.53
Kralingse Zoom	10	2	16	0.57
Voorschoterlaan	2	0	4	0.50
Gerdesiaweg	2	0	4	0.50
Oostplein	2	0	4	0.50
Blaak	2	0	4	0.50
Beurs	2	0	4	0.50
Eendrachtsplein	2	0	4	0.50
Dijkzigt	2	0	4	0.50
Coolhaven	2	0	4	0.50
Delfshaven	2	0	4	0.50
Marconiplein	2	0	4	0.50
Schiedam Centrum	20	2	36	0.53
Parkweg	2	0	4	0.50
Vijfsluizen	2	0	4	0.50
Pernis	2	0	4	0.50

D

OpenTrack Performance Analysis Tables

D.1. Network section overview

Table D.1: Overview of the different sections used throughout this thesis

East-west axis		
Section name	**Line(s)**	**Stations**
Binnenhof	A	Binnenhof Romeijnshof
Nesselande	B	Nesselande De Tochten Ambachtsland Nieuw Verlaat Hesseplaats
Alexander	A,B	Graskruid Alexander Oosterflank Prinsenlaan Schenkel
Capelle	C	De Terp Capelle Centrum Slotlaan
Trunk EW	A,B,C	Capelsebrug Kralingse Zoom Voorschoterlaan Gerdesiaweg Oostplein Blaak Beurs Eendrachtsplein Coolhaven Delfshaven Marconiplein Schiedam Centrum
Benelux	C	Parkweg Troelstralaan Vijfsluizen Pernis
Hoek van Holland	A,B	Not modelled, modelled as a cordon west of Schiedam Centrum

North-south axis		
Section name	**Line(s)**	**Stations**
RandstadRail	E	Den Haag Centraal Laan van NOI Voorburg 't Loo Leidschendam-Voorburg Forepark Leidschenveen Nootdorp Pijnacker Centrum Pijnacker Zuid Berkel Westpolder Rodenrijs Meijersplein Melanchthonweg Blijdorp
Trunk NS	D,E	Rotterdam Centraal Stadhuis Beurs Leuvehaven Wilhelminaplein Rijnhaven Maashaven Zuidplein Slinge
Spijkenisse	C,D	Rhoon Poortugaal Tussenwater Hoogvliet Zalmplaat Spijkenisse Centrum Heemraadlaan De Akkers

D.2. Comparison table Real vs OpenTrack: Current timetable Regularity

Table D.2: Comparison of regularity per section between real data and OpenTrack data

Regularity

			07:00 - 08:00			08:00 - 09:00			Total
Line	**Dir.**	**Section**	**Real [%]**	**OT [%]**	**Diff. [%]**	**Real [%]**	**OT [%]**	**Diff. [%]**	diff.
A			**18.4**	**26.5**	**+ 44**	**27.7**	**33.3**	**+ 20**	**+ 30**
	Northbound		**19.2**	**26.4**	**+ 37**	**27.3**	**28.5**	**+ 5**	**+ 18**
		Benelux	18.1	34.3	+ 90	23.9	32.0	+ 34	+ 58
		Trunk EW	22.3	25.4	+ 14	31.4	29.7	- 6	+ 3
		Alexander	15.8	21.6	+ 37	23.7	24.1	+ 2	+ 16
		Binnenhof	10.1	19.6	+ 94	14.9	18.3	+ 22	+ 51
	Southbound		**17.6**	**26.6**	**+ 51**	**28.1**	**38.1**	**+ 35**	**+ 42**
		Binnenhof	7.9	9.7	+ 22	12.0	18.4	+ 53	+ 41
		Alexander	16.5	28.7	+ 73	23.7	48.0	+ 103	+ 91
		Trunk EW	19.9	29.2	+ 47	33.7	41.1	+ 22	+ 31
		Benelux	16.0	23.6	+ 47	22.7	24.6	+ 8	+ 24
B			**21.9**	**42.3**	**+ 93**	**33.5**	**41.7**	**+ 25**	**+ 52**
	Northbound		**20.3**	**41.4**	**+ 104**	**28.6**	**38.6**	**+ 35**	**+ 64**
		Trunk EW	23.3	50.3	+ 116	37.6	41.1	+ 9	+ 50
		Alexander	21.3	40.4	+ 90	19.3	59.3	+ 208	+ 146
		Nesselande	11.8	18.6	+ 58	14.2	12.8	- 10	+ 21
	Southbound		**23.6**	**43.1**	**+ 83**	**38.2**	**44.8**	**+ 17**	**+ 42**
		Nesselande	4.4	14.5	+ 230	4.2	8.9	+ 112	+ 173
		Alexander	12.7	16.1	+ 27	14.8	30.6	+ 106	+ 70
		Trunk EW	34.3	61.9	+ 81	59.9	66.4	+ 11	+ 36
C			**28.7**	**42.1**	**+ 47**	**35.0**	**45.6**	**+ 30**	**+ 38**
	Northbound		**34.4**	**55.1**	**+ 60**	**36.5**	**48.7**	**+ 33**	**+ 46**
		Spijkenisse	48.4	45.4	- 6	43.9	81.9	+ 87	+ 38
		Benelux	18.0	27.3	+ 51	20.6	27.7	+ 34	+ 46
		Trunk EW	38.5	73.1	+ 90	43.1	43.3	0	+ 43
		Capelle	8.4	5.5	- 32	14.7	14.9	+ 1	- 11
	Southbound		**22.8**	**29.5**	**+ 29**	**33.5**	**42.7**	**+ 28**	+ 28
		Capelle	6.1	7.0	+ 15	6.3	11.2	+ 77	+ 47
		Trunk EW	23.9	29.9	+ 25	35.9	49.6	+ 38	+ 33
		Benelux	27.2	34.7	+ 27	48.5	45.8	- 6	+ 6
		Spijkenisse	27.1	40.1	+ 48	31.8	41.5	+ 30	+ 38
D			**31.3**	**19.6**	**- 37**	**34.6**	**32.6**	**- 6**	- 21
	Northbound		**23.1**	**17.1**	**- 26**	**23.3**	**22.8**	**- 2**	- 14
		Spijkenisse	16.6	16.5	- 1	15.2	26.3	+ 73	+ 34
		Trunk NS	29.1	17.9	- 39	30.5	19.3	- 37	- 38
	Southbound		**40.6**	**22.4**	**- 45**	**45.9**	**42.5**	**- 8**	- 25
		Trunk NS	59.9	17.1	- 71	62.3	51.3	- 18	- 44
		Spijkenisse	22.0	28.4	+ 29	27.8	30.9	+ 11	+ 19
E			**20.7**	**10.5**	**- 49**	**28.7**	**10.7**	**- 63**	- 57
	Northbound		**19.6**	**15.7**	**- 20**	**20.3**	**10.8**	**- 47**	- 34
		Trunk NS	25.9	25.7	- 1	28.8	14.8	- 49	- 26
		RandstadRail	14.3	6.6	- 54	15.2	8.1	- 46	- 50
	Southbound		**22.3**	**2.9**	**- 87**	**35.6**	**10.6**	**- 70**	- 77
		RandstadRail	11.0	0.7	- 94	18.2	2.4	- 87	- 89
		Trunk NS	43.0	8.1	- 81	57.6	21.4	- 63	- 71
Grand total			**24.6**	**27.4**	**+ 12**	**32.060**	**32.325**	**+ 1**	**+ 5**

D.3. Comparison table Real vs OpenTrack: Current timetable Delay

Table D.3: Comparison of punctuality per section between real data and OpenTrack data

Delay

Line	Dir.	Section	07:00 - 08:00 Real [sec]	07:00 - 08:00 OT [sec	07:00 - 08:00 Diff. [%]	08:00 - 09:00 Real [sec]	08:00 - 09:00 OT [sec]	08:00 - 09:00 Diff. [%]	Total diff.
A			**71**	**138**	**+ 95**	**125**	**214**	**+ 72**	**+ 80**
	Northbound		**76**	**167**	**+ 119**	**114**	**207**	**+ 55**	**+ 78**
		Benelux	93	146	+ 57	129	183	+ 43	+ 49
		Trunk EW	72	168	+ 134	129	191	+ 48	+ 79
		Alexander	79	186	+ 135	156	259	+ 66	+ 89
		Binnenhof	60	169	+ 182	115	262	+ 128	+ 146
	Southbound		**66**	**112**	**+ 70**	**116**	**22**	**+ 90**	**+ 83**
		Binnenhof	49	49	- 1	77	134	+ 74	+ 45
		Alexander	77	71	- 8	89	180	+ 103	+ 51
		Trunk EW	68	123	+ 80	128	246	+ 93	+ 88
		Benelux	54	158	+ 191	130	237	+ 82	+ 114
B			**59**	**162**	**+ 172**	**104**	**156**	**+ 49**	**+ 94**
	Northbound		**58**	**162**	**+ 236**	**113**	**157**	**+ 39**	**+ 105**
		Trunk EW	50	166	+ 236	90	115	+ 28	+ 101
		Alexander	71	235	+ 232	164	192	+ 17	+ 82
		Nesselande	65	226	+ 247	122	229	+ 88	+ 143
	Southbound		**61**	**131**	**+ 114**	**96**	**154**	**+ 61**	**+ 82**
		Nesselande	48	81	+ 67	47	55	+ 18	+ 43
		Alexander	74	100	+ 36	78	138	+ 77	+ 57
		Trunk EW	62	159	+ 155	121	204	+ 69	+ 98
C			**78**	**109**	**+ 39**	**90**	**170**	**+ 89**	**+ 66**
	Northbound		**94**	**108**	**+ 15**	**114**	**215**	**+ 86**	**+ 54**
		Spijkenisse	87	55	- 37	77	154	+ 100	+ 27
		Benelux	111	68	- 37	117	193	+ 64	+ 14
		Trunk EW	101	130	+ 29	134	243	+ 81	+ 59
		Capelle	55	187	+ 240	102	277	+ 171	+ 195
	Southbound		**61**	**109**	**+ 78**	**66**	**131**	**+ 99**	**+ 89**
		Capelle	45	37	- 17	45	77	+ 70	+ 27
		Trunk EW	59	92	+ 55	56	115	+ 107	+ 81
		Benelux	70	158	+ 125	85	161	+ 89	+ 105
		Spijkenisse	71	171	+ 141	86	180	+ 109	+ 124
D			**70**	**53**	**- 24**	**79**	**78**	**- 1**	**- 12**
	Northbound		**83**	**49**	**- 41**	**70**	**52**	**- 26**	**- 34**
		Spijkenisse	74	37	- 51	57	48	- 16	- 36
		Trunk NS	91	62	- 32	81	56	- 32	- 32
	Southbound		**55**	**57**	**+ 4**	**89**	**105**	**+ 18**	**+ 13**
		Trunk NS	58	52	- 10	95	99	+ 5	- 1
		Spijkenisse	52	63	+ 22	82	112	+ 36	+ 31
E			**82**	**26**	**- 68**	**131**	**43**	**- 67**	**- 68**
	Northbound		**84**	**34**	**- 59**	**123**	**54**	**- 56**	**- 57**
		Trunk NS	74	39	- 48	1005	58	- 42	- 44
		RandstadRail	92	30	- 67	137	51	- 63	- 64
	Southbound		**79**	**14**	**- 83**	**137**	**34**	**- 75**	**- 78**
		RandstadRail	66	4	- 94	105	7	- 93	- 94
		Trunk NS	103	37	- 64	178	69	- 61	- 63
Grand total			**72**	**96**	**+ 30**	**104**	**127**	**+ 22**	**+ 25**

D.4. Comparison table OpenTrack: Base Scenario 2021 Regularity

Table D.4: Comparison of regularity for the base scenario

Regularity

Line	Direction	Section	07:00 - 08:00			08:00 - 09:00		
			Cali. [%]	Base [%]	Diff. [%]	Cali. [%]	Base [%]	Diff. [%]
A			**26.486**	**17.316**	**- 35**	**33.319**	**29.603**	**- 11**
	Northbound		**26.378**	**19.278**	**- 27**	**28.515**	**39.773**	**+ 39**
		Benelux	34.337	–		32.032	–	
		Trunk EW	25.401	27.115	+ 7	29.713	58.954	+ 98
		Alexander	21.626	5.747	- 73	24.149	5.499	- 77
		Binnenhof	19.634	4.275	- 78	18.279	3.839	- 79
	Southbound		**26.586**	**15.458**	**- 42**	**38.106**	**19.885**	**- 48**
		Binnenhof	9.688	0.354	- 96	18.394	0.375	- 98
		Alexander	28.652	17.127	- 40	48.041	17.567	- 63
		Trunk EW	29.246	17.931	- 39	41.129	24.970	- 39
		Benelux	23.593	–		24.582	–	
B			**42.264**	**15.926**	**- 62 +**	**41.702**	**24.403**	**- 41**
	Northbound		**41.380**	**6.613**	**- 84**	**38.629**	**15.216**	**- 61**
		Trunk EW	50.332	6.025	- 88	41.084	22.843	- 44
		Alexander	40.444	11.508	- 72	59.336	9.809	- 83
		Nesselande	18.605	4.564	- 75	30.590	3.941	- 66
	Southbound		**43.135**	**25.610**	**- 41**	**44.832**	**34.045**	**- 24**
		Nesselande	14.536	1.141	- 92	8.944	1.139	- 87
		Alexander	16.078	10.082	- 37	30.590	10.411	- 66
		Trunk EW	61.911	40.993	- 34	66.435	55.903	- 16
C			**42.082**	**20.110**	**- 52**	**45.579**	**27.555**	**- 40**
	Northbound		**55.111**	**22.045**	**- 60**	**48.691**	**30.653**	**- 37**
		Spijkenisse	45.437	21.469	- 53	81.864	16.808	- 79
		Benelux	27.261	3.941	- 86	27.679	6.665	- 76
		Trunk EW	73.100	30.555	- 58	43.300	46.014	+ 6
		Capelle	5.647	4.360	- 23	14.859	21.153	+ 42
	Southbound		**29.509**	**18.211**	**- 38**	**42.715**	**24.231**	**- 43**
		Capelle	7.046	1.313	- 81	11.241	17.050	+ 52
		Trunk EW	29.921	23.953	- 20	49.551	29.096	- 41
		Benelux	34.650	4.057	- 88	45.758	8.395	- 82
		Spijkenisse	40.131	24.723	- 38	41.460	28.002	- 32
D			**19.578**	**11.113**	**-43**	**32.628**	**11.950**	**- 63**
	Northbound		**17.148**	**12.437**	**- 27**	**22.806**	**14.136**	**- 38**
		Spijkenisse	16.450	17.259	+ 5	26.306	14.685	- 44
		Trunk NS	17.890	7.542	- 58	19.306	13.592	- 30
	Southbound		**22.398**	**9.817**	**- 56**	**42.470**	**9.744**	**- 77**
		Trunk NS	17.064	4.099	- 76	51.291	8.480	- 83
		Spijkenisse	28.499	17.133	- 40	30.893	11.361	- 63
E			**10.538**	**8.632**	**- 18**	**10.696**	**12.408**	**+ 16**
	Northbound		**15.708**	**9.174**	**- 42**	**10.764**	**13.096**	**+ 22**
		Trunk NS	25.687	12.471	- 51	14.780	18.646	+ 26
		RandstadRail	6.643	6.9191	+ 4	8.135	9.185	+ 13
	Southbound		**2.889**	**8.092**	**+ 180**	**10.664**	**11.722**	**+ 10**
		RandstadRail	0.669	9.127	+ 1265	2.403	13.876	+ 478
		Trunk NS	8.093	6.274	- 22	21.438	7.965	- 63

Line	Direction	Section	07:00 - 08:00			08:00 - 09:00		
			Cali. [%]	**Base [%]**	**Diff. [%]**	**Cali. [%]**	**Base [%]**	**Diff. [%]**
D (rush hour service)			**–**	**14.728**		**–**	**16.485**	
	Northbound		**–**	**9.834**		**–**	**14.430**	
		Spijkenisse	–	7.762		–	8.319	
		Trunk NS	–	8.792		–	13.709	
		RandstadRail	–	14.235		–	23.643	
	Southbound		**–**	**21.866**		**–**	**18.532**	
		RandstadRail	–	33.075		–	34.349	
		Trunk NS	–	4.441		–	6.537	
		Spijkenisse	–	25.796		–	18.146	
Grand total			**27.420**	**14.910**	**- 46**	**32.325**	**20.828**	**- 36**

D.5. Comparison table OpenTrack: Base Scenario 2021 Delay

Table D.5: Comparison of regularity for the base scenario

Regularity

Line	Direction	Section	07:00 - 08:00			08:00 - 09:00		
			Cali. [sec]	**Base [sec]**	**Diff. [%]**	**Cali. [sec]**	**Base [sec]**	**Diff. [%]**
A			**138.5**	**72.5**	**- 48**	**213.8**	**74.1**	**- 65**
	Northbound		**166.6**	**74.4**	**- 55**	**206.8**	**74.8**	**- 64**
		Benelux	146.3	–		183.2	–	
		Trunk EW	167.7	54.9	- 67	190.8	55.5	- 71
		Alexander	186.0	128.5	- 31	258.8	127.6	- 51
		Binnenhof	169.4	132.1	- 22	115.0	162.0	- 50
	Southbound		**112.4**	**70.8**	**- 37**	**220.8**	**73.5**	**- 67**
		Binnenhof	48.6	1.9	- 96	134.3	1.9	- 99
		Alexander	71.0	33.3	- 53	179.6	33.0	- 82
		Trunk EW	123.2	94.1	- 24	245.6	98.2	- 60
		Benelux	158.4	–		237.3	–	
B			**162.0**	**93.1**	**- 43**	**156.0**	**94.9**	**- 39**
	Northbound		**193.4**	**88.8**	**- 54**	**157.5**	**91.5**	**- 42**
		Trunk EW	165.9	56.2	- 66	115.3	56.8	- 51
		Alexander	235.1	128.2	- 45	191.9	133.9	- 30
		Nesselande	225.7	152.8	- 32	228.6	157.0	- 31
	Southbound		**130.9**	**97.5**	**- 26**	**154.4**	**98.4**	**- 36**
		Nesselande	81.0	37.3	- 54	55.4	38.3	- 31
		Alexander	100.4	71.6	- 29	138.3	72.2	- 48
		Trunk EW	158.6	130.7	- 18	203.7	131.8	- 35
C			**108.6**	**82.4**	**- 24**	**170.3**	**155.7**	**- 9**
	Northbound		**108.2**	**98.9**	**- 9**	**212.5**	**171.9**	**- 19**
		Spijkenisse	54.6	56.0	+ 3	153.6	45.3	- 70
		Benelux	67.6	83.8	+ 24	192.9	97.8	- 49
		Trunk EW	130.3	115.3	- 11	242.8	235.2	- 2
		Capelle	186.8	181.9	- 19	276.9	289.5	+ 5
	Southbound		**109.0**	**66.2**	**- 39**	**131.4**	**138.30**	**+ 5**
		Capelle	37.3	13.2	- 65	77.1	117.8	+ 53
		Trunk EW	91.8	51.0	- 44	115.3	153.3	+ 33
		Benelux	158.3	101.2	- 36	161.3	135.5	- 16
		Spijkenisse	170.5	109.4	- 36	180.4	114.1	- 37
D			**52.7**	**42.8**	**- 19**	**78.4**	**48.8**	**- 38**
	Northbound		**48.8**	**37.2**	**- 24**	**51.8**	**49.7**	**- 4**
		Spijkenisse	**36.6**	**36.5**	0	47.9	35.7	- 25
		Trunk NS	61.7	37.9	- 39	55.6	63.5	+ 14
	Southbound		**57.2**	**48.3**	**- 16**	**105.0**	**47.9**	**- 54**
		Trunk NS	52.2	40.5	- 23	99.5	41.0	- 59
		Spijkenisse	62.9	58.4	- 7	112.4	56.8	- 49
E			**25.8**	**- 5.1**	**- 120**	**42.7**	**7.1**	**- 83**
	Northbound		**34.0**	**16.6**	**- 51**	**54.1**	**43.6**	**- 20**
		Trunk NS	38.5	23.8	- 38	58.2	44.8	- 23
		RandstadRail	30.0	11.7	- 61	51.5	42.7	- 17
	Southbound		**13.6**	**- 26.7**	**- 296**	**33.8**	**- 29.3**	**- 187**
		RandstadRail	3.8	- 62.3	- 1750	7.1	- 65.2	- 1015
		Trunk NS	36.8	35.9	- 2	68.6	33.5	- 51

Line	Direction	Section	07:00 - 08:00			08:00 - 09:00		
			Cali. [sec]	**Base [sec]**	**Diff. [%]**	**Cali. [sec]**	**Base [sec]**	**Diff. [%]**
D (rush hour service)			**–**	**18.4**		**–**	**27.1**	
	Northbound		**–**	**16.2**		**–**	**18.4**	
		Spijkenisse	–	24.2		–	22.6	
		Trunk NS	–	24.9		–	25.4	
		RandstadRail	–	- 7.6		–	2.4	
	Southbound		**–**	**21.5**		**–**	**35.7**	
		RandstadRail	–	2.4		–	- 0.5	
		Trunk NS	–	32.5		–	46.0	
		Spijkenisse	–	26.4		–	58.9	
Grand total			**93.9**	**52.7**	**- 44**	**127.0**	**70.3**	**- 45**

D.6. Comparison table OpenTrack: Scenario 150 Regularity

Table D.6: Comparison of regularity for the Scenario 150

Regularity

Line	Direction	Section	07:00 - 08:00			08:00 - 09:00		
			Base [%]	**150 [%]**	**Diff. [%]**	**Base [%]**	**150 [%]**	**Diff. [%]**
A			17.3	15.5	-11	29.6	15.9	-46
	Northbound		19.3	14.6	-24	39.8	16.9	-58
		Benelux	–	–	–	–	–	–
		Trunk EW	27.1	19.1	-29	59.0	22.3	-62
		Alexander	5.7	7.7	+ 35	5.5	8.5	+ 55
		Binnenhof	4.3	4.7	+ 10	3.8	5.2	+ 34
	Southbound		15.5	16.3	+ 6	19.9	14.9	-25
		Binnenhof	0.4	0.5	+ 42	0.4	0.5	+ 32
		Alexander	17.1	15.8	-8	17.60	16.30	-7
		Trunk EW	17.9	18.9	+ 6	25.0	16.5	-34
		Benelux	–	–	–	–	–	–
B			15.9	17.6	+ 11	24.4	19.8	-19
	Northbound		6.6	7.3	+ 10	15.2	11.1	-27
		Trunk EW	6.00	8.30	+ 38	22.8	15.9	-30
		Alexander	11.5	8.1	-30	9.8	8.1	-17
		Nesselande	4.6	5.4	+ 17	3.9	3.9	-2
	Southbound		25.6	28.4	+ 11	34.0	28.9	-15
		Nesselande	1.1	2.8	+ 149	1.1	2.6	+ 129
		Alexander	10.1	16.0	+ 59	10.4	16.4	+ 57
		Trunk EW	41.0	43.1	+ 5	55.9	43.8	-22
C			20.1	17.5	-13	27.6	22.9	-17
	Northbound		22.0	16.1	-27	30.7	24.8	-19
		Spijkenisse	21.5	16.5	-23	16.8	36.7	+ 119
		Benelux	3.9	7.7	+ 94	6.7	11.5	+ 73
		Trunk EW	30.6	20.1	-34	46.0	25.2	-45
		Capelle	4.4	5.0	+ 16	21.2	12.8	-39
	Southbound		18.2	18.9	+ 4	24.2	21.1	-13
		Capelle	1.3	5.2	+ 297	17.1	11.4	-33
		Trunk EW	24.0	18.8	-22	29.1	20.2	-31
		Benelux	4.1	10.6	+ 162	8.4	12.8	+ 53
		Spijkenisse	24.7	34.1	+ 38	28.0	35.9	+ 28
Ck			–	22.9	–	–	22.3	–
	Northbound		–	10.8	–	–	15.9	–
		Spijkenisse	–	10.9	–	–	21.2	–
		Benelux	–	9.8	–	–	11.4	–
		Trunk EW	–	11.3	–	–	16.4	–
		Capelle	–	9.8	–	–	13.6	–
	Southbound		–	31.5	–	–	28.7	–
		Capelle	–	10.5	–	–	12.6	–
		Trunk EW	–	39.4	–	–	35.0	–
		Benelux	–	10.5	–	–	12.6	–
		Spijkenisse	–	29.2	–	–	44.4	–

Line	Direction	Section	07:00 - 08:00			08:00 - 09:00		
			Base [%]	**150 [%]**	**Diff. [%]**	**Base [%]**	**150**	**Diff. [%]**
D			11.1	12.9	17	11.9	18.0	+ 51
	Northbound		12.4	12.0	-4	14.1	18.7	+ 32
		Spijkenisse	17.3	8.9	-48	14.7	17.4	+ 18
		Trunk NS	7.5	14.0	+ 86	13.6	20.0	+ 47
	Southbound		9.8	13.8	+ 41	9.7	17.4	+ 79
		Trunk NS	4.1	12.9	+ 215	8.5	17.6	+ 108
		Spijkenisse	17.1	15.3	-11	11.4	17.1	+ 51
E			8.6	9.3	+ 7	12.4	14.1	+ 14
	Northbound		9.2	11.4	+ 24	13.1	19.4	+ 48
		Trunk NS	12.5	9.3	-25	18.6	20.7	+ 11
		RandstadRail	6.9	13.0	+ 88	9.2	18.4	+ 100
	Southbound		8.1	7.2	-11	11.7	8.9	-24
		RandstadRail	9.1	3.7	-59	13.9	4.3	-69
		Trunk NS	6.3	12.6	+ 101	8.0	15.9	+ 100
Ds/Ek			14.7	14.4	-2	16.5	15.6	-6
	Northbound		9.8	19.7	+ 100	14.4	22.9	+ 59
		Spijkenisse	7.8	–	–	8.3	–	–
		Trunk NS	8.8	17.9	+ 104	13.7	22.4	+ 63
		RandstadRail	14.2	22.6	+ 59	23.6	23.7	0
	Southbound		21.9	8.2	-63	18.5	8.3	-55
		RandstadRail	33.1	4.8	-85	34.3	5.5	-84
		Trunk NS	4.4	11.6	+ 162	6.5	10.4	+ 58
		Spijkenisse	25.8	–	–	18.1	–	–
Grand total			14.9	15.5	+ 4	20.8	18.6	-11

D.7. Comparison table OpenTrack: Scenario 150 Delay

Table D.7: Comparison of delay for the Scenario 150

Delay

Line	Direction	Section	07:00 - 08:00			08:00 - 09:00		
			Base [sec]	**150 [sec]**	**Diff. [%]**	**Base [sec]**	**150 [sec]**	**Diff. [%]**
A			73	85	18	74	90	21
	Northbound		74	89	20	75	94	26
		Benelux	–	–		–	–	
		Trunk EW	55	70	27	56	76	37
		Alexander	129	146	14	128	150	17
		Binnenhof	132	148	12	132	150	14
	Southbound		71	81	15	74	85	16
		Binnenhof	2	3	41	2	3	29
		Alexander	33	33	0	33	33	0
		Trunk EW	94	111	18	98	118	20
		Benelux	–	–		–	–	
B			93	110	18	95	110	16
	Northbound		89	100	12	92	101	10
		Trunk EW	56	66	18	57	71	24
		Alexander	128	140	9	134	139	4
		Nesselande	153	165	8	157	160	2
	Southbound		98	120	23	98	120	22
		Nesselande	37	49	32	38	47	23
		Alexander	72	82	14	72	82	14
		Trunk EW	131	162	24	132	163	24
C			82	87	6	156	95	- 39
	Northbound		99	69	- 30	172	80	- 54
		Spijkenisse	56	19	- 66	45	26	- 43
		Benelux	84	49	- 41	98	58	- 40
		Trunk EW	115	93	- 20	235	105	- 55
		Capelle	152	105	- 31	290	118	- 59
	Southbound		66	105	58	138	111	- 20
		Capelle	13	44	231	118	58	- 51
		Trunk EW	51	94	85	153	98	- 36
		Benelux	101	137	36	136	141	4
		Spijkenisse	109	145	32	114	152	33
Ck			–	80		–	89	
	Northbound		–	40		–	67	
		Spijkenisse	–	1		–	15	
		Benelux	–	20		–	34	
		Trunk EW	–	62		–	84	
		Capelle	–	84		–	100	
	Southbound		–	108		–	111	
		Capelle	–	24		–	38	
		Trunk EW	–	92		–	109	
		Benelux	–	153		–	151	
		Spijkenisse	–	150		–	152	

Delay

Line	Direction	Section	07:00 - 08:00			08:00 - 09:00		
			Base [sec]	**150 [sec]**	**Diff. [%]**	**Base [sec]**	**150 [sec]**	**Diff. [%]**
D			43	62	44	49	86	76
	Northbound		37	35	- 5	50	72	44
		Spijkenisse	37	35	- 4	36	66	84
		Trunk NS	38	35	- 7	64	78	22
	Southbound		48	86	77	48	100	109
		Trunk NS	41	59	45	41	71	74
		Spijkenisse	58	130	123	57	137	140
E			39	42	9	50	52	4
	Northbound		25	50	102	46	66	42
		Trunk NS	24	34	42	45	44	- 1
		RandstadRail	25	62	146	48	83	73
	Southbound		53	35	- 33	54	38	- 29
		RandstadRail	63	25	- 60	65	26	- 60
		Trunk NS	36	52	44	34	57	70
Ds/Ek			24	43	84	31	50	60
	Northbound		23	49	114	23	59	161
		Spijkenisse	24	–		23	–	
		Trunk NS	25	34	36	25	43	67
		RandstadRail	19	75	301	18	85	376
	Southbound		24	37	50	40	41	3
		RandstadRail	13	21	65	13	21	69
		Trunk NS	33	53	61	46	56	23
		Spijkenisse	26	–		59	–	
Grand total			61	74	21	78	83	6

D.8. Comparison table OpenTrack: Scenario 120 Regularity

Table D.8: Comparison of irregularity for the Scenario 120

Regularity

Line	Direction	Section	07:00 - 08:00 Base [%]	07:00 - 08:00 120 [%]	07:00 - 08:00 Diff. [%]	08:00 - 09:00 Base [%]	08:00 - 09:00 120 [%]	08:00 - 09:00 Diff. [%]
A			17.3	41.5	140	29.6	31.0	5
	Northbound		19.3	60.9	216	39.8	39.1	-2
		Benelux	–	–		–	–	
		Trunk EW	27.1	86.2	218	59.0	48.9	-17
		Alexander	5.7	16.8	192	5.5	28.7	422
		Binnenhof	4.3	7.2	67	3.8	4.3	12
	Southbound		15.5	21.7	40	19.9	23.0	16
		Binnenhof	0.4	7.0	1889	0.4	3.5	842
		Alexander	17.1	19.6	14	17.6	40.1	128
		Trunk EW	17.9	24.8	38	25.0	19.4	-22
		Benelux	–	–		–	–	
B			15.9	19.9	25	24.4	29.5	21
	Northbound		6.6	17.1	159	15.2	19.0	25
		Trunk EW	6.0	24.9	313	22.8	25.2	11
		Alexander	11.5	12.2	6	9.8	19.4	97
		Nesselande	4.6	5.8	27	3.9	5.8	46
	Southbound		25.6	22.9	-11	34.0	40.6	19
		Nesselande	1.1	5.2	357	1.1	6.2	448
		Alexander	10.1	11.1	10	10.4	27.6	165
		Trunk EW	41.0	34.5	-16	55.9	58.5	5
C			20.1	36.1	79	27.6	40.3	46
	Northbound		22.0	43.3	96	30.7	47.2	54
		Spijkenisse	21.5	39.6	85	16.8	62.4	272
		Benelux	3.9	51.1	1197	6.7	77.4	1061
		Trunk EW	30.6	28.3	-7	46.0	24.2	-47
		Capelle	4.4	80.1	1736	21.2	83.3	294
	Southbound		18.2	30.6	68	24.2	33.3	37
		Capelle	1.3	4.1	212	17.1	27.5	61
		Trunk EW	24.0	30.9	29	29.1	31.5	8
		Benelux	4.1	21.2	422	8.4	24.3	189
		Spijkenisse	24.7	60.3	144	28.0	52.8	89
Ck			–	30.0		–	15.0	
	Northbound		–	16.2		–	10.6	
		Spijkenisse	–	–		–	–	
		Benelux	–	–		–	–	
		Trunk EW	–	16.2		–	10.6	
		Capelle	–	–		–	–	
	Southbound		–	38.8		–	19.5	
		Capelle	–	–		–	–	
		Trunk EW	–	38.8		–	19.5	
		Benelux	–	–		–	–	
		Spijkenisse	–	–		–	–	

Regularity

Line	Direction	Section	07:00 - 08:00			08:00 - 09:00		
			Base [%]	**120** [%]	**Diff.** [%]	**Base** [%]	**120** [%]	**Diff.** [%]
D			11.1	22.6	104	12.0	32.8	175
	Northbound		12.4	28.9	133	14.1	39.4	179
		Spijkenisse	17.3	47.3	174	14.7	47.8	226
		Trunk NS	7.5	10.2	35	13.6	29.9	120
	Southbound		9.8	16.3	66	9.7	26.4	171
		Trunk NS	4.1	10.7	161	8.5	28.4	235
		Spijkenisse	17.1	22.4	31	11.4	24.2	113
E			8.6	17.7	105	12.4	38.7	212
	Northbound		9.2	12.0	31	13.1	25.0	91
		Trunk NS	12.5	10.0	-20	18.6	22.8	22
		RandstadRail	6.9	13.9	101	9.2	26.6	190
	Southbound		8.1	26.9	232	11.7	54.8	368
		RandstadRail	9.1	38.9	326	13.9	56.9	310
		Trunk NS	6.3	5.8	-8	8.0	50.2	530
Ds/Ek			14.7	23.5	59	16.5	32.8	99
	Northbound		9.8	18.7	90	14.4	32.0	122
		Spijkenisse	7.8	–		8.3	–	
		Trunk NS	8.8	8.9	1	13.7	26.3	91
		RandstadRail	14.2	43.9	208	23.6	42.0	78
	Southbound		21.9	53.9	147	18.5	33.6	81
		RandstadRail	33.1	54.3	64	34.3	43.8	27
		Trunk NS	4.4	43.8	885	6.5	25.5	291
		Spijkenisse	25.8	–		18.1	–	
Grand total			14.9	27.6	85	20.8	34.0	63

D.9. Comparison table OpenTrack: Scenario 120 Delay

Table D.9: Comparison of delay for the Scenario 120

Delay

			07:00 - 08:00			08:00 - 09:00		
Line	**Direction**	**Section**	**Base [sec]**	**120 [sec]**	**Diff. [%]**	**Base [sec]**	**120 [sec]**	**Diff. [%]**
A			73	135	86	74	103	39
	Northbound		74	93	25	75	75	1
		Benelux	–	–		–	–	
		Trunk EW	55	67	23	56	55	0
		Alexander	129	159	24	128	126	-2
		Binnenhof	132	200	51	132	161	22
	Southbound		71	178	152	73	130	77
		Binnenhof	2	57	2894	2	20	936
		Alexander	33	88	165	33	57	73
		Trunk EW	94	233	147	98	174	78
		Benelux	–	–		–	–	
B			93	121	30	95	163	71
	Northbound		89	91	2	92	135	47
		Trunk EW	56	59	5	57	96	70
		Alexander	128	129	1	134	192	44
		Nesselande	153	153	0	157	207	32
	Southbound		98	153	56	98	192	95
		Nesselande	37	86	130	38	130	239
		Alexander	72	114	60	72	155	115
		Trunk EW	131	194	48	132	229	74
C			82	156	89	156	223	43
	Northbound		99	195	98	172	290	69
		Spijkenisse	56	188	235	45	309	581
		Benelux	84	164	95	98	244	149
		Trunk EW	115	233	102	235	296	26
		Capelle	152	138	-9	290	293	1
	Southbound		66	126	90	138	155	12
		Capelle	13	16	20	118	61	-48
		Trunk EW	51	119	134	153	141	-8
		Benelux	101	167	65	135	183	35
		Spijkenisse	109	196	79	114	244	114
Ck			–	78		–	81	
	Northbound		–	72		–	60	
		Spijkenisse	–	–		–	–	
		Benelux	–	–		–	–	
		Trunk EW	–	72		–	60	
		Capelle	–	–		–	–	
	Southbound		–	82		–	102	
		Capelle	–	–		–	–	
		Trunk EW	–	82		–	102	
		Benelux	–	–		–	–	
		Spijkenisse	–	–		–	–	

Delay

Line	Direction	Section	07:00 - 08:00			08:00 - 09:00		
			Base [sec]	**120 [sec]**	**Diff. [%]**	**Base [sec]**	**120 [sec]**	**Diff. [%]**
D			43	56	31	49	132	169
	Northbound		37	22	-41	50	119	140
		Spijkenisse	36	16	-55	36	133	273
		Trunk NS	38	28	-26	64	104	64
	Southbound		48	90	86	48	143	199
		Trunk NS	40	48	20	41	97	136
		Spijkenisse	58	135	132	57	195	242
E			39	45	16	50	82	63
	Northbound		25	39	59	46	97	108
		Trunk NS	24	24	2	45	62	39
		RandstadRail	25	53	110	48	122	157
	Southbound		53	55	4	54	64	19
		RandstadRail	63	64	2	65	54	-17
		Trunk NS	36	39	8	33	86	156
Ds/Ek			24	62	162	31	218	602
	Northbound		23	48	108	22	185	722
		Spijkenisse	24	–		23	–	
		Trunk NS	25	24	-3	25	168	560
		RandstadRail	19	109	482	18	214	1096
	Southbound		24	151	520	40	251	533
		RandstadRail	13	152	1084	13	160	1177
		Trunk NS	33	135	314	46	324	605
		Spijkenisse	26	–		59	–	
Grand total			61	100	63	78	147	88

D.10. Comparison table OpenTrack: Scenario 100 Regularity

Table D.10: Comparison of irregularity for the Scenario 100

Regularity

Line	Direction	Section	07:00 - 08:00			08:00 - 09:00		
			Base [%]	**100 [%]**	**Diff. [%]**	**Base [%]**	**100 [%]**	**Diff. [%]**
A			17.3	20.8	20	29.6	24.1	-19
	Northbound		19.3	25.3	31	39.8	26.8	-33
		Benelux	–	–		–	–	
		Trunk EW	27.1	25.5	-6	59.0	22.4	-62
		Alexander	5.7	33.3	479	5.5	49.0	790
		Binnenhof	4.3	10.1	137	3.8	10.6	175
	Southbound		15.5	16.8	9	19.9	21.2	7
		Binnenhof	0.4	6.3	1667	0.4	10.0	2578
		Alexander	17.1	19.4	13	17.6	38.3	118
		Trunk EW	17.9	17.4	-3	25.0	16.5	-34
		Benelux	–	–		–	–	
B			15.9	19.2	21	24.4	20.1	-18
	Northbound		6.6	12.7	92	15.2	20.7	36
		Trunk EW	6.0	9.2	53	22.8	24.1	5
		Alexander	11.5	16.4	42	9.8	17.4	77
		Nesselande	4.6	15.2	234	3.9	20.4	418
	Southbound		25.6	25.0	-2	34.0	19.5	-43
		Nesselande	1.1	10.5	816	1.1	17.1	1403
		Alexander	10.1	12.5	24	10.4	18.6	79
		Trunk EW	41.0	38.5	-6	55.9	20.7	-63
C			20.1	21.4	6	27.6	31.5	14
	Northbound		22.0	24.9	13	30.7	42.4	38
		Spijkenisse	21.5	27.0	26	16.8	113.7	577
		Benelux	3.9	10.1	157	6.7	27.1	306
		Trunk EW	30.6	25.1	-18	46.0	29.1	-37
		Capelle	4.4	37.2	753	21.2	13.9	-34
	Southbound		18.2	18.6	2	24.2	20.0	-18
		Capelle	1.3	3.1	133	17.1	3.9	-77
		Trunk EW	24.0	16.0	-33	29.1	15.7	-46
		Benelux	4.1	16.2	300	8.4	20.9	149
		Spijkenisse	24.7	45.3	83	28.0	50.5	80
Ck			–	24.3		–	25.2	
	Northbound		–	19.8		–	34.2	
		Spijkenisse	–	–		–	–	
		Benelux	–	–		–	–	
		Trunk EW	–	19.8		–	34.2	
		Capelle	–	–		–	–	
	Southbound		–	29.3		–	15.9	
		Capelle	–	–		–	–	
		Trunk EW	–	29.3		–	15.9	
		Benelux	–	–		–	–	
		Spijkenisse	–	–		–	–	

Regularity

Line	Direction	Section	07:00 - 08:00			08:00 - 09:00		
			Base [%]	**100 [%]**	**Diff. [%]**	**Base [%]**	**100 [%]**	**Diff. [%]**
D			11.1	25.9	133	11.9	31.1	160
	Northbound		12.4	13.2	6	14.1	20.5	45
		Spijkenisse	17.3	13.1	-24	14.7	22.8	55
		Trunk NS	7.5	13.2	75	13.6	18.4	35
	Southbound		9.8	38.8	295	9.7	41.4	325
		Trunk NS	4.1	41.6	916	8.5	27.8	227
		Spijkenisse	17.1	34.9	104	11.4	60.8	435
E			8.6	23.7	174	12.4	34.8	181
	Northbound		9.2	22.8	149	13.1	39.2	200
		Trunk NS	12.5	11.3	-10	18.6	27.0	45
		RandstadRail	6.9	32.3	367	9.2	47.6	418
	Southbound		8.1	25.0	209	11.7	30.5	160
		RandstadRail	9.1	32.1	252	13.9	35.3	154
		Trunk NS	6.3	9.1	44	8.0	21.3	167
Ds/F			14.7	35.1	138	16.5	28.7	74
	Northbound		9.8	14.4	47	14.4	20.2	40
		Spijkenisse	7.8	2.4	-68	8.3	20.6	148
		Trunk NS	8.8	8.9	1	13.7	15.1	10
		RandstadRail	14.2	23.6	66	23.6	28.3	20
	Southbound		21.9	61.5	181	18.5	37.4	102
		RandstadRail	33.1	93.5	183	34.3	54.6	59
		Trunk NS	4.4	32.5	631	6.5	21.6	231
		Spijkenisse	25.8	46.1	79	18.1	49.5	173
Grand total			14.9	24.1	62	20.8	28.6	38

D.11. Comparison table OpenTrack: Scenario 100 Delay

Table D.11: Comparison of delay for the Scenario 100

Delay

Line	Direction	Section	07:00 - 08:00			08:00 - 09:00		
			Base [sec]	**100 [sec]**	**Diff. [%]**	**Base [sec]**	**100 [sec]**	**Diff. [%]**
A			73	150	107	74	234	216
	Northbound		74	87	17	75	124	66
		Benelux	–	–		–	–	
		Trunk EW	55	68	24	56	108	94
		Alexander	129	128	-1	128	179	40
		Binnenhof	132	197	49	132	243	84
	Southbound		71	206	191	73	350	377
		Binnenhof	2	34	1683	2	63	3150
		Alexander	33	94	183	33	110	234
		Trunk EW	94	277	195	98	484	393
		Benelux	–	–		–	–	
B			93	128	37	95	208	119
	Northbound		89	107	21	92	128	40
		Trunk EW	56	69	22	57	96	68
		Alexander	128	129	1	134	177	32
		Nesselande	153	151	-1	157	189	20
	Southbound		98	146	50	98	285	189
		Nesselande	37	63	68	38	94	147
		Alexander	72	94	32	72	126	75
		Trunk EW	131	214	64	132	415	215
C			82	102	24	156	216	39
	Northbound		99	71	-28	172	135	-22
		Spijkenisse	56	35	-37	45	119	163
		Benelux	84	46	-45	98	104	6
		Trunk EW	115	100	-13	235	148	-37
		Capelle	152	60	-60	290	146	-50
	Southbound		66	127	91	138	303	119
		Capelle	13	15	12	118	16	-87
		Trunk EW	51	134	162	153	349	128
		Benelux	101	158	56	135	355	162
		Spijkenisse	109	163	49	114	310	171
Ck			–	127		–	296	
	Northbound		–	82		–	150	
		Spijkenisse	–	–		–	–	
		Benelux	–	–		–	–	
		Trunk EW	–	82		–	150	
		Capelle	–	–		–	–	
	Southbound		–	177		–	449	
		Capelle	–	–		–	–	
		Trunk EW	–	177		–	449	
		Benelux	–	–		–	–	
		Spijkenisse	–	–		–	–	

Delay

Line	Direction	Section	07:00 - 08:00			08:00 - 09:00		
			Base [sec]	**100 [sec]**	**Diff. [%]**	**Base [sec]**	**100 [sec]**	**Diff. [%]**
D			43	78	82	49	103	112
	Northbound		37	60	62	50	81	62
		Spijkenisse	36	30	-18	36	49	36
		Trunk NS	38	90	137	64	110	74
	Southbound		48	96	99	48	125	162
		Trunk NS	40	69	70	41	86	111
		Spijkenisse	58	132	126	57	181	218
E			39	147	279	50	236	371
	Northbound		25	179	629	46	266	473
		Trunk NS	24	87	264	45	187	318
		RandstadRail	25	256	916	48	320	572
	Southbound		53	93	76	54	206	284
		RandstadRail	63	109	75	65	167	156
		Trunk NS	36	57	58	33	280	735
Ds/F			24	183	677	31	364	1070
	Northbound		23	115	399	22	219	876
		Spijkenisse	24	3	-86	23	69	207
		Trunk NS	25	93	276	25	213	738
		RandstadRail	19	151	711	18	274	1430
	Southbound		24	271	1010	40	511	1187
		RandstadRail	13	245	1810	13	486	3783
		Trunk NS	33	288	785	46	537	1068
		Spijkenisse	26	400	1411	59	475	707
Grand total			61	128	109	78	231	195

D.12. Comparison table OpenTrack: Upgrades Scenario 120 Regularity

Table D.12: Comparison of irregularity [%] for the different upgrade variants for Scenario 120

Regularity

			07:00 - 08:00				08:00 - 09:00			
			Fixed block		Moving block		Fixed block		Moving block	
Line	**Direction**	**Section**	**GoA1**	**GoA3**	**GoA1**	**GoA3**	**GoA1**	**GoA3**	**GoA1**	**GoA3**
A			41.5	23.7	21.0	18.6	31.0	34.0	21.3	18.0
	Northbound		60.9	31.7	21.8	20.9	39.1	51.2	19.1	20.2
		Trunk EW	86.2	41.6	29.4	28.3	48.9	68.0	24.5	26.7
		Alexander	16.8	17.3	9.8	9.5	28.7	26.8	11.9	10.3
		Binnenhof	7.2	5.3	4.2	3.9	4.3	5.4	3.9	4.4
	Southbound		21.7	15.7	20.3	16.2	23.0	16.7	23.5	15.8
		Binnenhof	7.0	1.1	1.6	0.4	3.5	1.2	2.0	0.4
		Alexander	19.6	16.6	27.4	15.5	40.1	21.3	30.0	16.6
		Trunk EW	24.8	17.5	20.4	19.0	19.4	17.3	24.3	17.8
B			19.9	23.4	26.7	22.3	29.5	26.2	27.0	25.4
	Northbound		17.1	9.1	5.9	6.2	19.0	18.1	10.7	9.9
		Trunk EW	24.9	10.4	5.9	6.2	25.2	24.3	15.5	13.8
		Alexander	12.2	11.0	7.1	7.2	19.4	18.5	7.3	7.2
		Nesselande	5.8	5.4	5.8	6.4	5.8	4.9	3.9	4.4
	Southbound		22.9	38.2	48.7	39.1	40.6	34.6	43.8	41.5
		Nesselande	5.2	1.3	5.1	1.1	6.2	3.3	4.3	1.2
		Alexander	11.1	11.5	19.1	10.3	27.6	14.7	20.2	11.3
		Trunk EW	34.5	62.8	77.1	64.7	58.5	54.6	68.1	68.7
C			36.1	30.5	26.5	23.2	40.3	33.3	25.7	20.3
	Northbound		43.3	37.9	21.1	19.8	47.2	42.7	17.1	16.6
		Spijkenisse	39.6	32.1	6.4	6.4	62.4	46.1	5.9	6.2
		Benelux	51.1	47.1	6.2	6.5	77.4	78.9	9.6	9.3
		Trunk EW	28.3	37.3	28.9	26.6	24.2	20.8	23.9	23.4
		Capelle	80.1	39.3	34.4	33.6	83.3	83.9	14.9	13.5
	Southbound		30.6	24.9	30.6	25.8	33.3	23.6	34.2	24.2
		Capelle	4.1	4.5	3.2	3.5	27.5	4.8	4.1	3.8
		Trunk EW	30.9	22.7	37.0	28.5	31.5	27.6	46.5	29.1
		Benelux	21.2	13.9	12.3	11.0	24.3	13.3	14.8	12.7
		Spijkenisse	60.3	59.4	49.2	48.9	52.8	35.4	36.0	35.0
Ck			30.0	20.8	14.4	15.2	15.0	12.9	14.6	13.7
	Northbound		16.2	14.6	8.3	9.5	10.6	10.0	9.6	9.8
		Trunk EW	16.2	14.6	8.3	9.5	10.6	10.0	9.6	9.8
	Southbound		38.8	24.8	18.2	18.8	19.5	15.8	19.7	17.7
		Trunk EW	38.8	24.8	18.2	18.8	19.5	15.8	19.7	17.7

Regularity

Line	Direction	Section	07:00 - 08:00				08:00 - 09:00			
			Fixed block		Moving block		Fixed block		Moving block	
			GoA1	**GoA3**	**GoA1**	**GoA3**	**GoA1**	**GoA3**	**GoA1**	**GoA3**
D			22.6	19.7	11.4	11.2	32.8	28.4	17.5	16.9
	Northbound		28.9	25.0	7.4	7.4	39.4	35.8	9.3	9.2
		Spijkenisse	47.3	38.7	5.1	4.0	47.8	47.3	6.1	5.3
		Trunk NS	10.2	10.8	9.6	10.9	29.9	22.9	12.9	13.6
	Southbound		16.3	14.4	15.1	15.0	26.4	20.9	25.3	24.2
		Trunk NS	10.7	7.1	9.0	8.4	28.4	22.8	27.1	26.2
		Spijkenisse	22.4	22.5	21.9	22.2	24.2	18.7	23.3	21.8
E			17.7	14.8	6.4	6.5	38.7	38.0	11.2	10.9
	Northbound		12.0	10.8	8.0	8.1	25.0	24.7	9.3	10.2
		Trunk NS	10.0	10.3	10.4	11.2	22.8	18.4	10.9	11.9
		RandstadRail	13.9	11.2	5.7	5.3	26.6	29.5	8.1	9.0
	Southbound		26.9	21.4	3.9	3.9	54.8	53.3	13.6	11.7
		RandstadRail	38.9	30.3	1.7	2.0	56.9	51.6	6.1	5.4
		Trunk NS	5.8	5.7	7.8	7.1	50.2	57.0	29.9	25.3
Ek			23.5	22.8	8.5	8.9	32.8	31.7	13.5	14.2
	Northbound		18.7	19.7	9.4	9.6	32.0	28.5	15.0	15.2
		Trunk NS	8.9	10.0	6.0	6.6	26.3	20.8	8.6	7.8
		RandstadRail	43.9	44.8	17.8	17.1	42.0	41.9	25.7	27.5
	Southbound		53.9	41.8	4.1	5.3	33.6	34.9	12.0	13.3
		RandstadRail	54.3	42.3	1.4	1.8	43.8	41.4	4.3	3.5
		Trunk NS	43.8	33.5	15.0	21.9	25.5	29.8	18.2	20.9
Grand total			27.6	22.8	17.8	16.1	34.0	31.0	19.2	17.2

D.13. Comparison table OpenTrack: Upgrades Scenario 120 Delay

Table D.13: Comparison of dis-punctuality [sec] for the different upgrade variants of Scenario 120

Delay

			07:00 - 08:00				08:00 - 09:00			
			Fixed block		Moving block		Fixed block		Moving block	
Line	**Direction**	**Section**	**GoA1**	**GoA3**	**GoA1**	**GoA3**	**GoA1**	**GoA3**	**GoA1**	**GoA3**
A			135	97	75	75	103	85	79	73
	Northbound		93	105	82	83	75	80	84	83
		Trunk EW	67	81	61	61	55	56	63	62
		Alexander	159	167	139	145	126	136	145	141
		Binnenhof	200	201	143	150	161	180	145	146
	Southbound		178	89	68	67	130	90	74	63
		Binnenhof	57	5	7	2	20	4	9	2
		Alexander	88	34	37	34	57	36	41	33
		Trunk EW	233	123	90	89	174	124	97	84
B			121	100	107	92	163	130	114	92
	Northbound		91	92	89	90	135	134	86	89
		Trunk EW	59	60	56	57	96	93	55	56
		Alexander	129	130	131	132	192	193	126	127
		Nesselande	153	153	152	152	207	209	146	152
	Southbound		153	109	126	94	192	127	143	96
		Nesselande	86	38	79	38	130	58	76	39
		Alexander	114	74	105	71	155	89	112	74
		Trunk EW	194	150	153	124	229	169	181	127
C			156	126	70	69	223	185	73	70
	Northbound		195	126	55	52	290	245	60	59
		Spijkenisse	188	138	13	11	309	248	11	9
		Benelux	164	119	37	36	244	189	32	34
		Trunk EW	233	143	83	81	296	254	80	80
		Capelle	138	71	52	51	293	272	88	83
	Southbound		126	126	82	82	155	123	85	82
		Capelle	16	16	14	15	61	20	16	15
		Trunk EW	119	116	77	75	141	107	77	74
		Benelux	167	172	121	120	183	162	126	122
		Spijkenisse	196	199	118	120	244	216	124	118
Ck			78	60	40	39	81	68	48	47
	Northbound		72	56	43	41	60	60	54	53
		Trunk EW	72	56	43	41	60	60	54	53
	Southbound		82	63	37	39	102	75	43	41
		Trunk EW	82	63	37	39	102	75	43	41

Delay

Line	Direction	Section	07:00 - 08:00				08:00 - 09:00			
			Fixed block		Moving block		Fixed block		Moving block	
			GoA1	GoA3	GoA1	GoA3	GoA1	GoA3	GoA1	GoA3
D			56	53	33	33	132	94	38	38
	Northbound		22	22	19	21	119	58	22	22
		Spijkenisse	16	15	13	14	133	61	14	14
		Trunk NS	28	29	26	28	104	53	30	30
	Southbound		90	84	46	45	143	130	53	53
		Trunk NS	48	43	39	38	97	78	45	44
		Spijkenisse	135	129	54	52	195	187	63	64
E			45	10	20	20	82	42	27	28
	Northbound		39	31	17	17	97	89	19	22
		Trunk NS	24	24	16	17	62	53	19	19
		RandstadRail	53	38	19	17	122	116	19	24
	Southbound		55	-24	24	24	64	-12	37	35
		RandstadRail	64	-60	9	9	54	-53	9	8
		Trunk NS	39	39	51	50	86	79	99	92
Ek			62	56	22	21	218	171	35	35
	Northbound		48	49	24	23	185	134	31	32
		Trunk NS	24	26	18	18	168	94	23	22
		RandstadRail	109	109	37	35	214	203	45	49
	Southbound		151	100	13	15	251	208	38	37
		RandstadRail	152	103	8	10	160	131	12	9
		Trunk NS	135	43	33	36	324	268	59	59
Grand total			100	76	56	53	147	113	59	54

D.14. Comparison table OpenTrack: Upgrades Scenario 100 Regularity

Table D.14: Comparison of irregularity [%] for the different upgrade variants for Scenario 100

Regularity

Line	Direction	Section	07:00 - 08:00				08:00 - 09:00			
			Fixed block		Moving block		Fixed block		Moving block	
			GoA1	GoA3	GoA1	GoA3	GoA1	GoA3	GoA1	GoA3
A			20.8	17.0	23.2	23.9	24.1	20.6	27.5	26.3
	Northbound		25.3	22.5	28.4	28.7	26.8	23.6	35.7	33.8
		Trunk EW	25.5	26.9	16.5	16.5	22.4	15.7	19.8	16.0
		Alexander	33.3	19.8	65.2	66.1	49.0	54.2	90.5	92.7
		Binnenhof	10.1	6.9	5.6	5.6	10.6	6.0	4.4	6.0
	Southbound		16.8	12.2	18.6	19.7	21.2	17.6	19.3	18.9
		Binnenhof	6.3	0.4	0.4	0.3	10.0	0.7	0.6	0.6
		Alexander	19.4	8.5	27.3	28.3	38.3	28.9	28.3	27.3
		Trunk EW	17.4	15.4	18.1	19.3	16.5	15.8	18.7	18.5
B			19.2	16.9	28.6	28.3	20.1	15.2	29.6	24.9
	Northbound		12.7	11.4	25.6	27.4	20.7	16.2	23.6	22.4
		Trunk EW	9.2	8.7	9.2	9.6	24.1	13.7	20.1	18.7
		Alexander	16.4	12.9	37.4	40.7	17.4	18.6	22.0	20.8
		Nesselande	15.2	14.7	39.3	41.9	20.4	22.6	37.3	36.6
	Southbound		25.0	21.9	31.3	29.1	19.5	14.2	35.3	27.3
		Nesselande	10.5	2.0	8.4	2.2	17.1	8.7	10.7	2.4
		Alexander	12.5	5.3	15.4	9.1	18.6	10.5	20.5	9.5
		Trunk EW	38.5	40.0	49.7	51.3	20.7	17.9	50.4	43.7
C			21.4	18.5	27.9	26.2	31.5	24.2	24.3	20.1
	Northbound		24.9	20.5	29.4	26.6	42.4	27.0	22.7	17.3
		Spijkenisse	27.0	12.5	13.3	10.2	113.7	63.3	28.4	22.7
		Benelux	10.1	7.2	6.3	5.5	27.1	13.0	9.3	6.4
		Trunk EW	25.1	22.8	26.9	25.0	29.1	22.4	27.3	20.7
		Capelle	37.2	38.0	78.7	72.2	13.9	11.1	12.2	8.7
	Southbound		18.6	17.0	26.6	25.9	20.0	21.1	25.8	23.0
		Capelle	3.1	2.9	5.0	2.8	3.9	3.0	3.0	3.1
		Trunk EW	16.0	14.5	29.5	28.7	15.7	16.1	31.6	27.3
		Benelux	16.2	15.5	11.7	10.5	20.9	26.5	8.7	8.2
		Spijkenisse	45.3	40.6	52.4	53.7	50.5	50.4	43.8	41.1
Ck			24.3	22.0	31.4	19.8	25.2	12.9	38.5	22.0
	Northbound		19.8	19.5	23.9	16.9	34.2	14.3	18.2	18.0
		Trunk EW	19.8	19.5	23.9	16.9	34.2	14.3	18.2	18.0
	Southbound		29.3	24.7	39.0	22.8	15.9	11.3	58.9	26.1
		Trunk EW	29.3	24.7	39.0	22.8	15.9	11.3	58.9	26.1

Regularity

Line	Direction	Section	07:00 - 08:00				08:00 - 09:00			
			Fixed block		Moving block		Fixed block		Moving block	
			GoA1	GoA3	GoA1	GoA3	GoA1	GoA3	GoA1	GoA3
D			25.9	18.0	31.9	22.3	31.1	25.1	40.8	28.9
	Northbound		13.2	9.6	17.2	12.8	20.5	13.3	16.7	17.8
		Spijkenisse	13.1	7.6	7.5	5.9	22.8	14.5	7.8	7.5
		Trunk NS	13.2	11.6	26.7	19.4	18.4	12.2	25.6	28.1
	Southbound		38.8	26.5	46.5	31.8	41.4	37.0	64.9	40.0
		Trunk NS	41.6	26.3	56.2	31.6	27.8	25.2	77.5	35.7
		Spijkenisse	34.9	26.7	33.8	32.2	60.8	52.2	48.5	45.6
E			23.7	18.6	29.6	24.0	34.8	17.0	29.9	22.2
	Northbound		22.8	19.4	32.5	25.9	39.2	16.8	31.1	29.3
		Trunk NS	11.3	7.7	21.2	16.6	27.0	8.9	23.8	26.8
		RandstadRail	32.3	28.8	41.2	33.2	47.6	22.2	36.0	31.0
	Southbound		25.0	17.4	25.1	20.9	30.5	17.1	28.7	14.9
		RandstadRail	32.1	21.0	12.2	4.0	35.3	14.7	14.6	4.1
		Trunk NS	9.1	8.6	55.2	61.0	21.3	21.6	54.7	35.6
F			35.1	24.0	30.6	20.7	28.7	23.6	33.0	23.7
	Northbound		14.4	13.0	21.2	19.8	20.2	11.5	19.2	20.0
		Spijkenisse	2.4	0.5	0.1	0.2	20.6	8.9	11.8	11.2
		Trunk NS	8.9	8.0	15.0	16.1	15.1	7.7	16.4	19.4
		RandstadRail	23.6	21.5	31.8	26.2	28.3	18.2	26.2	23.8
	Southbound		61.5	37.4	42.2	21.8	37.4	36.0	47.1	27.7
		RandstadRail	93.5	51.7	38.7	12.4	54.6	53.1	42.4	17.3
		Trunk NS	32.5	24.8	43.2	28.2	21.6	19.3	47.0	32.0
		Spijkenisse	46.1	29.5	89.4	62.0	49.5	48.1	69.8	53.8
Grand total			24.1	19.1	29.1	24.2	28.6	20.3	30.9	23.8

D.15. Comparison table OpenTrack: Upgrades Scenario 100 Delay

Table D.15: Comparison of dis-punctuality [sec] for the different upgrade variants of Scenario 100

Delay

Line	Direction	Section	07:00 - 08:00				08:00 - 09:00			
			Fixed block		Moving block		Fixed block		Moving block	
Line	**Direction**	**Section**	**GoA1**	**GoA3**	**GoA1**	**GoA3**	**GoA1**	**GoA3**	**GoA1**	**GoA3**
A			150	141	78	79	234	213	95	92
	Northbound		87	89	67	67	124	112	97	96
		Trunk EW	68	66	64	63	108	92	78	75
		Alexander	128	132	83	84	179	163	154	155
		Binnenhof	197	239	84	85	243	240	155	161
	Southbound		206	187	88	89	350	314	93	89
		Binnenhof	34	2	2	2	63	5	4	4
		Alexander	94	71	49	50	110	69	52	49
		Trunk EW	277	261	116	118	484	460	123	117
B			128	117	93	87	208	194	109	96
	Northbound		107	106	77	80	128	130	91	91
		Trunk EW	69	67	64	67	96	93	74	71
		Alexander	129	128	80	84	177	178	114	114
		Nesselande	151	150	102	104	189	193	126	126
	Southbound		146	127	106	93	285	255	126	101
		Nesselande	63	38	53	40	94	53	60	39
		Alexander	94	73	86	76	126	82	95	75
		Trunk EW	214	199	142	127	415	407	164	134
C			102	96	84	83	216	199	86	79
	Northbound		71	63	75	76	135	93	72	67
		Spijkenisse	35	17	17	14	119	65	16	12
		Benelux	46	33	32	29	104	50	31	27
		Trunk EW	100	97	88	90	148	109	97	91
		Capelle	60	61	153	161	146	123	106	98
	Southbound		127	124	92	88	303	313	100	92
		Capelle	15	14	17	14	16	15	14	14
		Trunk EW	134	134	85	80	349	359	92	83
		Benelux	158	152	133	128	355	378	147	137
		Spijkenisse	163	152	142	142	310	329	152	142
Ck			127	113	74	76	296	225	74	82
	Northbound		82	82	86	82	150	90	83	79
		Trunk EW	82	82	86	82	150	90	83	79
	Southbound		177	147	62	69	449	375	65	85
		Trunk EW	177	147	62	69	449	375	65	85

Delay

Line	Direction	Section	07:00 - 08:00				08:00 - 09:00			
			Fixed block		Moving block		Fixed block		Moving block	
			GoA1	GoA3	GoA1	GoA3	GoA1	GoA3	GoA1	GoA3
D			78	72	43	43	103	83	48	48
	Northbound		60	53	27	28	81	44	29	32
		Spijkenisse	30	23	20	20	49	19	20	20
		Trunk NS	90	83	33	36	110	68	37	43
	Southbound		96	91	59	57	125	123	67	64
		Trunk NS	69	62	50	51	86	76	56	53
		Spijkenisse	132	129	71	64	181	184	82	79
E			147	88	80	67	236	95	79	96
	Northbound		179	147	102	81	266	128	88	85
		Trunk NS	87	87	48	38	187	80	47	63
		RandstadRail	256	195	144	114	320	161	116	100
	Southbound		93	-4	47	46	206	60	68	108
		RandstadRail	109	-28	11	6	167	-6	19	19
		Trunk NS	57	53	132	140	280	184	160	279
F			183	107	74	54	364	138	94	113
	Northbound		115	104	43	40	219	78	33	33
		Spijkenisse	3	0	0	0	69	11	6	5
		Trunk NS	93	83	28	28	213	70	31	33
		RandstadRail	151	141	69	62	274	111	45	43
	Southbound		271	110	113	72	511	198	157	198
		RandstadRail	245	76	70	20	486	88	70	52
		Trunk NS	288	136	145	112	537	269	220	313
		Spijkenisse	400	209	237	197	475	286	203	246
Grand total			128	102	76	70	231	156	85	87