Disruption analysis for the Rotterdam metro network

Master’s thesis

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Abstract

As with every railway network, disruptions have a huge impact on the operation of the metro network of Rotterdam. Maintenance can be scheduled to prevent disruptions, but this is costly. At the other hand, the costs of a disruption are unclear. A tool is desired to evaluate scheduled and unscheduled disruptions.

In a simulation the precise effect of disruptions within the network can be modelled. For the Rotterdamse Elektrische Tram (RET) a simulation model is developed to measure the consequences of disruptions related to the infrastructure. Focus lies on the opening of bridges and passing freight trains in the high-frequency metro network. The model uses the timetable, but also considers the variation in registered travel and dwelling times.

Results show the weak spots in the infrastructure of the network. Not only the track configuration, but also the use of the infrastructure plays a role. The effect of disruption scenarios can be tested with the simulation to minimize the effects of a disruption. In scheduling the simulation can be used to determine travel times on alternate routes. These can be used to optimize over scheduled disruptions. The simulation is verified using a full scope metro simulator and registered data of dwelling and travel times.

Samenvatting

Zoals bij elk spoorwegennetwerk hebben verstoringen een grote impact op de exploitatie van het metro netwerk van Rotterdam. Om verstoringen te voorkomen kan onderhoud worden gepleegd, maar dit is kostbaar. Aan de andere kant zijn de kosten van een verstoring onduidelijk. Een middel om geplande en ongeplande verstoringen te evalueren is gewenst.

In een simulatie kan het precieze effect van verstoringen binnen een netwerk gemodelleerd worden. Voor de Rotterdamse Elektrische Tram (RET) is een simulatie ontwikkeld om de gevolgen van infrastructurele verstoringen vast te leggen. Er zal worden gefocust op brugopeningen en passerende goederentreinen in het hoogfrequente metro netwerk. Het model maakt gebruik van de dienstregeling, maar kijkt daarnaast ook naar de variatie in geregistreerde halteer- en rijtijden.

De resultaten laten de kritieke plekken in de infrastructuur van het netwerk zien. Niet alleen de spoor configuratie, maar ook het gebruik van de infrastructuur spelen een rol. De effecten van verstoringsscenarios kunnen met de simulatie worden getoetst om de gevolgen van een verstoring te minimaliseren. In de planning kan de simulatie worden gebruikt om rijtijden van alternatieve routes te bepalen. Hiermee kan beter worden ingespeeld op geplande verstoringen. De simulatie is geverifieerd in een 1-op-1 metro simulator en met behulp van geregistreerde gegevens over de halteer- en rijtijden.
Acknowledgements

In my search for an internship I desired to combine my knowledge for math with my interest for public transport. Unfortunately there were no big companies in the area of Eindhoven satisfying my interests, so I decided to apply for an internship at the RET. Travelling for 3 hours by train and waking up at 6 am every day took some effort, but I really enjoyed the work during my research internship.

During my work at the RET I got to know a lot of people. It surprised me how open everyone was: making time to give me some data needed for the simulation was never a problem and everyone was open to explain things I wanted to know.

When starting my thesis in October 2014 I was very happy to work together with Joey Blangé to collect information and find out the needs for a simulation. Unfortunately the project was not what he expected, but I would like to thank him for the teamwork during the first weeks.

At the Inframanagement department I want to thank everyone for the nice and quite working environment, drinks they brought and the interest the support they gave me. After half a year I became the 'Wizzkid' at the 3rd floor. Furthermore I would like to thank Peter Voogt for his supervision during this period.

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For some figures the network maps that can be found at Sporenplan.nl are used. I would like to thank Sven Zeegers for his permission to use them in this report.

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1 Introduction

The metro network of Rotterdam, operated by the Rotterdamse Elektrische Tram (RET), is the largest metro network of the Benelux. Operating a metro network on this scale is a complex process and is constantly evaluated to improve performance. A lot of data is registered for this purpose, but only a small part of this data is analysed. Especially in the case of scheduled and unscheduled disruptions it is difficult to determine what problems arise and what the best way to handle these problems is. For this purpose there was a need to develop a simulation tool. The simulation tool was developed during one year of research during my internship between October 2014 and November 2015.

1.1 Problem description

Several simulations are already used by RET. The most detailed simulation is mainly used for training of new metro drivers. However, the RET simulation tools are not suitable for the simulation of interaction with other trains. The following main question is formulated for the development of the simulation:

Is it possible to develop a simulation tool for the metro network in such way that it can be used for evaluation of scheduled and unscheduled disruptions?

Two departments of the RET were involved: infrastructure management and the business office of operations. Every department has its own needs, but the simulation must be useful for both departments. First the needs for both departments are described (Chapter 1.1.1-1.1.2). Then then general requirements for a simulation are given (Chapter 1.1.3).

1.1.1 Infrastructure management

Scheduled maintenance can prevent unscheduled disruptions. Unfortunately performing maintenance to the infrastructure is costly. The maintenance must be scheduled in such way that the disruption costs are minimized. Disruption costs are measured in timetable hours or DienstRegelingsUur (DRU). The question that follows is:

What are the costs of an infrastructure related disruption, measured in DRUs?

Examples of infrastructure related disruptions are switch failures or power outage. At the moment such a disruption occurs it has immediate consequences for the train operations. In most cases some trains will be delayed due to diversions. Also (partial) cancellation of trains is possible. To answer the given question the following research questions are formulated:

- How are cancelled and delayed trains counted in terms of DRUs? (Chapter 4.3)
- What kind of disruptions can occur and how are they handled? (Chapter 5)

Note that disruptions not related to the infrastructure are out of scope for this thesis.
1.1.2 Business office of operations

The business office of operations or BedrijfsBureau Exploitatie (BBE) is involved in the making of the timetable. Every year, sometimes even more often, a new timetable is created. It is difficult to predict the effects of the changes that are made. In 2017 the Hoekse Lijn railway will become a part of the metro network, extending two existing metro lines. New problems arise with the opening of bridges and the sharing of tracks with freight trains in a high frequency rail network. A simulation can be helpful in this case and the following question is formulated:

*Is it possible to match the vehicle travel and dwelling times of the simulation such that they approach the real situation and the timetable including the Hoekse Lijn can be tested for robustness?*

Note that the travel and dwelling times are also important in the problem for infrastructure management, but not in such detail. To answer the question some research questions are formulated:

- How are dwelling times varying in reality? More specific, is there a cumulative effect of dwelling times in relation to delays and disruptions? (Chapter 6.1)
- How do the travel times in reality and travel times in the simulation compare? (Chapter 6.2)
- How often and how much time does the opening of bridges take? And what is the effect on the availability of the infrastructure? (Chapter 5.3)
- How much time does it take to let a freight train pass and how often does this occur? Also, what is the effect of passing freight trains on the availability of the infrastructure? (Chapter 5.4)

The BBE department was also interested in more detailed results about distances and partial travel times for use in their planning software as an improvement. A technical description for this specific issue is given in Appendix A.

1.1.3 Simulation requirements

When developing a simulation of a railway network it is necessary to obtain information about the network infrastructure, the rolling stock and the timetable. This is formulated in the research questions given below:

- In what way is the network constructed and what kind of security is used? (Chapter 2)
- What kind of rolling stock is present and where may it be used? (Chapter 3)
- What is the structure of the timetable? (Chapter 4)

Furthermore the RET had some software requirements: All used software has to be open source and be able to run on their local computers. To meet these requirements the simulation is programmed in Java (1.8) using the Netbeans development environment (8.0.2), which are both open source. In addition the JGraphT package (0.9.1) is used for graphs. Furthermore the R-project (3.2.1) is used for doing statistical analysis.
1.2 Previous research

The scheduling of maintenance in railway networks is a broad topic. Some models, but mostly outside the scope of the Inframanagement questions, are described in [2].

For the simulation of railway networks different commercial packages already exist like RAIL//SYS and OpenTrack. The network topology used in the commercial software is implemented in this simulation as well. OpenTrack also contains the ability for "analyzing the effects of system failures (such as infrastructure or train failures) and delays" according to their website. However, nothing is stated about the relation between system failures and the delay effects in relation to the timetable.
2 Infrastructure

In this chapter the metro network of Rotterdam is described in detail. First the network structure and the railway signalling are described. Subsequently, the network model used for the simulation is presented.

2.1 The metro network of Rotterdam

The metro network of Rotterdam contains 5 lines, numbered from A to E as is shown in figure 1. Most parts of the infrastructure are used by multiple lines.

![Figure 1: A map of the Rotterdam metro network including the extension planned for 2017. Source: RET](image)

The lines have the following directions:

- Line A: Vlaardingen West - Schiedam Centrum - Binnenhof
- Line B: Hoek van Holland Strand - Vlaardingen West - Schiedam Centrum - Nesselande
- Line C: De Akkers - Schiedam Centrum - De Terp
- Line D: De Akkers - Slinge - Rotterdam Centraal
- Line E: Slinge - Rotterdam Centraal - Den Haag Centraal

The extension of the network that is planned to open in 2017 is the part from Hoek van Holland Haven to Schiedam Centrum. The last part to Hoek van Holland Strand is planned to open in 2018.
Note that a part of the metro network is also connected to the tram network of The Hague. Between Laan van NOI and Leidschenven both metro and tram vehicles are using the same track.

### 2.2 Railway signalling system

The metro network consists of sections. Every section contains one or more segments. Every segment is welded to exactly two other segments at its endpoints. Furthermore every segment has a length and a speed limit. A train protection system is installed to prevent accidents. For the lines A to D Linienförmige Zugbeeinflussung (LZB) is used and for line E a version of Zugbeeinflussung (ZUB) is installed. ZUB is used for signalling where metro and tram vehicles make use of the same infrastructure. As the tram vehicles will not be modelled in this model LZB is used as basis for the simulation. Both systems make use of the described sections. Every section contains an electrical circuit to identify whether the section is occupied or free. A section is occupied from the moment that the first wheelset of a train has entered the section. When the last wheelset of the train has left the section it is set to free again.

To indicate the speed limit to the metro driver a cab signal is used. In LZB a new signal can be given in continuous time. As the simulation will run by discrete time events a simplification is made in the calculation of the speed limit. The speed limit is checked every time a train enters or leaves a section (see also Chapter 6.2). Every segment has a speed limit that depends on multiple factors. The highest speed limit is allowed on (almost) straight tracks, namely 80 or 100 kilometres per hour. The speed limit could be much lower at curves or switches, depending on the curvature of the track. LZB contains 11 different signals with speed limits of 0, 20, 35, 50, 60, 70 or 80 kilometres per hour. The other signals are used when certain restrictions are given to the driver besides the speed limit. The speed limit of 100 kilometres per hour is only allowed with ZUB and the new version of LZB that will be installed at the Hoekse Lijn.

To control the speed limit Automatische Trein Beïnvloeding (ATB) is used. ATB stops a train when the speed limit is violated. Speed reductions are given when a train approaches an occupied section or a segment with a lower speed limit. The speed reductions are given in ATB code tables. These tables are not used in the simulation, but instead speed reductions are modelled with a method that "looks ahead" and reduces the speed in time to meet new speed limits. This means that exceptions in the ATB code table, such as extra distance between trains due to inclination, are ignored in the simulation.

### 2.3 Model

For modelling the network a formulation based on the double vertex graph will be used. This type of graph was introduced by Montigel [7]. The double vertex graph is needed to prevent infeasible routes for route setting. In figure 2 an example of such a graph is given.

To model the network as a double vertex graph 5 types of elements are used: end of tracks, shunting yards lines, switches and crossings. A sketch of all elements is given in figure 3. In other literature [5] even more elements are defined, but those are not present in the metro
Figure 2: An example of a railway network represented as a double vertex graph. Note that every segment is modelled as a straight line in the double vertex graph. Every weld is represented as a double vertex.

network of Rotterdam. Note that the shunting yard is actually a simplification of the network and could also be modelled in detail using other elements. However, data for shunting movements is not provided and lies outside the scope of this thesis.

Figure 3: A sketch of all elements used to create a double vertex graph: (a) end of tracks, (b) shunting yards, (c) lines, (d) switches and (e) crossings.

A short description of every element will be given:

- **End of tracks**: An end of a track. Normally it is equipped with a buffer stop.

- **Shunting yards**: A shunting yard is a location where trips (see Chapter 4.1) start and end. As a shunting yard is simplified to a single element any disruptions at the shunting yard itself cannot be modelled.

- **Lines**: A line is an ordered list of connected sections. Every line could contain one or more stations. A line is directed and can be available in 0, 1 or 2 directions. The directions in the Rotterdam metro network are defined westbound (trains to De Akkers/Hoek van Holland) or eastbound (train to Den Haag Centraal/Nesselande/Binnenhof/De Terp). An initial direction and a current direction are given to every line. Further it is given whether a line is only available to train movements without passengers or to every train.

- **Switches**: Every switch is equipped with a point machine. This installation allows trains to go from one track to another. A switch contains exactly two segments.

- **Crossings**: At a crossing two segments cross at the same level, but they are not connected.
All described elements are put into two new directed graphs, one for each direction. This graph is used for train routing with and without disruptions. The following connections can be seen with the double vertex graph:

- Every double vertex in the double vertex graph will be represented by a line element with a direction given by the connected edges.

- It is desired to give directions between two switches or crossings, but only line elements have a direction. This is done by introducing an empty line without any sections, but with all other properties of a line.

- Crossings that are modelled as a single point make infeasible routes possible. Therefore every crossing is modelled as two vertices: one normal vertex and a dummy vertex. Every vertex is connected to a unique segment within a section, which is equivalent to an edge of a crossing in the double vertex graph.

An example of this newly created graph is given in figure 4. Note that the graphs for the Rotterdam metro network are acyclic. To model cyclic networks an artificial 'cut' has to be created where a train is given a new direction, even while the train itself continues running in the same direction. This problem is not yet present in the metro network of Rotterdam, but could rise with future extensions.

Figure 4: An example of a part of the network represented in a directed graph. The graph on the left is used for train routing in westbound direction, the other graph for trains in eastbound direction. Shown elements are a shunting yard (R), lines (L), empty lines ($L_e$) and switches (W).

With the use of the directed graph trains can be routed between two vertices. To identify the origin and destination of a train, stopping places or halteerpalen (HP) are defined. These
HPs could be stations, but also other places that are used for shunting or reversing a train. An HP is linked to a segment that lies either within a shunting yard or on a line. This means that HPs should not be created at crossings, switches or end of tracks. Every HP is put into a location that is of one of the next types:

- **Stations**: A station is a location where trains must stop to let passengers board and alight the train. Every station has a name and every track passing the station has its own HP.

- **Shunting Yards**: A shunting yard is a location where trains stop without passengers. Shunting yards could contain multiple HPs as they are a simplification of the real network.

The metro network of Rotterdam contains three shunting yards, namely:

- Waalhaven, which is used for rolling stock of lines D and E.
- ’s-Gravenweg, which is used for rolling stock of lines A, B and C.
- De Akkers, which is used for rolling stock of lines C and D.

A few other HPs are defined on other locations to reverse a train. For these places dummy stations are used. An overview of all HPs in the Rotterdam metro network is given in Appendix B.
3 Rolling stock

The metro network of Rotterdam is currently using rolling stock from one single manufacturer, namely Bombardier. Unfortunately not every train unit can be used on every line of the network due to different power supplies and wheel profile. The lines can be divided into three groups:

- **Lines A and B**
  Parts of the line use overhead line for power supply, other parts use a third-rail system.

- **Lines C and D**
  The whole line uses a third-rail system for power supply

- **Line E**
  Parts of the line use overhead line for power supply, other parts use a third-rail system.
  Also the wheel profile that is used is different from the other lines.

The rolling stock can be divided into five series of train units:

- **5300** (Type MG2/1): This is the only series without a pantograph and can only be used on lines C and D. The train units have a length of 30.5 meter.

- **5400** (Type SG2/1): These train units have just small differences with the 5300 series. An extra pantograph is added. The units can be used on lines A, B, C and D and can be coupled with the 5300 series. The length is also 30.5 meter.

- **5500** (Type RSG3): These train units are meant for use with line E and have a different look and seats. The length of these units is 42.71 meter.

- **5600** (Type SG3): These train units have just small differences with the 5500 series.
  Most units have a wheel profile that cannot be used on line E. These vehicles can be coupled with the 5500 and 5700 series and also have a length of 42.71 meter.

- **5700** (Type SG3): These train units are again similar to the 5500 and 5600 series, have a length of 42.71 meter and can be coupled together. These units are planned to operate on the new Hoekse Lijn, but can be used on other lines as well.

The number of available train units for every series is given in table 1. As mentioned above train units can be coupled to create longer trains. Also the maximum number of train units that can be coupled is given.

<table>
<thead>
<tr>
<th>Series</th>
<th># units</th>
<th>Max units lines A &amp; B</th>
<th>Max units line C</th>
<th>Max units line D</th>
<th>Max units line E</th>
</tr>
</thead>
<tbody>
<tr>
<td>5300</td>
<td>63</td>
<td>Not possible</td>
<td>3</td>
<td>4</td>
<td>Not possible</td>
</tr>
<tr>
<td>5400</td>
<td>18</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>Not possible</td>
</tr>
<tr>
<td>5500</td>
<td>22</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>5600</td>
<td>42</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>5700</td>
<td>16</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

*Table 1: An overview of the number of available train units per series and the maximum number of units that can be coupled.*
In the timetable all rolling stock is assigned to its own line, except for lines A and B. In the simulation all rolling stock is kept on its own line to prevent that trains run on parts of the network they are not allowed to.

The acceleration and deceleration are influenced by many factors. Both acceleration and deceleration depend on the current speed of a train. Also the driver’s driving style, the length of the train and the weight of the train (for 5300 and 5400) play a role. In the model for both acceleration and deceleration a simplification is made. A linear approximation is used that is based on measurements in practise. The parameters that are chosen to fit best to the reality are:

- Average acceleration: \(0.55 \text{ m/s}^2\).
- Average deceleration: \(0.5 \text{ m/s}^2\).

The choice of these parameters is discussed in Chapter 6.2. These values take into account that drivers don’t use the maximal possible acceleration and deceleration values to preserve the passenger comfort. A comparison to the maximal theoretical values for empty rolling stock is given in figure 5.

![Figure 5: The theoretical acceleration and deceleration curves compared to the values used in the model.](image)

As can be seen in almost all cases the theoretical values for both acceleration and deceleration are (much) higher than the values in practise, except for acceleration values at high speed.
4  Timetable

In this chapter the timetable will be described. The timetables at the RET are created using commercial planning software called HASTUS developed by the Canadian company GIRO. The created timetables are loaded into a database called RET Intermediair DataSysteem (RIDS). From this database another system called VerKeersLeider system (VKL) accesses the data again for practical use.

The timetable that is used in the simulation is imported from RIDS. The timetable structure will be described first. The realised data according to the timetable is registered every day as well using the VKL, which will be explained afterward. Finally the calculation of delays is explained in detail.

4.1  RIDS timetable

The timetable of the metro consists of circulations. Every circulation is a sequence of trips with origin and destination. Every train consists of units of the same type. Units can be coupled and uncoupled during a circulation. The timetable consists of 9 different types of actions, which are:

- **New circulation**
  This action creates a new circulation without a train. A circulation normally starts at a shunting yard, but it can also start at a (dummy) station after uncoupling a train into two trains.
  *Possible follow-up action:* Couple unit.

- **End of circulation**
  This action ends the circulation.
  *Possible follow-up action:* None.

- **Couple unit**
  A unit is coupled to the train or, if no train exists, a new train is defined containing one unit.
  *Possible follow-up action:* Couple unit or Add destination.

- **Uncouple unit**
  A unit is uncoupled. This unit will be left behind at the current location and can be used for other circulations at this location. If a unit is left behind at a (dummy) station a follow-up circulation is given.
  *Possible follow-up action:* Uncouple unit, Add characteristic or End of circulation.

- **Add destination**
  A new destination is given to the train including the direction where the train is going.
  *Possible follow-up action:* Add characteristic or Departure from station.

- **Add characteristic**
  A new characteristic is given to the train. A characteristic indicates whether a train can be used by passengers.
  *Possible follow-up action:* Uncouple unit, Add destination of Departure from station.
• **Arrival at station**
  An arrival of a train at the destination.
  
  *Possible follow-up action:* Uncouple unit, Add destination, Add characteristic or Departure from station.

• **Departure from station**
  A train departs from its origin. This action can never happen before the planned departure train.
  
  *Possible follow-up action:* Arrival at station or Arrival and departure from station.

• **Arrival and departure from station**
  This is an arrival and a departure at a station on the way. The train must stop and wait for the planned departure time.
  
  *Possible follow-up action:* Arrival at station or Arrival and departure from station.

For every timetable the default line configuration must be adjusted if some infrastructure (i.e. one track) is not available. Also when trains reverse at different places than normally it should be adjusted in the line configuration. Timetable 4818 is used as a basis in the simulation, which is a normal workday timetable without scheduled disruptions.

### 4.2 VKL logs

The VKL system is a traffic management system that registers all arrivals and departures from a station with their realised times. This data is put into a big VKL log file for every day. The generated data is used to verify the simulation for correctness. Some notes must be made about the correctness of the registered data.

- The data contains some entries that are not registered correctly or is missing. All data that could not be linked to an action of the timetable will not be used for verification. Also data with missing entries will be skipped.

- Only the part on line E with ZUB installed registers the arrivals and departures in such way they measure the exact dwelling times. For all other stations two times are registered: The time when last wheelset of a train enters the section linked to the station and the time when the last wheelset of the train has left this section.

- The entrance time of a section is a fail-safe event for security. This means the entrance of a section has happened exactly at the registered time. The clearance of a section is not a fail-safe event. A delay in the registration could have occurred, but it is assumed this is not the case.

A correction has to be made to get the dwelling time of a train at a station outside the ZUB part of the network. This is done in the following way:

- For all stations 11 seconds are added to the entrance time until the train has stopped at the station.

- For all stations 13 seconds are subtracted from the leaving time to get the departure of the station. An exception has been made for Nesselande, where only 6 seconds are subtracted.
4.3 Calculation of delays

To calculate the costs of a delay DRUs are used. A DRU is an hour in which a metro is in service for passenger transport according to schedule. The number of DRUs for a trip can easily be calculated by taking the difference between the departure time at the first station and the arrival time at the final station. A trip is delayed when at least a part of it was not performed according to schedule.

The method for measuring delays is not clearly defined. The registration of cancelled and delayed trains is done by different systems with different outcomes. Comparing these results is done manually and the outcomes are focused on cancelled trains, which are the most important measurement of quality for the local authorities. Two different kind of delays are measured in the simulation:

- **DRUs** where the metro is still going, but with a delay.
- **DRUs** where the metro is (partially) cancelled.

For measuring the delay, both the duration and the magnitude of the delay are taken into account. For example, if a trip takes 30 minutes and has a delay of exactly 30 minutes the whole trip, the delay will be $0.5 \text{ hour} \times 0.5 \text{ hour} = 0.25 \text{ hour}^2$ delay. As no measurement in DRU is currently used in practise, this multiplication will be used and presented as 0:15 DRU delay. For partial cancellations only the part of the trip that is cancelled is taken into account. For example, if a trip of 30 minutes is only cancelled over the last part of 10 minutes, a total of 0:10 DRU cancellation is registered. Both values will be given separately as they have different impact. Depending on the given penalties of the local authorities different strategies can be applied.

Finally it can be chosen to ignore small delays, such as delays less than 5 minutes. Also in the current measurements for the local authorities small delays are ignored.
5 Disruptions

This section describes all possible types of disruptions which can occur related to the infrastructure and the way that is dealt with them by the Centrale VerkeersLeiding (CVL). The new Hoekse Lijn extension contains two special disruptions that are not yet present in the Rotterdam metro network: bridge openings and the passage of freight trains. Both will be discussed in detail including the way they are implemented in the simulation.

5.1 Infrastructure related disruptions

Disruptions related to the infrastructure can be divided into different categories:

- **Section disruptions.** These disruptions occur when a section is occupied while it is supposed to be free. This means one or more sections cannot be used anymore. In reality, a train can override a section disruption by passing the disrupted sections with a speed of at most 10 kilometres per hour. However, in the simulation it will be assumed the track is totally blocked and it is faster to bypass the section over the track used for trains in the opposite direction.

- **Switch failures.** These disruptions can have different consequences: the switch can be used in only one direction, the switch cannot be used at all, the switch can only be passed with a reduced speed or a combination of these. To determine the importance of a switch only the effect of not using the switch at all is modelled.

- **Power outages.** These disruptions can occur in different degrees, from very local to the whole network. Power outages can be modelled with respect to a group of switches or lines.

All described disruptions have in common that a part the network is blocked and trains should be diverted. In reality multiple disruptions can happen at the same time. This could result in severe delays if, for example, two switches near each other are both malfunctioning. The effect of disruptions influencing each other are not modelled in the simulation.

5.2 Centralized traffic control

At the CVL the location of all trains is shown on digital screens. The train dispatcher can set and adjust the route setting of a train. In the undisturbed situation almost all routes are set automatically, as most tracks are only used by trains in one direction. At the stations where a train reverses an automated train reverse process is implemented (see Chapter 7.1.1). Scenarios are available to tell how trains should follow new routes when disruptions occur. As an example the scenarios for disruptions at Rotterdam Centraal are discussed below.

Every scenario is based on the past experiences of a train dispatcher. This does not imply that a scenario is the best to minimize the delays, but different scenarios could be compared in the simulation. The scenarios are created with the focus on running as much trains as possible. Depending on the penalty system given by the regional authorities this is also subject to change. Also it should be noted that train dispatchers could act depending on their own experiences and they don’t have to follow a prescribed scenarios. As an example the prescribed scenarios for Rotterdam Centraal are discussed in detail.
5.2.1 Scenarios for Rotterdam Centraal

For Rotterdam Centraal four disruption scenarios exist: three scenarios for each of the tracks and a scenario when all tracks are disrupted. The first three scenarios are given in figure 6.

![Disruption scenarios for Rotterdam Central](image)

Figure 6: Disruption scenarios for Rotterdam Central. The normal situation is given in the upper left corner. The other images show disruption scenarios M1.1 (upper right), M1.2 (lower left) and M1.3 (lower right). The disrupted tracks are indicated with thick gray arrows.

In the normal situation a primary and secondary track are given for the automated train reverse process. In all scenarios all trains are still operating, but are running from different tracks. The last scenario is more complex as trains have to be reversed and renumbered to other circulations. Furthermore trains running on line E between Rotterdam Centraal and Slinge are heading back to the shunting yard at Waalhaven until the disruption is over. This disruption scenario is given in figure 7.

![Disruption scenario M1.0](image)

Figure 7: Disruption scenario M1.0 where Rotterdam Central is completely unavailable.

The renumbering of trains is a process that is very much depending on the way the train dispatcher acts. The effects of these scenarios are not be modelled with the simulation due to limited time. A process to automatically renumber trains was recently implemented, but took years to develop.

5.3 Bridges

The Hoekse Lijn extension contains two bridges: one near Maassluis and one near Vlaardingen. Both bridges can be opened outside the peak hours, with the peak hours defined as:

- Morning peak hours: Monday to Friday (except holidays) from 6:45 am to 9:15 am.
- Evening peak hours: Monday to Friday (except holidays) from 3:45 pm to 6:30 pm.

The usage of the bridges varies. The Maassluis bridge is mostly used during the week by commercial vessels, while the Vlaardingen bridge is mostly used by leisure vessels during the weekends and holidays. The number of openings per day also varies a lot as shown by historical data from the year 2014. The number of openings can be vary from 0 up to 20 openings.
a day per bridge. Most bridge openings take around 3 to 4 minutes for Vlaardingen and 4 to 7 minutes for Maassluis as can be seen in figure 8.

![Bridge opening at Vlaardingen](image)

![Bridge opening at Maassluis](image)

*Figure 8: Duration of bridge openings over the year 2014 on the Hoekse Lijn*

The timetable of the Hoekse Lijn is fitted to the Maassluis bridge to minimize the impact of the bridge openings. This means that the bridge always opens after a train in eastern direction have passed. Trains in the western direction (to Hoek van Holland) are scheduled to pass one minute before. This way the impact of delays on the rest of the network is minimized. When a bridge is open, a train must wait until the bridge is closed again. It is desired to wait at the last station instead of in front of the opened bridge.

### 5.4 Freight trains

From Schiedam Centrum to Vlaardingen Oost both passenger trains and freight trains make use of the same southern track. The freight trains use a different security system, which limits them to a maximum speed of 40 km/h. Due to different train widths a secondary track is added along the station platforms for the freight trains. This parallel track has no influence on trains coming from the opposite direction as is shown in figure 9.

![Schiedam Nieuwland track 1](image)

![Schiedam Nieuwland track 2](image)

*Figure 9: Parallel track illustration at Schiedam Nieuwland station.*

At the moment a freight train enters the line the whole route up to the place where the freight train leaves the track must be free. A metro train can only enter the track after the freight train has passed a section or left the common track. The only exception is made for the crossing of the freight train on the northern track. The expected number of freight trains has a maximum of 3 per day. However, due to the irregular timetable of freight trains a path should be available every hour.

Other differences with between freight trains and normal trains are the train characteristics. The acceleration and deceleration are much lower due to the higher weight of the train. For both values $0.3m/s^2$ is estimated, but not verified. These values could also vary significantly depending on the weight of the train. Freight trains will consist of a locomotive with
at most 16 carriages with a total length of around 250 meter.

5.5 Model

Modelling disruptions is done by dividing the disruptions into two groups: active and passive disruptions. Active disruptions are disruption where trains are diverted into other routes. This is done by adjusting the graph described in Chapter 2.3. Creating such a disruption takes two steps.

1. Deleting the disrupted parts. For all sections that are not available the corresponding elements in the graph with all their connecting edges are deleted. This way no trains can be routed over the disrupted parts of the network.

2. Creating alternative routes. For the track in the opposite direction edges are added such that the track becomes available in both directions.

The newly created graph is used for the time that the disruption last. If the disruption has ended the old graph is restored and trains are routed according to their original route again.

Alternative routes create new problems as trains in both directions are running on a single track. If trains from both directions are approaching the single track, a decision should be made about the order in which trains are allowed to pass. This could be the first train arriving, but it could also be a delayed train in the opposite direction. Again it is not clearly defined what should happen and it mainly depends on the decision made by the train dispatcher. To make a fair balance a policy should be defined about the maximum number of trains passing in each direction. A maximum number of trains per direction does not have to be defined, but could result in a train waiting for a long time until all trains in the other direction have passed the single track.

The part where trains are running on a single track is identified with a single track area. This area contains all elements of the graph where trains in both directions are passing. A train is queued if it has to wait until the whole single track area is free again. A single track area is only available for trains in a single direction in such way that deadlocks are prevented.

Passive disruptions are disruptions where trains are waiting until the disruption is solved, which is the case with bridges and freight trains. A bridge will be modelled by occupying a set of sections. These sections will be reserved from the first sections after a station up to the bridge itself. When all these sections are reserved in both directions, the bridge can be opened. Before the bridge is closed completely a train is allowed to approach the bridge. This way the delays are minimized. A passing freight train is also modelled as a passive disruption.
6 Data analysis

To compare the simulation to the real situation an extensive data analysis was done. This was done using the log files of the VKL system (see Chapter 4.2) and the existing metro simulator. Both the dwelling times and the travel times are discussed in this chapter.

6.1 Dwelling times

The dwelling time is the time between the arrival and the departure of a train at a station. The dwelling time can be influenced by multiple factors:

- The time needed for passengers to board and alight.
- No permission to leave the station by a stopping signal.
- Disruptions: problems with the rolling stock or passengers that cause delays.

Disruptions caused by the rolling stock or passengers are not in the scope of this thesis. No permission to leave the station can have several causes:

- Waiting because the train is too early.
- Waiting because the route is occupied by another train.
- Waiting because an intersection has not yet been cleared.
- Waiting because of an open bridge or passing freight train.

The boarding and alighting of passengers is most interesting to study, as can be seen in studies like [4] and [6]. Some passenger influences that have effect on the boarding time are:

- The number of passengers boarding and alighting the train.
- The passenger load factor of the train.
- The spread of the passengers over the train and at the station.
- The passenger behaviour during boarding.

The main problems lie in obtaining sufficient data to estimate dwelling times and finding the right distribution over the day. The VKL log files contain almost all necessary data. Using a fixed correction (see Chapter 4.2) the dwelling times are estimated in the same way for every station.

It is desired to have a distribution of the minimal dwelling time needed at a station for every train. The early arrival of a train will be dealt with separately, as the dwelling time will be longer than strictly necessary. This is also the case when a route is occupied by another train. To get the desired distributions the VKL log files have to be filtered for departures only. Only the dwelling times of passenger trains in service are used. To filter out early arrivals the trains that are waiting for permission to continue will be left out as well. Finally, some errors in the registration are left out. In total around 20% of all stops is filtered as can
be seen in table 2. The other 80% is used to estimate the dwelling time distributions.

Unfortunately for some HPs it is still not possible to perform a good data analysis. Trains reversing at their final destination usually wait extra minutes giving insufficient data for dwelling times. Another reason is that some HPs are used for both trains changing direction and onward trains. For these stops a fixed dwelling time of 15 seconds is used.

The dwelling time distributions can be calculated in different level of precision. The following levels can be distinguished.

1. One distribution per HP only.
2. One distribution per HP per hour.
3. One distribution per HP per hour and depending on the headway to the last vehicle.

To see which kind of precision is needed in the simulation the effects have to be compared to each other. Then the desired distributions have to be calculated.

**6.1.1 Comparing different calculation methods**

A detailed analysis was done using all realised data over June 2015 as given in Appendix C. To get the busiest periods only the weekdays outside holidays are used. A distribution of the dwelling time is created for every HP and the means are compared. Afterwards detailed distribution are made for every HP using data for every block of one hours. All HPs showing an unexpected distribution are studied in detail and explained in the given appendix.

This study over June 2015 showed some undesired values in the distribution due a lack of data. To improve the approximation the data is extended to the period July 2014 until June 2015. The construction work done in June 2015 is now filtered out, as well as possible other seasonal effects. For every HP a distribution can be found in figure 10. Comparing the means shows only small differences to the results of June 2015 as given in figure 23. Also for the distributions per HP per hour show only small differences compared to June 2015.

The last factor that can influence the dwelling time is the headway between two trains. Disruptions cause infrequent headways between trains, which could result in accumulating delays. To measure the strength of this effect some of the busiest stations (Beurs and Zuidplein) are

---

<table>
<thead>
<tr>
<th>Description</th>
<th>Total number of events</th>
</tr>
</thead>
<tbody>
<tr>
<td>All registered events</td>
<td>191456</td>
</tr>
<tr>
<td>All registered departures</td>
<td>95737</td>
</tr>
<tr>
<td>All registered departures of passenger trains</td>
<td>91789</td>
</tr>
<tr>
<td>As above, but only without waiting signalling</td>
<td>80257</td>
</tr>
<tr>
<td>As above, but only where the dwelling time is registered</td>
<td>75461</td>
</tr>
</tbody>
</table>

Table 2: An indication of how many dwelling times are filtered to find the minimal dwelling time distributions. This data is over 5 random weekdays in 2015.
studied during the morning peak hour between 8 and 9 am. Unfortunately it is difficult to obtain sufficient data for cases with long headways as can be seen in figure 11. The resulting headway distributions are shown in figure 12.

The effect of delays can be seen in the headway figures at Beurs. At this station the busiest direction in the morning peak hours is HP 8139. The figures imply a linear increase in dwelling time in relation to the headway. However, an exponential increase is expected when the station platform is getting crowded.
When having sufficient data and a crowded network it is useful to apply the distribution that takes into account headways. For the Rotterdam metro network it is difficult to obtain sufficient data for long headways and the effect is small. Therefore the second step of precision is used in the simulation: a distribution per HP per hour.

6.1.2 Calculating the distribution

For every HP and for every block of one hour all dwelling times are sorted from the data as described in the previous section. This is done using Java. For every hour and every distribution the 25% and 75% quantiles are calculated to eliminate the data that have exceptional long or short dwelling times. All measurement between these quantiles are used to fit a discrete distribution. This data manipulation is done using R. The simulation will sample random values from this discrete distribution, depending on the HP and the hour.

6.2 Travel times

Accurate travel times are very important to make a reliable timetable. The travel times are depending on multiple factors as:

- Rolling stock characteristics: The vehicle length, the acceleration and deceleration curves.
- Passenger characteristics: The number of passengers inside the metro.
- Driver characteristics: The driving style of the driver.
- Network characteristics: The length, inclination and maximum speed allowed on a segment or discontinuous power supply.
- Operation: Waiting for other trains.
Figure 12: Analysis of headways vs dwelling times in morning peak hours at Beurs and Zuidplein. The data contains the headways per direction (Monday-Friday outside holidays, 8-9am, July 2014-June 2015).
For all characteristics assumptions have to be made. The number of passengers inside the metro is ignored, as the effect is minimal and only present in the 5300 and 5400 series (see Chapter 3). The simulation is run in discrete time. Two different models were implemented with different levels of accuracy:

1. Updating the simulation once per section, moving the train from segment to segment at once and ignoring the train length.

2. Updating the simulation every time a train leaves or enters a section, moving the train in two steps per segment and taking into account the train length.

Results of the first model showed large inaccuracies, mainly because of ignoring the train length on small section lengths. The second model is therefore used for further analysis and can be seen as a sequence of actions shown in figure 13.

![Figure 13: Actions involving the movement of trains.](image)

After every action a new maximum allowed speed limit is determined, but also distance and travel time until the next action. Technical details about the calculation of this data is given in Appendix D.

To verify the travel times the VKL logs are not sufficient. The normal situation is logged, but there is insufficient data for the disrupted scenarios. Therefore the existing full scope metro simulator was used. In two sessions experienced metro drivers was asked to drive all specific routes to measure the travel times. The first session was asked to drive all possible routes between Delfshaven, Coolhaven and Dijkzigt (16 in total). These results were used to determine the best acceleration and deceleration parameters for the rolling stock (see Chapter 3). Furthermore an extra parameter is used to lower the maximum speed limit. This value between 0 and 1 indicates that a driver is never driving exactly the maximum allowed speed but just below the speed limit. Some experiments in changing the acceleration, deceleration and this parameter showed that 0.95 gives the best approximation to reality. This means that for a speed limit of 80 km/h, the train never goes faster than 76 km/h. A comparison between the travel times in the full-scope metro simulator and the simulation results can be seen in table 3 and 4.

Compared to the full-scope metro simulator it can be seen that the travel times are at most around 12% away from the measured travel times. The biggest differences occur at places with a significant track inclination, which is not taken into account in the model. The second
### Table 3: The metro simulator travel times compared to the modelled simulation statistics.

<table>
<thead>
<tr>
<th>Route</th>
<th>HPs</th>
<th>Direction</th>
<th>Metro simulator</th>
<th>Simulation</th>
<th>Difference (in %)</th>
<th>Sum of squares</th>
</tr>
</thead>
<tbody>
<tr>
<td>DHV - CHV</td>
<td>8147-8145</td>
<td>E</td>
<td>72.83 s</td>
<td>68.04 s</td>
<td>-6.6%</td>
<td>5507</td>
</tr>
<tr>
<td>DHV - CHV</td>
<td>8147-8144</td>
<td>E</td>
<td>92.64 s</td>
<td>81.44 s</td>
<td>-12.1%</td>
<td></td>
</tr>
<tr>
<td>DHV - CHV</td>
<td>8146-8145</td>
<td>E</td>
<td>84.17 s</td>
<td>83.10 s</td>
<td>-1.3%</td>
<td>622</td>
</tr>
<tr>
<td>DHV - CHV</td>
<td>8146-8144</td>
<td>E</td>
<td>69.41 s</td>
<td>68.47 s</td>
<td>-1.4%</td>
<td></td>
</tr>
<tr>
<td>CHV - DZT</td>
<td>8144-8143</td>
<td>E</td>
<td>56.87 s</td>
<td>57.78 s</td>
<td>1.6%</td>
<td>484</td>
</tr>
<tr>
<td>CHV - DZT</td>
<td>8144-8142</td>
<td>E</td>
<td>60.09 s</td>
<td>58.22 s</td>
<td>-3.1%</td>
<td></td>
</tr>
<tr>
<td>CHV - DZT</td>
<td>8145-8143</td>
<td>E</td>
<td>62.06 s</td>
<td>57.59 s</td>
<td>-7.2%</td>
<td></td>
</tr>
<tr>
<td>CHV - DZT</td>
<td>8145-8142</td>
<td>E</td>
<td>65.50 s</td>
<td>66.94 s</td>
<td>2.2%</td>
<td></td>
</tr>
<tr>
<td>CVH - DHV</td>
<td>8145-8147</td>
<td>W</td>
<td>70.41 s</td>
<td>68.88 s</td>
<td>-2.2%</td>
<td></td>
</tr>
<tr>
<td>CVH - DHV</td>
<td>8145-8146</td>
<td>W</td>
<td>89.61 s</td>
<td>83.74 s</td>
<td>-6.6%</td>
<td></td>
</tr>
<tr>
<td>CVH - DHV</td>
<td>8144-8147</td>
<td>W</td>
<td>88.96 s</td>
<td>81.68 s</td>
<td>-8.2%</td>
<td></td>
</tr>
<tr>
<td>CVH - DHV</td>
<td>8144-8146</td>
<td>W</td>
<td>73.28 s</td>
<td>68.72 s</td>
<td>-6.2%</td>
<td></td>
</tr>
<tr>
<td>DZT - CHV</td>
<td>8143-8144</td>
<td>W</td>
<td>58.46 s</td>
<td>58.27 s</td>
<td>-0.3%</td>
<td></td>
</tr>
<tr>
<td>DZT - CHV</td>
<td>8143-8145</td>
<td>W</td>
<td>57.75 s</td>
<td>57.75 s</td>
<td>0.0%</td>
<td></td>
</tr>
<tr>
<td>DZT - CHV</td>
<td>8142-8144</td>
<td>W</td>
<td>60.00 s</td>
<td>58.14 s</td>
<td>-3.1%</td>
<td></td>
</tr>
<tr>
<td>DZT - CHV</td>
<td>8142-8145</td>
<td>W</td>
<td>61.49 s</td>
<td>66.03 s</td>
<td>7.4%</td>
<td></td>
</tr>
</tbody>
</table>

### Table 4: An overview of the metro simulator travel times compared to the modelled simulation.

session in the metro simulator was based on comparing the travel times at places with slopes. Another verification is done using the VKL logs for the normal situation. (See Chapter 8).
7 Simulation

In the previous chapters all necessary information was given to construct the metro network. To run the simulation some manual processes done by the CVL have to be automated. First the routing of trains is explained in detail including the automated train reverse process. For analysing the effect of a disruption the simulation should finish without creating a deadlock. Route setting and deadlocks prevention is explained next.

The simulation is based on discrete events based on the timetable (see Chapter 4) and movement of trains (see Figure 13). The simulation is executed over 24 hours from 4 am to 4 am the next day. All disruptions have to be defined before the simulation starts.

7.1 Routing

Routing is done using the network graph as described in Chapter 2.3. To find a route to the destination of a train several optimization criteria could be considered:

- Minimum distance to the destination.
- Minimum travel time to the destination.
- Minimum the number of switches on the way to the destination.
- Some preferred routing by a train dispatcher.

Unfortunately it is not always clear which route is best to choose. In the simulation it is assumed that the route passing the minimum number of switches is optimal. This is a reasonable assumption, as most switches are only used to handle disruptions. The algorithm of Dijkstra is used multiple times to determine the route. This is done using the following steps:

- Depending on the direction and characteristic of the train the right network graph is chosen.
- In the chosen network graph Dijkstra’s algorithm is applied with every edge having default weight. This results in a path with the lowest number of nodes in the network graph, which equals the path with the lowest number of crossings and switches.
- For every point in the network graph Dijkstra is applied again to find a shortest path within the element. In most cases this is a trivial Dijkstra algorithm, except for large groups of connected switches.

This way a route is not determined uniquely. If desired to pass a certain HP such a route must be calculated in two parts: a part up to the intermediate point and a route from this intermediate point.
7.1.1 Automated train reverse process

The automated train reverse process is used to increase the capacity at stations where trains turn around. When a train turns around normally two tracks are available with one preferred track. If the preferred track is occupied by another train the other track is chosen automatically. Choosing a track is done as late as possible, such that the most trains will go to their preferred track. This selection is only done in the simulation when a train has no reserved sections. The automated train reverse process is installed for the following stations in the Rotterdam metro network:

- Line A at Nesselande, trains to the east.
- Line B at Binnenhof, trains to the east.
- Line C at De Terp, trains to the east.
- Line A and B Schiedam Centrum shunting yard, trains to the west until the Hoekse Lijn extension is in service.
- Line C and D at De Akkers, trains to the west.
- Line C and D at De Akkers shunting yard, trains to the west.
- Line D at Rotterdam Centraal, trains to the east.
- Line E at Rotterdam Centraal, trains to the west.
- Line E at Den Haag CS, trains to the east.
- Line E at Slinge shunting yard, trains to the west.

Note that line C and D have two places to reverse. This is done due to the high frequency of trains at De Akkers. If the turnaround time is short the reverse process at De Akkers is used. If the train is too early and would keep the platform at De Akkers busy for too long, the train reverse process at De Akkers shunting yard is used. The simulation uses the reverse process as defined in the timetable.

7.2 Route setting and deadlock avoidance

Every section can be occupied or reserved by only one vehicle at a time. To prevent collisions routes has to be set. In practise reserved sections are sometimes cancelled to create routes for other trains, but this is not desired in the simulation. The approach is to minimize the number of reserved sections using the breaking distance of a train. Sections must be reserved for at least the length of the breaking distance of a train such that collisions between trains are avoided. The capacity is decreased if more sections are reserved than necessary. This is illustrated in figure 14.

It is not always possible to reserve a section. This could be because the section itself is occupied, but also because some other sections are occupied and a reservation would lead to a deadlock. Deadlocks are created by group of trains that are waiting for each other to continue. Deadlocks in relation to railway networks are studied before by Cui and Pachl.
Figure 14: A train blocking a crossing and switch for other trains. The left figure shows a reserved route (yellow) for a train (red) that is blocking a crossing. The right figure shows a reserved route blocking a group of switches, preventing the other train to leave the station.

8. The probability of a deadlock occurring highly depends on the network configuration. As the whole Rotterdam metro network has a double track layout almost every it is very rare a deadlock occurs in the normal situation. In disruptions it is not uncommon anymore. To reduce the probability of a deadlock appearing in the simulation circular wait events have to be prevented.

To determine whether a section can be reserved single track areas and turning areas are defined. The simulation makes uses of 3 different wait events:

- Waiting for a free section.
- Waiting for a free single track area.
- Waiting for a free reverse area.

A train has to wait when no section on its route can be reserved. If a train is not allowed to enter the next section a "Waiting for a free section" event is used in general, but if a track is used for trains in both directions a "Waiting for a free single track area" is used. This wait event is released if the whole single track area is cleared for trains in the other direction. A reverse area is used to determine whether enough capacity exists at the end of a line to reverse a train. An illustration of these areas is given in figure 15.

Figure 15: Illustration of a reverse area and two single track areas in the simulation. On the left as represented in the simulation, on the right a scheme of the same part of the network.

To reserve sections it must be noted that a route is built out of different areas with possibly segments in between. It is assumed that a disruption is never present at both sides of a
reverse area, such that the route only has to be set up to the next reverse area. This way a route can be represented as given in figure [16].

![Train route diagram]

**Figure 16: Schematic build of a train route. The part of the route after the reverse area is not taking into account for determining the block signalling.**

Using the given structure of a route, the route setting is done taking into account the following criteria:

- It is only allowed to reserve a switch or crossing if another section is available at the other side of the group of switches or crossing. This way the blocking of switches and crossings is minimized.

- If it is allowed to reverse on a line, this line is available to a single train only.

This results in the algorithm described below:

1. Determine the desired sections on the route to reserve by calculating the segments within the breaking distance.

2. Extend the selection until the last section is either connected to a line or shunting yard, such that switches and crossings are not unnecessary blocked.

3. Set marker for checked sections to 0 (no segments are checked yet).

4. Loop through the segments of the train until all desired sections are marked as checked.
   - Check whether the segment lies inside a new single track area. If so:
     - Check whether the single track area is free to enter (**). If not:
       - Shorten the desired sections up to this section.
       - If the last section is not connected to either a line or shunting yard: shorten the desired sections until it does. This way switches and crossings are not unnecessary blocked.
       - If no section can be reserved: check whether the train has already entered another single track area. If so: Create ”Waiting for a free section” event. Else: Create ”Waiting for a free single track area” event.
       - Go to step 5.
     - Continue to next segment.
   - Check whether the segment lies on a line or shunting yard. If so:
– Check whether the segment lies inside a reverse area without any free track. If so:
  * Shorten the desired sections up to this section.
  * If the last section is not connected to either a line or shunting yard, shorten the desired sections until it does. This way switches and crossings are not unnecessarily blocked.
  * If no section can be reserved: Create ”Waiting for a free reverse area” event.
  * Go to step 5.
– Note: the reached segment lies either inside: a double track area, shunting yard or a reverse area with a free track. Loop through all segments from the last checked section marker up to the reached segment.
  * Check whether the section is occupied or reserved by another train. If so:
    · Shorten the desired sections up to this section.
    · If the last section is not connected to either a line or shunting yard, shorten the desired sections until it does. This way switches and crossings are not unnecessary blocked.
    · If no section can be reserved: Create ”Waiting for a free section” event.
    · Go to step 5.
  * Increase last checked section marker by 1.
  • Continue to next segment.

5. If the checked section marker is greater than 0: Reserve all checked sections.

With this algorithm a route is never reserved over a longer distance than needed. Implementation of the algorithm showed that deadlocks were reduced to an acceptable level. Note however that deadlocks are not prevented for every network configuration. For this situation a more extended reservation system for sections have to be used as is described by Pachl [8]. This implementation makes it easier to experiment with different policies for the number of trains passing on a single track area. This is done during the step marked in the algorithm with (**). Only if all the conditions below are met a train has to wait to enter:

• If a train in the other direction is waiting to enter the single track area.
• If the maximum number of trains for the current direction is exceeded.
• If the train has not entered another single track area (if so, the policy will be ignored).
8 Results

One of the main goals of the project was to develop a simulation that could be used in practice by the RET. The simulation that is developed contains a Graphical User Interface and can be used by both involved RET departments. Results of the simulation tool are presented below.

8.1 Travel times results

The second session in the metro simulator (see also Chapter 6.2) was used for verification of the model whether it can be used in practise. These measurements are given in tables 5 and 6. Note that the measurements were done at places where differences were expected (as mentioned in Appendix A).

Almost all travel times calculated with the simulation give a good estimate compared to the travel times with the full scope metro simulator. Most travel times only varied only varied some seconds, which is also the case in reality depending on the metro driver.

Multiple reasons were found that could influence the travel times and were not modelled in the simulation. Some travel times show large differences with the simulation, but they could be explained. The reasons are given below, including an estimate of the effect on the travel time in seconds. The numbers correspond to the remarks in table 5.

1. A station lies on a downhill slope. As it is more difficult to come to a stop the station will be entered slower than other stations. The estimated extra travel time is about 10 seconds.

2. A station lies on an uphill slope. A driver must enter the station faster and it is easier to come to a halt. The travel time is shortened by roughly 6 – 8 seconds.

3. A part of the track lies on an uphill slope combined with a low speed limit. It gets more difficult to accelerate directly after the uphill part, creating an extra travel time of roughly 10 seconds depending on the length of the slope.

4. An interruption in a third-rail system prevents acceleration. The loss in travel times highly depends on the length of the train, the current speed and the length of the part without a third-rail system. Especially when a third-rail is interrupted on an uphill slope the extra travel time is significant.

5. The place to stop at a platform is situated far away from the middle of the segment. This effect is mainly seen on the RandstadRail part of line E. The travel time could differ up to 5 – 10 seconds.

6. An error in the speed limit of the full-scope metro simulator. Even the tested metro simulator is not free of bugs.

If the results with an explanation for a longer (or shorter) travel time are eliminated the measured distances are small. The average travel times is about 3 percent shorter than expected and a maximum unexplained difference of 15 percent of the travel time was found.
<table>
<thead>
<tr>
<th>Route</th>
<th>HPs</th>
<th>Direction</th>
<th>Metro simulator</th>
<th>Simulation</th>
<th>Difference</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>RHO - PTG</td>
<td>8016-8018</td>
<td>E</td>
<td>105.19 s</td>
<td>106.53 s</td>
<td>1.3%</td>
<td></td>
</tr>
<tr>
<td>RHO - PTG</td>
<td>8016-8021</td>
<td>W</td>
<td>140.78 s</td>
<td>126.23 s</td>
<td>-10.3%</td>
<td></td>
</tr>
<tr>
<td>RHO - PTG</td>
<td>8019-8021</td>
<td>W</td>
<td>108.53 s</td>
<td>105.81 s</td>
<td>-2.5%</td>
<td></td>
</tr>
<tr>
<td>RHO - PTG</td>
<td>8019-8018</td>
<td>W</td>
<td>147.11 s</td>
<td>125.47 s</td>
<td>-14.7%</td>
<td>3</td>
</tr>
<tr>
<td>PTG - RHO</td>
<td>8021-8019</td>
<td>E</td>
<td>111.18 s</td>
<td>106.81 s</td>
<td>-3.9%</td>
<td></td>
</tr>
<tr>
<td>PTG - RHO</td>
<td>8021-8016</td>
<td>E</td>
<td>146.84 s</td>
<td>127.15 s</td>
<td>-13.4%</td>
<td></td>
</tr>
<tr>
<td>PTG - RHO</td>
<td>8018-8016</td>
<td>E</td>
<td>114.05 s</td>
<td>106.29 s</td>
<td>-6.8%</td>
<td></td>
</tr>
<tr>
<td>PTG - RHO</td>
<td>8018-8019</td>
<td>E</td>
<td>148.38 s</td>
<td>125.47 s</td>
<td>-15.4%</td>
<td></td>
</tr>
<tr>
<td>RCS - BDP</td>
<td>8001-8703</td>
<td>E</td>
<td>93.69 s</td>
<td>97.85 s</td>
<td>4.4%</td>
<td>1</td>
</tr>
<tr>
<td>BDP - MTW</td>
<td>8703-8707</td>
<td>E</td>
<td>140.79 s</td>
<td>124.58 s</td>
<td>-11.5%</td>
<td>6</td>
</tr>
<tr>
<td>MTW - BDP</td>
<td>8708-8704</td>
<td>W</td>
<td>144.18 s</td>
<td>130.69 s</td>
<td>-9.4%</td>
<td></td>
</tr>
<tr>
<td>BDP - MTW</td>
<td>8704-8000</td>
<td>W</td>
<td>89.12 s</td>
<td>90.90 s</td>
<td>2.0%</td>
<td></td>
</tr>
<tr>
<td>BDP - MTW</td>
<td>8704-8700</td>
<td>W</td>
<td>120.89 s</td>
<td>100.09 s</td>
<td>-17.2%</td>
<td>3, 4</td>
</tr>
<tr>
<td>RHV - WHP</td>
<td>8008-8036</td>
<td>E</td>
<td>65.69 s</td>
<td>54.60 s</td>
<td>-16.9%</td>
<td>1</td>
</tr>
<tr>
<td>WHP - LHV</td>
<td>8036-8006</td>
<td>E</td>
<td>79.96 s</td>
<td>83.76 s</td>
<td>4.8%</td>
<td></td>
</tr>
<tr>
<td>RHV - WHP</td>
<td>8009-8036</td>
<td>E</td>
<td>74.00 s</td>
<td>59.41 s</td>
<td>-19.7%</td>
<td>1</td>
</tr>
<tr>
<td>RHV - WHP</td>
<td>8009-8035</td>
<td>E</td>
<td>65.89 s</td>
<td>55.06 s</td>
<td>-16.4%</td>
<td>1</td>
</tr>
<tr>
<td>WHP - LHV</td>
<td>8035-8007</td>
<td>E</td>
<td>85.26 s</td>
<td>88.12 s</td>
<td>3.4%</td>
<td></td>
</tr>
<tr>
<td>LHV - WHP</td>
<td>8006-8036</td>
<td>W</td>
<td>78.08 s</td>
<td>84.48 s</td>
<td>8.2%</td>
<td>2</td>
</tr>
<tr>
<td>WHP - RHV</td>
<td>8036-8008</td>
<td>W</td>
<td>72.81 s</td>
<td>54.01 s</td>
<td>-25.8%</td>
<td>3</td>
</tr>
<tr>
<td>WHP - RHV</td>
<td>8036-8009</td>
<td>W</td>
<td>99.10 s</td>
<td>59.37 s</td>
<td>-40.1%</td>
<td>3</td>
</tr>
<tr>
<td>LHV - WHP</td>
<td>8007-8035</td>
<td>W</td>
<td>81.35 s</td>
<td>89.33 s</td>
<td>9.8%</td>
<td>2</td>
</tr>
<tr>
<td>WHP - RHV</td>
<td>8035-8009</td>
<td>W</td>
<td>70.09 s</td>
<td>53.96 s</td>
<td>-23.0%</td>
<td>3</td>
</tr>
<tr>
<td>PKV - LVN</td>
<td>8735-8722</td>
<td>W</td>
<td>51.82 s</td>
<td>35.81 s</td>
<td>-30.9%</td>
<td>5 (twice)</td>
</tr>
<tr>
<td>FPA - LVN</td>
<td>8724-8722</td>
<td>W</td>
<td>73.00 s</td>
<td>67.52 s</td>
<td>-7.5%</td>
<td></td>
</tr>
<tr>
<td>LVN - NDP</td>
<td>8722-8720</td>
<td>W</td>
<td>116.99 s</td>
<td>118.16 s</td>
<td>1.0%</td>
<td></td>
</tr>
<tr>
<td>NDP - LVN</td>
<td>8719-8721</td>
<td>E</td>
<td>124.98 s</td>
<td>122.10 s</td>
<td>-2.3%</td>
<td></td>
</tr>
<tr>
<td>LVN - FRA</td>
<td>8721-8723</td>
<td>E</td>
<td>71.93 s</td>
<td>68.43 s</td>
<td>-4.9%</td>
<td></td>
</tr>
<tr>
<td>LVN - PKV</td>
<td>8721-8735</td>
<td>E</td>
<td>53.02 s</td>
<td>31.87 s</td>
<td>-39.9%</td>
<td>5 (twice)</td>
</tr>
<tr>
<td>SPC - ZPT</td>
<td>8027-8025</td>
<td>E</td>
<td>149.90 s</td>
<td>149.18 s</td>
<td>-0.6%</td>
<td>3</td>
</tr>
<tr>
<td>SPC - ZPT</td>
<td>8024-8022</td>
<td>E</td>
<td>147.10 s</td>
<td>141.32 s</td>
<td>-3.9%</td>
<td>3</td>
</tr>
<tr>
<td>ZPT - SPC</td>
<td>8022-8024</td>
<td>W</td>
<td>145.15 s</td>
<td>141.47 s</td>
<td>-2.5%</td>
<td></td>
</tr>
<tr>
<td>ZPT - SPC</td>
<td>8022-8027</td>
<td>W</td>
<td>176.93 s</td>
<td>164.78 s</td>
<td>-6.9%</td>
<td>3</td>
</tr>
<tr>
<td>ZPT - SPC</td>
<td>8025-8027</td>
<td>W</td>
<td>139.42 s</td>
<td>140.07 s</td>
<td>0.5%</td>
<td></td>
</tr>
<tr>
<td>ZPT - SPC</td>
<td>8025-8024</td>
<td>W</td>
<td>170.84 s</td>
<td>164.84 s</td>
<td>-3.5%</td>
<td>3</td>
</tr>
<tr>
<td>TSW - PNS</td>
<td>8044-8164</td>
<td>E</td>
<td>176.25 s</td>
<td>174.23 s</td>
<td>-1.1%</td>
<td></td>
</tr>
<tr>
<td>PNS - VSZ</td>
<td>8164-8162</td>
<td>E</td>
<td>166.68 s</td>
<td>161.15 s</td>
<td>-3.3%</td>
<td></td>
</tr>
<tr>
<td>VSZ - TSL</td>
<td>8162-8160</td>
<td>E</td>
<td>89.05 s</td>
<td>85.24 s</td>
<td>-4.3%</td>
<td></td>
</tr>
<tr>
<td>PWG - TSL</td>
<td>8157-8159</td>
<td>W</td>
<td>77.30 s</td>
<td>71.36 s</td>
<td>-7.7%</td>
<td></td>
</tr>
<tr>
<td>TSL - VSZ</td>
<td>8159-8161</td>
<td>W</td>
<td>85.16 s</td>
<td>85.44 s</td>
<td>0.3%</td>
<td></td>
</tr>
<tr>
<td>VSZ - PNS</td>
<td>8161-8163</td>
<td>W</td>
<td>172.91 s</td>
<td>162.34 s</td>
<td>-6.1%</td>
<td></td>
</tr>
</tbody>
</table>

Table 5: An overview of the metro simulator travel times compared to the modelled simulation (1).
Table 6: An overview of the metro simulator travel times compared to the modelled simulation (2).

<table>
<thead>
<tr>
<th>Route</th>
<th>HPs</th>
<th>Direction</th>
<th>Metro simulator</th>
<th>Simulation</th>
<th>Difference</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>PWG - SDM</td>
<td>8158-8156</td>
<td>E</td>
<td>83.85 s</td>
<td>84.28 s</td>
<td>0.5%</td>
<td></td>
</tr>
<tr>
<td>SDM - PWG</td>
<td>8155-8157</td>
<td>W</td>
<td>84.53 s</td>
<td>83.97 s</td>
<td>-0.7%</td>
<td></td>
</tr>
<tr>
<td>SDM - mcp 1 - MCP</td>
<td>8156-8148</td>
<td>E</td>
<td>136.67 s</td>
<td>124.78 s</td>
<td>-8.7%</td>
<td>4</td>
</tr>
<tr>
<td>SDM - mcp 1 - MCP</td>
<td>8155-8149</td>
<td>E</td>
<td>172.27 s</td>
<td>142.69 s</td>
<td>-17.2%</td>
<td></td>
</tr>
<tr>
<td>SDM - mcp 1 - MCP</td>
<td>8155-8149</td>
<td>E</td>
<td>131.77 s</td>
<td>124.67 s</td>
<td>-5.4%</td>
<td></td>
</tr>
<tr>
<td>MCP - mcp 1 - SDM</td>
<td>8148-8155</td>
<td>W</td>
<td>163.19 s</td>
<td>150.23 s</td>
<td>-7.9%</td>
<td>3</td>
</tr>
</tbody>
</table>

A second verification was done by comparing the travel times in the normal situation to the registered times in the VKL log files. These travel times are analysed per HP per direction and are given in Appendix E. The 10%, 25%, 50%, 75% and 90% quantiles are compared to the simulation results between Delfshaven, Coolhaven and Dijkzigt in table 7.

Table 7: An overview of the metro simulator travel times compared to the quantiles of VKL data from July 2014 to June 2015.

<table>
<thead>
<tr>
<th>Route</th>
<th>HPs</th>
<th>Model</th>
<th>VKL 10%</th>
<th>VKL 25%</th>
<th>VKL 50%</th>
<th>VKL 75%</th>
<th>VKL 90%</th>
</tr>
</thead>
<tbody>
<tr>
<td>DHV - CHV</td>
<td>8146-8144</td>
<td>68.47 s</td>
<td>58 s</td>
<td>59 s</td>
<td>61 s</td>
<td>62 s</td>
<td>64 s</td>
</tr>
<tr>
<td>CVH - DHV</td>
<td>8145-8147</td>
<td>68.88 s</td>
<td>60 s</td>
<td>60 s</td>
<td>61 s</td>
<td>63 s</td>
<td>65 s</td>
</tr>
<tr>
<td>CHV - DZT</td>
<td>8144-8142</td>
<td>58.22 s</td>
<td>50 s</td>
<td>51 s</td>
<td>53 s</td>
<td>54 s</td>
<td>56 s</td>
</tr>
<tr>
<td>DZT - CHV</td>
<td>8143-8145</td>
<td>57.75 s</td>
<td>52 s</td>
<td>53 s</td>
<td>54 s</td>
<td>56 s</td>
<td>59 s</td>
</tr>
</tbody>
</table>

It can be seen that all simulation data is close to the 90% quantiles, which is a good estimate for creating a robust timetable. However, this contradicts the previous verification a little bit where the travel times seemed a bit faster on average. This could be explained by the measuring technique and is discussed in the next chapter.

8.2 Disruption results

Disruption analysis was the main focus of the initial internship. Results were presented in [1], but the model was not verified in practise. A new disruption analysis is done using the results presented in the previous chapters.

For analysing the infrastructure of the metro network the impact of every switch, crossing and section has to be determined. For this purpose the network is divided into parts with equal impact. These network parts are mostly related to the scenarios as described in Chapter 5.2. A numbering of all scenarios with their region in the simulation is given in figure 17.

Besides the numbered scenarios some areas exist that are not connected to such a defined scenario. This mostly concerns (groups of) switches and crossings. Every switch not related to a scenario is studied separately, where three possible disruptions for a switch can occur:

- A switch cannot be used at all.
• A switch can only be used in the straight direction.

• A switch can only be used in the deflecting direction.

Only the effect of switches that cannot be used at all is studied in the simulation. Two common configurations for switches found in the network are given in figure 18.

Figure 18: Configuration for groups of switches. The left picture will be called an X-configuration and the right picture a V-configuration.

If a switch in an X-configuration fails the scenario of the line adjacent to the switch is applied. If a switch in a V-configuration fails this is only done for the two outer switches. The two inner switches have a greater impact and are analysed separately, mostly by combining two scenarios. The impact of a switch strongly depends on the line connected to it and the frequency of trains passing by.

The simulation is run 3 times for every scenario and the average result is taken. First a simulation is run over the normal situation. The results for both a deterministic case with dwelling times of 15 seconds at every stop and stochastic dwelling times are given in table 8.
As expected there are (almost) no delays in a normal situation with minimal dwelling times of 15 seconds per station. The delays of lines A, B and C together are relatively high when the dwelling times from reality are used. A reason for this could be a high estimation of the dwelling time that is logged in the VKL log files, but also suggest the timetable is too tight at some places.

All simulations are done according to timetable without rescheduling as suggested in some scenarios. Suggested rescheduling concerns cancellation of trains, which decreases the delays. To identify the effect of these measures the simulation further research is needed. However, the simulation can verify whether the suggested rescheduling measurements are justified.

As mentioned before the simulation uses a counter to give priority to trains in a single track area. The simulation is run for a 1 train per direction policy for all parts of the network. The parts of the network with the highest disruption impact are also simulated for 2 trains per direction policy.

### 8.2.1 Results for a one train per direction policy

For all parts of the network a disruption analysis is done using the simulation. As the timetable for the Hoekse Lijn is missing the extension of lines A and B is not considered. In the previous analysis done in [1] some areas couldn’t be analysed due to limitations in the simulation. The number of areas where the simulation cannot be used is largely reduced, but some limitations still exist in the current simulation. These areas are connected to the platform use at the stations Rotterdam Centraal (scenario M1), Slinge (scenario M9) and Schiedam Centrum (scenario M53). Which platform to use is very much depending on delays and the train dispatcher.

In total 104 disruptions are analysed for scenarios at lines A, B, C, D and E up to Leidschenven. The last part of line E is not analysed as tram vehicles using the same infrastructure are not modelled. Furthermore a total of 26 disruptions is analysed connected to switches having a great impact, mostly connecting two scenarios.

The results show large variations in delay, from almost nothing compared to the normal situation up to more than 3000 DRU per day. Also it must be noticed that the disruption impact on parallel tracks is mostly equal, except for places with switches that can only be crossed to one side. Sorting the results on impact a top 10 of bottlenecks in the network is given in table 9.

The bottlenecks almost coincide with the earlier bottlenecks presented in [1]. The top 5 of switches is given in table 10. The results in DRU are showing much larger impact as expected as the single track areas are
longer. Also these results show similar results with the analysis done earlier.

### 8.2.2 Results for a two trains per direction policy

For all previous results with a disruption value over 1000 DRU a day another policy is used in the simulation. Two trains are allowed to pass in each direction on a single track area before the direction is inverted.

The results show some interesting facts. In all cases a drop can be seen in the measured delays compared to the one train policy. On the part where the lines C and D are combined the impact of a disruption drops relatively much compared to the one train policy. This is probably caused by the irregular schedule with two trains shortly after each other in such way that a two train policy is a very good solution. Delays are reduced up to 80%. Also here it can be seen that the disruption impact is almost equal for parallel track parts.

### 8.3 Bridge openings

Trains waiting for a bridge opening must be waiting at a station. To accomplish this, a bridge can only open after all sections up to the station are reserved by the bridge. This is done by starting at the section near the station up to the bridge. If all sections are reserved the bridge is allowed to open. Bridge openings in the simulation at Maassluis and Vlaardingen are shown in figure [19].

Unfortunately the timetable of the Hoekse Lijn was not available yet in the right format to calculate the expected delays. However, a fictional bridge was modelled at another part of

### Table 9: An overview of the top 10 scenario bottlenecks.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Average delay over 3 runs</th>
</tr>
</thead>
<tbody>
<tr>
<td>M37.1 (Alexander to Prinsenlaan)</td>
<td>2354 DRU</td>
</tr>
<tr>
<td>M37.2 (Prinsenlaan to Alexander)</td>
<td>2385 DRU</td>
</tr>
<tr>
<td>M44.2 (Kralingse Zoom to Voorschoterlaan)</td>
<td>2547 DRU</td>
</tr>
<tr>
<td>M47.2 (Eendrachtsplein to Blaak)</td>
<td>3363 DRU</td>
</tr>
<tr>
<td>M3.1 (Pijnakker Zuid direction Den Haag)</td>
<td>3365 DRU</td>
</tr>
<tr>
<td>M47.1 (Blaak to Eendrachtsplein)</td>
<td>3399 DRU</td>
</tr>
<tr>
<td>M5.1 (Leuvenhaven to Rijnhaven)</td>
<td>3668 DRU</td>
</tr>
<tr>
<td>M45.1 (Voorschoterlaan to Blaak)</td>
<td>3686 DRU</td>
</tr>
<tr>
<td>M45.2 (Blaak to Voorschoterlaan)</td>
<td>3690 DRU</td>
</tr>
<tr>
<td>M5.2 (Leuvenhaven to Rijnhaven)</td>
<td>3741 DRU</td>
</tr>
</tbody>
</table>

### Table 10: An overview of the top 5 bottlenecks of switches.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Average delay over 3 runs</th>
</tr>
</thead>
<tbody>
<tr>
<td>M17.2+18.2 (switches 402 and 404)</td>
<td>2556 DRU</td>
</tr>
<tr>
<td>M48.2+49.2 (switches 1182 and 1184)</td>
<td>3476 DRU</td>
</tr>
<tr>
<td>M49.2+50.2 (switches 1176 and 1178)</td>
<td>3868 DRU</td>
</tr>
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</tr>
<tr>
<td>M47.1+48.1 (switches 1187 and 1189)</td>
<td>6769 DRU</td>
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Unfortunately the timetable of the Hoekse Lijn was not available yet in the right format to calculate the expected delays. However, a fictional bridge was modelled at another part of
the network to verify the working and impact on the schedule. Unfortunately the impact is very much depended on specific properties that are different at every place: distance to the nearest station, opening time of a bridge and the frequency of trains passing by. It is expected that the impact of a bridge opening on the timetable is limited, as long as the timetable is adjusted such that the bridge opens just after the passing train in the eastbound direction. To make sure the effect is limited a full timetable of the Hoekse Lijn should be imported into the simulation.

8.4 Freight trains

As with bridge openings the Hoekse Lijn timetable is still missing. The only results that are verified with the simulation are the time needed for a freight train to set the route and pass. The time needed in the simulation matches the calculated values of about 6 to 7 minutes.
9 Conclusion

As the results show the main question to develop a simulation tool is answered. Analysis can be done both with and without a timetable, which corresponds to scheduled and unscheduled disruption. The analysis done for both involved RET departments is summarized in this chapter.

9.1 Analysis done for Infrastructure Management

Using data from the infrastructure, timetable and CVL an extensive analysis for disruptions was done. A selection of disruptions caused by infrastructure failures was used to identify bottlenecks in the Rotterdam metro network. Even while not all kind of disruptions are modelled more insight is given in the weak spots of the network.

DRUs are used as an indicator for the impact of a disruption. At all parts of the network disruptions are modelled and ranked according to their impact. With this analysis changes in the infrastructure can be substantiated. The analysis of bottlenecks is showing the regions which are most vulnerable and can be used to adjust the maintenance schedule.

In Chapter 5 all kind of infrastructure disruptions were described including the way that is dealt with them by train dispatchers. The analysis can be extended to the Hoekse Lijn if a timetable is available.

9.2 Analysis done for Business office of operations

An extensive analysis for both dwelling times and travel times is presented in Chapter 6. Both travel and dwelling times are implemented in the simulation with reliable results.

The dwelling time analysis is done over a period of one month and a period of one year to observe the effects of seasonal differences. Only small differences were found, most related to construction work during the one month period that was observed. The cumulative effect of dwelling times in disruptions is analysed, but the effect is small and only seen at the busiest stations. The estimations for the dwelling time divided per HP and per hour are implemented in the simulation including a variation based on the registered data.

Travel times are verified in multiple ways: using a full-scope simulator and using registered data over a one year period. Matching a linear approximation for the acceleration and deceleration of a train the travel times are estimated with at most a 15 percent unexplained difference over the measured data.

Data for bridges was collected, but unfortunately the real effect of a bridge opening at the Hoekse Lijn could not be modelled. Due to a lack of data for the Hoekse Lijn timetable, which is still under construction at the time of writing, precise infrastructure effects could not be analysed yet. However, it is expected that the effect of an opening bridge will be small as the opening lasts relatively short.

Passing freight trains are expected to have a greater impact on the timetable. However,
this could not be verified due to a lack of data at the time of writing.
10 Discussion

In this section the assumptions that were made for building the simulation are discussed. During the development of the simulation intermediate results aroused interest for additional analysis. Limitations of the model and possible future research are described.

10.1 Model limitations

Some limitation exist in the model considering the infrastructure, timetable and the modelled disruptions.

Infrastructure

As mentioned some track properties as the inclination are left out showing some small differences in travel times. These differences should be corrected, but with the suggested corrections in Chapter 8 the travel times are reliable. To model the railway signalling system a simplification is made from continuous time to discrete time. Currently a new railway signalling is being installed in the metro network of Rotterdam. This new signalling can handle different speed limits within the same section while taking into account the train length. To model these details a more detailed acceleration and deceleration calculation is needed in continuous time. However, the expected differences in travel time are small.

All infrastructure data for the simulation is mainly read from text files in a specific format (see Appendix F). The format is chosen such that it is easy to handle, but it is not easy to exchange data with other simulation models. To this purpose it is useful to put the network into the RailML format, which is used by many other commercial simulation tools. More detailed information such as track inclination must also be added for these more advanced simulation tools.

Timetable

The timetable loaded into the simulation is imported from VKL. Unfortunately the VKL format is one of the last steps in the development of a timetable. At one hand this means that all information is most likely to be correct, but at the other hand it takes some effort to process the timetable to this format. Importing a timetable directly from HASTUS, where the timetable is created, could increase the usability of the model.

The used timetable does not distinguish rolling stock series, which limited the analysis to a fixed train length of 91.5 meter. Furthermore lines A, B and C are loaded in the VKL as a single line, which is the reason to analyse these lines together.

Disruptions

The amount of possible disruptions is huge, so not all disruptions are modelled. Only disruptions related to the infrastructure were modelled, but the simulation can be extended to model other disruptions as well. Examples of other common disruptions are problems related to the rolling stock or delays caused by passengers. Also the effect of multiple disruptions at
the same time is not modelled. Furthermore the effect of a disruption over the whole day are modelled, while most disruptions only last for several hours. This way the impact of every disrupted part in the network is similar. The simulation could be extended to determine the precise delays over a few hours.

The Hoekse Lijn operation is based on assumptions in the way bridges and freight trains are handled. These assumptions are based on past data of 2014. The number of bridge openings and freight trains can change until the Hoekse Lijn will start operating as a part of the metro network. Future developments should be taking into account.

10.2 Future research

Some suggestions for future research are given below.

Data analysis

A detailed analysis was done on dwelling and travel times using historical data. A lot of effects were shown and described. The dwelling times can be extended with more detailed analysis considering the relation between headways of trains and the dwelling time needed at busy stations. Also the effect of different train lengths is not studied in detail.

Currently the timetable is based on fixed dwelling and travel times. Costs can be decreased by optimizing the timetable based on the passenger demand and train length. Also the tolerance in the timetable can be verified using this data by looking at the time needed to catch up a delay.

Disruption analysis

The dispatching of trains on a single track is strongly influenced by human decisions. Defining dispatching rules can decrease delays in case of a disruption. An automated single track operation process is used in the Rotterdam metro network, but this implementation is not optimal.
A Detailed problem description for the planning software

To make an accurate timetable for the planning software HASTUS information is used about distances, dwelling times and travel times. Unfortunately the current data is not accurate enough and incomplete. Especially the making of timetables in case of construction work causes problems. First the network that is used in HASTUS is explained. Afterwards the desired results about distances and travel times are clarified.

A.1 Network representation in Hastus

Hastus contains a simplified version of the metro network. This model can be seen as a graph with nodes and weighted, directed edges. Not all nodes defined in Hastus are used. All nodes for ticket fares are left out as they are not interesting in the calculations.

The nodes that are used can be divided into two types of points: HPs (as defined before in chapter 2.3) and Intermediate Places (IPs). An IP is a point of interest directly before or after a group of switches and crossings. An example of these points is given in figure 20. Every HP and IP is linked to a segment. Given a route from one place to another place the distance and travel times can be calculated.

Figure 20: A track where distances and travel times will be measured. All HPs and IPs are shown.

A.2 Calculation of distances and travel times

In the current situation HASTUS makes use of distances and travel times between every pair of stations, which are used for creating the annual timetable. The distances that are currently used in HASTUS are inaccurate. More accurate distances are used in the simulation, but they are not yet available in the desired format to import into HASTUS. Therefore the distances between every pair of connected places have to be calculated in a 0.5 meter accuracy. Travel times have been verified using the VKL log files (see Chapter 4.2). The travel time between a HP and IP is also desired.

To model the travel times the network characteristics (except for the inclination), the rolling stock characteristics and an average driver speed are used. The driver characteristics are irrelevant for creating a timetable, as all drivers should be able to make it within the scheduled travel time. Therefore the simulation will be verified in practise and the travel times will be adjusted such that the timetable will be reliable. The desired accuracy for the travel times is 1 second.
The distances that are calculated are marked in figure 20 with red and yellow markers. The following situations can occur:

- Distance from $HP_b$ to $HP_e$.
- Distance from $IP$ to $IP$.
- Distance from $HP$ to $IP$.
- Distance from $IP_b$ to $IP_e$.

The calculated distance equals the travelled distance of a train between two points. It is assumed that a train stops at the centre of a segment linked to the $HP$. For an $IP$, the train stops either right in front of a group of switches and crossings or right after a group of switches and crossings. The distance depends on the train length as the position of a train inside a segment can differ. It is assumed all trains have a length of 91.5 meter, which is the most common train length. An example of a distance calculation is given by the blue line in figure 20. The blue line corresponds to the distance from IP1182/494 to HP8145.

The same train length will be used to calculate the desired travel times. For the parts in the network with a steep inclination the travel times have to be verified separately. Parts with a steep inclination exist on places where the metro changes from upper ground to lower ground. The metro network of Rotterdam contains the following of these places:

- Spijkenisse Centrum - Zalimplaat (tunnel underneath the Oude Maas)
- Rijnhaven - Wilhelminaplein - Leuvehaven (from upper to lower ground and crossing the Nieuwe Maas)
- Pernis - Vijfsluizen (tunnel underneath the Nieuwe Maas)
- Vijfsluizen - Troelstralaan (from upper to lower ground)
- Parkweg - Schiedam Centrum (from lower to upper ground)
- Schiedam Centrum - Marconiplein (from upper to lower ground)
- Voorschoterlaan - Kralingse Zoom (from lower to upper ground)
- Rotterdam Centraal - Blijdorp - Melanchtonweg (from lower to upper ground through a deep bored tunnel)

Like the distance calculation a travel time is split up in parts between two points. Another example is given by the green line in 20. The yellow markers give the following possible distances and travel times calculation:

- From IP1181/493 to HP8144.
- From IP1184/492 to HP8144.
- From IP1181/493 to IP1184/492.
B  List of all HP’s in the Rotterdam metro network

Figure 21: List of all HP’s in the Rotterdam metro network.
C Detailed analysis of dwelling time distribution over June 2015

In this chapter all dwelling times distribution over June 2015 are studied. The data of the VKL log files is read with a small Java application and analysed with R. An overview of the distribution per HP is given in figure 23. The abnormal results are studied in detail per HP.

Construction work between Hesseplaats and De Tochten

During June construction work was performed every workday between 10 am and 4 pm. Trains had to travel single track during this period. The construction work was not scheduled when the timetable was created and caused delays because of waiting trains. Trains had to wait at Hesseplaats and De Tochten to enter the single track part. These effects can be seen in figure 22.

Delays during this construction work period can be seen in the direction that a train had to wait only. In the other direction normal dwelling times apply. Even more interesting are the effects this unscheduled construction work had on other parts of the network. Trains that

Figure 22: Dwelling times at stations De Tochten and Hesseplaats, Monday-Friday in June 2015 (limited to 300s)

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Figure 23: Distribution of the dwelling time for every HP shown in a boxplot (Monday-Friday, June 2015).

had to merge with line B sometimes had to wait at Romeynshof or Capelsebrug to enter the part where the track was shared. These effects could be seen in figures 24 and 25.
Figure 24: Dwelling times at station Romeynshof in the direction of Schiedam Centrum, Monday-Friday in June 2015 (limited to 300 seconds)

Figure 25: Dwelling times at station Capelsebrug in the direction of Schiedam Centrum, Monday-Friday in June 2015 (limited to 300 seconds). Line C had to wait often for a delayed train of line A or B.

Construction work between De Akkers and Heemraadlaan

Because of construction work between De Akkers and Heemraadlaan line C was shortened and reversed in Spijkenisse Centrum. The reverse time of line C was about two minutes, which causes a division in the dwelling times between lines C and D as shown in figure 26.

Waiting for crossing trains

Some distributions show a bigger spread in dwelling times than others. Most of these can be directed to level-crossings where other trains had to pass the same track. This can be seen in the automated train reverse process at Heemraadlaan, but also at Den Haag Laan van NOI where light rail vehicles cross the same track. These dwelling times are shown in figures 27 and 28.
Crossings with road traffic

Crossings with road traffic can cause delays when the metro has to wait for permission to pass. Two busy road crossings can be found near Oosterflank and Alexander. At Alexander the delays caused by the crossing are minimal, as can be seen in figure 29.

The reason for this is the long time that is needed to ask permission to pass. After roughly 35 seconds the permission is given, but passengers where done with boarding and alighting earlier. Therefore the spread in dwelling times is also relatively small. In Oosterflank this effect is similar as can be seen in figure 30. However, a higher spread can be seen which could be caused by the boarding and alighting of passengers.
Figure 28: Dwelling times at station Den Haag Laan van NOI in the direction of Den Haag CS, Monday-Friday in June 2015 (limited to 300 seconds).

Figure 29: Dwelling times at station Alexander in the direction of Schiedam Centrum, Monday-Friday in June 2015.

Safe Haven

A last effect that can be seen is the Safe Haven principle at line E near Blijdorp, see figure 31. Safe Haven means that the permission to leave the station is only given if the next platform at Rotterdam Centraal is not occupied.

Especially in the peak hours it can be seen that a train has to wait for minutes if it arrives at the Blijdorp station. The reason why this only happens in the peak hours is (probably) related to the delay the train has on arrival. The waiting for an available platform at Rotterdam Centraal takes about a minute to two minutes. This is relatively high because most trains at Rotterdam CS change directions, which takes time also.
D Displacement of trains

After every action the position and the speed of a train are updated. Every train contains three lists of segments: all segments on the route to its destination, all segments that are currently occupied by the train and all segments that are reserved by the train. Furthermore the last segment passed is registered and also the position of the train within the front segment is registered. These values are shown in figure 31.

Every action contains 3 steps: finding the maximum allowed velocity, determining the displacement for the train in the time step and calculating the travel time. All steps are explained below.

D.1 Finding the maximum velocity

For finding the maximum velocity over a track the following factors have to be taken into account:
1. The maximum allowed velocity over the upcoming segments.
2. The distance needed for a train to stop.
3. The maximum allowed velocity on the tracks that are currently occupied by the train.

For the calculation the example in figure 33 is considered.

In the example a train is moving from HP 10 to 11 over the segments 1 to 6. Every segment has a maximum allowed velocity given with a gray line. The red train is currently occupying segments 3 and 4. The next calculation is made to determine the maximum allowed speed for leaving segment 3. The calculation is performed using the following steps:

1. Determine the first place where the train should come to a stop, in this case segment 6.
2. Using the maximum deceleration of the train, compute the maximum possible speed to come to a stop in time. If this is higher than the maximum allowed speed for this segment, take the maximum allowed speed.
3. Do the same for segment 5, indicated with the orange line. Now the maximum allowed speed for entering the next section is determined, say $v_{max}$. 

Figure 32: The parameters involved for measuring the position of a train.

Figure 33: An example of the maximum speed limit calculation.
The next step is to determine the maximum allowed speed on the segments that are currently occupied, say $v_{o_{\text{max}}}$. This is done by taking the minimum over all maximum speed limits. Using $v_{\text{max}}$ and $v_{o_{\text{max}}}$ the travel time can be calculated after determining the displacement.

A similar calculation is done when a section is occupied as can be seen in figure 34.

![Figure 34: An example of the maximum speed limit calculation with an occupied track.](image)

In this case the train must be stopped in segment 5 just before entering segment 6.

### D.2 Finding the displacement

The displacement $s$ is determined using figure 13. For every arrow a different case can be distinguished, which can be expressed in the units defined in figure 32. Let $O_1$ be the segment at the back of the train and $S_1$ the segment in front of the train.

- From departure at HP to enter new segment: $s = \text{length}(S_1) - x$.
- From enter new segment to enter new segment: $s = \text{length}(S_1)$.
- From enter new segment to leave segment: $s = \text{length}(t) - \sum_{i=2}^{n-1} \text{length}(O_i)$.
- From leave segment to enter new segment: $s = \text{length}(S_1) - x$.
- From leave segment to leave segment: $s = \text{length}(t) - \sum_{i=2}^{n-1} \text{length}(O_i)$.
- From leave segment to arrival at HP: $s = \text{length}(t) - \sum_{i=2}^{n-1} \text{length}(O_i)$.

Using $s$, $v_{\text{max}}$ and $v_{o_{\text{max}}}$ the travel time can be calculated.

### D.3 Travel time calculation

The travel time can be calculated using the maximum possible velocity and the displacement $s$. Four situations can be distinguished:

- An acceleration takes place where the maximum velocity is reached (1).
- An acceleration takes place where the maximum velocity is not reached (2).
• A deceleration takes place where the whole displacement is used for breaking (3).

• A deceleration takes place where only a part of the displacement is used for breaking (4).

Furthermore there are two situations where the train accelerates from a standstill and breaks within the same section:

• An acceleration from standstill and a deceleration takes place where the maximum velocity is not reached. (5).

• An acceleration from standstill and a deceleration takes place where the maximum velocity is reached. (6).

![Velocity-time diagrams](image)

*Figure 35: Velocity-time diagrams for situations 1 up to 3 (first row) and 4 up to 6 (second row).*

For all situations the velocity-time diagram is given in figure 35. Furthermore the following known constants and formulas are used:

• $a$ the maximum acceleration.

• $d$ the maximum deceleration.

• $v_b$ initial velocity.

• $v_e$ final velocity.

• $s = v_b t + \frac{1}{2} at^2$.

• $a = \frac{\Delta v}{\Delta t}$.

Now the travel time can be determined for all described situations.

• (1) Let $t_0$ be the time needed for acceleration such that $t_0 = \frac{v_e - v_b}{a}$. The displacement within $t_0$ is $s_0 = v_b t_0 + \frac{1}{2} a t_0^2$. The time that is travelled at maximum speed is $t_1 = \frac{s - s_0}{v_e}$. The total travel time becomes $t = t_0 + t_1 = \frac{v_e - v_b}{a} + \frac{s - s_0}{v_e}$.
(2) Using $s = v_b t + \frac{1}{2} a t^2$, the travel time $t$ can be calculated directly:

$$t = \frac{v_b}{a} + \sqrt{\frac{v_b^2}{a^2} + \frac{2s}{a}}$$

(3+4) The time needed for deceleration is $t_1 = \frac{v_b - v_e}{d}$, which is the travel time of situation (3). For (4) the displacement $s_1$ during deceleration can be calculated from $s_1 = v_e t_1 + \frac{1}{2} d t_1^2$. Now the time $t_0$ at maximum velocity can be calculated with $t_0 = \frac{s - s_1}{v_b}$. The total travel time becomes $t = t_0 + t_1 = \frac{s - s_1}{v_b} + \frac{v_b - v_e}{d}$.

(5) The total travel time contains an acceleration part $t_0$ and a deceleration part $t_1$. The displacement is given by $s = \frac{1}{2} a t_0^2 + \frac{1}{2} d(t - t_0)^2 = \frac{1}{2} a^2 t^2 (a + d)^2 + \frac{1}{2} d^2 (a + d)^2$. Therefore the total travel time is given by:

$$t = \sqrt{2s \frac{a + d}{ad}}$$

(6) Using the maximum speed $v_{\text{max}}$ the displacement can be expressed as $s = \frac{1}{2} a t_0^2 + v_{\text{max}} t_1 + \frac{1}{2} d t_2^2$ with total travel time $t = t_0 + t_1 + t_2$. The total acceleration and deceleration are equal to the maximum speed $v_{\text{max}} = a t_0 = dt_2$. This can be rewritten to $t_0 = \frac{v_{\text{max}}}{a}$, $t_2 = \frac{v_{\text{max}}}{d}$. Now $t_1 = t - t_0 - t_2 = t - \frac{v_{\text{max}}}{a} - \frac{v_{\text{max}}}{d} = \frac{t a d - v_{\text{max}} a - v_{\text{max}} d}{a d}$. Combining everything in the displacement equation gives:

$$s = \frac{1}{2} a \frac{v_{\text{max}}^2}{a^2} + v_{\text{max}} \frac{t a d - v_{\text{max}} a - v_{\text{max}} d}{a d} + \frac{1}{2} d \frac{v_{\text{max}}^2}{d^2} = v_{\text{max}} t - \frac{v_{\text{max}}^2 (a + d)}{2 a d}$$

The total travel time is now given by:

$$t = \frac{s}{v_{\text{max}}} + \frac{v_{\text{max}} (a + d)}{2 a d}$$

Note however that situation (6) is only used on small distances where the maximum speed limit is reached for a short period of time. The model therefore makes use of situation (5) as a simplification for situation (6).

Note also that situations (1) and (4) can be extended if the maximum allowed velocity is higher within the segment than in the next segment. Because of the short segment length the metro drivers rarely use this extra acceleration knowing they need to decelerate a few seconds later.
## E Travel time measurements

In this chapter all analysed travel times are given over the period July 2014 to June 2015. This was done over the same data as the dwelling times, so only for Monday to Friday outside the holidays. The results are marked with their final destination and direction. So for example travel times in the eastbound (O) direction from Stadhuis (HP 8003) to Rotterdam Centraal (HP 8001) are marked as hp8001rO. The values are rounded in seconds and the 10%, 25%, 50%, 75% and 90% quantiles are given below.

|       | hp8000rW | hp8000rO | hp8000rO | hp8004rW | hp8005rO | hp8006rW | hp8007rO | hp8008rW | hp8009rO | hp8010rW | hp8011rO | hp8012rW | hp8013rO | hp8014rW | hp8015rW | hp8016rW | hp8017rO | hp8018rW | hp8019rO | hp8020rW | hp8021rO | hp8022rW | hp8023rO | hp8024rW | hp8025rO | hp8026rW | hp8027rO | hp8028rW | hp8028rO | hp8029rO | hp8031rW | hp8031rO | hp8035rO | hp8036rW | hp8041rO | hp8042rW | hp8043rW | hp8044rO | hp8092rO | hp8093rO | hp8094rO | hp8095rO | hp8096rO | hp8097rW | hp8098rO | hp8099rW |
|-------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
| 10%   | 83       | 78       | 66       | 60       | 40       | 38       | 48       | 48       | 77       | 49       | 57       | 59       | 103      | 101      | 108      | 103      | 108      | 115      | 115      | 121      | 121      | 113      | 113      | 118      | 127      | 118      | 127      | 118      | 127      | 118      | 127      | 118      | 127      |
| 25%   | 84       | 79       | 67       | 61       | 41       | 39       | 50       | 48       | 79       | 50       | 59       | 61       | 105      | 103      | 111      | 105      | 111      | 115      | 115      | 121      | 121      | 113      | 113      | 118      | 127      | 118      | 127      | 118      | 127      | 118      | 127      | 118      | 127      | 118      | 127      | 118      | 127      |
| 50%   | 86       | 82       | 69       | 67       | 42       | 40       | 51       | 49       | 81       | 51       | 62       | 62       | 107      | 105      | 115      | 108      | 115      | 115      | 121      | 121      | 113      | 113      | 118      | 127      | 118      | 127      | 118      | 127      | 118      | 127      | 118      | 127      | 118      | 127      | 118      | 127      | 118      | 127      |
| 75%   | 88       | 87       | 71       | 78       | 44       | 42       | 53       | 51       | 84       | 52       | 65       | 64       | 110      | 108      | 121      | 113      | 121      | 121      | 113      | 113      | 118      | 127      | 127      | 118      | 127      | 127      | 118      | 127      | 118      | 127      | 118      | 127      | 118      | 127      | 118      | 127      | 118      | 127      |
| 90%   | 91       | 117      | 74       | 83       | 45       | 43       | 54       | 53       | 87       | 54       | 68       | 66       | 113      | 112      | 127      | 118      | 127      | 127      | 118      | 127      | 127      | 118      | 127      | 127      | 118      | 127      | 118      | 127      | 118      | 127      | 118      | 127      | 118      | 127      | 118      | 127      | 118      | 127      |

E 58
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F Syntax of input files

The simulation uses txt-files to read all necessary data. All data is separated by tabs and every file has its own specific format. The files are described here.

Network data

- **bruggen** This file contains all infrastructure data for bridges. The first three line with comments are skipped. Every line contains tab separated values with:
  - First line Name of bridge.
  - Second line Eastbound sections to be reserved for an opening bridge.
  - Third line Westbound sections to be reserved for an opening bridge.

- **eindpunten** This file contains all end of tracks. The first line with comments is skipped. Every line contains a section connected to the end of track.

- **goederenspoor** This file contains all freight tracks. The first line with comments is skipped. Every line contains tab separated values with:
  0 Name of freight track.
  Next items Sections connected to the freight track.

- **haltepalen** This file contains all HPs. The first line with comments is skipped. Every line contains tab separated values with:
  0 Number of HP.
  1 Section connected to the HP.
  2 Short name for location.
  3 Track number for to the HP.

- **intermediateplaces** This file contains all IPs. The first line with comments is skipped. Every line contains tab separated values with:
  0 Number of switch connected to IP.
  1 Number of section connected to IP.

- **krusingen** This file contains all crossings. The first line with comments is skipped. Every line contains tab separated values with:
  0 Section connected to crossing.
  1 First section at east side in network adjacent to crossing.
  2 Second section at east side in network adjacent to crossing.

- **lijnen** This file contains all lines. The first line with comments is skipped. Every line contains tab separated values with:
  0 Direction (W for westbound, E for eastbound).
1 Usage of line (E for exploitation, R for shunting only).
2 Number of directions (0, 1 or 2).
3 Reversing allowed (T for true, F for false).
4 Section adjacent to the beginning of the line.
5 Section adjacent to the end of line.

Next items Sections connected to the line.

- **rangeerterreinen** This file contains all shunting yards. The first line with comments is skipped. Every line contains tab separated values with:
  0 Name of shunting yard.
  1 Section containing the shunting yard.

- **sectiedelen** This file contains all segments. The first line with comments is skipped. Every line contains tab separated values with:
  0 Section containing the segment.
  1 Length of segment.
  2 First section adjacent to segment.
  3 Second section adjacent to segment.
  4 Maximum velocity allowed on segment.

- **wisselcomplexen** This file contains all groups of switches. The first line with comments is skipped. Every line contains tab separated values with:
  1 and next sections Section numbers ordered in eastbound direction.

**Timetable data**

- **dienstregeling** This file contains the timetable including shunting movements for all trains. The first line with comments is skipped. Every line contains an action with tab separated values containing the following data at the described position:
  1 Line (M005 for lines ABC, M009 for line D and M010 for line E).
  2 Circulation number.
  3 Number of action within the circulation.
  4 Schedules time of action.
  6 HP where the action takes place.
  8 Type of action.
  10 If characteristic is changed: New characteristic of train.
  13 If destination is changed: HP of new destination.
  17 If train is coupled: Name of coupled train.
  19 Direction of train (1 for westbound, 2 for eastbound).
Simulation data

- **automatischkeren** This file contains the stations with an automated train reverse processes. The first line with comments is skipped. Every line contains tab separated values with:
  0 Lines the process is applied to.
  1 Direction of train the process is applied to.
  2 Primary HP
  3 Alternative HP
  4 Abbreviation of location

- **boten** This file contains the times of boats passing a bridge. The first line with comments is skipped. Every line contains tab separated values with:
  0 Name of bridge to pass.
  1 Time of passage.

- **goederentreinen** This file contains the times of passing freight trains. The first line with comments is skipped. Every line contains tab separated values with:
  0 Name of freight track.
  1 Time of passage.

- **hpdist** This file contains all data used to calculate dwelling times. The data is given per HP per hour. Every HP and hour contain 3 lines with the following data.
  First line The name of the HP and the hour where the distribution applies, given as `hpXXXXhYY`. Here `XXXX` is the number of the HP and `YY` the hour of the day (i.e. 07 represents the time block from 7 to 8 am).
  Second line List of integer values separated by tabs containing all possible dwelling times.
  Third line List of double values between 0 and 1, separated by tabs. These numbers represent the probability that the dwelling time occur. These values sum up to 1.

- **scenarios** This file contains the data for all disruption scenarios. The first two lines with comments are skipped. Every scenario is build out of a first line and actions containing the scenario.
  First line This line contains a by tab separated values with:
    0 Short name of scenario.
    1 Full name of scenario.
  Next lines Actions related to the scenario. Possible actions are:
    BD Followed by a list of section numbers. The related points in the network graph are disrupted.
    ESG Followed by a list of section numbers. The related points in the network graph form a single track area.
Graphical User Interface (GUI) data

- **lijnenxy** This file contains the coordinates for the lines showing the tracks. Every line contains tab separated values with:
  
  0 X-coordinate for plotting begin of track.
  1 Y-coordinate for plotting begin of track.
  2 X-coordinate for plotting end of track.
  3 Y-coordinate for plotting end of track.

- **sectiesxy** This file contains the coordinates to plot all sections. The first line with comments is skipped. Every line contains tab separated values with:
  
  0 Name of section.
  1 X-coordinate for plotting section.
  2 Y-coordinate for plotting section.
  3 If the section is connected to a HP: Plot direction of platform (N, O, Z or W).
List of Abbreviations

ATB Automatische Trein Beïnvloeding. 9

BBE BedrijfsBureau Exploitatie. 6

CVL Centrale VerkeersLeiding. 18, 29, 41

DRU DienstRegelingsUur. 5, 17, 38, 39, 41

HP Halteerpaal. 11, 12, 23, 25, 28, 29, 35, 36, 41, 43, 46, 48, 49, 54, 55, 58, 61

IP Intermediate Place. 45, 46, 61

LZB Linienförmige Zugbeeinflussung. 9

RET Rotterdems Elektrische Tram. 5, 15

RIDS RET Intermediair DataSysteem. 15

VKL VerKeersLeider system. 15, 16, 22, 27, 28, 36, 38, 43, 45, 48

ZUB ZUgBeeinflussung. 9, 16

List of Railroad terminology

board and alight in- en uitstappen. 12, 22

diversion omleiding. 5

dwelling time halteertijd. 6, 16, 22

power outage stroomstoring. 5, 18

route setting rijweg instellen. 9, 18

shunting yard rangeerterrein. 9, 12, 15

switch failure wisselstoring. 5, 18

train dispatcher treindienstleider. 18, 19, 21, 29, 48, 41
References


