Robust public transport from a passenger perspective:

A study to evaluate and improve the robustness of multi-level public transport networks

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Preface

This report shows the results of my graduation research. With this report, I finish the Master study Transport, Infrastructure and Logistics at Delft University of Technology. With this research, I could combine my passion for public transport with scientific knowledge about the interesting field of transportation gained over the last five years.

This thesis is performed at Goudappel Coffeng. First of all, I would like to thank all my colleagues of Goudappel Coffeng for their valuable support and interest in my research and me as a person. Thank you for making me feel a real 'Goudappelaar'. Second, I would like to thank my thesis committee – Niels van Oort, Rob van Nes, Jan Anne Annema and Bart van Arem – for their critical, valuable and inspiring feedback on intermediate products and for supporting me to finish my thesis in time. Without your support, this would not have been possible.

Besides, some people I would like to thank especially: Ties Brands of Goudappel Coffeng, for your interest in my research and for your help in using OmniTRANS; the 'OV team' of Goudappel Coffeng, for all your interest, ideas and nice activities; Bas Bussink, Daan Koning and John Voerman of HTM for all valuable information about Chipcard data and disturbances; Stephan van IJperen, Edwin Roukema and Jeroen Henstra of RET for all your information and for showing me the CVL; Rein Klein Schiphorst of ProRail for your information about the 'versperringsmaatregelen'; and Rogier Potter and Jan van der Reest for your valuable information.

Last but not least, I would like to thank my parents and brother Taco for their support during my whole study. Tinka, Ellen and Sascha: thanks for your everlasting interest in my work and for all your care, time and flexibility to meet and take me out when I had time.

I would like to dedicate this report to my colleague of The Hague Public Transport Museum Hans Grool, public transport lover to the bone, who passed away during my thesis at much too young age.

Menno Yap

Den Haag, February 2014

Summary

Introduction

Disturbances in public transport are an important issue for passengers, public transport operators and infrastructure managers. After the occurrence of large disturbances, there is often a strong call from passengers and society to make the public transport network less vulnerable - and therefore more robust - against these types of events. Despite the mentioned importance of considering robustness, the next limitations can be formulated regarding the way robustness of public transport networks is currently considered:

- When evaluating and improving robustness of public transport networks against large non-recurrent disturbances, a passenger perspective is not included to its full extent. There is a strong focus on independent network levels operated by a single public transport operator, instead of considering the integral, multi-level public transport network available for passengers.
- In general, limited quantitative data is available about disturbances which occur on multi-level public transport networks and about the effects of these disturbances on passengers. Also there is limited knowledge about the robustness performances of different network levels relative to each other.

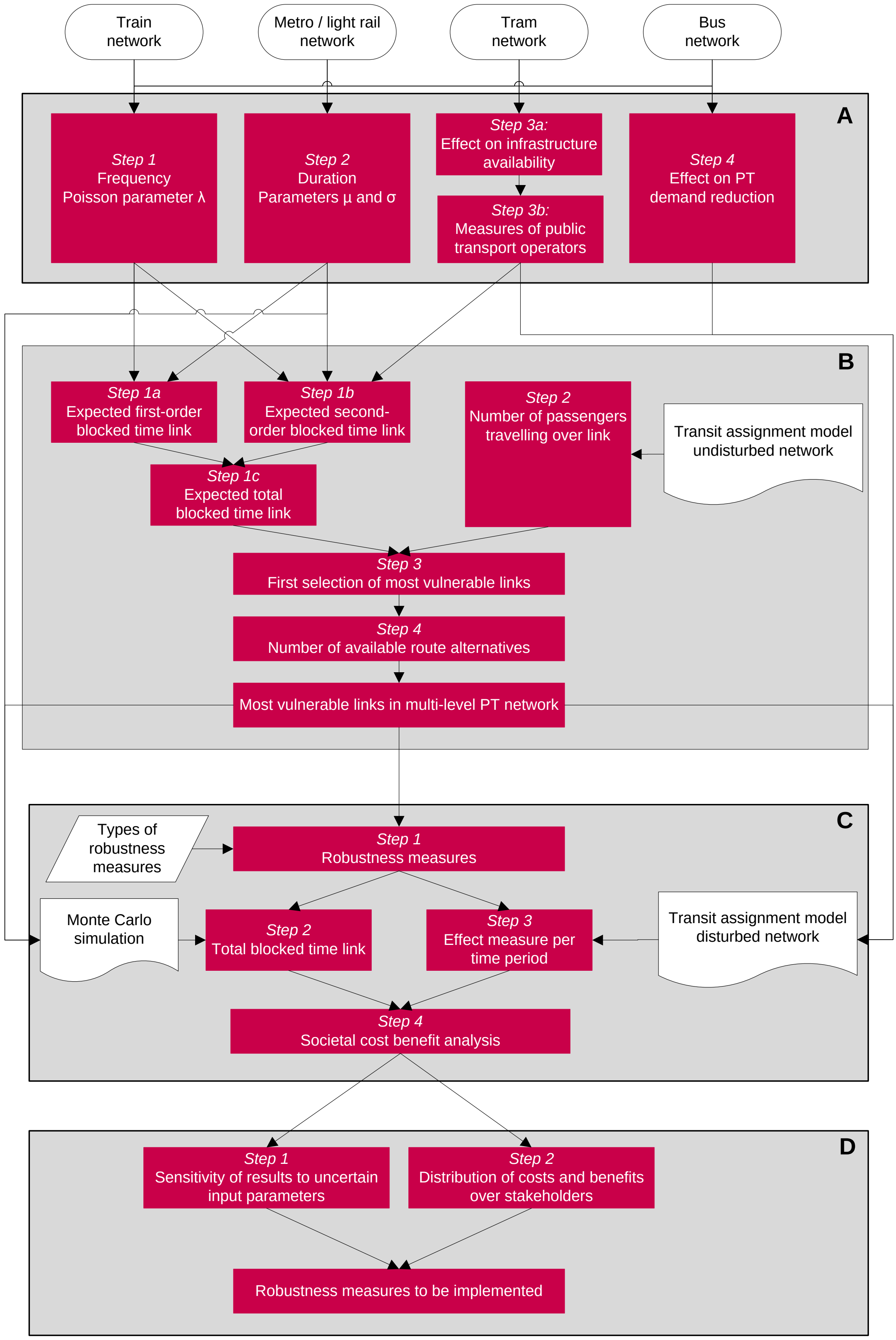
Given these limitations, the following main research question is formulated:

> **What methodology can be developed to evaluate the robustness of multi-level public transport networks and to evaluate robustness effects of measures for the case study network between Rotterdam and The Hague?**

In this study, robustness is related only to major discrete events: large, non-recurrent events which affect infrastructure availability. In line with this, the next definition of robustness is used in this study:

> *'Robustness is the extent to which the network is able to maintain the function it was originally designed for under circumstances which strongly deviate from plan'*.

In this study a methodology is developed to evaluate the robustness of multi-level public transport networks and to evaluate proposed robustness measures. The figure on the next page shows the developed methodology, which consists of four different phases. The multi-level public transport network between Rotterdam and The Hague in The Netherlands is used as case study network to illustrate the developed methodology.

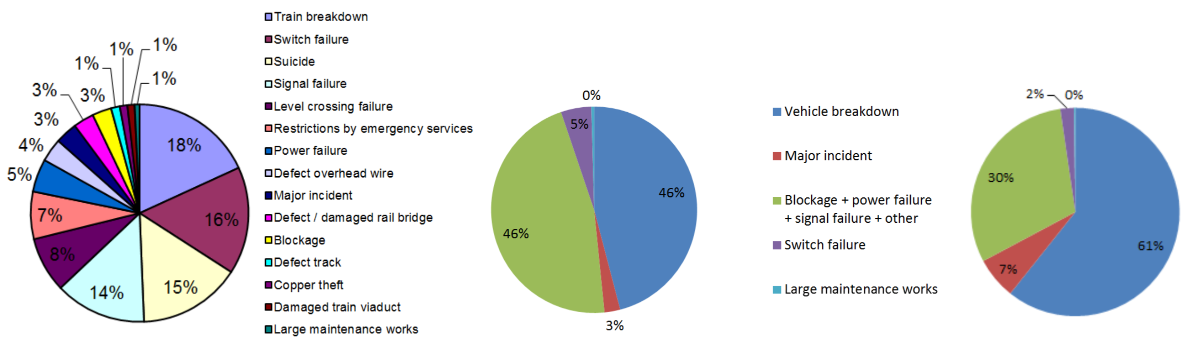

Train network
Metro / light rail network
Tram network
Bus network
A
Step 1
Frequency
Poisson parameter λ
Step 2
Duration
Parameters μ and σ
Step 3a:
Effect on infrastructure availability
Step 3b:
Measures of public transport operators
Step 4
Effect on PT demand reduction
B
Step 1a
Expected first-order blocked time link
Step 1b
Expected second-order blocked time link
Step 2
Number of passengers travelling over link
Transit assignment model undisturbed network
Step 1c
Expected total blocked time link
Step 3
First selection of most vulnerable links
Step 4
Number of available route alternatives
Most vulnerable links in multi-level PT network
C
Types of robustness measures
Step 1
Robustness measures
Monte Carlo simulation
Step 2
Total blocked time link
Step 3
Effect measure per time period
Transit assignment model disturbed network
Step 4
Societal cost benefit analysis
D
Step 1
Sensitivity of results to uncertain input parameters
Step 2
Distribution of costs and benefits over stakeholders
Robustness measures to be implemented

Phase A: Characterization of different major discrete event types on the multi-level public transport network based on frequency, duration, impact on infrastructure availability and impact on public transport demand

In this first phase, different major discrete event types on different network levels are identified and characterized based on the frequency with which they occur, the duration and the impact on infrastructure availability and public transport demand. All information in this study is calculated as much as possible based on empirical, real-world data. Based on the case study network, the following conclusions are formulated:

- For all major discrete events on the train network, it is statistically shown that the frequency of events per time period can be modelled by a Poisson distribution. A Poisson distribution is also assumed for the modelling of the frequency of events on the bus, tram and metro network per time period.
- On the Dutch train network, the major discrete event types 'vehicle breakdown', 'switch failure', 'suicide' and 'signal failure' occur with the highest frequency per time period: together these four event types are responsible for 63% of all events occurring on the train network.
- The major discrete event type 'vehicle breakdown' occurs with the highest frequency on train, metro/light rail and tram networks. Vehicle breakdowns are responsible for 61%, 46% and 18% of all major discrete events on the tram network, metro/light rail network and train network, respectively.
- Train networks are more robust against vehicle breakdowns and major incidents in terms of frequency, compared to metro/light rail, tram and bus networks. Especially tram networks seem to be relatively vulnerable to vehicle breakdowns and major incidents.

The figures below show the relative frequency of different event types on the train network (left), metro/light rail network (middle) and tram network (right).



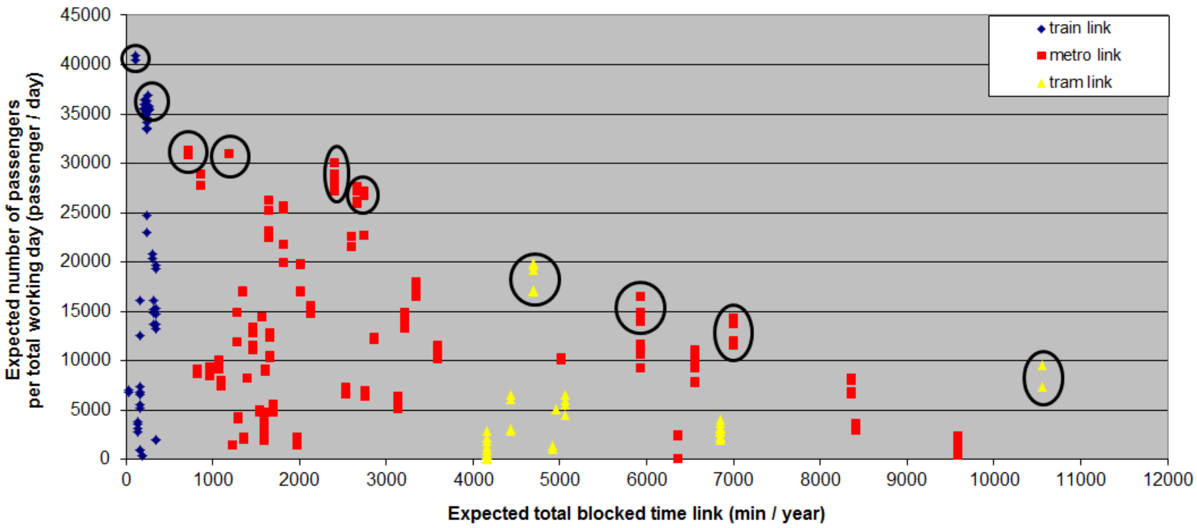
- The duration of suicide events on train networks can be modelled by using a normal distribution.
- The duration of large maintenance works on train networks can be modelled by a Bernoulli distribution when the possibility on delays in maintenance works is neglected.
- The duration of all other major discrete event types identified on the train, metro/light rail and tram network can be described by a lognormal distribution.
- The average duration of major discrete events on the bus/tram/metro network is slightly larger than one hour, whereas the average duration of events on the train network varies between one and four hours for different event types.

Based on a limited Chipcard dataset for the urban public transport network of Rotterdam and The Hague, the impact of major discrete events with a high level of predictability on reduction of public transport demand is estimated:

- In a case study when large maintenance works affect tram services in Rotterdam, a public transport demand reduction of 14% is empirically found on average over all affected trips on a working day.
- In a case study when large maintenance works affect tram line 9 in The Hague, the empirically found reduction in public transport demand between 50% and 56% can be considered as upper bound on a weekend day.

Phase B: Identification of the most vulnerable links in the multi-level public transport network

In phase B, a methodology is developed to identify the most vulnerable links in a multi-level public transport network. The average frequency, average duration and impact of each event type on infrastructure availability as determined in phase A are used as input for this methodology. As can be seen on page iii, this methodology consists of four steps. When this method is applied to the case study network, the figure below shows the result after the first three steps are taken: the link segments which have a high expected blocked time and also have a large impact on passengers form a Pareto front. Links up or near this Pareto front can be considered as most vulnerable.



From this figure, the following conclusions can be formulated:

- The identified most vulnerable link segments are from different network levels. This indicates that there is not one network level which is clearly most vulnerable or most robust.
- Links on the train network are especially vulnerable because many passengers experience hindrance in case of a disturbance. The expected blocked time of train links is relatively low.
- Compared to train links, metro/light rail and tram links suffer more often from disturbances. Especially busy metro and tram links are therefore vulnerable in the multi-level network.

When also the fourth step of this methodology is applied, the list of vulnerable links is reduced based on the assessment of number of route alternatives available for each link segment located up or near the Pareto front. For the case study network, the next link segments are identified as most vulnerable:

- Delft – Schiedam (train link segment);
- Switches Gerdesiaweg / Voorschoterlaan – Kralingse Zoom (metro link segment);
- Brouwersgracht – The Hague Central Station (tram tunnel The Hague) (tram link segment);
- Rodenrijs – Melanchtonweg (metro link segment);
- Laan van NOI – Forepark (metro/light rail link segment).

Phase C: Development of robustness measures for the identified vulnerable links and evaluation of measures

When the most vulnerable links in a multi-level public transport network are identified, in a next step major discrete events can be simulated on these links. Also, measures can be developed to improve the robustness of these links. Very generally speaking, the next types of robustness measures are expected to be promising, given the characteristics of major discrete events on different network levels as shown in phase A and phase B:

- Prevention-focused measures which can reduce the frequency of vehicle breakdowns (can be applied on all network levels) or can reduce the frequency of suicide events on the train network;
- Small infrastructure design measures which can realize extra turning facilities or an emergency bypass;
- Temporary service network design measures which improve network redundancy or flexibility;
- Measures like incident management and better travel information, focusing on improvements of the network resilience.

For one of the link segments which is identified as most vulnerable in phase B, the remaining parts of the total methodology are illustrated. For the metro/light rail link segment Laan van NOI – Forepark, the temporary service network design measure 'extra intercity stops at Zoetermeer and The Hague Ypenburg' is developed. In this measure, intercity services between Gouda and The Hague make two additional stops at the original sprinter stations Zoetermeer and The Hague Ypenburg, only in case of a disturbance on the metro/light rail link Laan van NOI – Forepark. This increases the number of multi-level transfer possibilities and improves the quality of the train link Zoetermeer / The Hague Ypenburg – The Hague (operated by the NS) as back-up route for the blocked metro/light rail link Laan van NOI – Forepark (operated by the HTM and RET).

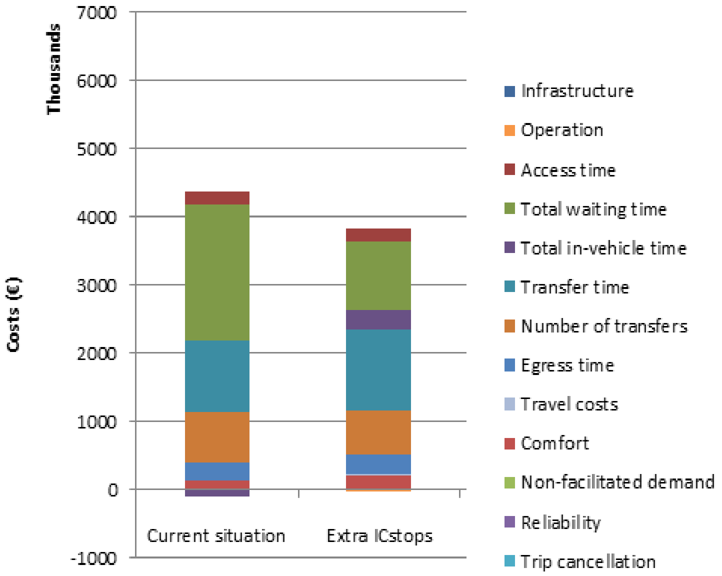
After measures are developed, the next method is used to evaluate the effects of these measures:

- Use Monte Carlo simulation to determine the total time a link segment is blocked per year, differentiated to each time period distinguished in the used transit assignment model. Because of the stochasticity related to the duration and frequency of different major discrete event types as identified in phase A, Monte Carlo simulation is used to generate values for the frequency and duration from a Poisson and (log) normal distribution, respectively.
- When passengers are assigned to the disturbed network, for each time period distinguished in the transit assignment model (in this study: 1st hour morning peak, 2nd hour morning peak, evening peak, remaining part of working day, weekend day) the societal effects of an event can be calculated.
- When the total blocked time for a link segment is known for each time period, the difference in societal costs of disturbances between the situation without measure and the situation when a measure is applied can be calculated for a certain time by using a societal cost benefit analysis.

For the case study measure, the following effects are found:

- The link segment Laan van NOI – Forepark is blocked by major discrete events during 1.5% of all operation hours. For a period of 10 years, simulation results indicate that the link segment is blocked for $1.0*10^3$ hours.
- When no measures are taken, the costs of non-robustness – the societal costs of major discrete events – for a period of 10 years equal € $4.3*10^6$. The average societal costs of one major discrete event on this link segments equal € $5.4*10^3$.
- When this measure is applied, the costs of non-robustness over 10 years equal € $3.9*10^6$. The average societal costs of one disturbance then equal € $5.0*10^3$, thereby reducing the costs of non-robustness by 8%.
- The Net Present Value of this measure over a period of 10 years equals € $3.4*10^5$.

The next figure shows the societal effects of this measure. The different aspects of the total costs of non-robustness are compared between the situation without measures taken and the situation when this measure would be applied. It can be seen that especially the waiting time is reduced because of this measure. This is because the frequency of train services from/to the multi-level transfer stations Zoetermeer and The Hague Ypenburg is doubled. The additional costs because of the longer in-vehicle time for through passengers in the intercity services and the slightly lower comfort level do not outweigh the benefits from the reduction in waiting time for passengers affected by the disturbance. The fraction of affected passengers who use the back-up train link increases from 24% to 43% because of this improved transfer possibility.



Phase D: Implementation of measures

In this phase it is analyzed whether proposed measures can be implemented. The results of the sensitivity analysis to uncertain input values and the distribution of financial / societal costs and benefits over the stakeholders involved in this multi-level network are used to underpin this decision. A sensitivity analysis is performed to the total duration that a link segment is blocked, the value of time and the effect of travel information. The sensitivity of results to this last aspect is assessed qualitatively.

It can be concluded that sufficient travel information, flexibility of public transport operators and more cooperation between public transport operators are requirements for a successful implementation of especially temporary service network design measures, for which the network of another public transport operator temporarily functions as back-up for a blocked network part of a certain operator.

For the case study measure, the following results can be shown:

- The Net Present Value of this measure 'extra intercity stops' is relatively sensitive to different input values used for total blocked time and value of time. The Net Present Value is especially sensitive to different values of time. Also qualitatively it can be stated that the Net Present Value of this measure is sensitive to the amount of travel information provided to passengers.
- The largest part of the financial costs comes at formal responsibility of the NS, because of the additional timetable hours the NS needs to make. In order to increase the willingness of the NS to cooperate in the implementation of this measure, it seems reasonable to compensate the NS for the additional costs they have to make. Clearly, the NS have to make financial costs because of a disturbance on the network of HTM and RET. Compensation of these costs could be done by the HTM, RET or the Stadsgewest Haaglanden, or by a combination of these stakeholders.
- The measure 'temporary extra intercity stops at Zoetermeer and The Hague Ypenburg' is recommended to be implemented, especially because this measure offers an alternative which can be implemented easily. No infrastructure needs to be constructed for this measure. However, providing passengers with sufficient information about the improved transfer possibilities is a requirement for a successful implementation.

Conclusions and recommendations

In this study, a methodology is developed which enables the evaluation of the current robustness of multi-level public transport networks, as well as the evaluation of proposed robustness measures. The case study shows that it is worth to consider another network level as back-up in case a certain network level is blocked. The result of the case study indicates that from a societal point of view, there is still room to improve the robustness of multi-level public transport networks.

The developed methodology can especially be developed further by incorporating en-route route choice possibilities in the transit assignment model. Further research is recommended especially to gain more knowledge about the behaviour of passengers in case they are confronted with major discrete events and in case they are confronted with crowded vehicles.

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List of abbreviations

BTM	Bus / tram / metro
HTM	The Hague Tram Company (in Dutch: Haagsche Tramweg Maatschappij)
I/C ratio	Intensity/Capacity ratio
IC	Intercity train service
NPV	Net Present Value
NS	Dutch Railways (in Dutch: Nederlandse Spoorwegen)
RET	Rotterdam Electric Tram (in Dutch: Rotterdamse Elektrische Tram)
PT	Public Transport
PTO	Public Transport Operator
SPR	Local train service (in Dutch: sprinter)
VoT	Value of Time

1

Introduction

1.1 Problem definition

Disturbances in public transport are an important issue for passengers, public transport operators and infrastructure managers. After the occurrence of large disturbances, there is often a strong call from passengers and society to make the public transport (PT) network less vulnerable - and therefore more robust - against these types of events. For example, after the large impact of snowfall on the supplied PT services during the winters of 2010, 2011 and 2012 in The Netherlands, politicians and passengers call for improvements of the robustness of PT networks against these circumstances. Although disturbances in public transport can never be prevented completely, it is important to reduce the (negative) effects of these disturbances for passengers.
Despite the mentioned importance of considering robustness and the passenger effects of disturbances, three limitations can be formulated regarding the way robustness of PT networks is currently considered.

First, currently most attention is paid to the improvement of robustness of PT networks against daily, small, recurrent delays which do not influence infrastructure availability. For urban PT networks this research strongly focuses on service reliability, indicating the matching degree between scheduled and actual PT operations (Van Oort, 2011). For example, on a tactical level holding points at strategic locations on a PT line can be used to improve service reliability, showing the trade-off between reliability on the one hand and speed on the other hand (Van Oort et al., 2012). On a strategic level an urban PT network design dilemma can be found between line length and reliability, since in general both the number of transfers and service reliability decrease with increasing line length. Therefore, line length can be used as network design measure to influence service reliability (Van Oort & Van Nes, 2009). Focusing on infrastructure design, terminal configurations can be used as measure to improve service reliability (Van Oort & Van Nes, 2010). For train networks, on a tactical level there is a focus on the design of robust timetables to mitigate effects of recurrent disturbances (see for examples Hansen and Pachl (2008)). A more robust timetable can for example be realized by adding sufficient running time supplements between stations and by adding sufficient buffer time between consecutive trains. On an operational level, for example the dispatching support tool ROMA is developed for the NS (the Dutch Railways) to optimize real-time disruption management to deal as well as possible with all kinds of circumstances or events (Corman et al., 2010).
However, there is hardly literature in which the robustness of PT networks against large, non-recurrent disturbances - which lead to infrastructure unavailability - is evaluated and quantified. One of the limited exceptions is the work of Tahmasseby (2009). In this work a methodology is developed to incorporate the

effects of large, non-recurrent disturbances in design choices for infrastructure and service network (lines, stops and frequencies) for a single-level urban tram network.

Second, robustness of PT networks is currently considered for each network level or for the network of each public transport operator (PTO) separately. In general, PTO's usually consider and optimize only the part of the total network they are operating. However, passengers often use PT services on different network levels in their door-to-door trip, often operated by different PTO's. When each PTO only optimizes the part of the network she is operating, it is possible that different optimized sub networks lead to a sub optimal total network from a passenger perspective. This is because interactions between different network levels are not fully considered.

Van Nes (2002) shows that – depending on the chosen network design objective – single-level and multi-level PT network optimization can indeed lead to different networks in terms of stop spacing, line spacing and frequencies. Also research performed by Goudappel Coffeng (2012) and Liemburg et al. (2012) clearly illustrates the relevance of considering interactions between different network levels. In their study, the PT network in the Randstad Zuidvleugel area of The Netherlands is considered. In this area, especially around the largest cities The Hague and Rotterdam, the PT network has a relatively high line density with different PTO's operating parts of the total network. The interaction between the design of the national / interregional and regional PT network level is illustrated by the effect of including station Schiedam Centrum as Intercity train station on changing passenger streams in different metro lines in Rotterdam. Including Schiedam Centrum as Intercity train station *(decision of the NS)* leads to a shift in passenger streams between Spijkenisse (south of Rotterdam) and The Hague. Instead of using the metro between Spijkenisse and Rotterdam Central Station (which is a very crowded line) and then transferring to the train to destinations in the direction of The Hague, using the metro from Spijkenisse to Schiedam (which is a relatively quiet line) and there transferring to the Intercity train becomes an attractive route alternative *(effect for the RET as metro operator of Rotterdam)* (see Figure 1.1). This study illustrates that a change in the network design on a national / interregional level improves the distribution of passengers on a regional level and therefore improves the supplied quality to passengers on the total door-to-door trip.

From a passenger perspective, also the robustness of a PT network against disturbances should not be considered for each PTO and thus for each single network level separately. Since passengers are concerned with the total door-to-door trip, the integral multi-level PT network should be considered when analyzing and improving robustness, regardless which PTO's are operating different parts of the multi-level network. Also from an operator perspective this can be of value, since passengers usually base their mode choice on the relative perceived disutility of the total door-to-door trip by public transport compared to other mode alternatives. Focusing on the improvement of robustness of the multi-level network can therefore have more beneficial effects on mode choice, compared to focusing on the improvement of robustness of sub networks only. Regarding small, recurrent disturbances Lee developed a framework to calculate service reliability effects in a multi-level PT network (Lee, 2013). Tahmasseby (2009) considered a single-level urban tram network to calculate the effects of major, non-recurrent disturbances. A methodology to evaluate and quantify the effects of non-recurrent events in multi-level PT networks is not developed yet.

Third, in general limited quantitative data about non-recurrent disturbances in public transport and the effects on passengers is available. When comparing research on robustness of road networks and public transport networks in The Netherlands, it can be concluded that research on road networks is already in a more developed phase. For road networks in The Netherlands, probabilities on the occurrence of different types of incidents on highways per million vehicle kilometres are known, specified for peak / non-peak hours and different road characteristics. Also, the average effect of a certain type of incident on vehicle loss hours is quantified (Kennisinstituut voor Mobiliteitsbeleid, 2010a). Similar probabilities and effects are hardly quantified when analyzing robustness of public transport networks in The Netherlands (Kennisinstituut voor Mobiliteitsbeleid, 2010b). Without this quantitative data, it is difficult to evaluate different policies and measures to improve the robustness of PT networks against large disturbances.

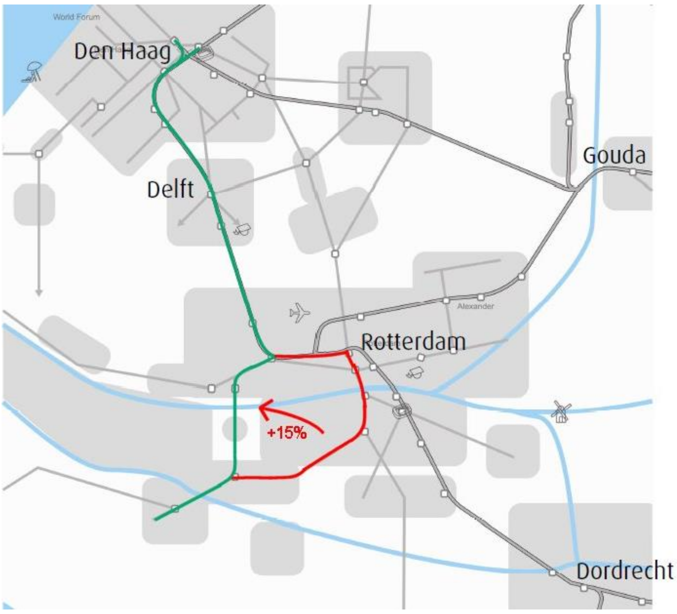

Figure 1.1: Effect of including train station Schiedam Centrum as Intercity station on passenger streams between Spijkenisse and The Hague (Goudappel Coffeng, 2012)

The following conclusions can be formulated regarding current approaches which consider robustness of PT networks:

- When evaluating and improving robustness of PT networks against large non-recurrent disturbances, a passenger perspective is not included to its full extent. There is a strong focus on independent network levels operated by a single PTO, instead of considering the integral, multi-level PT network available for passengers. This means that in case of large disturbances, the effect of the availability of other network levels of other PTO's on passengers is not considered.
- In general, limited quantitative data is available about disturbances which occur on multi-level PT networks and about the effects of these disturbances on passengers. Also there is limited knowledge about the robustness performances of different network levels relative to each other.

1.2 Research objectives and research question

1.2.1 Research objectives

This study aims to close the two gaps as mentioned in chapter 1.1 when considering robustness of PT networks. The study elaborates on the work done by Tahmasseby (2009), Van Oort (2011) and Lee (2013), extending their approaches to evaluate passenger impacts of non-recurrent disturbances in a multi-level PT network (see Figure 1.2). A methodology is developed to evaluate the robustness of an integral multi-level PT network and to evaluate the effects of infrastructure design measures and service network design measures on the robustness of this multi-level PT network.

A case study is used to apply and illustrate this methodology. The area in the Randstad Zuidvleugel between The Hague and Rotterdam is selected as case study to apply the methodology (see Figure 1.4 in chapter 1.5). This area is selected because in this area different PTO's are providing PT services on different network levels. Besides, there are train, metro, tram and bus lines which together offer parallel connections between parts of the case study area. This redundancy in some parts of the network possibly allows passengers to make some interesting route choices in case they face disturbances. This makes it an interesting case to really investigate the effect of focusing on robustness of multi-level networks operated by different PTO's.

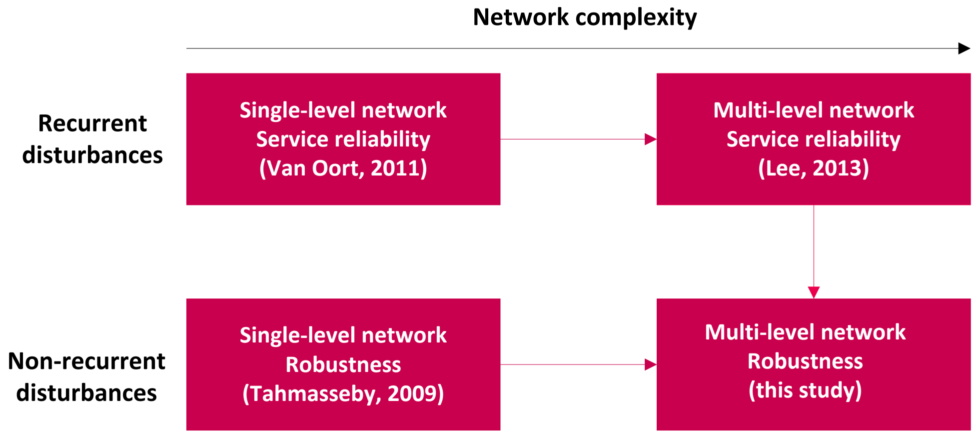

Figure 1.2: Categorization of study based on network complexity and type of disturbances

For this study, both a theoretical and practical main objective are formulated.

- The **theoretical main objective** of this study is to develop a methodology to evaluate public transport robustness and to evaluate the effects of measures on robustness from a passenger perspective, *by* extending and adapting methodologies used for the evaluation of robustness of road networks and single-level urban tram networks to multi-level public transport networks.
- The **practical main objective** of this study is to contribute to the improvement of the quality of the multi-level public transport network between Rotterdam and The Hague, *by* evaluating the robustness effects of proposed infrastructure design measures and service network design measures.

1.2.2 Research question

For this study, the following main research question is formulated:

What methodology can be developed to evaluate the robustness of multi-level public transport networks and to evaluate robustness effects of measures for the case study network between Rotterdam and The Hague?

To answer the main research question, the following sub questions are formulated:

Theoretical / methodological sub questions

1. What are the main characteristics of major discrete events in multi-level public transport networks in terms of frequency, duration and impact on infrastructure availability and passenger demand?
2. What methodology can be developed to identify vulnerable links in a multi-level public transport network?
3. What methodology can be developed to design measures to improve the robustness of multi-level public transport networks?
4. What methodology can be developed to evaluate the societal costs of major discrete events and to evaluate the effects of robustness measures?

Sub questions related to the multi-level public transport case study network between Rotterdam and The Hague

5. What are the most vulnerable links in the multi-level public transport network between Rotterdam and The Hague?
6. What are the societal costs of major discrete events on the most vulnerable links of the multi-level public transport network between Rotterdam and The Hague?
7. What are the effects of proposed robustness measures on the multi-level public transport network between Rotterdam and The Hague?
8. How are the effects of proposed measures to improve the robustness of the multi-level public transport network between Rotterdam and The Hague distributed over the different stakeholders?

The different terms used in the formulated research questions are defined in the next chapter.

1.3 Definitions

The next terms are defined in this chapter:

- Robustness;
- Vulnerability;
- Multi-level public transport network;
- Societal effects.

1.3.1 Robustness

In literature, a variety of definitions of robustness of networks is used. Ziha (2000) defines system robustness as the capacity of a system to respond to adverse conditions. Holmgren (2007) indicates that robustness of electric power systems “signifies that the system will retain its system structure (function) intact (remain (nearly) unchanged) when exposed to perturbations”. Robustness of a railway system is defined by Goverde (2012) as the ability of the system to withstand design errors, parameter variations (for example realized process times which deviate from planned process times) and changing operational conditions (like limited infrastructure availability or severe weather conditions). Van Nes et al. (2007) define robustness as the degree to which a system or component can function in a correct manner in case of invalid or conflicting input. Robustness of road networks is defined by Immers et al. (2011) as the extent to which the network is able to maintain the function it was originally designed for under all kind of circumstances. Parbo et al. (2013) define the robustness of a railway system as the ability of the system to resist consecutive delays. When defining robustness, Cadarso and Marín (2012) compare the network performance of the considered network with the performance of other possible or relevant networks. A network is called robust if a network, in case of failures on network links, still provides better transport services to a high proportion of passengers than other networks or means of transportation. The Kennisinstituut voor Mobiliteitsbeleid (2010ab) defines robustness of road networks and train networks as the extent to which extreme travel times for passengers owing to incidents can be prevented.
Based on the overview of different definitions of robustness found in literature, it can be concluded that there is no clear-cut definition of robust PT systems. It seems to be a rather complex concept for which different definitions and, as a consequence, different operationalizations are used in scientific research and practice.

An aspect almost all definitions have in common is the strong network-oriented focus. In general, these definitions of robustness focus on the ability of the network to deal with certain circumstances, events or incidents. Robustness is considered as a network characteristic, which influences the PT services supplied to passengers in case of certain circumstances or conditions.
Robustness is in some definitions only related to major incidents (Kennisinstituut voor Mobiliteitsbeleid, 2010ab), whereas in other definitions it is related to each kind of circumstance which leads to a deviation from plan (Immers et al., 2011; Van Nes et al., 2007). In that case, both major incidents and small deviations are captured in the definition. In road networks and single-level urban PT networks, a distinction is made between these event types based on their level of regularity (Snelder, 2010; Tahmasseby, 2009). On the one hand, there are recurrent events with a high level of regularity. These events occur with a relative high frequency and often lead to minor deviations in demand or supply. These events have no (or hardly) influence on infrastructure availability. Events of this type are indicated by Tahmasseby (2009) as ‘minor quasi continuous events’. On the other hand, there are non-recurrent, irregular events. These events, identified by Tahmasseby (2009) as ‘major discrete events’, occur not in any pre-defined pattern, affect infrastructure availability and often cause large deviations from planned demand and/or supply. Table 1.1 shows some examples of how different event types occurring on transportation networks can be classified according to their level of regularity.

Table 1.1: Classification of events in transportation networks based on their level of regularity (Snelder, 2010; Tahmasseby, 2009)

Minor quasi continuous events (recurrent events)	Major discrete events (non-recurrent events)
Weekend traffic	Extreme weather conditions
Bridge openings	Defective infrastructure
Small maintenance activities	Large maintenance activities
Small incidents	Big accidents or calamities

As mentioned in chapter 1.2.1, this study focuses on infrastructure design and service network design measures to improve the robustness of a multi-level PT network against major discrete events. Measures focusing on improving service reliability because of minor quasi continuous events are already discussed in Van Oort (2011) and Lee (2013). Therefore, in this study robustness is related to major discrete events only. In line with this, the next definition of robustness is used in this study:

> *'Robustness is the extent to which the network is able to maintain the function it was originally designed for under circumstances which strongly deviate from plan'*.

In this definition, robustness is related to the extent that a network can maintain its original function under certain conditions. The function a PT network originally has is defined as *'providing connections between network nodes within the expected travel time, against the expected travel costs and with the expected travel comfort.'* This definition shows that the function of a PT network is related to connectivity, travel time, travel costs and travel comfort. This means that robustness against major discrete events, as network characteristic, can be evaluated based on the effects of these events on passengers' travel time, costs and comfort and connectivity between nodes. This evaluation is in line with the method applied by Van Oort and Van Leusden (2012) to evaluate service reliability effects of recurrent events.

1.3.2 Vulnerability

A term related to robustness is vulnerability. In fact, vulnerability and robustness are each other's opposites. A network which is highly vulnerable is very sensitive to deviations in demand and supply from regular, planned circumstances. This means that a very vulnerable network cannot provide connections between nodes within the expected travel time, against expected travel costs and with expected travel comfort in case of a relatively small deviation in demand and/or supply. On the other hand, a very robust network is very insensitive for demand or supply fluctuations. This shows that vulnerability and robustness are inversely related to each other. A network which is very vulnerable is not robust, and vice versa (Tahmasseby, 2009). As can be concluded from Table 1.1, both internal causes (like vehicle breakdowns as type of calamity) and external causes (like extreme weather) can lead to fluctuations in demand and/or supply. In this study both types of causes are included, since from a passenger perspective both types can have negative consequences regardless whether the cause is internal or external.

1.3.3 Multi-level public transport network

In PT networks different network levels can be distinguished, which are hierarchical related to each other. Each network level is considered to have two functions: providing transport for its own trips, and facilitating access to and egress from the higher-level network. Figure 1.3 shows the hierarchical relation between different network levels and the two functions of each network level. When considering multi-level PT networks in The Netherlands, the following network levels can typically be distinguished for this study (Van Nes, 2002):

- National / international level (international trains; long distance intercity trains);
- Interregional level (intercity trains)
- Regional level (Sprinter trains; some bus services);
- Agglomeration level (metro, light rail; some tram and bus services);
- Urban level (urban tram and bus services).

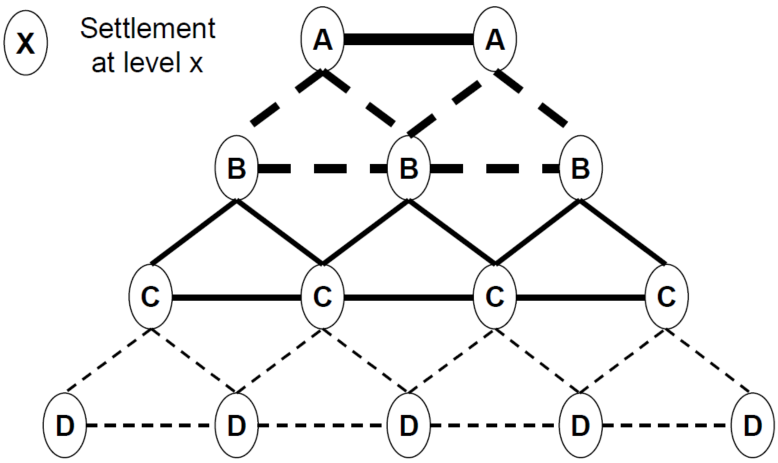

Figure 1.3: Hierarchical relation between different network levels (A-D) in a multi-level PT network (Van Nes, 2002). Each line type represents connections provided by a certain network level. This illustrates the two functions of each network level: connecting settlements on its own level and connecting these settlements with settlements on the next higher network level

1.3.4 Societal effects

In this study the societal effects of proposed measures are evaluated. This means that not only the monetary cost and benefits of measures are considered, but all societal costs en benefits. In this study, these societal effects include - amongst investment costs, maintenance costs and travel costs and benefits - the effects on travel time, travel comfort en reliability. Also, it is checked whether the capacity of alternative routes is sufficient to facilitate all PT demand in case of a major discrete event. In the work of Tahmasseby (2009), comfort and capacity effects are not included in the evaluation of measures. In this study, a passenger perspective is further adopted by including these effects in the evaluation of measures in a multi-level PT network. Evaluating measures from a societal perspective makes sense, since important benefits of robustness measures are expected to be benefits from less additional travel time and less reduction in comfort level in case of major discrete events. Focusing on monetary effects only would therefore substantially underestimate the total societal effects of robustness measures.

1.4 Scientific and societal relevance

Given the formulated theoretical and practical research objectives in chapter 1.2.1, it can be concluded that this study has both a scientific contribution and a societal contribution. The relevance of the research can therefore – in line with the two main research objectives – be divided in a scientific relevance and a societal relevance.

Scientific relevance

- Methodological: the scientific relevance of this study is to extend and adapt the current methodologies used for evaluating robustness of single-level PT networks and road networks to develop of a new methodology suitable for evaluating robustness of multi-level PT networks.
- Theoretical: the scientific relevance of this study is also related to insight gained about the considered system. This study shows how different PT network levels interact with each other in case of major discrete events. Besides, it gives insight in the main characteristics (like frequency, duration and impact) of different major discrete event types occurring on different levels of multi-level PT networks, in an absolute way and relative to each other. This study also gives insight in the reaction of passengers on these events as consequence.

Societal relevance

- From a societal perspective this study can be of relevance for passengers, but also for public transport operators and the public transport authority that provides a concession to a PTO. This study is relevant from a societal perspective because it shows the effects of proposed measures on the PT network between Rotterdam and The Hague. It shows how the quality of public transport offered to passengers can be improved while reducing societal costs. This principle of improving public transport against lower societal costs can also be found for improvements of service reliability of public transport and becomes increasingly important in times where PT budgets are cut (Van Oort, 2013). For PTO's and public transport authorities, results of this study can give guidelines what measures can be worth to implement to improve the robustness and PT services as a whole of the considered case study network.

1.5 Scope

1.5.1 Scope robustness measures

In this study, different measures are proposed to improve the robustness of the multi-level PT network. Proposed measures in this study are either focusing on infrastructure design changes, or on service network design changes (changes in lines, stops and frequencies). Measures focusing on robust timetable design and measures focusing on optimization of real-time scheduling in case of major discrete events are not considered in this study, since several studies to these topics are already performed (as explained in chapter 1.1). However, Tahmasseby (2009) shows that the reduction of total societal costs because of large infrastructure design measures (like the construction of a bypass tram connection for a vulnerable link) is limited. Therefore, this study focuses on relatively small infrastructure design measures at strategic locations, for which relatively high societal benefits are expected. Tahmasseby (2009) also shows that the total societal costs because of structural service network design measures (like a structural reduction of the line length of a vulnerable tram line, to keep the negative effects of major discrete events more local) often hardly decrease, or even slightly increase. This is because – despite the occurrence of major discrete events – in practice most of the time the PT network is undisturbed. This means that the societal benefits of robustness measures during the few times the network is disturbed do not outweigh the additional societal costs when there are no disturbances. Therefore, in this study there is focused on temporary service network design measures, which are only adopted in case of a major discrete event. This means that when no major discrete events occur, the standard service network is operated. During major discrete events, the service network is then adjusted to reduce societal costs of the event.

It should be mentioned that this study only focuses on infrastructure design measures and temporary service network design measures. Other types of measures which may improve robustness without changing the network design (for example: applying a stricter long-term maintenance policy for rolling stock, or improving information supply during major discrete events) are not considered.

1.5.2 Geographic scope

As mentioned, as case study the multi-level PT network between Rotterdam and The Hague in the Randstad Zuidvleugel in The Netherlands is considered. Figure 1.4 shows the geographic scope of the case study area. The following networks are included in this case study area:

- Train network The Hague Central Station / Laan van NOI – Rotterdam – Barendrecht; The Hague Central Station – Zoetermeer Oost; Rotterdam Central Station – Rotterdam Alexander; Schiedam Centrum – Hoek van Holland (all operated by the NS);

- Light rail network The Hague – Zoetermeer / Rotterdam (RandstadRail) (operated by the RET and HTM) and the metro network of Rotterdam (operated by the RET);
- Tram network of Rotterdam (operated by the RET) and The Hague (operated by the HTM);
- Regional bus network of Rotterdam (operated by the RET) and The Hague, including the Westland area between The Hague and Hoek van Holland / Maassluis (operated by Veolia Transport);
- Urban bus network of Rotterdam (operated by the RET), The Hague (operated by HTMBuzz), Delft and Zoetermeer (both operated by Veolia Transport).

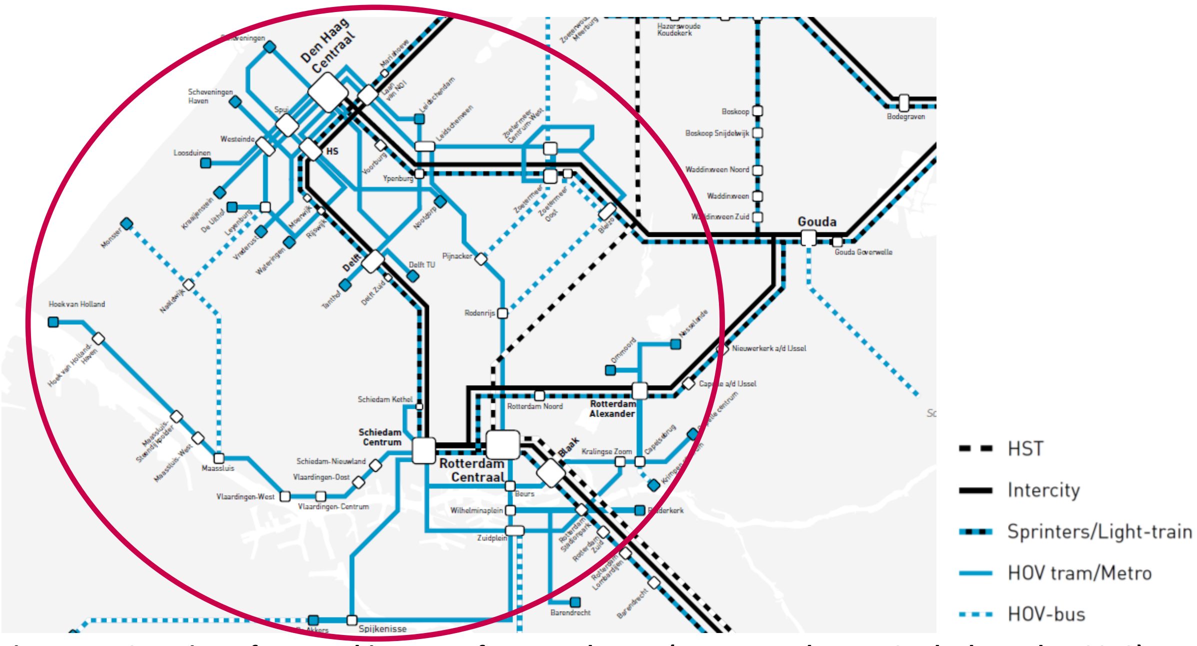

Figure 1.4: Overview of geographic scope of case study area (Programmabureau Stedenbaanplus, 2012)

In this area only line-bound PT is considered. No demand-responsive PT systems are included in this study. The robustness of PT networks on a national, (inter)regional, agglomeration and urban level within this area against major discrete events is evaluated. Relevant PT lines outside this area are considered fixed. These lines can function as back-up in case a major discrete event occurs on one of the PT lines within the case study area. However, the robustness of PT lines outside the selected geographic area is not evaluated.

1.6 Thesis outline

The structure of this thesis report is as follows. First, in chapter 2 a characterization of relevant major discrete events for the different levels of the multi-level PT network takes place. Different major discrete event types are characterized based on frequency of occurrence, duration, the effect on infrastructure availability and the impact on PT demand. In chapter 3, a methodology is developed to identify the most vulnerable links in a multi-level PT network, based on the frequency, duration and impact on infrastructure availability of different major discrete event types as determined in chapter 2. When the most vulnerable links in the network are identified in chapter 3, measures can be proposed to reduce the vulnerability of these links, and thus improve the robustness of these links and the considered network. As explained, proposed measures in chapter 4 are only related to infrastructure design and temporary service network design. The effects of these measures on the network and passengers streams are analyzed as well in chapter 4. In chapter 5, the proposed measures are evaluated by using a societal cost-benefit analysis. In this evaluation, the frequency, duration and impact on infrastructure availability and PT demand of different major discrete event types as characterized in chapter 2 are used as input. The societal costs of different major discrete events are compared for the situation without taking measures and the situation after taking a specific measure. Also the implementation process of promising measures is shortly discussed in chapter 5. This is done by investigating the distribution of financial and societal costs and benefits over the involved stakeholders (passengers, different PTO's, different transport authorities). In chapter 6, conclusions are formulated in order to answer the research question as formulated in this chapter. Also, recommendations for further research and further improvements of the developed methodology are provided. Figure 1.5 visualizes the structure of this report.

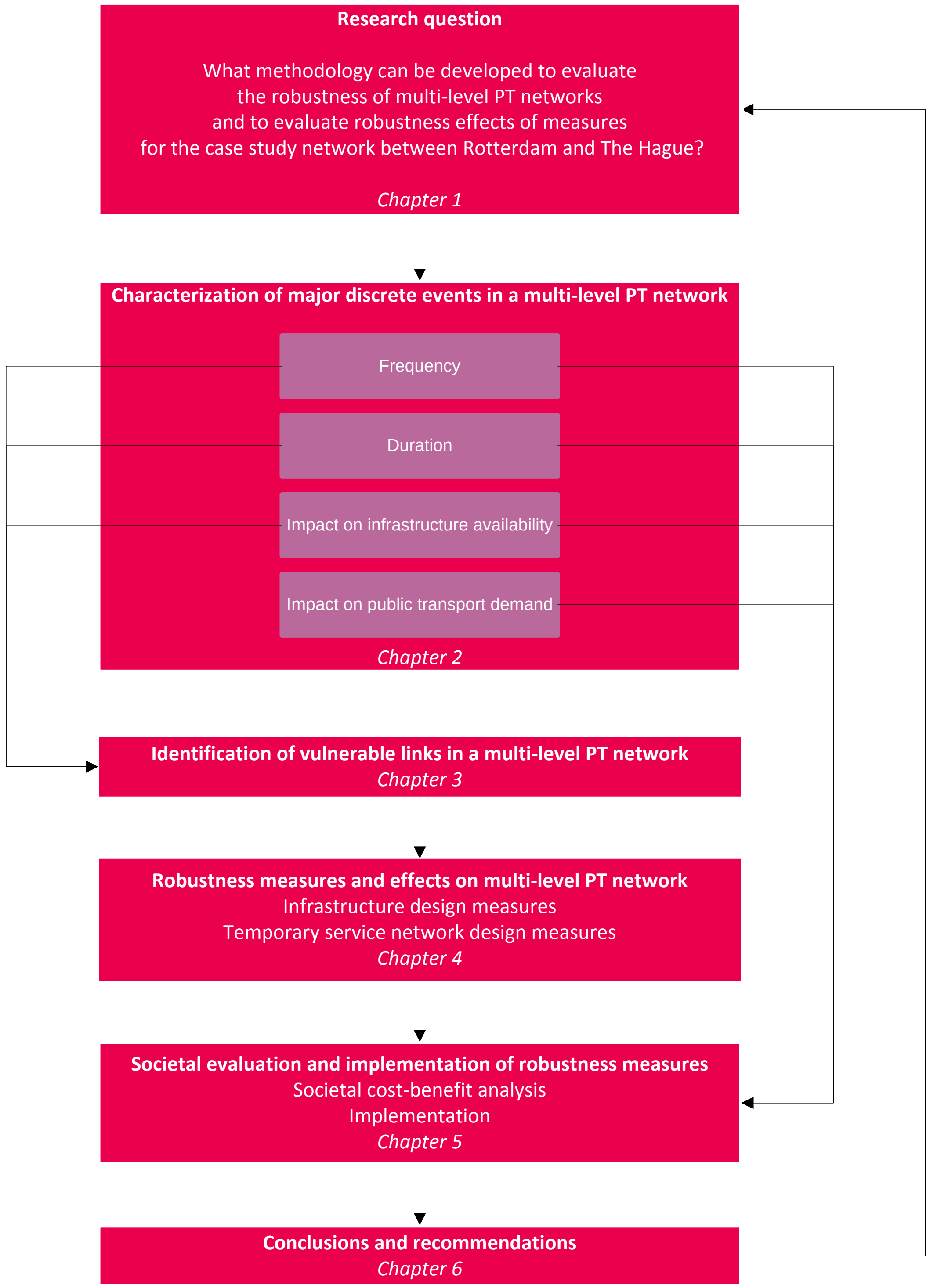

Figure 1.5: Report structure

2

Characterization of major discrete events in a multi-level PT network

This chapter focuses on the characterization of major discrete events which occur on different levels of a public transport (PT) network. In chapter 2.1, different major discrete event types are discussed which occur on the train network and bus/tram/metro (BTM) network. In chapter 2.2, the frequency with which these different major discrete event types occur is shown, whereas chapter 2.3 shows the duration of these event types. In chapter 2.4, the impact of different event types on infrastructure availability is analyzed. Chapter 2.5 discusses the effect of different event types on PT demand. At last, chapter 2.6 shows the most important conclusions.

2.1 Major discrete event types

2.1.1 Major discrete event types on train network

To determine the major discrete event types which occur on the Dutch train network (on an international / national, interregional and regional network level), a database is used which stores historic data about all major discrete events which occurred on the Dutch train network from January 2011 to August 2013. This database with information about events is available as application programming interface (API). Based on this API historic data is available which specifies the date, time, location, duration and cause of any major discrete event which occurred on the train network in The Netherlands since 2011 (thereby also considering events on the network of regional train operators like Arriva and Veolia Transport). This information is derived from the announcements at stations in case of a major discrete event. The first time and last time a certain event type is announced via the information signs at train stations is automatically logged, based on which an event in stored in a certain category. Based on this API, these data is translated to a website which is public accessible (Rijdendetreinen, 2013). For this study, it is expected and assumed that all major discrete events of relevance for passengers which occurred in reality are indeed displayed on the information signs at train stations. This means that the available data in the database is expected to be representative for the real frequencies and durations of different event types.
This database is used because no historic data on a disaggregate level from the NS or ProRail is available for this study. ProRail publishes aggregate information about some event types. However, with these aggregate data it is not possible to perform detailed analyses regarding the probability distribution functions which can approximate the frequency and duration of different event types.

The categorization of major discrete event types on the train network in this study is in general based on the categorization applied in this database. Two adjustments are however made in this categorization:

- *Combining similar categories.* A disadvantage of the used database is that quite similar events which are announced slightly differently are considered as two different categories by this API. For example, when considering the categories of major discrete events in this API, there is a category 'switch failure' and a category 'a defect switch'. To use reliable input data regarding major discrete events for this study, events which are very similar or even the same in reality are manually combined into a smaller number of functional and more intuitive categories.
- *No separate category for severe weather conditions*. In databases and literature (see for example Rijdendetreinen (2013); Snelder (2010); Tahmasseby (2009)) severe weather conditions like heavy snowfall are often indicated as separate event type. However, in practice snowfall is not an event which directly influences the PT network by itself. Snowfall increases the frequency and duration of certain other major discrete event types, like switch failures, vehicle breakdowns and signal failures. Since switch failures, vehicle breakdowns and signal failures are already considered as separate event type in the database, considering snowfall as separate event type leads to double counts: the effects of snowfall are already incorporated in several other event types. This also applies for the category 'lightning', whose effects are already incorporated in the database by the event 'power failure'.

The first column of Table 2.1 shows the remaining types of major discrete events which are considered in this study for the train network. In total, 15 different event types are distinguished.

2.1.2 Major discrete event types on BTM network

When analyzing major discrete events for bus (urban / agglomeration / regional network level), tram (urban / agglomeration network level) and metro / light rail (agglomeration level), no database containing historic data is public available. For the analysis of major discrete events on the BTM network a limited internal database of a Dutch urban PTO is used. This database contains the following information:

- An overview of all major discrete events, including duration and cause per event, which occurred during one week (September 30th, 2013 – October 6th, 2013) on the bus, tram and metro network;
- An overview of the cumulative duration of events per major discrete event type per week for bus, tram and metro separately, for a period of 8 weeks (August 12th, 2013 – October 6th, 2013). No data about the frequency with which different event types occurred per week is available for these 8 weeks: only the total duration of all events of a certain event type per week per mode is given;
- The total number of major discrete events which occurred per week for bus, tram and metro separately, for a period of 18 weeks (June 3rd, 2013 – October 6th, 2013).

Compared to the database available for major discrete events on the train network, the dataset for events on the BTM network is more limited. This means that it is not possible to distinguish between different BTM event types as detailed as it done for events on the train network, since insufficient data is available for each single event type to base reliable statistical analyses on. Although a more detailed analysis of characteristics of different event types can certainly give valuable information, using a functional categorization in which different event types are combined is sufficient for the evaluation of the robustness of networks. In this functional categorization it is important that event types are only combined if they can mainly be predicted by the same variable (for example: two event types of which the frequency of occurrence mainly depends on the amount of vehicle-kilometres), if they have the same effect on infrastructure availability (for example: two event types which both lead to a total blockage of infrastructure) and if they have the same level of predictability (for example: two unpredictable events). This categorization is explained in more detail further in this chapter (chapter 2.2.2 and chapter 2.4) and in chapter 3. The importance of these constraints for the categorization of event types is clarified in chapter 3 when identifying the most vulnerable network links.

The three most right columns of Table 2.1 show the remaining functional categories used in this study for major discrete events on the bus, tram and metro / light rail network. As can be seen, different event types on the BTM network are combined in one functional category.

Table 2.1: Overview of major discrete event categories for train, metro / light rail, tram and bus network

Train network	Metro / light rail network	Tram network	Bus network
Vehicle breakdown	Vehicle breakdown	Vehicle breakdown	Vehicle breakdown
Major incident	Major incident	Major incident	Major incident
Switch failure	Switch failure	Switch failure	
Blockage	Blockage	Blockage	Blockage
Restrictions by emergency services	Restrictions by emergency services	Restrictions by emergency services	Restrictions by emergency services
Defect / damaged bridge	Defect bridge	Defect bridge	Defect bridge
Power failure	Power failure	Power failure	
Defect track	Defect track	Defect track	
Defect overhead wire	Defect overhead wire	Defect overhead wire	
Signal failure	Signal failure		
Suicide			
Level crossing failure			
Damaged train viaduct			
Copper theft			
Large maintenance work	Large maintenance work	Large maintenance work	Large maintenance work

In this study, the light rail network operated by the HTM between The Hague Laan van NOI and Zoetermeer (see Figure 1.4 in chapter 1.5) is characterized together with the metro network of Rotterdam. This is because these networks have some important characteristics in common. In terms of functionality, these networks both function on an agglomeration level. Vehicles on both networks have an own right of way, and on both networks a signalling system is used to separate vehicles. Also, the network part between The Hague Laan van NOI and Leidschenveen is physically operated by both the metros of the RET and the light rail vehicles of the HTM. Given these similarities, the characterization of these two network types together can be justified.

In Table 2.1 different major discrete event types are mentioned. With the event type ‘major incident’, all collisions with other trains, metros, trams and busses, collisions with other traffic and persons (other than suicide) and derailments (not for busses) are indicated. A ‘blockage’ indicates several external causes of track blockage together, like a tree on the tracks, car on the tracks, dismantling a bomb from WWII or a collision between external parties on a PT track. Obviously, switch failures, power failures and defect tracks or overhead wire do not occur on bus networks. Signal failures do not occur on tram networks as well, since in general no signals are used on the tram network to guarantee that sufficient distance to the previous vehicle is kept. Suicides, damaged viaducts and copper theft can theoretically also occur on tram and metro / light rail networks. However, this is either not very plausible, or no data about these event types is available in the database used for the characterization of BTM events. Therefore, these event types are not considered for the BTM network levels.

2.2 Frequency of major discrete event types

2.2.1 Frequency of major discrete event types on the train network

For each of the major discrete event types for the train network as mentioned in Table 2.1, the frequency is determined based on the available data. In this chapter, the applied method and results are shortly described.

1: Theoretical expectation

From a theoretical perspective, it is expected that the frequency with which different event types occur per time period follows a Poisson distribution. This is because the properties of the Poisson distribution are assumed to be satisfied (McClave & Sincich, 2011):

- For each time interval with equal length the probability on an event is equal. This also means that the expected number of major discrete events per time period is equal for all time periods, when these time periods have an equal length.
- The probability on a major discrete event in a certain time interval is independent from the probability on an event in another disjunct time interval. This is explained by the memoryless of Poisson processes, which is proved below by expression (2.1). Since the interarrival times between events follow an exponential distribution in case the number of events per time period follows a Poisson distribution, the exponential distribution function is used in this expression.

$$P(T > s + t \parallel T > s) = \frac{P(T>s+t)}{P(T>s)} = \frac{1-F(s+t)}{1-F(s)} = \frac{e^{-\lambda(s+t)}}{e^{-\lambda s}} = e^{-\lambda t} = P(T > t) \qquad (2.1)$$

With parameters:

With parameters:	T	$occurrence\ of\ event\ T$
	s	$time\ period$
	t	$time\ period$
	$F(x)$	$exponential\ distribution\ function$

2: Statistical testing of seasonal influences

The assumption that the expected number of events per time period is equal for all time periods with equal length only applies if no other variable systematically influences the occurrence of events. However, for some event types weather can be an important factor influencing the number of events per time period. This means that the average number of events per time period can differ between different seasons for these events. In that case, the mentioned assumption is violated. To capture the possible correlation between weather / season and the frequency of some event types, for these event types it is first statistically tested whether the average number of events differs significantly between different seasons. No parametric one-way ANOVA test could be performed, since for all event types the assumption that the number of events per time period follows a normal distribution in each season is violated when testing this by performing a Kolmogorov-Smirnov test (with Lilliefors correction applied since the parameters of the hypothesized normal distribution are not known on beforehand) and Shapiro-Wilk test. In some cases, also the assumption of homogeneity of variances between seasons is violated (De Vocht, 2006). Therefore, a non-parametric Kruskal-Wallis test is performed to test whether seasonal differences in average number of events per time period exist.

Table 2.2: Overview of categories based on seasonal differences in frequency of different event types on the train network

Event type	Category 1	Category 2
Vehicle breakdown	Spring / summer / winter	Autumn
Signal failure	Spring	Summer / autumn / winter
Level crossing failure	Autumn / winter	Spring / summer
Power failure	Spring / autumn / winter	Summer
Blockage	Spring / winter	Summer / autumn

Table 2.2 shows the event types for which the Kruskal-Wallis test is significant, indicating differences in average number of events per time period in different seasons. Appendix A1 discusses the statistical testing of seasonal differences for each event type separately. The average number of vehicle breakdowns during autumn is significantly higher than in other seasons. This can be explained because of slippery tracks during autumn, caused by leaves of trees falling on the tracks. This causes more damage to the wheels of rolling stock. During spring, the average number of signal failures is lower than during other seasons. This can be explained because

spring is a relatively quiet period in terms of weather influences. During summer, extreme heat can lead to malfunctioning of signals, whereas during autumn leaves might give additional detection problems. Snow and very low temperatures might also increase the frequency of signal failures during winter. Level crossing failures are expected to be especially sensitive to high temperatures during summer and (late) spring because of the risk of overheating. The sensitivity to leaves and snow during autumn and winter is limited, because the installation of the level crossing is mainly located in a closed environment. The results of statistical testing for differences in the frequency of power failures between seasons are also in line with expectations. During summer in general more lightning takes place, causing the frequency of power failures to increase in this season. As explained, different types of events are bundled in the category 'blockage'. Therefore, it is less clear how the difference for this event type between spring and winter on the one hand, and summer and autumn on the other hand can be explained. A possible explanation can be that because of heavy lightning – mostly occurring in the summer - and severe storms – mostly occurring during autumn – tracks are more often blocked by fallen trees. However, given the limited frequency of such extreme weather, it is likely that other factors underlie these differences as well.

3. Statistical testing of Poisson distribution

For each event type - and in case significant seasonal differences exist also for each seasonal category - it is statistically tested whether the empirical distribution fits a Poisson distribution, in line with theoretical expectations. For each event type or category, based on empirical data a Poisson parameter λ is estimated. By performing a Chi Square test it is tested whether significant differences exist between the empirical frequencies and expected frequencies based on the estimated Poisson parameter. In case the two assumptions when performing a Chi Square test are not satisfied (all expected cell frequencies > 1; at least 80% of all expected cell frequencies >5), some values of event frequencies are combined into larger categories in order to satisfy the assumptions of the Chi Square test (De Vocht, 2006). In case the Chi Square value is not significant when using $\alpha=0.05$, the empirical data can be approximated by a Poisson distribution with Poisson parameter λ reflecting the average number of events per time period.

To capture correlations between a certain season and the frequency with which some event types occur, it is statistically tested whether seasonal differences in frequency exist. Additionally, the available data clearly shows that the frequency of certain event types during heavy snowfall is very atypical. On these days, the frequency of some event types is a multiple of its regular average frequency during winter. To prevent bias in the analysis because of these heavy snow days, a special snow scenario is developed. This scenario can only occur during the winter season. Based on historic data of the KNMI (2013), on average 11 snow days during one winter are assumed. The remaining days during the winter are considered as regular days. From the data available it becomes clear that the frequency of vehicle breakdowns, switch failures and signal failures differs significantly from regular days in the winter period. Therefore, based on the snow days which occurred in the period between January 2011 and August 2013, a separate Poisson parameter is estimated and statistically tested for these three event types in case of a heavy snow day during winter. In that way, the correlation between heavy snowfall and the frequency of vehicle breakdowns, switch and signal failures is captured. When events would be simulated on the different links of the network, the higher Poisson parameter value for these events during snow increases the probability that such events are simulated simultaneously on different links of the network. Especially the simultaneous occurrence of events like switch failures and vehicle breakdowns is a main characteristic on the train network during snowfall in reality.

Table 2.3: Average number of different major discrete event types per week on the whole Dutch train network

Major discrete event type	Spring	Summer	Autumn	Winter - regular	Winter - snow
Vehicle breakdown	5.0	5.0	6.9	5.0	11
Major incident	1.0	1.0	1.0	1.0	1.0
Switch failure	4.7	4.7	4.7	4.7	46
Blockage	0.6	1.1	1.1	0.6	0.6
Restrictions by emergency services	2.1	2.1	2.1	2.1	2.1
Defect / damaged bridge	0.9	0.9	0.9	0.9	0.9
Power failure	1.1	2.2	1.1	1.1	1.1
Defect track	0.4	0.4	0.4	0.4	0.4
Defect overhead wire	1.0	1.0	1.0	1.0	1.0
Signal failure	3.0	4.4	4.4	4.4	11
Suicide	4.5	4.5	4.5	4.5	4.5
Level crossing failure	2.8	2.8	1.9	1.9	1.9
Damaged train viaduct	0.3	0.3	0.3	0.3	0.3
Copper theft	0.3	0.3	0.3	0.3	0.3
Large maintenance work	0.3	0.3	0.3	0.3	0.3

Table 2.3 shows the average frequency with which different major discrete event types in different seasons occur per week, which equals the estimated Poisson parameter. These values are average frequencies per week for the whole Dutch train network (and not for the train network within the case study area only). In Appendix A2, the statistical distribution fitting process for each event type separately is explained. An important conclusion is that for almost all event types the empirical distribution fits the theoretical expected Poisson distribution. In almost all cases, when applying a 0.05 significance level the calculated Chi Square value is smaller than the critical Chi Square value. Only the distribution of the frequency of signal failures during summer, autumn and winter does not fit a Poisson distribution when applying $\alpha=0.05$. However, when applying $\alpha=0.01$, also in this case the empirical distribution fits a Poisson distribution. In combination with the theoretical properties of a Poisson distribution and the statistical results for all other event types, the use of a Poisson distribution to approximate the frequency of signal failures per time unit can be assumed as well.
Some of the values of Table 2.3 can be verified by using the aggregate data which are published by the train infrastructure manager ProRail. Based on the years 2011 and 2012 ProRail indicates that the average number of major incidents (derailments and collisions with trains, cars and other traffic together) equals 0.9 per week, which is comparable with the value of 1.0 per week found in this study as average over the period between January 2011 and August 2013. Regarding the average number of suicides per week, ProRail reports a value of 4.0 based on 2011 and 2012. This value is slightly lower than the average value of 4.5 per week determined based on the API. However, also in this API it can clearly be seen that on average the number of suicides in 2013 is higher than in 2011 and 2012. Excluding values from 2013 therefore leads to a comparable value as reported by ProRail (2013b). This verification indicates that the values gained from the API seem reasonable and in line with aggregate data published directly by ProRail. Therefore, it is expected that this data can be used to gain reliable information about different major discrete event types occurring on the train network.

The relative share of the different event types in the period between January 2011 and August 2013 is shown in Figure 2.1. From Table 2.3 and Figure 2.1, it can be concluded that vehicle breakdowns, switch failures, suicides and signal failures are the major discrete event types which occur most frequently on the train network in The Netherlands. Together, these four event types are responsible for almost two-third of all events occurring on the train network per time period (averaged over different seasons). Besides, during heavy snowfall the frequency of vehicle breakdowns and signal failures per time period is more than doubled. It can be concluded that especially switches are very sensitive to snow, since the frequency of switch failures increases with almost a factor 10 during heavy snow, given the available data. The frequency of large maintenance works per time unit is the lowest, compared to other event types. However, the values for maintenance works shown here are only concerned with work during regular train operation hours. Maintenance works during the night, when no trains are scheduled, are not considered since these maintenance works do not influence passengers.

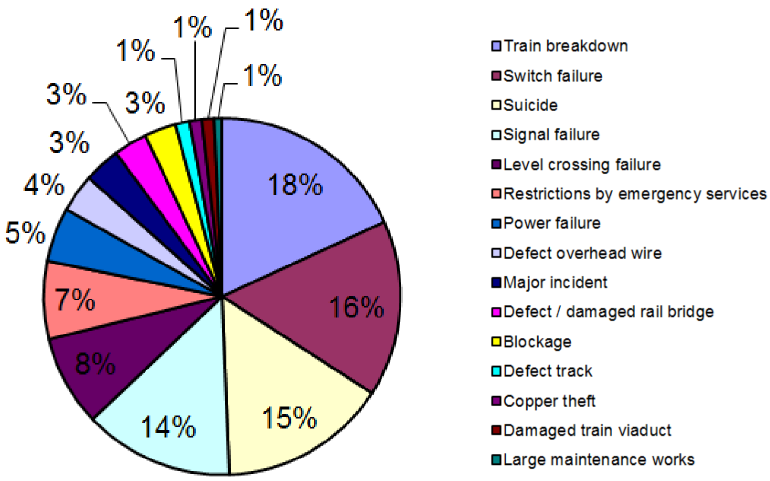

Figure 2.1: Relative frequency of different major discrete event types on the Dutch train network averaged over different seasons

Table 2.4: Assumed predictors per major discrete event type

Major discrete event type	Predictor	Assumption
Vehicle breakdown	Vehicle-km	No freight trains considered
Major incident	Vehicle-km	
Switch failure	Link length	Equal density of switches over the network
Blockage	Link length	
Restrictions emergency services	Link length	
Defect / damaged bridge	Nr of bridges	
Power failure	Link length	
Defect track	Track length	
Defect overhead wire	Track length	
Signal failure	Link length	Equal density of signals over the network
Suicide	Link length	No location specific influences considered
Level crossing failure	Nr of level crossings	
Damaged train viaduct	Link length	Equal density of train viaducts over the network
Copper theft	Link length	
Large maintenance works	Vehicle-km	No location specific influences like soil type considered

Table 2.3 shows the average frequency of events for the Dutch train network as a whole. These values can also be translated to the considered train network of the case study (see chapter 1.5.3). To this end, for each event type the most important factor is determined which predicts the occurrence of a specific event type on a specific link of the network.

Table 2.4 shows which predictors for each event type are assumed. It should be mentioned that generic predictors are used in this study. For example, for suicide events it is assumed that these events occur random on the train network. This means that a link with a longer link length is assumed to have a higher probability on the occurrence of a suicide event, compared to shorter links. In practice, also location specific influences like the location of mental hospitals near train tracks are an important predictor for suicide events on certain locations. These types of location specific influences are however not considered in this study. Since no detailed information is available about the specific locations of all switches and signals in the network, as simplification it is assumed that the density of switches and signals is equal for the whole network. In that case, link length can be used as factor to predict the number of switch and signal failures per network link. A similar assumption is made for the event 'damaged train viaduct'. It is realized that in reality differences exist in switch and signal density on the network, especially between links with a large share of open track and links with a large share of interlockings and junctions (Pachl & Hansen, 2008). For the event types 'level crossing failure' and 'defect / damaged rail bridge', specific locations are included to a certain extent. Since the total number of level crossings and movable rail bridges for the whole Dutch train network and the location of level crossings and movable rail bridges on the case study train network are known, the total frequency of these event types is distributed only over links having a level crossing or movable rail bridge (ProRail, 2013c). For other links of the case study network, no occurrence of these event types is assumed. For vehicle breakdowns, major incidents and large maintenance work, it is assumed that they mainly depend on the number of vehicle-kilometres per time period on a certain link. Assuming that each train has a similar mean-time-to-failure, longer links with more trains per hour will suffer more from vehicle breakdowns compared to shorter links with a lower train intensity. At last, a distinction is made between link length and track length of links in the network. The link length does not consider the number of tracks per link, whereas track length does incorporate this. This means that a four-track link having link length X has a track length of $4X$. Only in case of single-track, link and track length are equal. This distinction is especially relevant when considering the events 'defect track' and 'defect overhead wire'. For these event types, track length is expected to be a better predictor for event frequency per link than link length. Since the considered train network is fully electrified, no correction has to be applied for network parts containing non-electrified tracks.

Table 2.5: Overview of some basic characteristics of the total train network and case study train network (values in the 2^nd column derived from ProRail (2013a))

	Total Dutch train network	Train network case study
Link length (km)	3.063	85
Track length (km)	7.033	208
Train-kilometres (km/year)	139 million	7.7 million
Number of level crossings	1.614	15
Number of movable rail bridges	56	3

Table 2.6: Average frequency of different major discrete events per week on the case study train network

Major discrete event type	Spring	Summer	Autumn	Winter - regular	Winter - snow
Vehicle breakdown	0.28	0.28	0.38	0.28	0.58
Major incident	0.05	0.05	0.05	0.05	0.05
Switch failure	0.13	0.13	0.13	0.13	1.27
Blockage	0.02	0.04	0.04	0.02	0.02
Restrictions by emergency services	0.06	0.06	0.06	0.06	0.06
Defect / damaged bridge	0.05	0.05	0.05	0.05	0.05
Power failure	0.03	0.06	0.03	0.03	0.03
Defect track	0.01	0.01	0.01	0.01	0.01
Defect overhead wire	0.03	0.03	0.03	0.03	0.03
Signal failure	0.08	0.12	0.12	0.12	0.32
Suicide	0.13	0.13	0.13	0.13	0.13
Level crossing failure	0.08	0.08	0.05	0.05	0.05
Damaged train viaduct	0.01	0.01	0.01	0.01	0.01
Copper theft	0.01	0.01	0.01	0.01	0.01
Large maintenance work	0.002	0.002	0.002	0.002	0.002

Table 2.5 shows some general values about the Dutch train network in 2012, derived from ProRail (2013a). For the train network of the case study, total link length and track length are determined based on Both & Van der Gun (2009) and Sporenplan (2013a). Based on these values and the NS timetable of 2014, the vehicle-kilometres for the case study train network are calculated (NS, 2014). In this calculation only scheduled passenger trains are considered, since the share of freight trains on the specific case study network is almost negligible compared to passenger trains. The most important freight train trips take place southern from the case study network, between Kijfhoek and Germany / Belgium.

Based on the values presented in Table 2.3 and Table 2.5 and the assumed predictors for each event type as shown in Table 2.4, for each event type the average number of events per week for the case study train network can be calculated. Resulting values are shown in Table 2.6.

2.2.2 Frequency of major discrete event types on the BTM network

As explained in chapter 2.1, data availability about major discrete events on the bus, tram and metro network is limited, compared to data availability for events occurring on the train network. The applied method and results to characterize the frequency of major discrete event types on the BTM network are shortly described in this chapter.

1. Theoretical expectation

From a theoretical perspective it is expected that empirical frequencies of major discrete event types on the BTM network per time period can be approximated by a Poisson distribution, since the same two properties as formulated in chapter 2.2.1 for the frequency of events on the train network are assumed. However, as mentioned in chapter 2.1, detailed data about the number of events per event type is only available for one week on the network of one Dutch urban PTO. This means that the available sample size is not large enough to test statistically whether the empirical distribution can be fitted to a theoretical probability density distribution. This is because the expected cell frequencies in case of a small sample size are such low, that the assumptions for performing a Chi Square test are violated (De Vocht, 2006). Therefore, in this study it is *assumed* for each event type that the number of events occurring within a certain time period on the BTM network follows a Poisson distribution. This assumption is based on theory and based on statistical evidence that the empirical distribution of the number of events per time period for event types on the train network also fits a Poisson distribution (see chapter 2.2.1).

2. Estimation of Poisson parameter per season

Since a Poisson distribution is assumed for the number of BTM events per time period, there is focused on the estimation of the Poisson parameter for each event category mentioned in Table 2.1. For this estimation, the limited data available about disturbances on the BTM network is combined with patterns which can be deduced from the events occurring on the train network. Since events occurring on the train network are analyzed in a relatively detailed way, some of this information can be useful to estimate the Poisson parameters for BTM events in different seasons. Given the data availability as described in chapter 2.1, the next steps are taken:

- For the single week for which information about all events, causes and durations on the network of one Dutch urban PTO is available, the average duration over all events is calculated for bus, tram and metro separately. The average duration is not calculated for each event category separately, given the fact that for some event categories only one or two data points are available in that specific week, on which no reliable conclusions can be built. Table 2.7 shows the average duration of events on the bus, tram and metro network over all event categories together. It also shows the number of events of that single week on which the average duration is based. Calculating the duration for all event categories together means that it is assumed that the different event categories per mode have on average an equal duration. For the events available in that specific week, it is checked whether there are strong correlations between a certain event type and duration. Although some differences could be noted (for example: the duration of power failures is often larger than the duration of vehicle breakdowns), very generally speaking no large outliers or strong correlations could be detected.

Table 2.7: Average duration of major discrete events on the metro/light rail, tram and bus network

	Metro network	Tram network	Bus network
Number of measured events in one week	N = 47	N = 50	N = 90
Average duration of events (min)	76	67	64

- Based on the average duration of an event on the bus, tram or metro network and based on the available cumulative duration per event type per week for a period of 8 weeks, an estimation of the number of events per event type per week can be made for these 8 weeks. This is done by dividing the cumulative duration per event type by the average duration of an event, again thereby assuming that the average duration is equal for the different event types.
- Based on the estimated number of events for each event type per week and the data available about the total number of events on the BTM network per week, for these 8 weeks the relative share of each event type can be determined. This can be done by dividing the number of events of a certain type by the total number of events in that same week. It is assumed that – at least for each season – the share of event types is more or less equal. Because the absolute number of events can heavily fluctuate over different weeks, the relative share of each event type to the total number of events is considered as a more stable and therefore more reliable measure.
- Since significant seasonal differences in average frequency for certain event types are found for the train network, seasonal differences can also be expected to exist between similar events on the BTM network. Therefore, the share of each event type to the total number of events is determined per season. This is because it might be possible that the share of a certain event type differs between seasons, in case a certain event type is heavily sensitive for certain weather or seasonal influences.
- For a period of 18 weeks during summer and autumn, the total number of events per week is known for bus, tram and metro. By multiplying the share of a specific event type in a specific season (summer or autumn) with this total number of events per week, the Poisson parameter can be estimated for summer and autumn separately, or for these two seasons together if no seasonal differences are expected for a certain event type.
- In case no seasonal differences are expected for the Poisson parameter representing the frequency of an event type per time period, the estimated value for summer and autumn together can also directly be used as Poisson parameter for spring and winter. However, in case there are significant seasonal differences in frequency for similar event types on the train network, it is necessary to adjust the estimated BTM Poisson parameter for summer and autumn to make it suitable as parameter for spring and winter. Since no data about the frequency of BTM events during spring and winter is available at all, the patterns between different seasons found on the train network are used. The ratio between the estimated Poisson parameters for a train event in different seasons is used as starting point for the estimation of the parameters for a comparable BTM event in spring and winter. In appendix A3, per event type it is explained how the BTM Poisson parameter for spring and winter is estimated based on these patterns found for events on the train network.

Based on the sample of events of one urban PTO (data and source are confidential), results can be generalized to the case study area Rotterdam – The Hague. For different event types, the same predictors are assumed as shown in Table 2.4 for events on the train network. The only exception is that link length is used as predictor for a defect bridge, since no detailed data is available about the locations of all movable bridges on the BTM network in the case study area. Besides, since all tram, metro and light rail network links consist of the same number of tracks (one track per direction), there is no need to distinguish between 'link length' and 'track length' as predictor.
As explained in chapter 2.1, different event types are functionally combined into larger event categories for BTM events, given the limited data sample available. This functional categorization is shown in Table 2.1. For events on the bus network, 'blockages', 'restrictions by emergency services' and 'defect bridge' are combined, whereas for events on the tram network this nest is expanded with the event types 'power failure', 'defect track' and 'defect overhead wire'. For events on the metro network, this event category is further expanded with the event 'signal failure'. Events are only combined into one event category for a specific mode if the same predictor is assumed to underlie it. Else, it is not possible to generalize the data from the specific operator to

the case study area without introducing bias in the analysis. In this case, for all events combined into one category the factor 'link length' is used as predictor.

Table 2.8: Overview of some basic tram and metro / light rail network characteristics of the case study area

	Tram network case study	Metro/light rail network case study
Link length RET part (km)	74	79
Link length HTM part (km)	110[1]	26
Link length total (km)	184	100[2]
Vehicle-kilometres RET part (km/year)	0.13 million	0.15 million
Vehicle-kilometres HTM part (km/year)	0.18 million	0.05 million
Vehicle-kilometres total (km/year)	0.31 million	0.20 million

[1] Station The Hague Laan van NOI is considered as border between tram and light rail network for the HTM network, since between Laan van NOI and Zoetermeer a signalling system is used, there is exclusive right of way and v_{max} increases from 50 km/h to 80 km/h

[2] The network part between station The Hague Laan van NOI and Leidschenveen is operated by both the RET and HTM. Therefore, this network part of 5 kilometres is included in the calculation of the total link length for the network of each of these operators. This explains why the total metro/light rail link length is 5 kilometres less than the sum of the separate link lengths per PTO, thereby preventing double counts

Table 2.8 shows some basic values regarding the total link length and vehicle-kilometres on the tram and metro/light rail network of the case study. Link length is estimated using Google Maps (2013). The number of vehicle-kilometres is estimated using these link lengths and based on the frequencies as mentioned in the (planned) timetable of the HTM and RET for 2014 (HTM, 2013; Stadsregio Rotterdam, 2013). The estimated link length of the Rotterdam metro network is verified. RET Metro (2013) indicates that the total length equals 78.3 kilometres nowadays. The performed estimation by using Google Maps results in a link length of 79 kilometres (see Table 2.8), indicating that these estimations are reliable. No values could be found or estimated regarding the total link length and number of vehicle-kilometres for the bus network in this case study area. This is because bus links can often not be identified that clear, given the fact that busses often share their road with private car users. Besides, the bus network has a substantial higher number of lines and covers a substantial larger area, compared to tram, metro/light rail and train. This makes estimation of these values quite difficult and time consuming.

Table 2.9 and Table 2.10 present the estimated Poisson parameters, representing the average number of events per event type or event category per week on the tram and metro / light rail network considered in the case study. Since no data about link length en bus-kilometres could be determined for the case study bus network, it is not possible to generalize the confidential data about events on the bus network to the bus network of the case study. However, more generic values can still be shown for events on the bus network (see chapter 2.2.3). No empirical data was available about the frequency of large maintenance works. Therefore, the values calculated by Tahmasseby (2009) for the frequency of work zones on the tram network of The Hague are applied for this event type for both the tram and metro/light rail network. Again, only large maintenance works during regular PT service hours are considered, explaining the relatively low frequency.

Figure 2.2 and Figure 2.3 show the share of different event types or categories for the tram and metro/light rail network (averaged over the different seasons). From Figure 2.2, Figure 2.3, Table 2.9 and Table 2.10 it can be concluded that vehicle breakdowns are by far the most dominant cause of an event on tram and metro/light rail networks. On tram networks, this event type is responsible for more than 60% of all events, whereas on the metro/light rail network almost 50% of all events which occur are vehicle breakdowns. Although the share of vehicle breakdowns on the train network is smaller (18%: see Figure 2.2), also on the train network vehicle breakdowns are ranked first as event type having the highest frequency. This indicates that vehicle breakdowns are apparently one of the most vulnerable aspects during PT operations. On the tram and metro/light rail network, the combined event category is also relatively high. For the tram network, this might be explained because trams have no exclusive right of way. Because of separated or shared right of way with other traffic, track blockages – as part of this category - are more likely to occur. The share of major incidents, switch failures and large maintenance works is for both the tram and metro/light rail network limited in terms of frequency.

Table 2.9: Average frequency of different major discrete event types per week on the case study tram networks of Rotterdam and The Hague together

Major discrete event type	Spring	Summer	Autumn	Winter - regular	Winter - snow
Vehicle breakdown	32	32	49	32	68
Major incident	4	4	4	4	4
Blockage + restrictions emergency services + power failure + other	15	21	24	15	15
Switch failure	1	1	1	1	11
Large maintenance work	0.12	0.12	0.12	0.12	0.12

Table 2.10: Average frequency of different major discrete event types per week on the case study metro / light rail network of Rotterdam and The Hague together

Major discrete event type	Spring	Summer	Autumn	Winter - regular	Winter - snow
Vehicle breakdown	11	11	16	11	20
Major incident	0.7	0.6	0.7	0.7	0.7
Blockage + restrictions emergency services + power failure + signal failure + other	10	14	13	13	18
Switch failure	1	1	1	1	11
Large maintenance work	0.12	0.12	0.12	0.12	0.12

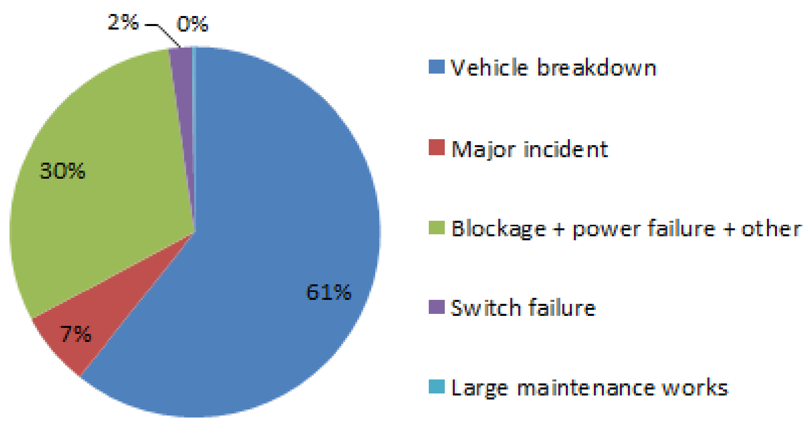

Figure 2.2: Relative frequency of different major discrete event types on the tram network of the case study area Rotterdam – The Hague averaged over different seasons

2.2.3 Comparison of robustness performance between different PT network levels

The estimated values for the frequency with which different major discrete event types occur on different network levels in chapter 2.2.1 and 2.2.2 are specified for the case study area of this research between Rotterdam and The Hague (see Table 2.6, Table 2.9 and Table 2.10). However, as can be concluded from Table 2.5 and Table 2.8, link length and vehicle-kilometres differ substantially between the different PT network levels in this case study area. Therefore, it is interesting to present values about the frequency of different events on a more generic level, independent from network size, line length or frequencies of different lines within the considered study area. Table 2.11 expresses the average number of events against a generic measure, depending on the assumed predicting factor (see Table 2.4). The probabilities are based on values averaged over the different seasons, in case seasonal differences exist. Also for the bus network, values can

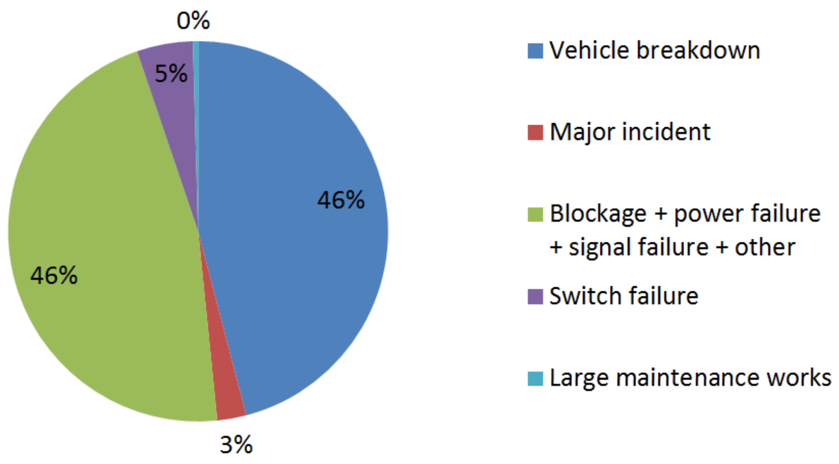

Figure 2.3: Relative frequency of different major discrete event types on the metro / light rail network of the case study area Rotterdam – The Hague averaged over different seasons

now be presented. Based on the calculation of the total link length and vehicle-kilometres of the associated bus network of the urban PTO which provided data about major discrete events, these generic values could be calculated. For combined event categories for the bus, tram and metro network no values are shown, since such value combined from different event types has limited interpretational meaning.

Table 2.11: Expected number of events per event type and network type

	Train network	Metro/light rail network	Tram network	Bus network
	Expected number of events per million vehicle-kilometres			
Vehicle breakdown	2.11	61.4	120	57.7
Major incident	0.37	3.31	12.9	11.0
Large maintenance work	0.11	0.59	0.39	
	Expected number of events per 1000 kilometres link length per year			
Switch failure	101	677	368	
Blockage	14.4			
Restrictions by emergency services	35.7			
Power failure	23.3			
Signal failure	72.1			
Suicide	76.4			
Level crossing failure	39.9			
Damaged train viaduct	5.09			
Copper theft	5.09			
	Expected number of events per 1000 kilometres track length per year			
Defect track	2.96			
Defect overhead wire	7.39			
	Expected number of events per movable rail bridge per year			
Defect / damaged bridge	0.84			

From Table 2.11, some interesting conclusions can be derived. Regarding the frequency of vehicle breakdowns, it can be concluded that most vehicle breakdowns per million vehicle-kilometres occur on tram networks, followed by vehicle breakdowns on the bus network and metro/light rail network. On the train network, the fewest vehicle breakdowns occur. One of the explanations why the frequency of vehicle breakdowns is substantially higher on tram, bus and metro networks, is the lower average speed compared to train networks. Since the values are expressed per million vehicle-kilometres, it should be noted that because of the lower level function of these modes in the multi-level network, stop spacing and average speed are also lower than for trains. This means that the number of vehicle-kilometres per time period is substantially lower for tram, bus and metro compared to trains. This pattern is supported by the result that the average number of vehicle breakdowns per million vehicle-kilometres is lower for metro's – having a higher average speed because of the agglomeration level on which metros function – than for trams (functioning more on an urban level). However, average speed does not explain all found differences. The average speed of trains is about 3-4 times higher than the average speed of trams and busses, while the expected number of events per million vehicle-kilometres for tram, bus and metro/light rail is much higher than 3-4 times the value for train networks. Besides, the expected value for vehicle breakdowns on bus networks is about twice as high as the value for tram networks, whereas the value for bus breakdowns is based on an urban bus network only, which hardly differs in average speed from trams. From this study, no clear explanation for this difference can be derived directly. It seems that also the intrinsic character of different modes and vehicle types contributes to these differences. The expected number of vehicle-breakdowns on a highway lies in the range 2.25 - 2.87 per million vehicle-kilometres (Kennisinstituut voor Mobiliteit, 2010a). Since the average speed of trains and cars on highways is comparable, it can be concluded that the number of vehicle breakdowns on the train network is comparable with the number of vehicle breakdowns occurring on highways. In terms of frequency, train networks seem to be slightly more robust against vehicle breakdowns compared to cars on highways of road networks.

Regarding major incidents, it can be concluded that the frequency of events per million vehicle-kilometres is lowest on train networks, followed by metro, bus and tram networks. Three explanations are suggested for the differences between train and metro networks on the one hand, and tram and bus networks on the other hand. First, trains and metros both have exclusive right of way, explaining the relatively low value compared to major incidents on tram and bus networks where much more conflicts with other traffic occur because of separated or shared right of way. Second, as explained above, differences in average speed between train, metro and bus / tram can partially explain the increasing values for major incidents with decreasing average speed for the different modes. Third, on the train and metro/light rail network a signalling system is used. This system guarantees in almost all cases that sufficient distance is kept between consecutive trains or metros. On tram and bus networks in general no signalling system is applied. This means that the driver is fully responsible for keeping sufficient distance to downstream vehicles, which makes those networks more vulnerable to human errors. For highways, the expected number of major incidents per million vehicle-kilometres lies between 0.50 and 0.64 (Kennisinstituut voor Mobiliteit, 2010a). This means that on train networks fewer major incidents occur than on highways of road networks. Again, one of the explanations can be the fact that the car driver is fully responsible for keeping sufficient distance to other traffic, while train drivers are supported by an automatic train protection system. The relative breaking distance determines the distance between cars, whereas the absolute breaking distance determines the distance between two consecutive trains.

Switch failures occur fewest on train networks, followed by tram networks. On metro/light rail networks, switch failures occur most frequent. The difference in frequency of switch failures between tram networks and metro/light rail networks might be explained because tram drivers are allowed to pass a disturbed switch under some conditions, what means that the effect of a switch failure on the passenger often remains limited. On metro (and train) networks, a switch failure is coupled to the signalling system, prohibiting a train or metro to pass the disturbed switch. The fact that switch failures occur more often on metro networks than on train networks can (partially) be explained because the switch density is higher on metro networks because of the lower-level function and shorter stop spacing, leading to a higher frequency of switch failures per kilometre link length. An interesting aspect for further research is to compare the mean-time-between-failure per switch for tram, metro and train networks. Then, there can be corrected for the number of switches per kilometre network. For this study such comparison could not be made because of the assumption of an equal switch density on the network, since no data about specific locations and number of switches was available.

2.3 Duration of major discrete event types

2.3.1 Duration of major discrete event types on the train network

This chapter shows the applied method and results to analyze the duration of different major discrete event types on train networks.

1. Theoretical expectations

Because of the existing variations in duration of a major discrete event type in different cases, it is not sufficient to use a measure of central tendency only to represent the duration of an event. The duration should therefore be considered from a stochastic perspective. In general, a lognormal distribution seems a suitable probability density function to describe the duration of events. Tahmasseby (2009) uses a lognormal distribution to approximate the duration of different event types on an urban tram network. The advantage of using a lognormal distribution is that only nonnegative values can occur, which is in line with reality. Besides, the right-tailed distribution can represent more extreme durations - which sometimes occur after a severe major discrete event - in a realistic way (for example the duration of a derailment, which is substantially longer than the average duration of an event of the category 'major incident' on a train network). Using a normal distribution introduces a certain probability on a value drawn from the distribution which is smaller than zero, thereby conflicting with reality. This probability depends on the values found in the data for the average and standard deviation, because values of this symmetric distribution can in theory lie between [-∞,∞]. Therefore, from a theoretical perspective a lognormal distribution is considered as most promising distribution type to approximate the duration of events.

2. Sample from database

The database described in chapter 2.1 also contains the start and end time of each logged event on the train network. However, start and end time can only be determined manually from this database. Given time considerations, it was not possible to consider the duration of each event separately in this study. Therefore, a sample from this total dataset is taken for each identified major discrete event type. For each event type, the duration is determined for the first event of each month in the period January 2011 – August 2013, leading to a sample size of 32 events per event type. Given the fact that events of a certain type in different months occur independently from each other, and given this sample size, applying the central limit theorem on the (log transformed) data means that the data set can be approximated by a (log)normal distribution.
Additionally, it is also statistically tested whether the data from the sample can be approximated by a normal or lognormal distribution. This is done by visual inspection of the histogram of these data per event type, checking the level of skewness and kurtosis of the curve and by performing a Kolmogorov-Smirnov test and Shapiro-Wilk test. Since no parameters of the distribution are known on beforehand, Lilliefors correction is applied when performing the Kolmogorov-Smirnov test. The Shapiro-Wilk test is also applied because this test is more powerful than a Kolmogorov-Smirnov test (Nornadiah & Yap, 2011). Therefore, in case the Shapiro-Wilk test is not significant, there is stronger evidence that the (log transformed) empirical data follows a (log)normal distribution.
In case the statistic value of the Kolmogorov-Smirnov and Shapiro-Wilk test are not significant for the (log transformed) data, there is strong evidence that the empirical data can be approximated by a (log)normal distribution. However, in case a (log)normal distribution could not statistically be shown, a suitable probability distribution function is determined based on literature, visual inspection of the histogram and the central limit theorem. Appendix A4 discusses the testing on (log)normality for all event types separately. In case a lognormal distribution is used to describe the duration of an event type, the parameters μ and σ are determined based on the mean m and variance v of the empirical dataset by applying formulas (2.2) and (2.3) (MathWorks, 2014).

$$\mu = \ln(m^2 / \sqrt{v + m^2}) \tag{2.2}$$

$$\sigma = \sqrt{\ln(v \,/\, m^2 + 1)} \tag{2.3}$$

Table 2.12 shows the resulting probability distribution functions which are used to describe the duration of different event types. In general, it can be concluded that in most cases a lognormal distribution could statistically be shown using a significance level of 0.05. For most of the event types, both the Kolmogorov-Smirnov (K-S) test and Shapiro-Wilk (S-W) test are not significant. For some events, the S-W test shows significant results, whereas the K-S test is not significant. This is consistent with the fact that the S-W test has more power than the K-S test. In general, the resulting p-values support the expectations from theory and literature. However, for the event 'suicides' a normal distribution fits the empirical dataset significant better than a lognormal distribution. The probability that the duration of a suicide event would be smaller than zero in case of applying a normal distribution with parameter values as shown in Table 2.12 equals 0.00016 and can therefore be neglected. Therefore, for this event type a normal distribution is assumed. Besides, for large maintenance works a Bernoulli distribution is assumed. Based on a sample, it can be concluded that almost all maintenance works which occur during regular train operation hours last for either 1 day or 2 days. When possible delays during maintenance works are neglected, a fixed duration of 1 or 2 days fits in this case the empirical data better than a (log)normal distribution. In the sample taken, 80% of the large maintenance work events last for 2 days (most often during weekends), whereas 20% of the maintenance work events last for 1 day. Based in this sample, parameter values for the Bernoulli distribution are set equal to p=0.8 (representing a duration of 2 days) and q = 1-p = 0.2 (representing a duration of 1 day).

Table 2.12: Distribution of duration of different major discrete event types on the train network

Major discrete event	Distribution	Mean *m* Standard deviation *s*	Parameters μ and σ	K-S test p-value	S-W test p-value
Vehicle breakdown	Lognormal	m = 107 min s = 96	μ = 4.38 σ = 0.77	.200	.274
Major incident	Lognormal	m = 145min s = 106	μ = 4.76 σ = 0.65	.200	.426
Switch failure	Lognormal	m = 140 min s = 123	μ = 4.66 σ = 0.76	.146	.098
Blockage	Lognormal	m = 97 min s = 80	μ = 4.32 σ = 0.72	.200	.541
Restrictions by emergency services	Lognormal	m = 88 min s = 96	μ = 4.09 σ = 0.89	.200	.277
Defect rail bridge	Lognormal	m = 118 min s = 98	μ = 4.51 σ = 0.72	.011	.104
Power failure	Lognormal	m = 144 min s = 108	μ = 4.75 σ = 0.67	0.200	.003
Defect track	Lognormal	m = 217 min s = 188	μ = 5.10 σ = 0.75	0.200	.471
Defect overhead wire	Lognormal	m = 229 min s = 176	μ = 5.20 σ = 0.68	0.200	.392
Signal failure	Lognormal	m = 153 min s = 107	μ = 4.83 σ = 0.63	.200	.047
Suicide	Normal	m = 155 min s = 43	μ = 155 σ = 43	.200	.368
Level crossing failure	Lognormal	m = 91 min s = 76	μ = 4.25 σ = 0.73	.066	.155
Damaged train viaduct	Lognormal	m = 62 min s = 35	μ = 3.99 σ = 0.53	.200	.455
Copper theft	Lognormal	m = 196 min s = 130	μ = 5.10 σ = 0.60	.181	.339
Maintenance works	Bernoulli		p = 0.8 (2d) q = 0.2 (1d)		

From Table 2.12 can be seen that the average duration of an event type differs between one and almost four hours. Especially solving defects regarding the track or overhead wire takes a long time on average. On the other hand, blockages, restrictions by emergency services and restrictions because of a damaged train viaduct take on average relatively short. The latter can be explained because visual inspection of a train viaduct is needed after being hit by a car, for example (Van der Reest, 2013). In case no serious damage can be found, train services are no longer disturbed after this inspection. The low average duration of this event type is probably caused because relatively often no serious damage can be found after inspection. In general, it can be concluded that the standard deviations of the duration of all event types are relatively large, indicating that durations are likely to be found in a quite large range around the average value. This indicates that using a measure of central tendency only is not sufficient to capture the range of duration values found in reality. This also shows that prediction of the duration of events can be complicated, given the uncertainty regarding the duration.

In general, no seasonal differences are expected regarding the duration of events. The frequency in which some event types occur can be different in some seasons, but in general there is no reason to assume that the duration of events differs as well between seasons. The only exception made is regarding the duration of events during heavy snow. In chapter 2.2 is mentioned that during heavy snowfall the frequency of vehicle breakdowns, switch and signal failures increases substantially. Given the fact that during heavy snow failures will occur more often simultaneously on different locations in the network, it seems not illogical that the duration to solve a certain event increases given a certain amount of resources available. Therefore, for these three event types the parameters of the distribution functions are estimated and statistically tested based on data available from periods of heavy snowfall. Given the limited number of heavy snow days in the considered time period of the used database, the duration of all events of these three event types during heavy snow days is used to calculate parameter values, instead of taking a sample from this dataset.
From Table 2.13 can be concluded that the duration of switch failures indeed increases on average with more than 50 minutes (+36%). Also the variance around this higher average value increases, indicating more uncertainty to passengers regarding the duration. Regarding signal failures, it can be seen that especially the variance increases substantially. This indicates more extreme outliers in the duration of such an event, whereas the average duration of signal failures remains unchanged. However, the average duration of vehicle breakdowns even decreases somewhat, compared to regular circumstances. Although this seems to be contradictory, it can be explained by anticipatory behaviour of the train operating companies. In case heavy snow is forecasted, these companies usually locate additional locomotives at some strategic locations, which can pull a defect train to a next station from the open track. Because of this expansion of resources, it might be possible that defect trains are moved faster from the track during heavy snow than during regular circumstances.

Table 2.13: Distribution of duration of different major discrete event types on the train network during snow

Major discrete event	Distribution	Mean *m* Standard deviation *s*	Parameters μ and σ	K-S test p-value	S-W test p-value
Vehicle breakdown	Lognormal	m = 99 min s = 90	μ = 4.26 σ = 0.85	.200	.834
Switch failure	Lognormal	m = 191 min s = 198	μ = 5.09 σ = 0.69	.065	.012
Signal failure	Lognormal	m = 154 min s = 155	μ = 4.77 σ = 0.67	.200	.153

2.3.2 Duration of major discrete event types on the BTM network

In chapter 2.2 the average duration of events on the bus, tram and metro network is already discussed as part of the method to determine the frequency of events on the BTM network. As explained, for all event types of a certain network type (metro/light rail, tram or bus) one function is estimated representing the duration of all these event types together. The reader is referred to chapter 2.2.2 for a detailed explanation. In this chapter, it is sufficient to indicate that a lognormal distribution is applied to model the duration of events on the BTM network. Except theoretical considerations, a lognormal distribution is also statistically tested. Table 2.14 summarizes the most important information. The K-S test is not significant for all three event types when using α=0.05. For the duration of events on the metro and tram network, the S-W test is also not significant. The duration of events on the bus network follows a lognormal distribution to a lesser extent compared to the duration of events on the tram and metro network. This causes the more powerful S-W test to be significant when testing if the duration of events on the bus network fits a lognormal distribution, whereas the K-S test still shows p-values > 0.05. The estimated parameter values of the lognormal distribution for all major discrete event types together per mode are also shown in Table 2.14. Comparing the average duration of major discrete events on the BTM network with the train network, it can be seen that the average duration of events on the BTM network is lower than for all event types on the train network, except the event type 'damaged train viaduct'. Besides, the variance of the duration of events on the tram and bus network is in general smaller than the variance of the duration of events on the train and metro/light rail network. A possible explanation can be that the duration of an event on train and metro/light rail networks depends more heavily on the specific location than for tram and bus networks. For train and metro/light rail networks, it is possible that some locations are substantial less accessible than other locations, leading to longer durations to solve an event. It can be expected that these differences in accessibility are hardly relevant on an agglomeration/urban level on which trams and busses operate.

Table 2.14: Distribution of duration of different major discrete event types together on the BTM network

Mode	Distribution	Mean *m* Standard deviation *s*	Parameters μ and σ	K-S test p-value	S-W test p-value
Metro / light rail network	Lognormal	m = 76 min s = 115	μ = 3.74 σ = 1.09	.200	.524
Tram network	Lognormal	m = 67 min s = 48	μ = 4.00 σ = 0.64	.200	.617
Bus network	Lognormal	m = 64 min s = 55	μ = 3.88 σ = 0.74	.160	.029

2.4 Impact of major discrete event types on infrastructure availability

As mentioned in chapter 1.3.1, recurrent events are assumed to have no or only a very limited influence on infrastructure availability. Non-recurrent, major discrete events as considered in this study do affect infrastructure availability. The different major discrete event types as described in chapter 2.1 can have different effects on infrastructure availability. From a passenger perspective it is relevant to investigate what impact each event type has on infrastructure availability, since PTO's adapt their remaining PT services supplied to passengers based on infrastructure availability. Different measures are taken by PTO's in case for example a link is only blocked in 1 direction, compared to the situation where a link is blocked in both directions as a consequence of a major discrete event. For the different events distinguished for the train network, a two-step approach is applied to investigate the effects on infrastructure availability.

- First, a qualitative assessment of the expected effects on infrastructure availability per event type is performed. This assessment is based on expert judgment after an interview held with a dispatcher of the NS working at the Operation Control Centre Rail (OCCR) in Utrecht (Van der Reest, 2013). The exact results of this interview can be found in appendix A5. Based on the qualitative assessment, for the majority of major discrete event types a fixed effect on infrastructure availability can be assumed. For a few event types it seems that there is no clear 1-to-1 relation between event type and effect on infrastructure availability. In different situations, those event types can have different effects on infrastructure availability. Based on the qualitative assessment, it can be concluded that this is mainly the case for the event types 'switch failure', 'signal failure', 'level crossing failure' and 'copper theft'. Especially for these four event types, situation specific factors play an important role in determining the final effect on infrastructure availability.

- For the mentioned four event types in a second step a quantitative assessment is performed as well. Based on a sample taken from the available database to estimate the duration of events (N=32) (see chapter 2.3), it is roughly analyzed how in this sample the distribution over different infrastructure availability effects can be described. Table 2.15 shows the results of this assessment.

Table 2.15: Effect of different major discrete event types on infrastructure availability in sample

Major discrete event type	Less trains (50% infrastructure availability)	No trains (0% infrastructure availability)
Switch failure	80%	20%
Signal failure	90%	10%
Level crossing failure	90%	10%
Copper theft	80%	20%

The percentages gained from the sample are used to get an indication of the effects of different event types on infrastructure availability. Events in the sample which occur on single-tracks are excluded from analysis, because there are no single-tracks in the case study area. By excluding events occurring on single-track, it is aimed to use a sample which is as representative as possible for the case study network. Combining the results from the qualitative and quantitative assessment results in an overview of estimated effects of different event types on infrastructure availability (see Table 2.16). In this overview, events are classified into three categories. Events either block a network link to its full extent (0% link availability), or block a network link partially (50% link availability), or events block 1 track of a link. Depending on the number of tracks per link, it is possible that the last two categories are in fact similar (in case a link consists of 1 track per direction). In case a link is partly blocked, a PTO can decide whether to use the remaining tracks for PT services in one direction, or for (a part of the) PT services in both directions.

Table 2.16: Effect of different major discrete event types on infrastructure availability

1 track of link blocked	50% of the tracks of link blocked: 50% link availability	100% of the tracks of link blocked: 0% link availability
Vehicle breakdown Defect track	Signal failure: p=0.9 Copper theft: p = 0.8 Level crossing failure: p=0.9 Switch failure: p = 0.8	Signal failure: q = 1 - p = 0.1 Copper theft: q = 1 – p = 0.2 Level crossing failure: q = 1 - p = 0.1 Switch failure: q = 1 – p = 0.2 Power failure Defect overhead wire Defect / damaged rail bridge Damaged train viaduct Suicide Major incident Restrictions by emergency services Track blockage

The classification as shown in Table 2.16 is also applied to events on the BTM network. The categorization of BTM event types in one event category (in chapter 2.1) is made in such way that only events are clustered together which are expected to have a similar effect on infrastructure availability. This will become important when vulnerable network links are identified (see chapter 3). This means that major discrete event types on the BTM network are only combined in one category if both the assumed predictor is similar for all event types (see chapter 2.2: vehicle-km or link length) and the expected effect on infrastructure availability is similar for all event types (0% or 50% link availability). Therefore, the functional categorization of major discrete event types on the BTM network as shown in Table 2.1 is based on these two aspects, leading to four different functional categories (because on the BTM network the blockage of 1 track always equals 50% link availability).

2.5 Impact of major discrete event types on public transport demand

The event types as categorized in chapter 2.1 can also be classified based on the effect on public transport demand. In general, it is assumed that the effect of an event on PT demand depends on the level of predictability. An unpredictable event, which occurs on a random moment and location without announcing it on beforehand, is expected to have only route choice effects. Passengers have to adjust their route, but since the occurrence of the event is not known on beforehand it is not expected that passengers change their mode choice, destination choice or trip frequency choice. Therefore, no reduction of PT demand is assumed in case of an unpredictable event. It should however be noted that this assumption is expected to hold only to a certain limit. In case a certain network link is relatively often blocked because of major discrete events, it is possible that passengers travelling via this link who are familiar with the situation change mode choice on the long term even when no event occurs, to prevent the risk on being hindered by a disturbance.
On the other hand, if it is known on beforehand on which time and location a certain event will occur, it is expected that some passengers will change their mode, destination or trip frequency choice. In case of large maintenance works, original PT travellers for example may decide to use the bicycle or car, decide to work from home or decide to cancel a planned trip. However, in literature no values are known about the quantitative effect of predictable major discrete events on public transport demand reduction. From all event types mentioned in this study, all event types can be considered as 'unpredictable' except the event 'large maintenance works'. In this study, a first attempt is made to estimate the effect of a predictable event like large maintenance work on PT demand reduction. For this analysis, there is made use of a (limited) set of OV-Chipcard data of the RET (PTO in Rotterdam) and HTM (PTO in The Hague). The last years, most PT passengers in Rotterdam and The Hague are travelling by using an OV-Chipcard, leading to a large amount of new data which is available for analyses in the area of public transportation.

2.5.1 Case study Rotterdam: maintenance works between Central Station and Kruisplein

In Rotterdam, from Monday September 30th, 2013, large maintenance works started on the tram network between the tram stops Central Station and Kruisplein in the city centre. Since almost all tram lines of the RET usually pass the link Central Station – Kruisplein, these maintenance works had major consequences for the tram network and supplied tram services to passengers. Figure 2.4 shows the original network and adjusted network as was communicated to passengers. The adjustments are shortly summarized:

- Tram line 2/20: rerouted via Beurs – Stadhuis instead of Vasteland – Eendrachtsplein – Kruisplein;
- Tram line 4: split in two parts (Marconiplein – Lijnbaan and Central Station – Bergweg);
- Tram line 7: rerouted via Lijnbaan – Beurs – Stadhuis instead of Kruisplein – Central Station – Stadhuis;
- Tram line 8: split in two parts (Spangen – Lijnbaan and Central Station – Bergweg);
- Tram lines 21/23/24: rerouted via Eendrachtsplein - Lijnbaan instead of Kruisplein – Central Station.

OV-Chipcard data of the metro, tram and bus network of the RET of Monday September 23rd and Monday September 30th, 2013 are used for this analysis. These days are selected in order to analyze two days which are as most comparable as possible:

- Data of both days is from the same workday of the week (Monday), correcting for differences in PT demand per week day;
- Data of both days is from the same season (autumn), correcting for seasonal differences in travel demand;
- Data of both days is coming from a working period: no holidays took place during both days;

- On both days there was no rain, correcting for different mode choices because of weather influences (Weerverleden, 2013ce).

By selecting days which eliminate some noise on beforehand, it is tried to control the basic situation for the two days as much as possible. The provided OV-Chipcard data consists of the number of check-ins and check-outs per stop, per PT line of the RET (metro, tram and bus) and per time interval. In The Netherlands, in case of a transfer between different urban PT vehicles, one has to check-out in the first vehicle, before checking-in in the second vehicle again. In the provided data, no chipcard numbers are identified. This means that it is not possible to construct the whole public transport trip a passenger made by RET vehicles. Only data per trip leg (per vehicle) are known.

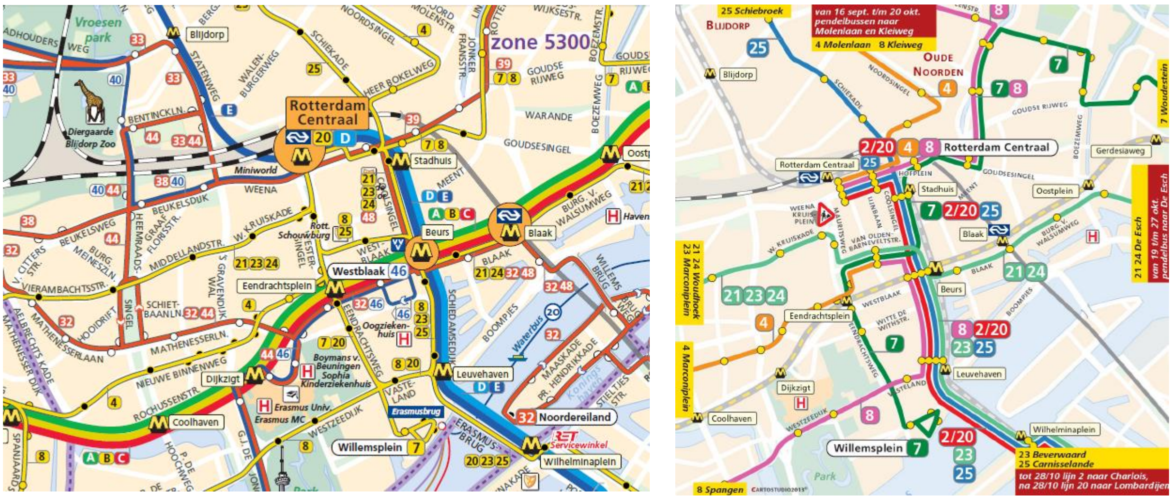

Figure 2.4: Overview of tram network in the city centre of Rotterdam on a regular day (left) and during the maintenance works between Central Station and Kruisplein (right) (RET, 2013cf)

It is assumed that – given the adjusted network in case of maintenance works – passengers originally travelling by tram via the blocked links use either tram or metro lines in their adjusted PT route choice to reach their destination. Given the network lay-out, it is most likely that passengers can either stay in their rerouted tram, or have to make an additional transfer to another tram or metro to reach the destination for the RET part of the trip. The few bus lines in this area of the city centre are not expected to be an attractive alternative for most of the passengers, compared to the available tram and metro lines in this area.

Because the number of check-ins in RET bus lines is not expected to be influenced by these maintenance works, the number of check-ins in the RET bus network is used as reference. Comparing the number of check-ins in all RET bus lines together, the number of check-ins increases with 7% on September 30th compared to September 23rd. Apparently, because of non-identified factors there are 7% more travellers on September 30th independent from the maintenance works.

In case the maintenance works would *only* lead to route choice effects – so no reduction in PT demand – a similar 7% increase in number of check-ins would be expected for tram and metro as well. The assumption made here is that the passenger increase is equal for the different modes. However, comparing the number of check-ins for the affected tram lines between those days cannot be performed directly. This is because many passengers who originally travelled without transfer will have to make an additional transfer to another tram or metro line, because of these maintenance works. The maintenance works will increase the average number of transfers per trip. This means that exactly the same amount of passengers will produce more check-ins during the maintenance works due to extra transfers. Since only the number of check-ins is available – and no total trip data – a correction has to be applied for the additional number of transfers people have to make. In case no demand reduction takes place, this means that more than 7% increase in check-ins is expected on tram and metro lines which can be an alternative for the affected tram lines.

Therefore, for all stop pairs of each tram line which is affected by the maintenance works, it is constructed what the most likely route alternative would be for passengers in the adjusted network. This is done manually. In this construction, the most likely route alternative for each affected trip which could be made without transfer in the original network is selected. In reality, different route alternatives for each stop pair might be available. However, for each affected stop pair only one route alternative is constructed based on an expert judgment. Appendix A6 gives an exact overview of the affected stop pairs per tram line and the assumed route alternative in the adjusted network. In this appendix it is also mentioned at which stops a possible additional transfer is likely to be made. Based on this analysis, a list of tram and metro stops is identified where all additional transfers are likely to occur because of these maintenance works. By multiplying the additional number of transfers with the number of passengers travelling between a specific affected stop pair, the total number of expected check-ins at these stops can be calculated, thereby also incorporating the generic 7% PT demand increase as found for the bus network. Figure 2.5 shows for all stops at which an additional transfer possibly takes place the relative change in number of check-ins found between September 23rd and September 30th.

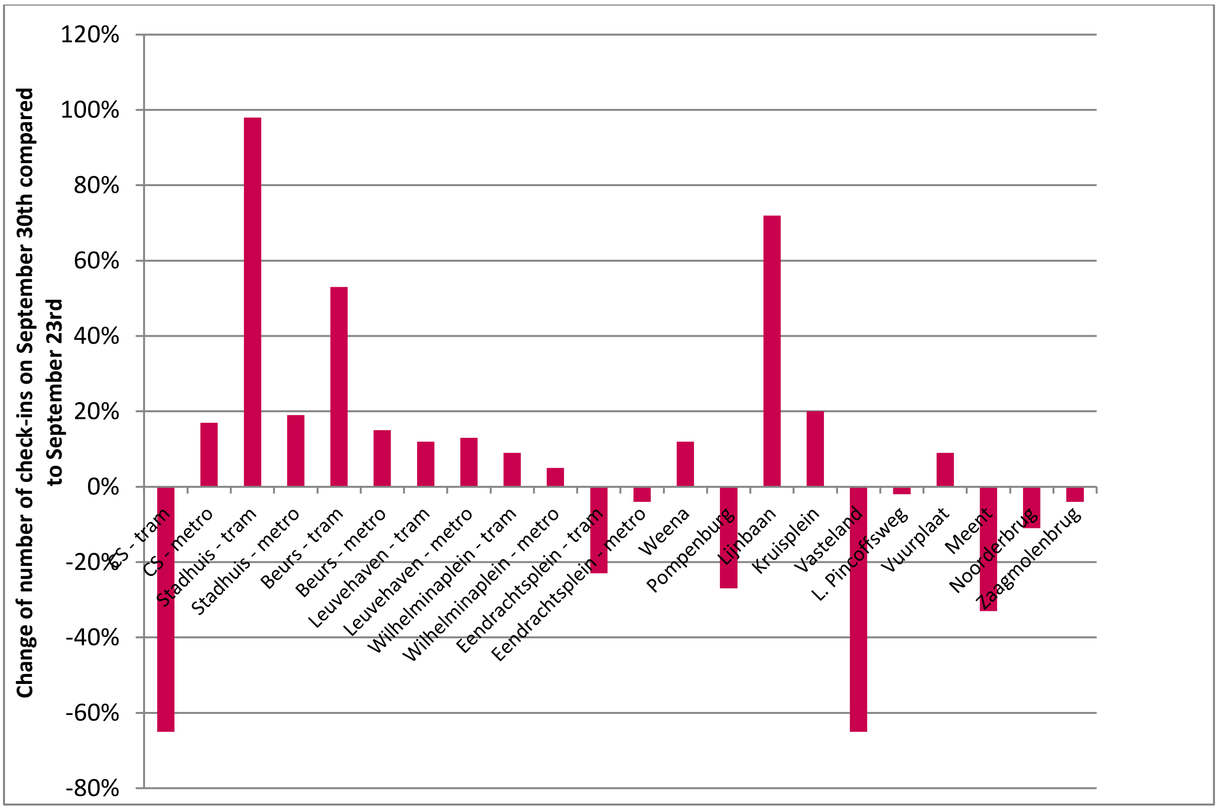

Figure 2.5: Relative change of number of check-ins between September 23rd and September 30th (CS = central station Rotterdam)

In case affected passengers would only adjust their route choice, no PT demand reduction occurs. In that case, the expected number of check-ins at all the mentioned possible transfer locations in Figure 2.5 would be the sum of the number of check-ins by regular passengers - multiplied with the generic increase of 7% - and the number of check-ins from passengers making an additional transfer at that stop, also multiplied by 7%. Since passengers can sometimes choose between different stops to make their transfer, the total expected number of check-ins at all possible transfer locations in Figure 2.5 together is compared with the total realized number of check-ins at these stops together (instead of comparing the number of check-ins per tram / metro stop separately).

From Figure 2.5 a substantial increase in number of check-ins can be seen for the tram stops Stadhuis, Beurs and Lijnbaan, indicating that especially these stops are used as transfer location by passengers who are affected by the maintenance works. Also the metro lines D and E seem to be used as route alternative between Central Station, Stadhuis, Beurs, Leuvehaven and Wilhelminaplein, given the increase in number of check-ins at these metro stops and the substantial reduction in check-ins at the tram stop Central Station. The results of this analysis show that the total number of realized check-ins is 14% lower than the expected number of check-ins in case no demand reduction would have occurred, while there is corrected for the additional number of transfers and a generic increase in PT demand between the two days considered. Therefore, it can be concluded that in this case of maintenance works on a working day, PT demand is reduced by 14% on all OD-pairs which are affected by the maintenance works.

Some notes of reflection have to be made regarding this analysis. On the one hand, a demand reduction of 14% might be a slight overestimation. Because no data are available for the whole RET trip made by a passenger, the expected number of additional transfers is calculated based on the affected trip leg. For this trip leg, it is analyzed how many additional transfers are required in the adjusted network. However, in practice passengers will change their route choice not per trip leg, but for the whole trip made as a whole. It is therefore possible that for the total trip over the RET network, 'smarter' route alternatives can be found for which less additional transfers are required. Also, despite the assumption that the number of check-ins in RET busses is not influenced at all by the maintenance works, for a small number of stop pairs some specific bus lines might be a route alternative: between Beukelsweg / Beukelsdijk / Vierambachtsstraat / Middellandstraat and Central Station and between Blaak / Keizerstraat / Station Zuid and Central Station the bus lines 38 and 48 might be a route alternative, respectively. In both cases, the difference between expected and realized number of check-ins would be smaller than is assumed now, leading to a smaller PT demand reduction because of predictable major discrete events.
On the other hand, the assumed demand reduction might be a slight underestimation. The number of check-ins over all RET bus lines together is used as reference in this analysis, since busses are not considered as route alternative in the affected city centre. However, it is possible that passengers, who usually travel by tram over the disturbed area, also travel another part of their trip by bus. In case these passenger decide to change mode, destination or trip frequency choice, the number of check-ins over all RET busses is also influenced by the maintenance works. This would mean that without these works, the increase in check-ins in busses would be even larger than 7%. In that case, the difference between expected and realized check-ins would become larger, leading to a larger PT demand reduction than is calculated now.
For the sake of simplicity, it is assumed that these two effects cancel out each other to a large extent. Since no total trips can be constructed based on the available data, a demand reduction of 14% because of predictable major discrete events is assumed as best estimate for a working day. It should be mentioned that the distribution of this demand reduction over different OD-pairs can differ substantially. For very short trips, it is more likely that passenger decide to use the bicycle or decide to walk to their destination. On the other hand, for very long trips, the relative impact of a detour on a small part of the total trip is limited. Therefore, it is expected that demand reduction will be larger for short distances, and smaller for long distance PT trips.

2.5.2 Case study The Hague: maintenance works between Madurodam and Central Station (tram line 9)

In The Hague, tram line 9 (see Figure 2.6) between Scheveningen and Vrederust is the busiest tram line of the urban PTO HTM. In the period between September 2nd and September 22nd, 2013, maintenance works had to be performed on the track of tram line 9 between Madurodam and Central Station. During these three weeks, tram line 9 was divided in two parts. One part of the tram line was operated between Scheveningen and Madurodam, whereas the other part of the line was operated between Vrederust and Central Station. An additional bus service (operated as bus line 69) connected both parts of the line between Central Station and Madurodam via the Raamweg (see Figure 2.7). This bus service did not stop at all tram stops on the blocked track: only the tram stops Madurodam, Laan Copes van Cattenburch, Dr. Kuyperstraat and Central Station were served. The other tram stops Riouwstraat, Javabrug and Korte Voorhout between Madurodam and Central Station were not served during these three weeks. The adjusted PT network can be summarized as follows:

- Tram line 9: Vrederust – Central Station – city centre – Central Station – Vrederust;
- Shuttle tram line 9: Scheveningen Noorderstrand – Madurodam v.v.;
- Shuttle bus line 69: Madurodam – Laan Copes van Cattenburch – Dr. Kuyperstraat – Central Station v.v.

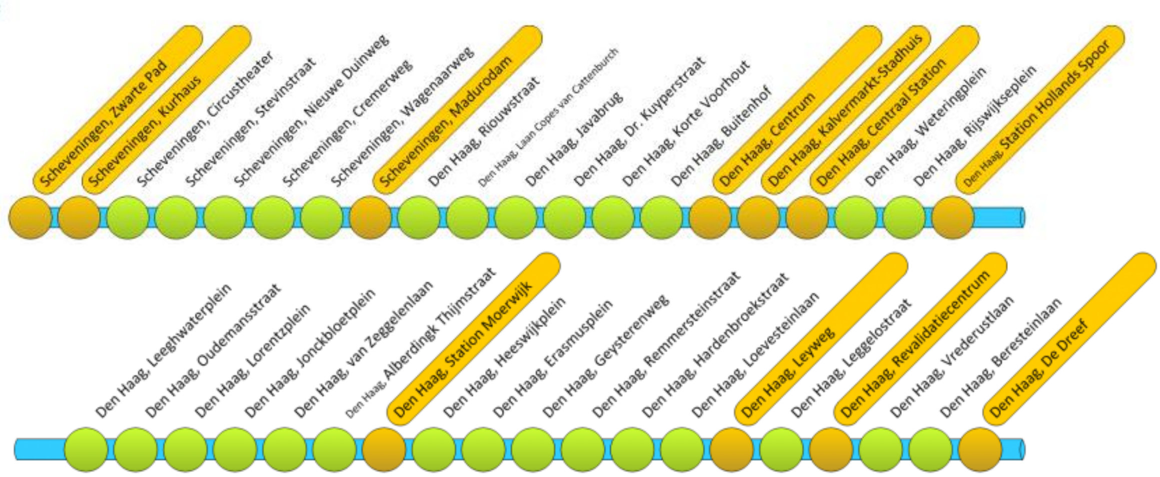

Figure 2.6: Overview of route of HTM tram line 9 between January 6th 2013 and December 22nd 2013 (OV Haaglanden, 2013)

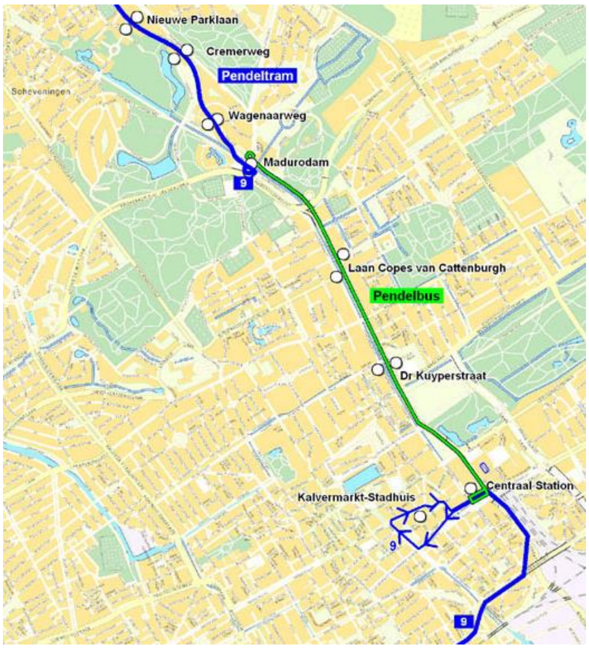

Figure 2.7: Overview of adjusted PT network during maintenance works between Madurodam and Central Station (HTMfoto.net, 2013)

To get insight in the effect of these planned maintenance works on PT demand, OV-Chipcard data of three different Sundays are analyzed: September 8th, September 15th and September 29th, 2013. By using Chipcard data from three Sundays in September, there is corrected for PT demand fluctuations over different days in the week and for seasonal demand differences. As can be seen, two of the three selected days are during the maintenance works. On September 29th, the route of tram line 9 between Madurodam and Central Station was in operation again. Therefore, September 29th is used as reference day to compare the number of passengers on September 8th and September 15th with. In the provided Chipcard data it is possible to determine the whole PT trip made by travellers in HTM vehicles, because a fictive unique number is added to identify which trip legs are made with the same chipcard. In the provided dataset also the check-in time and travelled passenger-distance for each trip leg is indicated. The check-out time per vehicle is unknown. Different trip legs travelled by a person using the same unique chipcard number are combined to one total PT trip if the following condition is satisfied:

$$T_{check-in,n+1} < T_{check-in,n} + \frac{s_n}{v_{tram}} + t_{transfer} \quad (2.4)$$

With parameters:

$T_{check-in,n}$	*check – in time on trip leg n*
s_n	*passenger – distance per trip leg n*
v_{tram}	*average speed of tram*
$t_{transfer}$	*maximum allowed transfer time*

In this study an average speed of 19 km/h is assumed for trams, in line with the indicated average speed of trams in The Hague (Gemeente Den Haag, 2013). The maximum allowed time between the check-out in vehicle *n* and the next check-in in vehicle *n+1* which is considered as a transfer in urban PT networks in The Netherlands equals 35 minutes. When the time between the check-out in vehicle *n* and the next check-in in vehicle *n+1* is shorter than 35 minutes, no new start fare is deduced from the Chipcard when checking-in in vehicle *n+1*. By using formula (2.4), based on a similar criterion it can be determined whether two trip legs are combined to one PT trip. Such formulation is necessary since no check-out times are known. In this formula, it is assumed that the average speed of trams of HTM is equal on the whole network. In reality, there are of course differences in average speed between for example the city centre and suburbs. Formula (2.4) gives a general approximation whether two trip legs can be considered as one PT trip, without considering location specific differences in the network. If the condition as shown by formula (2.4) is satisfied, *n* trip legs are combined to one PT trip having the check-in stop of trip leg *n=1* as origin and the check-out stop of trip leg *n=n* as destination.

First, the total number of check-ins on the whole tram and bus network of HTM is compared for the three considered Sundays to correct for differences in PT demand independent from the maintenance works. Table 2.17 shows the relative change in number of PT trips on September 8th and September 15th compared to September 29th. Apparently, because of unidentified factors the total number of PT trips made by tram and bus in The Hague is 9% and 7% lower than on September 29th, respectively. In this analysis, it is assumed that differences in PT demand on affected OD-pairs which deviate from the average differences in demand found for The Hague as a whole can be attributed to the maintenance works.

Table 2.17: Relative number of PT trips made on September 8th and September 15th compared to September 29th

Date	Number of PT trips
September 8th, 2013	91%
September 15th, 2013	93%
September 29th, 2013	100%

In this analysis, it is investigated how PT demand is changed on PT trips which are affected by the maintenance works. In total, six categories (A-F) of affected stop pairs are identified for which the effect on PT demand is investigated:

- A: From stops Zwarte Pad and Kurhaus to stops Riouwstraat – Korte Voorhout, Central Station/Schedeldoekshaven – Rijswijkseplein and Jonckbloetplein – De Dreef;
- B: From stops De Dreef – Jonckbloetplein, Rijswijkseplein – Central Station/Schedeldoekshaven and Korte Voorhout – Riouwstraat to stops Kurhaus and Zwarte Pad;
- C: From stops Circustheater – Wagenaarweg towards Vrederust to all stops in the HTM network except tram stops Circustheater – Madurodam;

- D: From all stops in the HTM network except tram stops Madurodam – Circustheater to stops Wagenaarweg – Circustheater towards Scheveningen Noorderstrand;
- E: From stops Madurodam – Korte Voorhout towards Vrederust to all stops in the HTM network;
- F: From all stops in the HTM network to stops Korte Voorhout – Madurodam towards Scheveningen Noorderstrand.

Categories A and B are formulated because of the existence of tram line 1 between Scheveningen, the city centre of The Hague and Delft. Between Scheveningen and the city centre, this tram line uses another route than tram line 9 (with equal length) and is therefore not hindered by the maintenance works. This means that tram line 1 serves as alternative for passengers travelling from stops Zwarte Pad and Kurhaus (both tram lines 1 and 9 stop here) to a large part of The Hague without having to make an additional transfer and without additional travel time. From the tram stops Zwarte Pad and Kurhaus, an additional transfer because of these maintenance works is only required when travelling to the tram stops which are exclusively served by tram line 9 and not by tram line 1 (Riouwstraat – Korte Voorhout; Central Station/Schedeldoekshaven – Rijswijkseplein and Jonckbloetplein – De Dreef) (and vice versa).
Categories C and D analyze how PT demand is changed for passengers starting their PT trip on a tram stop between Scheveningen and Madurodam towards Vrederust. The only destination stops which are excluded from the analysis are the stops on the track between Scheveningen and Madurodam itself. For example, passengers travelling from Circustheater to Madurodam do not experience any hindrance of the maintenance works, because of the operation of the shuttle tram line 9 between Scheveningen and Madurodam.
At last, categories E and F show the affected PT trips which start or end between Madurodam and Central Station. Because tram services between Madurodam and Central Station are totally cancelled, PT trips from these stops towards Vrederust to all stops in the HTM network (and vice versa) are affected by the maintenance works. PT trips from the stops between Madurodam and Central Station towards Scheveningen are already captured in category D and category B (to stops Wagenaarweg – Zwarte Pad).

The expected number of PT trips for all these six categories – based on the generic decrease in PT demand of 9% and 7% on September 8th and September 15th respectively – in case no demand reduction would occur because of the maintenance works is compared with the realized number of PT trips. The relative difference between expected and realized number of PT trips can be considered as the PT demand reduction caused by a predictable event type like maintenance works. Table 2.18 shows the results of this comparison for all these six categories separately and in total. As can be seen from this table, the reduction of PT demand is substantial. For categories E and F, the demand reduction is less than for the other categories. This might be explained by the fact that shuttle bus line 69 operates with a high frequency, therefore supplying an acceptable PT route alternative from/to stops between Madurodam and Central Station. Passengers travelling from stops between Circustheater and Madurodam towards a destination further than Central Station have to make two additional transfers: one transfer to bus line 69 at Madurodam and one transfer to tram line 9 at Central Station. It seems plausible that especially for these passengers – partly represented by categories C and D – the supplied PT alternative is relatively unattractive, leading to changes in mode choice, destination choice or trip frequency choice. In total, based on this empirical data a demand reduction between 50% and 56% is found.

Table 2.18: PT demand reduction because of large maintenance works on tram line 9

Category	Demand reduction September 8th	Demand reduction September 15th
A	71%	66%
B	71%	66%
C	70%	73%
D	52%	50%
E	31%	13%
F	27%	16%
Total	56%	50%

When comparing the demand reduction found for maintenance works in Rotterdam and The Hague, substantial differences can be found. In Rotterdam a demand reduction of 14% is found, whereas in The Hague a demand reduction of 50-56% is observed. Two explanations can be formulated for these differences. First, the distribution of trip purposes differs substantially between the Rotterdam case and The Hague case. In Rotterdam, data of a working day (Monday) is considered, whereas in The Hague data from a weekend day (Sunday) is analyzed. During weekdays, the share of commuter and business trip purposes is substantially higher than during the weekend. During the weekend, leisure is a more important trip purpose. Commuters and business travellers are usually more obliged to make a certain trip to a certain location. Passengers having a leisure purpose can decide more easily to cancel a trip (trip frequency choice) or the change the destination of a trip. Besides, commuters and business travellers often have more knowledge about the network since these passengers travel more frequently. Therefore, these passengers are expected to use available route alternatives within the PT network more easily than leisure passengers. Second, compared to September 29th, there was substantial more rainfall on September 8th and September 15th (Weerverleden, 2013abd). This can indicate that the PT demand reduction may partly be explained by weather influences instead of the influence of the event, indicating a slight overestimation of the PT demand reduction as found in this analysis. Especially regarding leisure passengers going to/from Scheveningen, it seems reasonable that bad weather can heavily influence trip production and destination. During a workday, bad weather usually has a positive effect on the share of PT in the mode choice distribution. However, for leisure trip purposes bad weather can have a negative effect on trip production which is larger than the positive effect on PT share in the mode choice distribution.

It can be concluded that the reduction in PT demand in case of predictable major discrete events depends on the distribution of trip purposes. During work days in which business and commuting are the most dominant trip purposes, PT demand reduction is substantially less than during weekend days in which leisure purposes are more dominant. For week days, a PT demand reduction of about 14% is found in case of large maintenance works in Rotterdam. For weekend days, the observed demand reduction of 50-56% in The Hague can be considered as an upper bound. This is because it was not possible to control for weather influences which might also affected demand reduction, when comparing PT demand during and after the large maintenance works.

2.6 Conclusions

In this chapter different major discrete event types which occur on different levels of a multi-level PT network are characterized based on their frequency, duration and impact on infrastructure availability and public transport demand. Results of this study give new insights in characteristics of major discrete events because a strong data driven approach is used in all analyses. All information derived about frequency, duration and impact on infrastructure availability and PT demand is calculated as much as possible based on empirical, real-world data. Besides, to our best knowledge this is the first study in which major discrete events on a certain network level are characterized relative to other PT network levels.

Regarding the frequency with which different major discrete event types occur, the following conclusions are formulated:

- For all major discrete event types on all considered network levels, a Poisson distribution is suitable to describe the frequency with which an event occurs per time period.
- On the Dutch train network, the major discrete event types ‘vehicle breakdown’, ‘switch failure’, ‘suicide’ and ‘signal failure’ occur with the highest frequency per time period: together these four event types are responsible for 63% of all events occurring on the train network.

- The major discrete event type ‘vehicle breakdown’ occurs with the highest frequency on train, metro/light rail and tram networks. Vehicle breakdowns are responsible for 61%, 46% and 18% of all major discrete events occurring on the tram network, metro/light rail network and train network, respectively. Reducing vehicle breakdowns therefore offers large potential for improvements of the robustness of multi-level PT networks by reducing the probability on an event.
- The expected number of vehicle breakdowns per million vehicle-kilometres equals 2.11 on train networks, 57.7 on bus network, 61.4 on metro/light rail networks and 120 on tram networks.
- The expected number of major incidents per million vehicle-kilometres equals 0.37 on train networks, 3.31 on metro/light rail networks, 11.0 on bus networks and 12.9 on tram networks.
- Also after correcting for differences in average speed between different modes, it can be concluded that train networks are more robust against vehicle breakdowns and major incidents in terms of frequency, compared to metro/light rail, tram and bus networks. Especially tram networks seem to be relatively vulnerable to vehicle breakdowns and major incidents.
- In case of heavy snowfall, the frequency with which vehicle breakdowns and signal failures occur on the train network is more than doubled. The frequency of switch failures during heavy snow increases with a factor 10 compared to the frequency during regular winter days on the train network.

The next conclusions are formulated based on analyses performed to the duration of different major discrete events on the multi-level PT network:

- The duration of suicide events on train networks can be modelled by using a normal distribution.
- The duration of large maintenance works on train networks can be modelled by a Bernoulli distribution when the possibility on delays in maintenance works is neglected.
- The duration of all other major discrete event types identified on the train, metro/light rail and tram network can be described by a lognormal distribution.
- The average duration of major discrete events on the BTM network is slightly larger than one hour (in the empirical data values of 76 minutes for the metro/light rail network, 67 minutes for the tram network and 64 minutes for the bus network are found).
- Both the average duration and variance of the duration of major discrete events on the train network are larger compared to these values for major discrete events on the BTM network.

Based on a limited set of OV-Chipcard data, an empirical analysis is performed to the impact of major discrete event types on PT demand in urban PT networks. Based on this analysis, the following conclusions are formulated:

- When major discrete events with a low level of predictability occur, only route choice effects are expected. In case of events with a high level of predictability, both a route choice effect and effect on PT demand (which can be explained by mode choice, destination choice or trip frequency choice) are expected.
- In case of major discrete events with a high level of predictability on a work day – like large maintenance works which are announced on beforehand – a PT demand reduction of 14% is empirically found on affected OD-pairs.
- When predictable events occur on a weekend day, the PT demand reduction is larger compared to week days. A PT demand reduction between 50% and 56% as empirically found can be considered as upper bound.
- The distribution of trip purposes seems to be important when determining the impact of an event on PT demand. Empirical data suggests that PT demand reduction is larger in case the share of leisure trips is larger, compared to days when commuting and business are the most dominant trip purposes.

3

Identification of vulnerable links in a multi-level PT network

In this chapter, the characteristics of major discrete events as described in chapter 2 are used as input to identify the most vulnerable links in a multi-level public transport (PT) network. For road networks different methodologies are already developed to identify the most vulnerable links of a network. However, no such method is developed yet to identify vulnerable links in a multi-level PT network in a systematic way. Therefore, first in chapter 3.1 a literature review is performed to methodologies applied in road networks to identify vulnerable links. Chapter 3.2 describes the methodology developed to identify those links in multi-level PT networks. At last, in chapter 3.3 this methodology is applied to the case study area between Rotterdam and The Hague.

3.1 Methodologies for the identification of vulnerable links in a road network

The different methodologies and criteria used in literature to assess robustness of road networks can be divided in two groups (Knoop et al., 2012).

- Full computation methods. In these methods, on each separate link of the network disturbances are simulated. The effect of these disturbances is for example measured by the number of vehicle-loss hours. Examples in literature can be found in Jenelius (2007) and Knoop et al. (2007). The advantage of these methods is the completeness: for all links the effects of a disturbance can be calculated and compared in order to identify the most vulnerable links. The largest disadvantage is the very long computation time, since simulation of disturbances on each link separately is required. These methods are therefore better suitable for relatively small networks.
- Pre-selection of vulnerable links. These methods are generally developed to overcome the disadvantage of very long computation times of full computation methods. In these methods, criteria are specified to pre-select a smaller number of most vulnerable links in a network. Only on these selected links, disturbances are simulated in a second step. In these methods it can be necessary to perform one single basic assignment without disturbances first, in order to use the assignment output to calculate values for (some of) the specified criteria. In literature, examples can be found in Tamminga et al. (2005), Tampère et al. (2008) and Immers et al. (2011). The advantage of these methods is clearly the reduction in computation time and the more structural approach underlying these methods (Snelder, 2010). A disadvantage however is that the remaining selection of links depends on the criteria applied. Besides, research shows that different criteria do not always predict

the most vulnerable links in a correct or consistent manner, when comparing the results of full computation methods with pre-selection methods using different criteria (Snelder, 2010; Knoop et al., 2012).

3.1.1 Pre-selection criteria for road networks

In literature, a variety of criteria can be found to pre-select the most vulnerable links of a road network. The overview of the most used criteria below is derived from Knoop et al. (2012).

1. $I_i^1 = q_i \,/\, (1 - q_i \,/\, C_i)$ (3.1)

2. $I_i^2 = \frac{1}{L_i \,/\, q_i\,(l_i * k_{ji} - q_i / v_{fi})}$ (3.2)

3. $I_i^3 = \begin{cases} q_i \,/\, (1 - q_i \,/\, C_i) & if\ C_i \leq 2500 \\ 0\ otherwise \end{cases}$ (3.3)

4. $I_i^4 = (q_i \,/\, (1 - q_i \,/\, C_i)) * p_i = I_i^1 * p_i$ (3.4)

5. $I_i^5 = I_i^2 * p_i * \sum_{upstream\ links\ j\ of\ i} I_j^1$ (3.5)

6. $I_i^6 = I_i^3 * p_i * \sum_{upstream\ links\ j\ of\ i} I_j^1$ (3.6)

7. $I_i^7 = \sum_{upstream\ links\ j\ of\ i} I_j^1$ (3.7)

8. $I_i^8 = q_i \,/\, C_i$ (3.8)

9. $I_i^9 = q_i - C_i^b$ (3.9)

10. $I_i^{10} = risk\ of\ gridlock$

11. $I_i^{11} = risk\ by\ limited\ availability\ of\ alternative\ routes$

With parameters for each link *i*:
I_i^n $criterion\ n\ for\ link\ i$
q_i $flow\ on\ link\ i\ (pcu/hour)$
C_i $capacity\ on\ link\ i\ (pcu/hour)$
C_i^b $remaining\ capacity\ on\ link\ i\ at\ blocking\ (pcu/hour)$
v_{fi} $free\ flow\ speed\ on\ link\ i$
k_{ji} $jam\ density\ of\ link\ i$
L_i $length\ of\ link\ i$
l_i $number\ of\ lanes\ on\ link\ i$
p_i $incident\ probability\ on\ link\ i$

Criterion 1 as expressed by formula (3.1) shows the Incident Impact Factor, which shows that the impact of a major discrete event on a road will be larger in case the flow on a certain link *i* increases compared to the capacity of that link (Tampère et al., 2008; Immers et al., 2011). The denominator of formula (3.2) expresses the time it takes after the occurrence of a major discrete event on link *i* before a queue reaches the upstream link. A faster spillback effect indicates a larger impact of the event according to the second criterion. Criterion 3 also shows the Incident Impact Factor, but in this case this factor is only valid for links having a capacity ≤ 2500 pcu/hour. This is because also major discrete events occurring on links having a smaller capacity can have large network wide effects. Criterion 4 also incorporates the probability on an event on a certain link *i*, next to the impact of an event. Criteria 5 and 6 also consider both the probability and effect of an event. However, these criteria incorporate the spillback effects to upstream links as well. Criterion 6 expresses this only for links having a capacity $\leq$ 2500 pcu/hour, for the same reason as explained above. In formula (3.7) the Incident Impact Factor is summed for all upstream links *j* of link *i.* This criterion incorporates the spillback effects to upstream links by using the different link Incident Impact Factors. Criterion 8 uses the intensity / capacity (I/C) ratio of a link as indicator for the vulnerability of a link. At last, criterion 9 captures the effect of an event on infrastructure availability. The impact of an event will - ceteris paribus - be larger when less capacity is remaining after a blockage (Knoop et al., 2012). In general, criteria 10 and 11 are not calculated quantitatively. There are different heuristics which focus on links on which the occurrence of a major discrete event can lead to a gridlock. The number of available route alternatives is usually determined qualitatively based on an expert judgment, since the number of available routes differs per origin-destination (OD) pair (Tampère et al., 2008; Immers et al., 2011).

3.1.2 Assignment on road networks

When an assignment on a road network is performed, a distinction can be made between static and dynamic assignment, and between en-route route choice possibility and no en-route route choice possibility (Knoop et al., 2012). When an assignment is performed in case of an event on a certain link, in general a dynamic assignment is used for road networks. Compared to a static assignment, a dynamic assignment can better show the development of congestion over time in case demand and/or supply are changing because of an event.

In case drivers are confronted with a disturbance during their trip, a fraction of these drivers will change their route in response to this disturbance. This means that some drivers will change their route during their trip. In general, it depends on the level of information drivers have about the location and expected duration of an event, and the knowledge drivers have about alternative routes, whether a driver changes route during the trip. Li (2008) and Tampère et al. (2008) indicate the importance of the incorporation of en-route route choice when performing an assignment in case of major discrete events. However, these authors also note that it is very difficult to model en-route route choice in a correct manner, because of the uncertainty related to human behaviour, information availability and knowledge about the network. The route choice distribution of an assignment performed for the undisturbed situation can be considered as a worst-case result in a disturbed situation, because it assumes that all drivers do not change their route despite the event they are confronted with. On the other hand, an equilibrium assignment performed based on the network with a certain disturbance on a certain location can be considered as a best-case assignment. This assignment assumes that all drivers have full information about the disturbance and have full knowledge about the network to select a route alternative given this disturbance. In reality, the reaction of drivers will be somewhere in between these extremes. No real equilibrium situation is expected to be realized. Some drivers – having sufficient information and knowledge about the network – will adapt their route choice, whereas other drivers will stay on the route they would have chosen in case no disturbance would have occurred. Immers et al. (2011) use the route choice effects from the dynamic user equilibrium assignment with no events and the dynamic user equilibrium assignment based on the network with the event as lower bound and upper bound, between which the effect of an event in reality will be. Knoop et al. (2012) use a dynamic non-equilibrium traffic simulator (D-SMART) which incorporates en-route route choice, thereby directly calculating the effect of an event (Zuurbier et al., 2006).

In case a basic assignment without disturbances needs to be performed first in order to use the output for some values of specified pre-selection criteria, the incorporation of en-route route choice is not required for that first step. In the undisturbed situation, it can be expected that drivers have no reason to change their route choice during the trip. In that case, a dynamic assignment model with no en-route route choice, like INDY, is suitable (Bliemer, 2005; Bliemer, 2007).

3.2 Methodology for the identification of vulnerable links in a multi-level PT network

Based on the literature study performed to methodologies and criteria used to identify vulnerable links in a road network, in this study a methodology is developed to identify vulnerable links in a multi-level PT network. As mentioned, using full computation methods often leads to very long computation times and is therefore most often only applicable to smaller networks. Real-life multi-level PT networks are in general more complex than smaller single-level networks, often leading to a high number of links. This means that in many cases computation time is expected to become unacceptable long when one wants to simulate major discrete events on each link of the multi-level PT network separately. Therefore, a methodology is developed to identify vulnerable links based on specified pre-selection criteria in the first place. In a second step, major discrete events are simulated only on those links which are expected to be most vulnerable.

3.2.1 Pre-selection criteria in multi-level PT networks

When analyzing the different criteria used to pre-select vulnerable links in road networks (see chapter 3.1), three conclusions can be formulated.

First, some criteria used for road networks only focus on the impact of a major discrete event (I_i^1, I_i^3, I_i^7), whereas other criteria consider both the probability on an event on a link and the impact of an event explicitly (I_i^4, I_i^5, I_i^6). Criteria which only focus on the impact of an event assume implicitly an equal probability on an event on each link in the network. In case the probability on an event is incorporated explicitly, it allows for the possibility to use one or multiple predictors for the occurrence of events. For example, in research performed by Immers et al. (2011) and Knoop et al. (2012), it is assumed that the probability on an event increases with the traffic intensity. Tamminga et al. (2005) use the I/C ratio, traffic intensity, share of trucks and road type as predictors for the occurrence of an event on a specific link.
The results of the characterization of major discrete events in multi-level PT networks as described in chapter 2.2 show the importance of considering the probability on an event explicitly as well. For the different major discrete event types, different predictors are identified to estimate the probability on an event on links on different network levels. This probability depends on link length, track length, vehicle-kilometres and the presence of level crossings and rail bridges on a link. Also, the probabilities are different on different network levels, given the different characteristics of these levels. This shows that it is not sufficient to assume an equal probability on events for all links in a multi-level PT network. Criteria to pre-select vulnerable links in a multi-level PT network should therefore consider both the probability (using multiple predictors) and the impact of an event on passengers explicitly.

Second, when estimating the impact of an event on a road network some relation between the traffic intensity and capacity is used ($I_i^1, I_i^4, I_i^7, I_i^9$). The Incident Impact Factor (I_i^1) for example shows – based on car traffic flow theory - that the impact of an event will be larger in case of a higher traffic intensity, and in case of a higher I/C ratio, ceteris paribus.
However, in public transport networks the I/C ratio is less relevant when estimating the impact of an event. In general, in PT networks congestion between different PT vehicles is very limited compared to congestion between vehicles on road networks, also in case of disturbances. In PT networks, the impact of a major discrete event is mainly related to the number of passengers affected by that event, instead of the I/C ratio of PT vehicles on a certain link or the number of passengers in relation to the supplied capacity on that link. This means that for multi-level PT networks, the passenger flow on a link is a better estimator for the impact of an event than the I/C ratio or Incident Impact Factor as used for road networks. Although it is not possible to calculate the effect of an event on a certain link for passengers in terms of travel time, costs, comfort and reliability without using a full computation method, the passenger intensity on a link can be used as proxy to represent the impact of an event. In (multi-level) PT networks no special attention has to be paid to links having

a smaller capacity (as expressed by I_i^3 and I_i^6) given the main focus on passenger flow instead of on link capacity.

Third, when estimating the impact of an event on road networks some criteria only focus on the impact on the considered link *i* itself ($I_i^1, I_i^3, I_i^4, I_i^8, I_i^9$), whereas other criteria also consider spillback ($I_i^2, I_i^5, I_i^6, I_i^7$) or gridlock effects ($I_i^{10}$) to adjacent links *j*.
In public transport networks, spillback effects occur in another way than in road networks. Given the limited congestion between PT vehicles, there is no or only a limited direct spillback effect to PT vehicles on adjacent links in case of an event. However, PT services on other links in the network can certainly be affected by a major discrete event. Public transport operators (PTO's) usually take fixed measures in case a certain major discrete event type occurs on a certain link. These measures (in Dutch: 'versperringsmaatregelen' (VSM)) describe for each link and for each effect an event can have on link availability (partly blocked link; totally blocked link) how the supplied PT services are adapted. They describe for example which train series are shortened or split in two parts, or they describe the rerouting or splitting of certain tram lines in case of an event.
In general, different types of measures are applied on different network levels and for different impacts on infrastructure availability. In case of 0% infrastructure availability, train and metro services are often split into two separate parts or shortened if the event takes place near the final station of a line. The location where a split line turns depends on the capacity of the adjacent stations and the availability of switches. Rerouting train and metro lines does not happen that often, because in general a limited number of parallel lines near the blocked line are available (ProRail, 2013; HTM, 2013). In case of partly blocked infrastructure, a part of the train services usually remains unaffected, thereby using fewer tracks than normal on the affected link. Another part of the train services is cancelled or shortened, because of the limited remaining capacity on a certain link. For tram networks rerouting is more often used as measure in case of a major discrete event, since especially near the city centre alternative routes are often available. Rerouting can be done in one or in both directions, depending on the effect of an event on infrastructure availability. In case no alternative routes are available, or if only routes leading to large detours are available, a tram service is usually split in two parts or shortened. The location to where a line is split or shortened depends on the availability of switches (for two-directional trams) and turning facilities near an affected link (HTM, 2013; RET, 2013b). Bus services are usually rerouted in case of an event, since many parallel route alternatives are often available on the road network.
Although a dynamic spillback effect to adjacent links occurs very limited in PT networks, it can be concluded that other links can certainly be influenced by a major discrete event by a kind of 'static' spillback effect, depending on the measures applied by the PTO. This means that PT services on a link can be affected because of a first-order effect – an event occurring on that link *i* itself – and because of a second-order effect. This second-order effect plays a role in case of an event occurring on an adjacent link *j,* leading to measures taken by the PTO or infrastructure manager which also affect PT services on the considered link *i*. Therefore, when identifying vulnerable links in (multi-level) PT networks, the consideration of both the first-order and second-order effects is necessary to determine the vulnerability of a link from a passenger perspective. Focusing on first-order effects only can lead to a substantial overestimation of the robustness of a link, in case PT services on that link are often affected because of the occurrence of events on adjacent links, for example because of a lack of switches. For (multi-level) PT networks, gridlock effects are not of relevance.

Based on the formulated conclusions, the next 5 pre-selection criteria are formulated to identify the most vulnerable links in a multi-level PT network.

1. $I_r^1 = \sum_p \sum_m \sum_t \quad \lambda_{m \subseteq M,t,N} * (x_{p,r}/x_{p,N}) * d_{m,t}$ (3.10)

2. $I_r^2 = \sum_s \sum_p \sum_m \sum_t \quad \lambda_{m \subseteq M,t,N} * (x_{p,s}/x_{p,N}) * d_{m,t}$ (3.11)

3. $I_r^3 = I_r^1 + I_r^2$ (3.12)

4. $I_i^4 = q_i$ (3.13)

5. $I_i^5 = risk\ by\ limited\ availability\ of\ alternative\ routes$

With parameters for each link *i*:
I_i^n criterion n for link i
I_r^n criterion n for link segment r
p predictor for major discrete event type
t time period of the year
m major discrete event type
M subset of major discrete event types predicted by p
λ average frequency of major discrete event type per time unit
d average duration of major discrete event type
s link segment affecting PT on link segment r in case of event
N total network
$x_{p,r}$ value of p on link segment r
q_i passenger flow on link i

I_r^1 represents the first-order effect: the expected time a link segment *r* is blocked because of a major discrete event on that link segment *r* itself. The expected time a link segment is blocked is the product of the expected frequency of a certain major discrete event type *m* and the expected duration *d* of this event type, summed over all different major discrete event types and summed over all seasons. To calculate this first-order effect, the results of the characterization of major discrete events in multi-level PT networks from chapter 2 can be used. The estimated Poisson parameters ƛ - representing the average frequency of an event per time period on the considered case study network *N* (see Table 2.6 for the train network, Table 2.9 for the metro/light rail network and Table 2.10 for the tram network) - the average duration of each major discrete event type (see Table 2.12, Table 2.13 and Table 2.14) and the effect on infrastructure availability (1 track blocked, 50% of infrastructure blocked, 100% of infrastructure blocked: see chapter 2.4) for each network level as estimated in chapter 2 can be used. Because of seasonal differences in average frequency with which some event types occur, and because of differences in average frequency and duration of some event types during heavy snow, a distinction can be made between different time periods *t* of a year. In total, 5 different time periods can be considered: spring, summer, autumn, regular winter and heavy snowfall during winter. To fully consider those seasonal fluctuations over the year, it is necessary to calculate I_r^1 at least per year. In this calculation, only average values for frequency and duration are used. The assumed distribution functions are not considered yet given time constraints. The expected time a specific link is blocked is calculated from the ratio between the value of the assumed predictor for a major discrete event type x_p on that link segment *r* and x_p on the total considered network *N*. In this calculation, link segments are used instead of links. This is because measures of PTO's are not taken for each link separately, but for link segments. A link segment can be considered as a stretch of links located between two locations where route choice options are available (for example locations having switches or turning facilities). Because the same measures will be taken by a PTO in case of an event on each link $i \in r$, the expected total time a link *i* is blocked because of first- and second-order effects together will be equal for all those links $i \in r$. Therefore, it is sufficient to consider link segments instead of links when calculating the value of this criterion.

I_r^2 represents the second-order effect: the expected time a link segment *r* is blocked because of the occurrence of a major discrete event on another link segment *s*. As explained, all link segments *s* for a link segment *r* can be determined based on the measures taken by a PTO in case of an event on a certain link with a certain effect on infrastructure availability. This second-order value is calculated based on similar values for frequency and duration as used to calculate the first-order effects of a certain link segment. I_r^3 represents the expected total time a certain link segment *r* is blocked, as sum of the first-order and second-order effects. From a passenger

perspective especially this third criterion is important, since this value represents the expected time a passenger experiences affected PT services on a link segment, regardless whether this blockage is caused by an event on this same link segment or on an adjacent link segment.
On the one hand, the first three criteria represent the expected time a link segment is blocked, thereby considering both the probability on an event and the duration of an event explicitly. By applying these three criteria, links on which a relatively high number of events with long durations occur are considered as vulnerable. On the other hand, it is important to consider the impact of an event as well. Therefore, I_i^4 represents the impact of a major discrete event by the number of passengers travelling over that link per considered time period. Because the number of passengers per time period can be different on each link $i \in r$, this value is calculated for each link *i* separately instead of for a link segment *r* as a whole. Together, the third and fourth criteria show which links in the multi-level PT network events are relatively often blocked, while the impact of such blockage on passengers is relatively high. This type of links is expected to be especially vulnerable from a passenger perspective. By using I_i^5 extra attention is paid to links having limited route alternatives available. First, a selection of vulnerable links is made based on criteria I_i^3 (which equals $I_i^1 + I_i^2$) and I_i^4. Then a second selection step takes place by assessing the number of available route alternatives in a qualitative way by criterion I_i^5 for the links remaining from the first selection step.

3.2.2 Assignment on multi-level PT networks

In this study, passenger assignment on a multi-level PT network is performed by using a transit model of OmniTRANS. In this chapter, transit modelling and assignment in OmniTRANS are shortly described.

Network representation

The network in OmniTRANS is divided in a number of zones which function as origins and destinations for a certain number of PT trips. Each zone is represented by a centroid, a point which can be considered as centre of a certain zone. The transportation network can be represented as a directed graph, which consists of nodes and one-directional links. Bi-directional links in the network can be considered as two one-directional links. The links in the network either connect two nodes, or connect a centroid and node. A link connecting a centroid and a node is a virtual link which is indicated as connector. Transit lines begin and end at a certain node in the network and follow a predefined order of links and nodes between the start node and end node. For each transit line the travel time between stops is used as input for the model. For a limited set of relevant transit lines, also the seat capacity and crush capacity (which equals the sum of seat and standing capacity) of PT vehicles are used as input. Public transport stops are nodes in the network where passengers can enter, leave or transfer to a certain transit line.

In the model used in this study a frequency-based transit service network representation is used. This means that for all transit lines only the frequency is used as information about the timetable. In this network representation, the waiting time for a transit line is assumed to be half of the interarrival time between two PT vehicles of a transit line. This means that arrivals at stops are assumed to occur in a random pattern. This assumption especially holds for transit lines having a high frequency. In case transit lines have a low frequency, it is more likely that passengers will plan their arrival at a stop based on the specific schedule of transit lines to prevent long waiting times. In that case, the assumption of random arrivals is less realistic.
A schedule-based network representation allows the calculation of more precise waiting times than half of the interarrival time. In this network representation, the exact schedule of transit lines is used as input instead of the frequency of transit lines only. This allows the incorporation of coordinated transfers between transit lines - for example a cross-platform transfer - in a realistic manner. Whereas nodes in a frequency-based network only represent a certain location, nodes in a schedule-based network represent a certain location and a certain time (Van der Gun, 2013).

It can be concluded that a schedule-based network representation is more realistic than a frequency-based network representation. When modelling the effects of major discrete events, performing a schedule-based assignment can give more realistic outcomes than a frequency-based assignment regarding realized waiting times. However, computation times also increase substantially when performing a schedule-based assignment on a large transit network in OmniTRANS compared to a frequency-based assignment. In this study a frequency-based network representation is used because of computation time limitations and because the frequencies of transit lines in the densely populated case study area between Rotterdam and The Hague are usually high, which justifies the assumption of random arrivals at a transit stop to a larger extent. Therefore, it is expected that in this specific study differences between realized waiting time and waiting time calculated based on a frequency-based assignment are limited.

In the used OmniTRANS transit model, public transport is the main mode of each trip. However, private modes like walking, bicycle and car can be used for access to / egress from the public transport trip. The public transport network part of the model can be considered as a supernetwork (Van der Gun, 2013). In this supernetwork, different public transport modes on different network levels are connected to each other by transfer links. This shows the multi-level character of the public transport part of the model, in which the network levels of high speed trains, intercity trains, sprinters, metros, light rail vehicles, trams and busses are connected to each other, thereby forming one public transport supernetwork.
Multiple combinations of private access and egress modes are possible for a public transport trip. In case walking and bicycle are considered as private access and egress modes, the three access/egress combinations walk-walk, walk-bicycle and bicycle-walk are in theory possible. This also allows the consideration of real multimodal trips in this model, where for example the car is used as access mode to a Park & Ride facility where a transfer to public transport as main mode is made. Using multiple access/egress modes requires that first trip matrices need to be generated for each access/egress combination separately, which also increases the total computation time of an assignment. Given this disadvantage regarding computation time, in this study only walking is considered explicitly as access and egress mode. By changing the walking speed on some walk links, the use of faster modes like bicycles for access and egress is incorporated implicitly in the model. Given the focus of this study on multi-level PT networks instead of a focus on real multimodal networks, this simplification regarding the access/egress mode combinations can be justified.

Time periods

In OmniTRANS transit models the PT demand for an average working day is used. For these working days, three time periods of the day are distinguished: the morning peak, evening peak and remaining part of the working day. This last time period consists of the very early hours before the morning peak, the hours between morning and evening peak and the hours after the evening peak. The morning peak consists of a time period of 2 hours between 7a.m. and 9a.m. The evening peak also consists of a period of 2 hours, between 4p.m. and 6p.m. This means that initially three different PT trip matrices are used as input for the model, showing the number of trips between each OD-pair during the morning peak, evening peak and remainder of the working day.
In this study, there is a strong focus on passenger effects of a major discrete event. Especially in case of large disturbances, it can be expected that the load factor on alternative transit lines increases, leading to a lower comfort level on those lines. Therefore, it is deemed important to incorporate the effects of major discrete events on comfort level and crowding in this study. When using a certain PT trip matrix as input for PT demand in a certain time period, it is implicitly assumed that PT demand is uniformly distributed over this time period when calculating the effects on comfort level. Usually, the load factor of PT services outside peak hours is relatively low. In case the PT demand for the remaining part of the working day is not distributed uniformly over the different hours, the effects on crowding levels are expected to remain limited. However, during peak hours the load factor of transit lines is usually high. In case PT demand is not distributed uniformly over the two hours of a peak period, crowding effects can be underestimated significantly for the busiest part of the peak period in case PT demand is averaged over the whole time period. Therefore, the distribution of demand over the two hours of both peak periods is checked. Table 3.1 shows that during the morning peak 35% of the

number of morning peak trips are made between 7a.m. and 8a.m., whereas 65% of the morning peak trips are made between 8a.m. and 9a.m (CBS, 2013). This table shows that PT demand in the morning peak is clearly not uniformly distributed. On the other hand, Table 3.1 shows that the average number of trips is distributed uniformly over the two evening peak hours.

In order to analyze the effects of major discrete events on comfort level and crowding in an adequate manner, the morning peak is divided in two sub periods: a first hour morning peak between 7a.m. and 8a.m. and a second hour morning peak between 8a.m. and 9a.m. Then, for each hour of the morning peak it can be analyzed how the passenger flow relates to the supplied capacity in case of large disturbances. This means that in this study in total four time periods are modelled. The original morning peak PT trip matrix is multiplied by 0.35 and 0.65 respectively, in order to construct PT trip matrices for each hour of the morning peak separately. It should however be mentioned that in reality the passenger distribution over the two peak hours differs per transit line: in this study an average distribution is assumed for the whole multi-level PT network because no transit line-specific knowledge about this distribution is known.

Table 3.1: Distribution of average number of trips per person over peak periods (CBS, 2013)

Time period	Average number of trips per person per hour of the day	
	Absolute	Relative
7a.m. – 8a.m.	0.12	35%
8a.m. – 9a.m.	0.23	65%
Total morning peak	*0.35*	*100%*
	Absolute	**Relative**
4p.m. – 5p.m.	0.23	50%
5p.m. – 6p.m.	0.23	50%
Total evening peak	*0.46*	*100%*

Trip assignment

In this study is mainly focused on assignment effects of major discrete events. In general, trip generation, trip distribution and modal split are assumed constant. Most major discrete event types which are considered in this study have a low level of predictability. In case major discrete events with a low level of predictability occur, it can be assumed that the PT trip matrices remain unchanged (no effect on trip frequency, destination and mode choice). Only in case of major discrete events with a high level of predictability, it is expected that PT demand is reduced (see chapter 2.5). Based on the empirical findings on PT demand reduction in case of large maintenance works, for these event types the original PT demand is reduced for affected OD-pairs. Because the OmniTRANS model uses PT demand values for an average working day, the PT demand reduction empirically found during a working day is used in the model. As explained in chapter 2.5, during working days a PT demand reduction of 14% is found. Therefore, in case of large maintenance works as predictable major discrete event, the demand on all affected OD-pairs is reduced by 14%. In case only a fraction of the PT demand of a certain OD-pair is affected by large maintenance works because of the chosen route alternative, the demand reduction of 14% is only applied to this fraction of the total demand on that OD-pair. For predictable major discrete events the effect on trip generation, production and modal split is therefore only taken into account implicitly in this study. The PT demand is reduced with a certain percentage. However, it is unknown whether these lost PT travellers change their mode choice, destination choice or trip frequency choice.

For the assignment of PT trips over the network OmniTRANS uses the Zenith algorithm. Below, the procedure of this algorithm is shortly described based on Veitch and Cook (2011) and OmniTRANS (2013).

- First, a candidate set of feasible access stops (first boarding) and feasible egress stops (last alighting) is constructed by checking which stops lie within a specified search radius around centroids in the model.
- Second, feasible paths are constructed between each access stop – egress stop combination by using a reverse propagation algorithm. From each destination node all transit lines are processed in reversed direction to calculate the (generalized) costs from stops on these transit lines to this destination node.

- Third, in case a stop is found in this reversed search procedure which is already processed earlier, a logit transit line choice model is applied to determine the fractions of each processed path. This logit model can be expressed by formula (3.14). The logit scale parameter λ indicates the degree to which passengers choose the transit line with lowest generalized costs, therefore reflecting the knowledge passengers have about the available transit line alternatives. A higher value of λ indicates that more passengers prefer the cheapest transit line in terms of generalized costs.

$$P_a = \frac{F_a e^{-\lambda C_a}}{\sum_{x \in T} F_x e^{-\lambda C_x}} \qquad (3.14)$$

With parameters:		
	P_a	*probability to board transit line a*
	F_a	*frequency of transit line a*
	C_a	*generalized costs of choosing to board transit line a*
	λ	*logit scale parameter for transit line choice*
	T	*set of feasible transit lines*

- Fourth, based on the proportions of passengers choosing transit line $a \in T$ at a certain stop *x*, the generalized costs of using this stop *x* can be calculated by using formula (3.15). This formula shows that the weighted sum of the generalized costs of chosen transit lines and perceived waiting time at stop *x* are added together to calculate the total generalized costs of using stop *x*.

$$C_{stop} = \sum_{x \in L_s} P_x C_x + \alpha_{wt} T_{wait} \qquad (3.15)$$

With parameters:		
	α_{wt}	*weightfactor of waiting time*
	T_{wait}	*combined waiting time*
	L_s	*set of transit lines*

- Fifth, in case a stop allows a transfer to other transit lines, it is calculated whether the generalized costs of using this transfer are lower than the original generalized costs at that stop. If that is the case, this transfer is added as new branch in the reversed search process.
- Sixth, when all candidate origin nodes are reached by the reversed search algorithm, the passenger demand from each origin zone is distributed over the found access stop candidates by using a logit access stop choice model. This logit model is expressed by formula (3.16). The logit scale parameter ϕ expresses the extent to which passenger favour the access stop candidate having the lowest generalized costs (which can be calculated by using formula (3.15)). A higher value of ϕ indicates that more passengers prefer the cheapest alternative in terms of generalized costs, thereby indicating that passengers have more knowledge about the available alternatives.

$$P_a = \frac{e^{-\varphi C_a}}{\sum_{x \in S} e^{-\varphi C_x}} \qquad (3.16)$$

With parameters:		
	P_a	*proportion of passengers boarding at candidate stop a*
	C_a	*generalized costs of choosing to board at candidate stop a*
	φ	*logit scale parameter for access stop choice*
	S	*set of access candidate stops for an origin*

- Seventh, the generalized costs for each origin centroid can be calculated as weighted sum of the generalized costs over all access candidate stops, as expressied by formula (3.17).

$$C_{origin} = \sum_{x \in S} P_x C_x \qquad (3.17)$$

Formula (3.18) expresses the function with which the generalized costs C of a route alternative are calculated which are used as input for the assignment procedure. From this formula it can be concluded that only monetized perceived travel time components are used in the calculation of the generalized costs which are used as input for the assignment. Formula (3.18) shows that travel costs and travel comfort are not included in this generalized cost function. This is explained below.

$$C = T * VoT = (\alpha_a t_a + \alpha_w \sum_{x=1}^{n_t+1} t_{w,x} + \alpha_{in} \sum_{y=1}^{n_t+1} t_{in,y} + \alpha_{n_t} n_t + \alpha_t \sum_{z=1}^{n_t} t_{t,z} + \alpha_e t_e) * VoT \quad (3.18)$$

With parameters:

C	$generalized\ travel\ costs$
T	$generalized\ travel\ time$
VoT	$value\ of\ time$
t_a	$access\ time\ from\ origin\ to\ PT\ service$
t_w	$waiting\ time\ for\ boarding\ PT\ service$
t_{in}	$in-vehicle\ time\ in\ PT\ service$
n_t	$number\ of\ transfers\ between\ PT\ services$
t_t	$transfer\ walking\ time\ to\ PT\ service$
t_e	$egress\ time\ from\ PT\ service\ to\ destination$
α_x	$corresponding\ weight\ for\ travel\ time\ components$

This study focuses on a passenger perspective when considering the effects of major discrete events. Therefore, in the performed assignment during a major discrete event barrier-free travelling for passengers is assumed given the adjusted PT network. This means that it is assumed that passengers have full information about the location of a certain event, the consequences of this event on supplied PT services, and that passengers have full knowledge about route alternatives available within the multi-level PT network. By assuming full information and full network knowledge, this study shows how the total multi-level PT network can be used as back-up for a blocked part of the network. In order to realize these effects, passengers need to be provided with full information about the event and route alternatives in the multi-level network. Given the increasing use of smart phones, in reality a tendency can be observed that passengers are indeed provided with an increasing amount of information about disturbances and route alternatives. This study aims at showing how the available multi-level PT network *can* be used from a passenger point of view, when no information or knowledge barriers exist. Therefore, in the assignment in case of a major discrete event the value of the logit scale parameters – representing the level of knowledge of passengers about route alternatives – is not changed compared to the undisturbed situation. In that case the pure effect of a major discrete event on passengers can be analyzed, without introducing noise in the results because of a changed value for the logit scale parameter.
In this study barrier-free travelling also means that passengers are not assumed to pay for the extra kilometres they have to travel by public transport because of a major discrete event. Given the passenger perspective in this study, it is assumed that passengers are compensated by a PTO for possible additional costs they have to make when they have to make a detour or when they have to transfer to PT services of another PTO. By assuming no additional travel costs for passengers, this study shows how the remaining part of the available multi-level PT network can be used from a passenger point of view in case of disturbances. Therefore, travel costs are not included as component in the generalized cost function as shown by formula (3.18).

Especially during major discrete events, the comfort level (because of a high passenger load factor) and crowding effects occurring on alternative routes are important from a passenger perspective. Since the number of passengers on some route alternatives can increase substantially because of an event, the comfort level for passengers on this route can decrease. It is even possible that a route alternative in the multi-level PT network is not able to accommodate the passenger demand, in case demand exceeds supplied crush capacity. Despite the importance of these comfort and crowding effects, these aspects are not incorporated in the generalized cost function used for the assignment. Both theoretical and practical arguments underlie this decision:

- In case the comfort level is incorporated in the generalized cost function, it means that passengers base their route choice on the comfort level of PT services as well. During an undisturbed situation this is a reasonable assumption: passengers who have experience with the load factor and comfort level on different routes can incorporate this component in their route choice (see for example Bel, 2013). However, in case of major discrete events it is questionable whether passengers change their route choice because of crowding effects. In general, it is expected that in case of major discrete events for most passengers the most important goal is to reach their planned destination by using the disturbed network. Therefore it is expected that comfort level has no or only very limited effects on route choice during major discrete events, since passengers realize that crowding effects can be unavoidable in case of such events. Additionally, passengers do not have knowledge or information about the crowding and comfort level in PT services during major discrete events on beforehand to incorporate in their route choice.
- From a theoretical perspective it is questionable what behaviour passengers show in case they want to board a PT service which has already reached its crush capacity. It is likely that a part of the passengers will skip this specific service and will try to board the next vehicle of the same service. However, it is also possible that some passengers change their route choice when they are confronted with very crowded PT services on a certain route. When the crush capacity of PT vehicles would be incorporated in the assignment, it is assumed that passengers adapt their route choice in case of severe crowding. In the used model, it is not possible to model the alternative in which passengers keep using the same route, but after skipping one or more PT services first. Because the route in the transportation network remains the same, it is not possible in OmniTRANS to model this as a separate alternative. Therefore, incorporating crush capacity as constraint in the assignment assumes that all passengers who do not fit in a PT service change route choice. When crush capacity is not incorporated in the generalized cost function of the assignment, it is assumed that all passengers who do not fit in a certain PT service do not change their route choice, but just extend their (transfer) waiting time by skipping (a) crowded service(s). The behaviour of passengers in reality during major discrete events is expected to lie between these two extremes. None of the two approaches mentioned is expected to be fully consistent with behaviour of passengers in reality.
- In case capacity is included in the generalized cost function for the assignment, it means that an iterative assignment procedure needs to be performed which is comparable to a stochastic user equilibrium assignment on road networks. Although this is possible when performing a transit assignment in OmniTRANS, the calculation time increases with factor N, with N being the number of iterations required until convergence is reached. Besides, as mentioned in chapter 3.1.2 no real equilibrium situation is expected in case of major discrete events.
- Additionally, when performing an iterative transit assignment in OmniTRANS, it is not possible yet to specify a convergence criterion on beforehand. This means that the assignment results of different numbers of iterations need to be compared manually to determine whether differences between the results of iteration N and iteration $N+1$ are small enough to assume convergence. This manual comparison also increases computation times substantially.

It can be concluded that from a theoretical perspective the incorporation of capacity in the generalized cost function on beforehand can be correct for a part of the travellers. For another part of travellers it is expected to be more realistic that route choice is not changed in case they are confronted with crowded PT services. In combination with the substantial increase in computation time when performing an iterative assignment procedure, it is decided not to capture capacity in the assignment on beforehand. After the assignment is performed, the effect of realized passenger streams on the comfort level experienced by passengers is calculated independent from the model. Also it is checked manually if passenger flows on certain links do not exceed the supplied capacity.

Appendix B1 compares the assignment results of an uncongested transit assignment for different logit scale parameters and compares the assignment results between an uncongested and capacity constrained (iterative) transit assignment procedure for a simulated major discrete event on the train link between Rijswijk and Delft. In addition to the theoretical explanation as mentioned above, this appendix shows that the distribution of passenger streams over the multi-level PT network is relatively insensitive to different values of the logit scale parameter.

In this study a static assignment is performed. In road networks it is common to use a dynamic assignment when modelling the effects of disturbances. Although the use of a dynamic transit assignment can be of value, the use of a static transit assignment can be explained because congestion between PT services hardly occurs during major discrete events. As explained in chapter 3.2.1, in case of an event on a certain location PT services are adjusted based on standard operating procedures. Because no real congestion effect between PT vehicles occurs, the need to use a dynamic assignment procedure in order to model queuing effects in an accurate way is substantially less in PT networks.

In the study no en-route route choice is included in the assignment. Given the assumption made in this study that passengers have full information about the disturbance and adjusted network, it means that passengers route choice takes place pre-trip only. Before the start of a trip passengers can decide the route alternative they take given the full information they have about the adjusted network caused by a disturbance. Note that this assumption neglects the dynamics in route choice when passengers are confronted with a major discrete event during their trip. These passengers begin their trip in an undisturbed situation and base their route choice on the undisturbed network. During their trip however some event occurs on the route they initially planned. In that situation, even if passengers have full information some en-route route choice takes place in reality. Given the limitations of the static assignment model used, in this study this transition phase between the undisturbed and disturbed situation is not incorporated explicitly. On a very aggregate level it is however expected that these dynamics cancel out each other: en-route route choice is neglected in case during a trip a disturbance occurs, but also in case during a trip a disturbance is solved. In the last case, passengers first started their route choice based on the disturbed network, and might adjust their route choice during the trip when the disturbance is solved in reality. Therefore no structural bias of the assignment results is expected because of neglecting these dynamics, although it can definitely be of interest to get insight in en-route route choice behaviour of passengers in case they are confronted with a disturbance.

3.2.3 Methodology for identification of vulnerable links in a multi-level PT network

Given the criteria formulated in chapter 3.2.1 for the identification of vulnerable links in a multi-level PT network, a four-step methodology can be developed. This methodology consists of the following steps:

Step 1: Calculate the expected time a link segment r is blocked per (multiple of a) year ∀ link segments r of the multi-level PT network

- First calculate the first-order effects (criterion I_r^1): the total expected time a link segment *r* is blocked because of the occurrence of different major discrete event types on this link segment *r* itself;
- Then calculate the second-order effects (criterion I_r^2): the total expected time a link segment *r* is blocked because of the occurrence of different major discrete event types on adjacent link segments $j_1 \ldots j_n$, causing the considering link segment *r* to suffer from reduced or cancelled PT services as well;
- Calculate the total expected time a link segment *r* is blocked (criterion I_r^3) by summing the first-order and second-order effects ($I_r^1 + I_r^2$).

Step 2: Determine the impact of a major discrete event by using the number of passengers travelling over a link i per time period

- First perform one assignment of PT passengers over the undisturbed multi-level PT network using a transit assignment model, without the inclusion of major discrete events;
- Then determine the number of passengers travelling over each link *i* per time period (criterion I_i^4), using the output of the performed assignment.

Step 3: Determine the links in the multi-level PT network which have high values for both criteria I_r^3 and I_i^4

- Plot the links of the multi-level PT network against each other based on total expected blockage time (criterion I_r^3) and the number of passengers travelling over that link *i* (criterion I_i^4);
- The most vulnerable links in the multi-level PT network based on these two criteria can be identified based on the Pareto front they form.

Step 4: Assess the number of alternative routes available in the multi-level PT network in case of a major discrete event occurring on a link

- Assessment qualitatively for the remaining links on the Pareto front how many alternative routes in the multi-level network are available (criterion I_i^5);
- Filter the list of vulnerable links located on the Pareto front of step 3 further, by excluding links for which many route alternatives in the multi-level PT network are available.

After these four steps of the developed methodology are taken, a list of most vulnerable links of the multi-level PT network is remaining. In a second step, major discrete events can be simulated on links remaining on this list.

3.3 Identification of vulnerable links for the multi-level PT case study network

The methodology developed to identify vulnerable links in a multi-level PT network as described in chapter 3.2.3 is applied to the case study network between Rotterdam and The Hague. The geographic scope of the multi-level PT network is described in chapter 1.5. Links of the bus network in this case study area are not considered here, since it is assumed that the impact of a major discrete event on a bus link will be very limited. This is because usually many alternative routes near the blocked link are possible in the bus network. The passenger effect of blockages of bus links is therefore considered to be very limited.
In total, 54 train link segments, 92 metro/light rail link segments and 339 tram link segments are identified in the case study network. Appendix B2 shows an overview of all link segments of the case study network and the related number with which each link segment can be identified.

Step 1: Calculate the expected time a link segment r is blocked per (multiple of a) year ∀ link segments r of the multi-level PT network

When determining the second-order effects for links on the train, light rail and tram network, the measures which are taken by PTO's and infrastructure managers in reality are used in this study as well. ProRail, HTM and RET provided an overview of the measures they take (in Dutch: 'versperringsmaatregelen') in case of a major discrete event on each location in the case study network. Only for the metro network in this case study area no information was available about the measures taken in reality. For this study, it is assumed that metro lines are divided in two separate parts in case a major discrete event occurs on a certain link, regardless whether this event leads to 0% or 50% infrastructure availability. The metro services are then shortened on both sides of the event to the last station where switches are available for turning. This assumption is made based on the type of measures taken by PTO's in case a major discrete event occurs on the light rail network. The measures taken for events on the metro network are expected to be comparable to measures taken on the light rail network.

Figure 3.1 shows the resulting values on criteria I_r^1, I_r^2 and I_r^3 for all link segments of the train network in the case study area. These values are calculated using formulas (3.10), (3.11) and (3.12). In general, from this figure it can be concluded that second-order effects are quite dominant in the calculation of the total expected time a link segment is blocked. For almost all links, the second-order effect is substantially larger than the first-order effects. The next link segments on the train network are expected to be blocked most:

- Link The Hague Central Station – Voorburg, Voorburg – The Hague Ypenburg, The Hague Ypenburg – Zoetermeer and Zoetermeer – Zoetermeer Oost in both directions (link numbers 47 – 54): this can mainly be explained by the large second-order effect. In case of an event on one link between The Hague and Gouda, train services on all other links between these stations are affected as well.
- Link Rotterdam Central Station – Rotterdam Noord and Rotterdam Noord – Rotterdam Alexander in both directions (link numbers 43 – 46): also for these links the contribution of the second-order effect is large. In case of an event on one link between Rotterdam and Gouda, train services on all links between these stations are affected.
- Link Maassluis – Maassluis West (link numbers 31 – 32): the second-order effect on this link is especially high because the train services on this link are affected in case an event occurs on the west side of this link between Hoek van Holland and Maassluis West, but also in case an event occurs on the east side of this link between Schiedam Centrum and Maassluis.
- The expected blockage time of the train links Rijswijk – Delft, Delft – Delft Zuid and Delft Zuid – Schiedam Centrum (numbers 11 – 16) is higher than for the train links The Hague HS – The Hague Moerwijk, The Hague Moerwijk – Rijswijk and the stretch of links between Rotterdam Central Station and Barendrecht (numbers 7 – 10 and 19 - 26). This can be explained because on the latter group of links two tracks per direction are available, whereas for the first group only one track per direction is available for the same train intensity. The effects of vehicle breakdowns and defect tracks (see Figure 2.16 in chapter 2.4) are larger on a two-track link than on a four-track links, which is supported by the data from Figure 3.1.

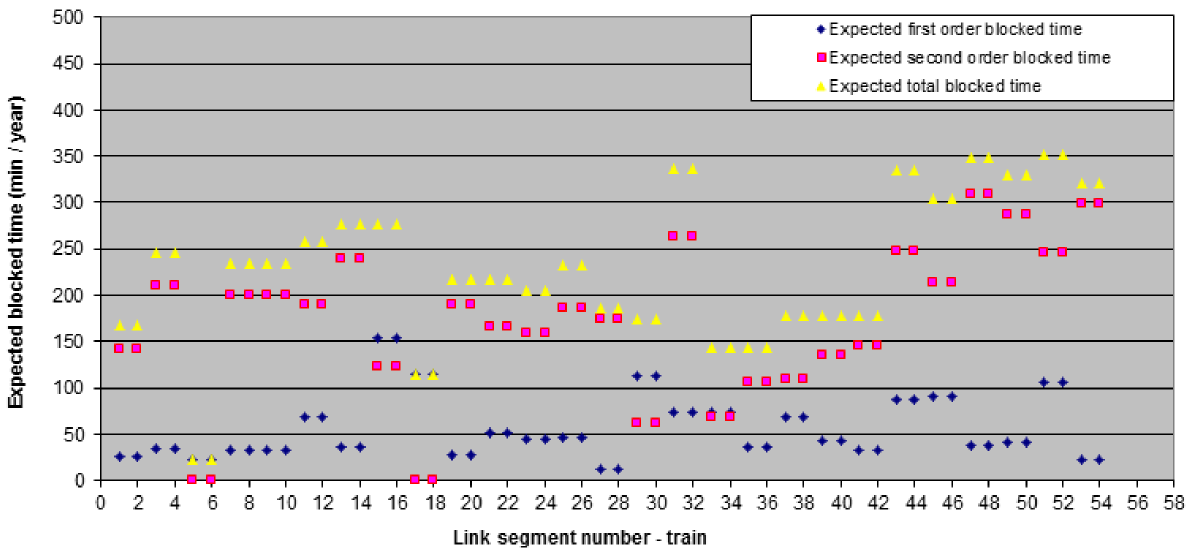

Figure 3.1: Expected blocked time per link segment of the train network of the case study

Figure 3.2 shows the resulting values on criteria I_r^1, I_r^2 and I_r^3 for all link segments of the metro/light rail network in the case study area. Based on this figure, the next conclusions can be formulated:

- For almost all links on the Rotterdam part of the metro network the first-order effect is equal to the second-order effect (link numbers 283 – 352). This can be explained because in Rotterdam switches are available near almost every metro stop. Therefore, the effect of a disturbance is kept very local: only metro services on that link (in both directions) are cancelled. Because of the availability of switches, in most cases on both sides of the blocked link metro services can be supplied until the last station before the blocked link.
- A large difference can be seen between the expected time link segments are blocked on the metro network in Rotterdam (link numbers from 283) and on the metro/light rail network towards The Hague (link numbers until 282). For the links on metro line E between Rotterdam Central Station and

The Hague Central Station, and for links on the light rail network between The Hague and Zoetermeer, the expected blockage time is substantially higher compared to values for the metro links in Rotterdam. This can be explained because the number of switches applied on the metro/light rail network at the side of The Hague is significantly lower than for the Rotterdam part of the network (Sporenplan, 2013b). This leads to large increases in second-order blockage time on these links.

- The link segment between Zoetermeer Centrum West and Zoetermeer Segwaert via Voorweg Hoog in both directions (link numbers 267 – 268) has the highest expected total blockage time. This is because on this link segment with a link length of almost 9 kilometre and 9 stops no switches are available. An event occurring in one direction somewhere on this long link segment therefore leads to the cancellation of PT services on this whole link segment.

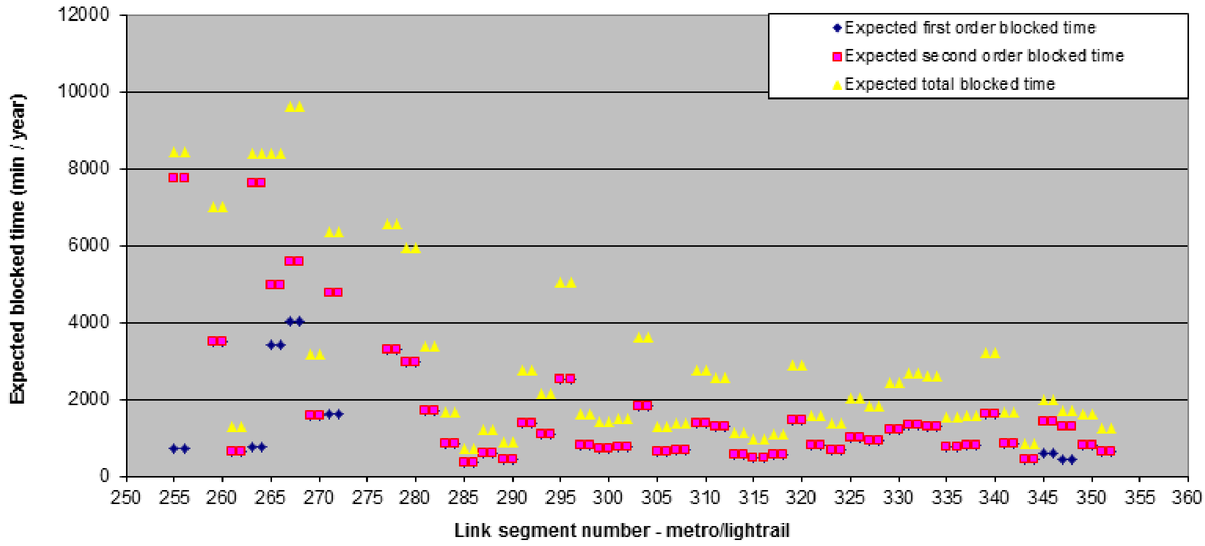

Figure 3.2: Expected blocked time per link segment of the metro/light rail network of the case study

Figure 3.3 shows the resulting values on criteria I_r^1, I_r^2 and I_r^3 for all link segments of the tram networks of The Hague (link numbers until 258) and Rotterdam (link numbers from 353) in the case study area. Based on this figure, the next conclusions can be formulated:

- In general, the total expected blockage time for link segments on the tram network of Rotterdam is somewhat lower than the expected blockage time for link segments of the tram network of The Hague. This can be explained because in general more parallel (sometimes unused) tram tracks are available in Rotterdam, which function as back-up in case of major discrete events (Sporenplan, 2013b). This leads especially to lower values for the second-order effects, compared to the links on the tram network of The Hague.
- Link segments having a large expected blockage time are mainly link segments at the end of a tram line. Usually, the number of turning facilities and switches decreases near the end of a tram line (compared to the centre where usually many turning possibilities and route alternatives are available). Besides, in case an event occurs on a link segment just before this last link segment of a line, usually the tram services on this last link segment are also cancelled. Therefore, both first-order and second-order effects on these types of link segments are high. For example, this can be seen at the link segment of tram line 25 in Rotterdam between the Breeplein and final destination Carnisselande, which has a length of almost 7 kilometres (link numbers 472 - 473).
- The tram link between tram stop Ternoot and station Laan van NOI via the Beatrixkwartier (operated by RandstadRail lines 3 and 4) has the highest expected blocked time (link numbers 257 – 258). This can be explained because of the large second-order effects. In case an event occurs somewhere on the

light rail network between station Laan van NOI and Leidschenveen, tram services on this link are cancelled as well.

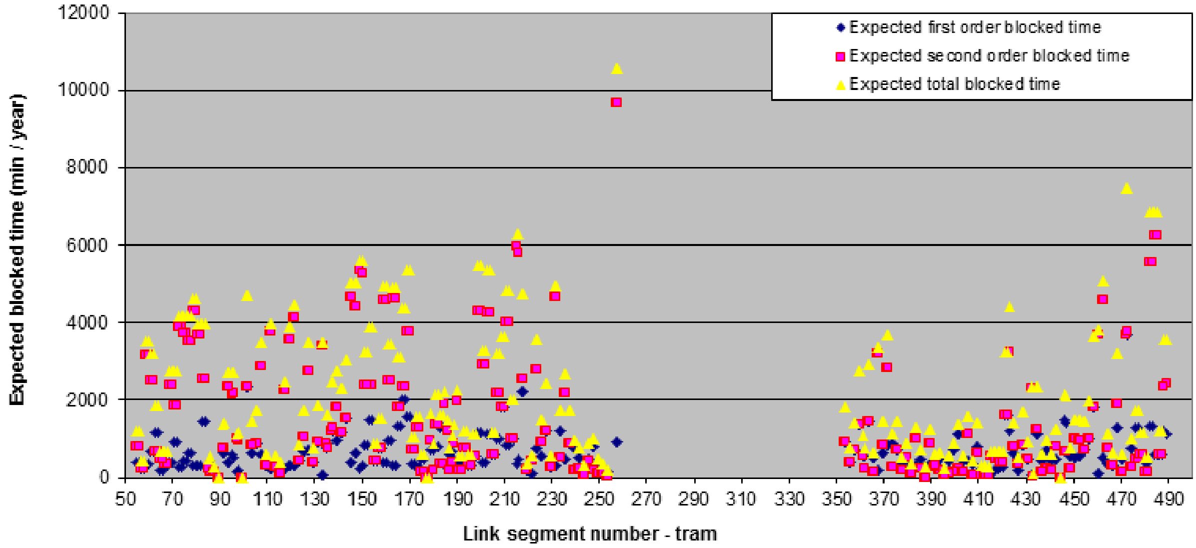

Figure 3.3: Expected blocked time per link segment of the tram network of the case study (left: The Hague; right: Rotterdam)

Figure 3.4 shows the results when all link segments of the integral multi-level PT network are considered. The expected time a train, metro/light rail and tram link segment is blocked is shown in this figure. The next conclusions can be formulated:

- In terms of expected blockage time, train network links are most robust. The expected time a train link segment is blocked is considerably lower than the expected time a tram or metro/light rail link segment is blocked.
- In terms of expected blockage time, in general the links of the tram network of The Hague (yellow points left) can be considered as most vulnerable, followed by link segments of the metro/light rail network and link segments of the tram network of Rotterdam (yellow points right).
- Especially on the metro/light rail network between The Hague and Zoetermeer / Rotterdam Central Station higher expected blockage times are found, compared to values calculated for metro link segments in Rotterdam.

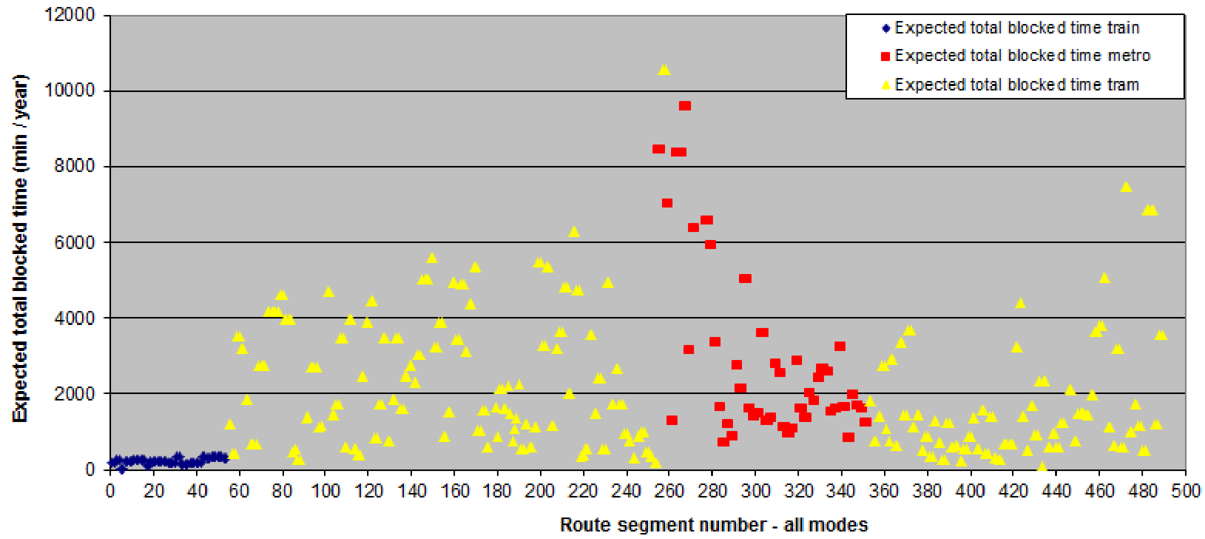

Figure 3.4: Expected blocked time per link segment of the multi-level PT network of the case study (yellow left: tram network The Hague; yellow right: tram network Rotterdam)

- When considering the whole multi-level PT network, the tram link segment Ternoot – station Laan van NOI (link numbers 257 – 258) and light rail link segment through Zoetermeer (Zoetermeer Centrum West – Voorweg Hoog – Segwaert) (numbers 267 – 268) are most vulnerable in terms of expected blockage time per time period.

Step 2: Determine the impact of a major discrete event by using the number of passengers travelling over a link i per time period

For this case study area, the regional model of OmniTRANS developed for the area of Rotterdam is used as starting point to perform a first basic assignment without disturbances. This model mainly focuses on the PT network around Rotterdam. However, on a more aggregate level also the most important PT lines in other provinces of The Netherlands are included in this model, as well as a few zones in Germany and Belgium. Given the focus of this study on the total area between Rotterdam and The Hague, especially the public transport network of the area around The Hague is upgraded in order to realize a comparable level of detail between the public transport network in the area of Rotterdam and The Hague. For all PT lines it is checked whether the frequencies used in the model are consistent with the current timetable of the different PTO's in this area (HTM, 2013; NS, 2013a; RET, 2013b; Veolia Transport, 2013).
The Rotterdam part of the model was already calibrated by comparing the number of passengers produced by the model with passenger counts at 650 locations in the area of Rotterdam. The calibration shows that the number of passengers produced by the model resembles the values found in reality to a large extent: for a period of 24 hours the values for 92% of all measurement locations produced by the model do not differ significantly from the values found in the passenger counts. Only at 3% of the measurement locations a clear difference between produced and measures passenger values is found. Because of the good calibration results of this model, the Rotterdam PT network in the model is left unchanged where possible. Only when large differences were found in route or frequency of a transit line between the model and reality, this is adjusted in the model. Besides, for all relevant PT lines values for seat capacity and crush capacity are added.
The regional model for the year 2015 is used to perform the assignment, because this is the first year in the future for which a PT trip matrix is available in the model. Table 3.2 shows some basic characteristics of the final model used to perform the assignments. In appendix B3, an overview is given of the frequency and capacity assumed for the most relevant rail bound transit lines in the model.

Table 3.2: Main characteristics of multi-level model used to perform transit assignments

Number of zones:	5.791	**Number of transit lines:**	2.131
Number of nodes:	105.751	**Number of time periods:**	4
Number of links:	115.524	**Number of main PT modes:**	14
Number of stops:	12.660	**Private access / egress modes:**	walk

Figure 3.5 shows the results after one basic transit assignment is performed without major discrete events. The number of passengers travelling over a link *i* during the first and second hour of the morning peak, evening peak and remainder of the working day are added together to get one value reflecting the number of passengers travelling on link *i* during one average working day.
Due to time limitations, in this step an additional selection is performed. Links which have a large expected blockage time while many passengers travel over that link, are considered as vulnerable. When comparing the number of passengers travelling on train, metro/light rail and tram links, it can be stated that in general the fewest passengers per time period are travelling on tram links. This means that tram links which have a low expected blockage time compared to other tram links can be excluded from the search process. Tram links with a low expected blockage time are – ceteris paribus – more robust than tram links having a high expected blockage time. Besides, these tram links are – ceteris paribus – more robust than train or metro/light rail links because of the lower number of passengers travelling on a tram link (lower impact). This means that tram links with a low expected blockage time are not expected to remain as most vulnerable links in a multi-level PT

network. Therefore, only busy tram links having a large expected blockage time are considered in the next steps of the methodology.

Based on Figure 3.5 the next conclusions can be formulated:

- In terms of number of passengers affected by a disturbance, train links and metro/light rail links are overall more vulnerable than tram links.
- Regarding train links mainly links on the track The Hague HS – Rotterdam – Barendrecht (numbers 7 – 26) are vulnerable in terms of number of passengers influenced by an event. The links between Schiedam and Hoek van Holland (numbers 27 – 42) are less vulnerable because of the lower number of passengers travelling over these links per day.
- The train link between Schiedam Centrum and Rotterdam Central Station is most often used by passengers on an average working day in the whole multi-level PT network considered.
- The busiest metro/light rail links can be found in the centre of Rotterdam. Especially the metro links between Stadhuis, Beurs, Leuvehaven, Wilhelminaplein, Rijnhaven and Maashaven in north-south direction (numbers 283 – 292) and the links between Wilhelminaplein, Blaak, Oostplein, Gerdesiaweg, Voorschoterlaan and Kralingse Zoom in east-west direction (numbers 328 – 332) are vulnerable in terms of number of passengers travelling over those links.
- Regarding the remaining tram links, the number of passengers travelling on the link segment Brouwersgracht – Grote Markt – Spui – The Hague Central Station (numbers 101 and 102) is clearly larger than the number of passengers travelling on other tram links. This link segment represents the tram tunnel built under the city centre of The Hague. During peak hours, 36 trams per hour per direction use the tram tunnel, indicating that a high number of passengers use this link segment (HTM, 2013). This means that this link is vulnerable in terms of the number of passengers which would be affected by a major discrete event.

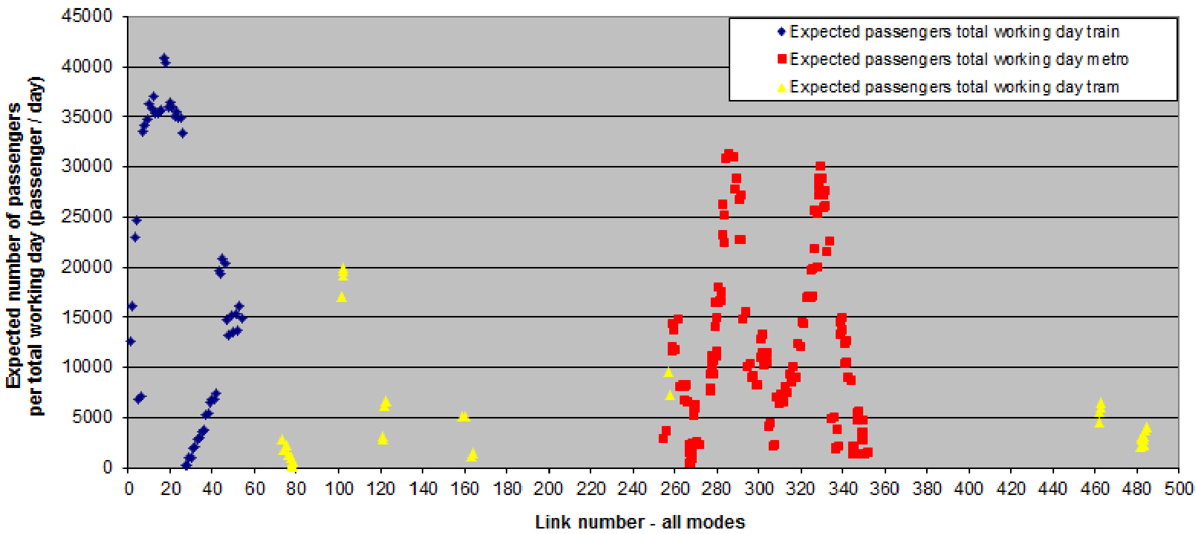

Figure 3.5: Expected number of passengers per average working day on links in the multi-level PT network

Step 3: Determine the links in the multi-level PT network which have high values for both criteria I_r^3 *and* I_i^4

In step 1 and 2, the vulnerability of links of the multi-level PT network is assessed separately in terms of expected time a link is blocked because of major discrete events and in terms of number of passengers that would experience hindrance in case an event occurs. In this step these two aspects of vulnerability are combined, indicating which links are overall most vulnerable. From Figure 3.6 – 3.9 it can be seen that a Pareto front is formed by links which are considered most vulnerable based on those two aspects together. These are links which suffer for a relatively long period per year from blockages, and where a relatively large number of passengers experiences hindrance when such blockage occurs. Figure 3.6, Figure 3.7 and Figure 3.8 show which links are considered to be most vulnerable for the train, metro/light rail and tram network, respectively. When determining the most vulnerable links, it is important to consider not only links which are located exactly on the Pareto front, but to consider links which are located just behind the Pareto front as well. Because of the different assumptions made when determining the parameter values for frequency and duration of event types in chapter 2.2 and 2.3 and because of simplifications made in the used transit model, the global position of links is more important than the exact position.

The links on the train network which are indicated as most vulnerable in Figure 3.6 are mainly links having a high passenger load, high train intensity and only one track per direction. When considering the links of the metro/light rail network in Figure 3.7, also different links can be identified on the Pareto front. On the one hand, there are links having a relatively high expected blocked time. These are links located on metro line E between Rotterdam and The Hague and on the light rail track between The Hague and Zoetermeer. On the other hand, some links are identified as vulnerable mainly because of the very large passenger loads, especially in the city centre of Rotterdam. For the tram network, the most vulnerable links can clearly be identified from Figure 3.8. The pair of links on the right hand side of this figure shows the link between Ternoot and Laan van NOI via the Beatrixkwartier. The other vulnerable links are the links of the tram tunnel of The Hague between the Brouwersgracht and Central Station. Because of the very high passenger load and because no switches or other flexibilities are available in this tram tunnel, these links are identified as very vulnerable as well.
When integrating the figures of vulnerable links for all modes separately in one plot representing the vulnerability of links in the multi-level PT network, also a Pareto front of vulnerable links is formed. The links located on or near to the Pareto front in Figure 3.9 can be considered as most vulnerable links in the whole multi-level PT network considered for this case study. It can be seen that some train links are identified as most vulnerable because of the very high passenger load. Tram and metro/light rail links are often considered most vulnerable because of the relatively high expected total blocked time, sometimes in combination with high passenger loads as well. Table 3.3 shows the (rounded) values on criteria I_r^3 and I_i^4 for all links of the multi-level network which are located on / near the Pareto front.

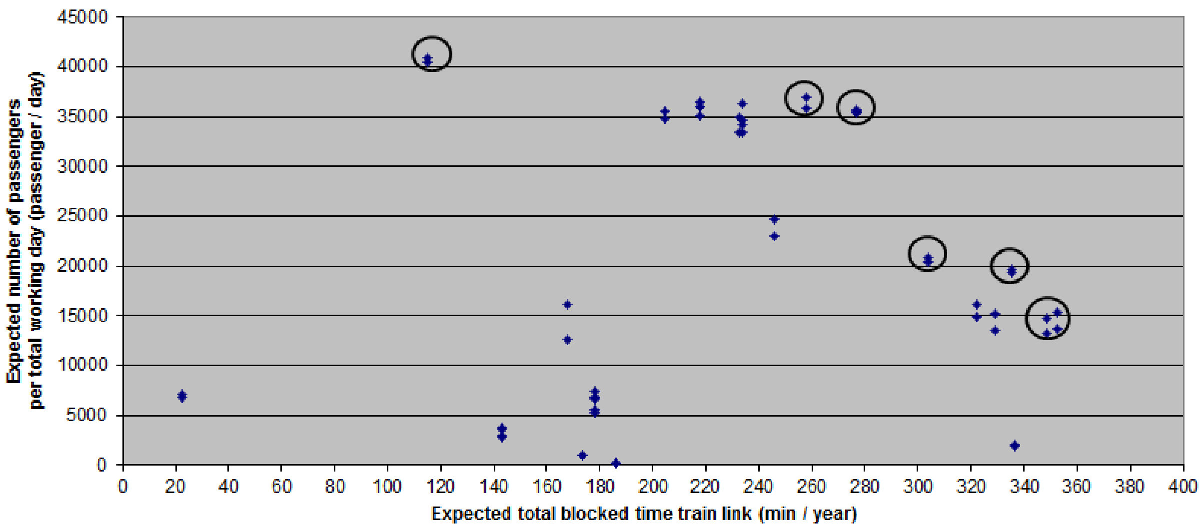

Figure 3.6: Vulnerability of links of the train network of the case study area

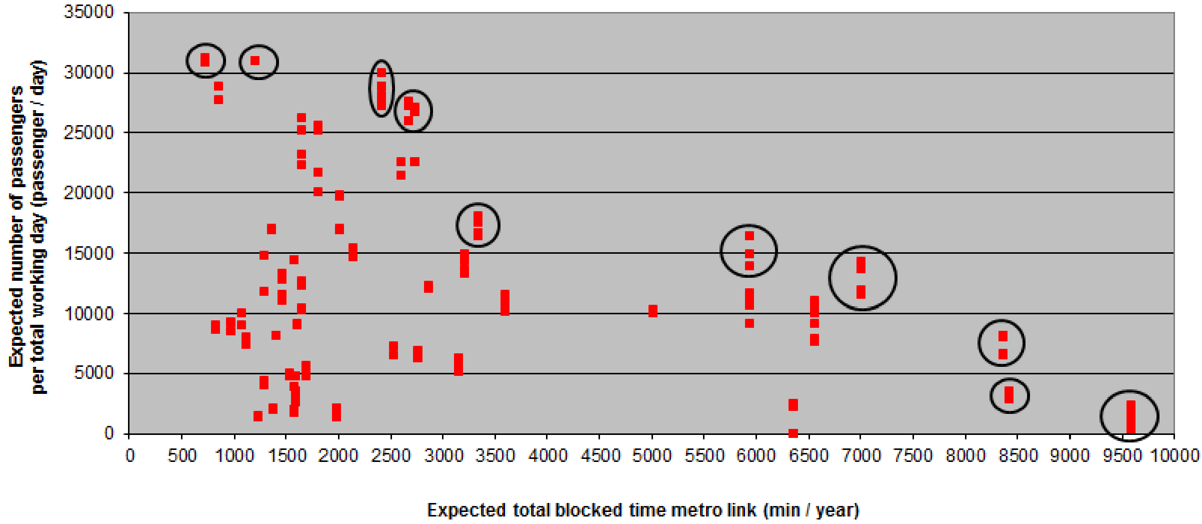

Figure 3.7: Vulnerability of links of the metro/light rail network of the case study area

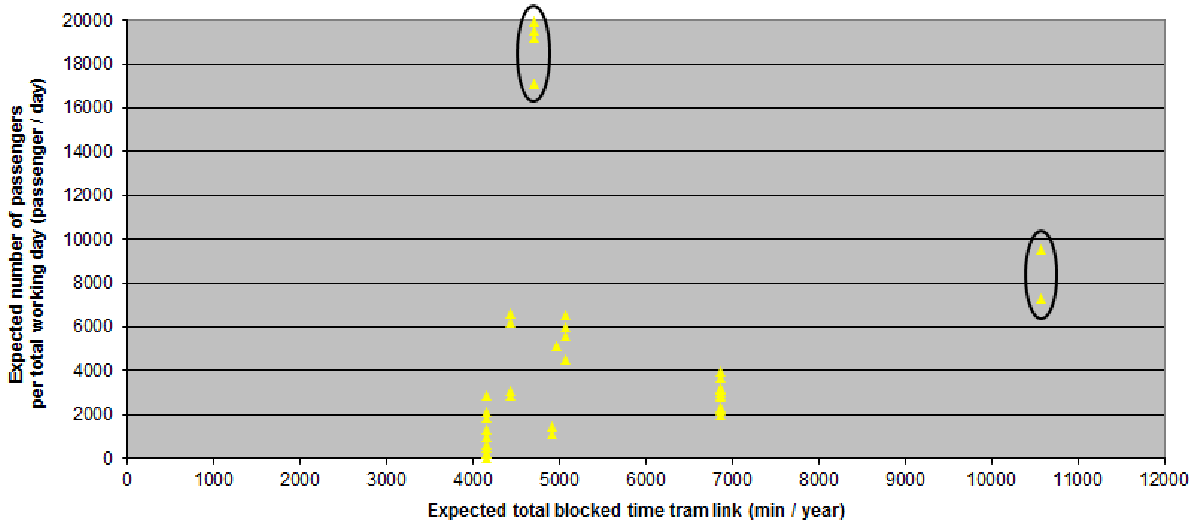

Figure 3.8: Vulnerability of links of the tram network of the case study area

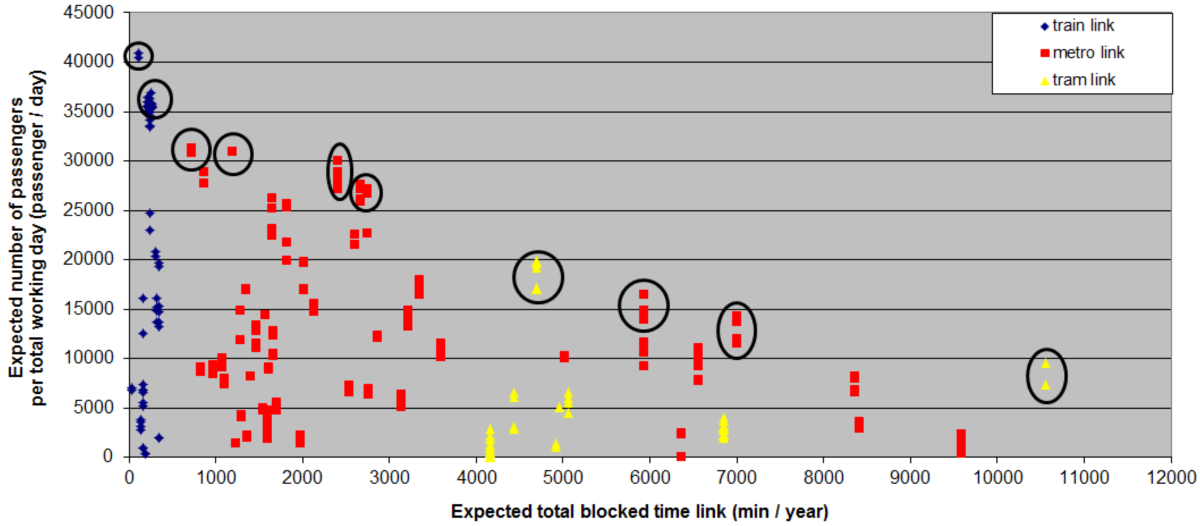

Figure 3.9: Vulnerability of links of the multi-level PT network of the case study area

Table 3.3: Overview of most vulnerable links of the multi-level PT network of the case study area between Rotterdam and The Hague

Link	Mode	Expected total blocked time (*10^3 min/year)	Expected number of passengers (*10^3 passengers/working day)
Schiedam – Rotterdam CS	Train	0.1	41
Rotterdam CS – Schiedam	Train	0.1	41
Delft – Delft Zuid	Train	0.3	35
Delft Zuid – Delft	Train	0.3	35
Delft Zuid – Schiedam	Train	0.3	36
Schiedam – Delft Zuid	Train	0.3	36
Rijswijk – Delft	Train	0.3	36
Delft - Rijswijk	Train	0.3	37
Beurs – Leuvehaven	Metro	0.3	31
Leuvehaven - Beurs	Metro	0.3	31
Leuvehaven – Wilhelminaplein	Metro	1.2	31
Wilhelminaplein - Leuvehaven	Metro	1.2	31
Blaak – Oostplein	Metro	2.4	29
Oostplein – Blaak	Metro	2.4	30
Oostplein – Gerdesiaweg	Metro	2.4	28
Gerdesiaweg – Oostplein	Metro	2.4	29
Gerdesiaweg – switches Gerdesiaweg/Voorschoterlaan	Metro	2.4	27
Switches Gerdesiaweg/Voor-schoterlaan – Gerdesiaweg	Metro	2.4	28
Switches Gerdesiaweg/Voor-schoterlaan – Voorschoterlaan	Metro	2.7	27
Voorschoterlaan - switches Gerdesiaweg/Voorschoterlaan	Metro	2.7	28
Voorschoterlaan – Kralingse Zoom	Metro	2.7	26
Kralingse Zoom – Voorschoterlaan	Metro	2.7	26
Rijnhaven – Maashaven	Metro	2.7	27
Maashaven – Rijnhaven	Metro	2.7	27
Brouwersgracht – Grote Markt	Tram	4.7	17
Grote Markt – Brouwersgracht	Tram	4.7	20
Grote Markt – Spui	Tram	4.7	17
Spui – Grote Markt	Tram	4.7	20
Spui – The Hague CS	Tram	4.7	17
The Hague CS - Spui	Tram	4.7	19
Rodenrijs – Meijersplein	Metro	5.9	14
Meijersplein - Rodenrijs	Metro	5.9	15
Meijersplein – Melanchtonweg	Metro	5.9	16
Melanchtonweg - Meijersplein	Metro	5.9	16
Laan van NOI – Voorburg ’t Loo	Metro / light rail	7.0	14
Voorburg ’t Loo – Laan van NOI	Metro / light rail	7.0	14
Voorburg ’t Loo – Leidschendam-Voorburg	Metro / light rail	7.0	12
Leidschendam-Voorburg – Voorburg ’t Loo	Metro / light rail	7.0	14
Leidschendam-Voorburg – Forepark	Metro / light rail	7.0	12
Forepark – Leidschendam-Voorburg	Metro / light rail	7.0	14
Ternoot – Laan van NOI	Tram	11	10
Laan van NOI - Ternoot	Tram	11	7.3

Step 4: Assess the number of alternative routes available in the multi-level PT network in case of a major discrete event occurring on a link

In this step is qualitatively assessed how many alternative routes are available in the multi-level PT network in case an event occurs on a link. Adjacent links which are identified as most vulnerable links in the multi-level PT network (see Table 3.3) are combined first, before the assessment takes place. As indicated, the number of available route alternatives differs per OD-pair. Therefore it is not possible to quantify the number of available route alternatives within a reasonable time without the use of advanced algorithms. A qualitative assessment of available route alternatives based on the available multi-level PT network is therefore performed. Table 3.4 shows the result.

Table 3.4: Qualitative assessment of available route alternatives

Link	Number of available route alternatives	Examples of available route alternatives
Schiedam – Rotterdam CS v.v.	Sufficient	RET metro lines ABC RET tram lines 21 and 24 RET bus line 38
Delft – Schiedam v.v.	Limited	Train / metro / tram / bus between Schiedam and Rotterdam; RET metro line E / RET bus line 40
Rijswijk – Delft v.v.	Medium	HTM tram line 1 Veolia bus line 130
Beurs – Wilhelminaplein v.v.	Sufficient	RET tram lines 20, 23 and 25
Blaak – switches Gerdesiaweg / Voorschoterlaan v.v.	Medium	RET tram lines 21 and 24 RET tram line 7
Switches Gerdesiaweg / Voorschoterlaan – Kralingse Zoom v.v.	Limited	-
Rijnhaven – Maashaven v.v.	Medium	RET tram lines 20/23/25 – 2 RET bus line 77
Brouwersgracht – The Hague CS v.v. (tram tunnel)	Limited	-
Rodenrijs – Melanchtonweg v.v.	Limited	-
Laan van NOI – Forepark v.v.	Limited	-
Ternoot – Laan van NOI v.v.	Sufficient	NS trains HTM tram line 2

Based on the qualitative assessment of available route alternatives in the multi-level PT network, the list of vulnerable links of Table 3.4 can be reduced further. Only links for which the number of available route alternatives is indicated as 'limited' are remaining in the last selection of most vulnerable links:

- Delft – Schiedam (train link segment);
- Switches Gerdesiaweg / Voorschoterlaan – Kralingse Zoom (metro link segment);
- Brouwersgracht – The Hague Central Station (tram link segment);
- Rodenrijs – Melanchtonweg (metro link segment);
- Laan van NOI – Forepark (metro/light rail link segment).

3.4 Conclusions

In this chapter a methodology is developed to identify the most vulnerable links of a multi-level PT network. Figure 3.10 summarizes the steps of this methodology, including the required input and resulting output.

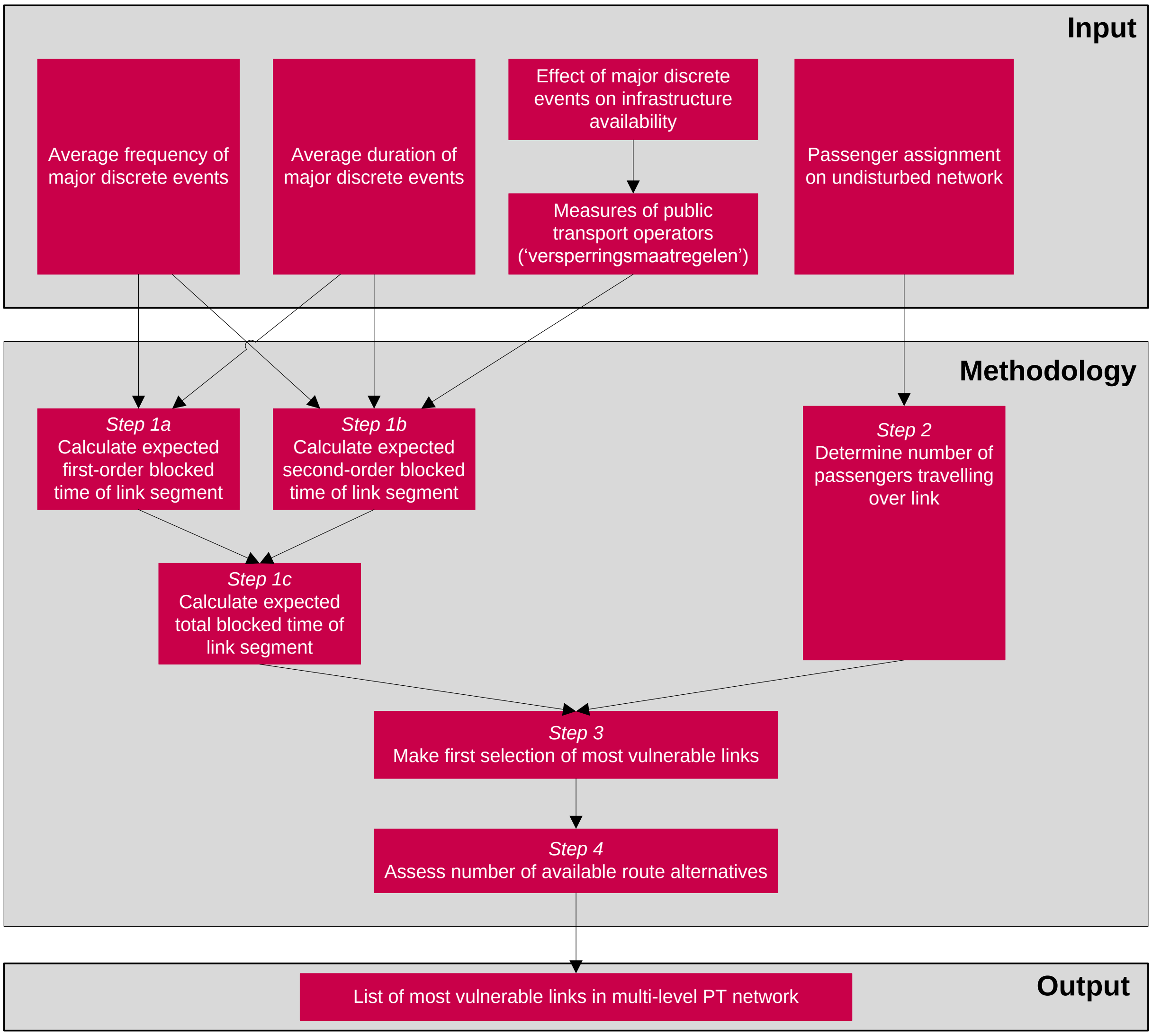

Figure 3.10: Schematic overview of developed methodology to identify vulnerable links in a multi-level PT network

The developed methodology is successfully applied to the multi-level case study network between Rotterdam and The Hague. As result, the next link segments in this case study network are identified as most vulnerable:

- Delft – Schiedam (train link segment);
- Switches Gerdesiaweg / Voorschoterlaan – Kralingse Zoom (metro link segment);
- Brouwersgracht – The Hague Central Station (tram tunnel The Hague) (tram link segment);
- Rodenrijs – Melanchtonweg (metro link segment);
- Laan van NOI – Forepark (metro/light rail link segment).

In a second step, after this methodology to identify vulnerable links is applied, major discrete events can be simulated on all these remaining link segments in order to determine the impact of a major discrete event exactly. However, the main goal of this study is to develop a *methodology* to evaluate the robustness of multi-level PT networks and measures proposed to improve the robustness. Given this strong methodological focus and given time constraints, in the remaining part of this study major discrete events are simulated only on two of the link segments which are indicated as most vulnerable:

- Brouwersgracht – The Hague Central Station (tram tunnel The Hague);
- Laan van NOI – Forepark.

In this study robustness measures are developed and evaluated for these two link segments only.

4

Robustness measures and effects on the multi-level PT network

In this chapter different robustness measures are developed, which aim to improve the robustness of the two vulnerable link segments of the case study multi-level public transport (PT) network which are identified in chapter 3.4. Chapter 4.1 discusses different types of robustness measures. It also shows the results of screening possible measure types for the two considered vulnerable link segments. In chapter 4.2 the measure 'detour of tram lines around tram tunnel The Hague' is discussed. Chapter 4.3 and chapter 4.4 discuss the measures 'extra intercity stop at Zoetermeer and The Hague Ypenburg' and 'extra switches near Leidschendam-Voorburg', respectively. In all these three chapters, first the robustness measure is described. Then, the effects of this measure on passenger streams in the multi-level PT network and the effects on comfort level are compared to the disturbed situation in which no measures are taken.

4.1 Types of robustness measures

Measured proposed to improve the robustness of road networks can be classified based on the element of robustness to which they relate most. Snelder (2010) distinguishes five different elements. First, there are measures focusing on the prevention of major discrete events. Second, there are measures which aim to improve the redundancy of the network by supplying route alternatives or back-up routes. Third, measures can reduce the extent to which the effects of a major discrete event spread over the network, indicated as compartmentalization. Fourth, measures can improve the resilience of the network, which means that the network, passenger or public transport operator (PTO) is able to respond faster to a disturbance. Fifth, measures can improve the flexibility of a network in case of major discrete events. Snelder (2010) gives several examples of robustness measures which can be applied on road networks on a strategic, tactical and operational level. In order to identify possible measures suitable to improve the robustness of multi-level PT networks, different measures as mentioned by Snelder (2010) are adapted. Table 4.1 shows an overview of possible measures which can be applied to improve the robustness of multi-level PT networks, classified to the robustness element which is influenced most by the measure. Note that this is not a complete overview of all possible types of measures: the measures used in this table must be considered as examples of measures in different categories.

Table 4.1: Examples of measures to improve robustness of multi-level PT networks

Robustness element	Possible robustness measures	Expected effect
Prevention	A1: Increase frequency of maintenance of rolling stock A2: More separated / own right of way on BTM network A3: Cut down trees near train and tram tracks A4: Separate train tracks physically from the environment (e.g. by using barriers)	Fewer vehicle breakdowns Fewer blockages because of incidents on road network Fewer blockages by trees during storing Fewer major incidents, suicides and blockages by trees during storm
Redundancy	B1: Increase capacity of a back-up route for a vulnerable link B2: Increase fleet redundancy B3: (Temporary) extend a certain transit line to form a route alternative for a vulnerable link B4: Increase the number of train tracks on a link	More capacity and higher comfort level on back-up route Higher frequency or more capacity on an alternative route during an event Additional route alternative during an event available Unbundling of train services; extra route alternative in case only 1 track is blocked
Compartmen-talization	C1: Construct switches, tail tracks or other turning facilities on a link segment	Lower second-order blocked time on a certain link segment
Resilience	D1: Improve incident management D2: Improve quality of travel information	Shorter duration of events Better use of available route alternatives
Flexibility	E1: (Temporary) increase the number of transfer possibilities at multi-level transfer points in the network E2: Realize a new emergency bypass which is available as route alternative during disturbances	More possibilities to use available route alternatives on a different network level PT services are less disrupted in case of an event

Based on literature and the results of the characterization of different major discrete event types (see chapter 2), a general screening of these types of measures can be performed.

Regarding measures focusing on prevention of events, measure types A1 and A4 seem most promising. This is because the frequency with which vehicle breakdowns occur per time period is the highest of all event types on all network levels (see chapter 2.2). Therefore, measures which reduce the frequency of vehicle breakdowns can have potential to reduce the total frequency of events substantially. Measure type A4 can be promising to apply on train networks because this measure can reduce the frequency of suicide events, which occur relatively often on train networks compared to other event types. Given the relatively low frequency of blockages, the effect of measure types A2 and A3 is expected to be more limited: reducing the frequency of blockages has a relatively small effect on the total reduction of events per time period.

When screening measures focusing on improving network redundancy, measure types B2 and B3 seem most promising. Given the fact that per time period relatively few major discrete events occur, results of Tahmasseby (2009) indicate that the benefits of large infrastructure design measures and structural service network design measures do not outweigh the additional costs during the undisturbed situation. This means that a structural increase in capacity (measure B1) and a structural increase in number of tracks per link (measure B4) are expected to be too expensive compared to the benefits. The cost-effectiveness of measure B4 can be doubted as well, because a substantial part of the major discrete event types leads to 0% infrastructure availability (see Figure 2.1 and chapter 2.4). When these event types occur, there are no benefits from having additional tracks on a certain link. Measure B2 can be promising because some redundancy in fleet size enables a flexible allocation of these additional vehicles to back-up routes in case of a disturbance on a certain location. Measure type B3 is – generally speaking – expected to be promising when the transit line extension is applied on a temporary base. In that case, sufficient (societal) benefits might be gained during disturbances to outweigh the additional costs of this extension. When this measure type would be applied in a structural way, it is expected that the extra costs during undisturbed PT operations are substantially larger than the (societal) benefits during disturbed operations.

Measure C1 might be promising in case substantial reductions in second-order blocked time can be realized. Since the costs for infrastructure construction are high, this type of measure is expected to be beneficial from a societal perspective only for long link segments. In that case, additional turning possibilities on this link segment might reduce second-order blocked time of a link segment substantially.
Both measure types D1 and D2 can have beneficial effects. Reducing event duration can especially be relevant for events on the train network, since the average duration of events on this network is relatively high compared to the average duration of events on the BTM network (see chapter 2.3). Improving travel information can be promising since the investment costs of this measure type are generally low.
For similar reasons as mentioned above, measure type E1 might be promising in case this measure has a temporal character. When the flexibility to transfer between different levels of the PT network is improved during disturbances only, the additional costs are expected to remain within limits. Measure type E2 is expected to be feasible only in case no major infrastructure constructions are required. Given the high costs of infrastructure construction, this measure type might be feasible only if the required infrastructure adjustments to realize an emergency bypass are limited.

Given the general conclusions regarding the feasibility of different types of robustness measures, it is analyzed whether the promising measure types can be applied to the two specific locations of the case study network: the link segment Brouwersgracht – Central Station and link segment Laan van NOI – Forepark. In general, it is very difficult to quantify the effects of prevention-focused measures like measure types A1 and A4. For example, it is difficult to estimate how much reduction in vehicle breakdowns can be realized in case a stricter maintenance policy would be applied. Also when incident management is improved, it is hard to quantify the effects on the duration of events. Therefore, these effects could be investigated by performing a what-if analysis. Since the two considered link segments in this study are tram and metro/light rail link segments, the effects of measure types A4 and D1 on reducing the frequency of suicide events and the duration of events are expected to be limited. In general, the effects of improving travel information (measure type D2) are very hard to quantify as well. Since in this study a barrier-free travelling is assumed during disturbances (see chapter 3.2), this measure type is not considered further.
For the link segment Laan van NOI – Forepark there is not another transit line which offers parallel services to a certain extent. Therefore, increasing capacity or extending a certain alternative transit line is not expected to be feasible for this specific link segment. For the link segment Brouwersgracht – Central Station, there are some bus lines (both urban and regional bus lines) which end at the Grote Markt in The Hague. In theory, it is possible to extend one or more of these lines to Central Station in case the tram tunnel is blocked. However, the capacity supplied by these bus lines together is very low compared to the original capacity supplied via the tram tunnel (at most 8 busses per hour per direction with a crush capacity of 90 passengers per bus can be supplied, compared to 36 tram services per hour per direction with a crush capacity between 189 and 432 passengers per vehicle). Therefore, the back-up function when extending these bus lines is expected to be very limited in this specific case and is not further considered.
Additional turning facilities (measure type C1) cannot be realized within a tunnel and is therefore not a feasible type of measure for the link segment Brouwersgracht – Central Station. For the link segment Laan van NOI – Forepark, this can however be a way to improve robustness given the relatively long length of this segment.
Especially the link segment Laan van NOI – Forepark is located between transit lines of different network levels. Therefore, measure type E1 – increasing the number of multi-level transfer possibilities – might be feasible to improve the robustness of this link segment. Measure type E2 – the realization of an emergency bypass – can be feasible for the link segment Brouwersgracht – Central Station, given the availability of other tram infrastructure in the surrounding of the tram tunnel. Because no metro/light rail infrastructure is available near the link Laan van NOI – Forepark, this measure type is not expected to be feasible here.
This means that measures developed to improve the robustness of the specific link segment Brouwersgracht – Central Station are expected to be most feasible when they focus on the realization of an emergency bypass for which limited infrastructure needs to be constructed. Measures developed for the specific link segment Laan van NOI – Forepark are expected to be most feasible when they focus on an increase in multi-level transfer

possibilities during disturbances or when they focus on the realization of additional turning facilities on this link segment.

4.2 Detour of tram lines around tram tunnel The Hague

4.2.1 Description of measure

The measure 'detour of tram lines around the tram tunnel of The Hague' is developed in order to improve the robustness of the link segment between the tram stop Brouwersgracht and tram stop The Hague Central Station. These stops are connected by a tram tunnel, which is built underneath the city centre of The Hague (further in this chapter indicated as 'TTGM' ('tram tunnel Grote Markt'). In this tram tunnel, there are two tram stops Grote Markt and Spui (see Figure 4.1 left). No switches are located in this tunnel. On this line segment between Brouwersgracht and Central Station, tram serviced are operated with a very high frequency. In total, four different lines are operated via the TTGM. Two of these lines are urban tram lines (line 2 and 6), whereas the other two lines are part of the RandstadRail light rail network (line 3 and 4). During peak hours, short services of these lines 3 and 4 (indicated as line 3K and 4K) are also operated in addition to the regular services. Both the light rail lines and urban tram line 2 are operated by a bi-directional vehicle type having a width of 2.65m (a so called Regio Citadis: see appendix B3), whereas the other urban tram line 6 is operated by an older one-directional urban tram type having a width of 2.35m (a so called GTL-8). During peak hours the total frequency of services via the TTGM equals 36 vehicles per hour per direction, indicating that many passengers are affected in case a disturbance occurs somewhere in the tunnel.

In the current situation, in case a major discrete event occurs somewhere in the TTGM all tram services via the TTGM in both directions are cancelled. This is regardless the type of major discrete event and regardless the effect a major discrete event has on infrastructure availability. In case of both 50% and 0% infrastructure availability because of an event, tram services in both directions via the TTGM are cancelled. Table 4.2 shows the measures taken by the HTM as PTO in the current situation, in case a major discrete event occurs in the tram tunnel. As can be seen, the three PT lines operated by bi-directional vehicles are split in two parts. On one side these lines turn near the tram stop Brouwersgracht, using the switches located over there. On the side of Central Station, these lines turn near Central Station using the long tail track over there. During peak hours the short services of line 3K between Loosduinen and Central Station and short services of line 4K between Monstersestraat and Central Station are cancelled, because of the limited capacity of the switches near the Brouwersgracht. The trams used for the operation of tram line 6 cannot use the switches and tail track near the Brouwersgracht and Central Station, because these are one-directional trams. However, an emergency track is available on the side of the Brouwersgracht. This bypass connects the Brouwersgracht to the city centre and Central Station via ground level, thereby bypassing the tram tunnel. Therefore, the route of tram line 6 is also divided in two parts. One part of the line is detoured from the Brouwersgracht via the Prinsegracht, Jan Hendrikstraat, Gravenstraat and city centre to Central Station, where this line turns via the city centre back to the Brouwersgracht and Leyenburg. The other part of the line is shortened to the stop Stuyvesantplein, and then rerouted to train station The Hague Laan van NOI where a turning loop for one-directional trams is available. This means that this part of the line is not connected to Central Station anymore. The bypass used by tram line 6 between the Brouwersgracht and Central Station can currently only be used by the smaller GTL-8 trams, since the wider Regio Citadis vehicles cannot pass each other at some parts of this emergency route.

Figure 4.1 (right) shows how the PT network is currently adjusted when an event occurs in the TTGM. A clear disadvantage of the current measures in case of an event is that all lines are divided in two parts. This leads to additional transfers for many passengers. Additionally, 3 out of 4 tram lines do not offer a direct connection between the south-western part of The Hague and the city centre and Central Station anymore. Given the large number of passengers travelling from/to the city centre or Central Station, many passengers have to make a detour and/or additional transfer to reach their destination.

Table 4.2: Overview of adjusted PT services in case of a major discrete event in the TTGM when no measures are taken

PT tram line	Frequency peak (veh/hr/direction)	Disturbed situation
Line 2 Kraayenstein – Leidschendam Leidsenhage	6	Line 2a: Kraayenstein – Brouwersgracht Line 2b: Central Station – Leidschendam Leidsenhage
Line 3 Loosduinen – Zoetermeer Centrum West	6	Line 3a: Loosduinen – Brouwersgracht Line 3b: Central Station – Zoetermeer Centrum West
Line 3k Sav. Lohmanplein – Central Station	6	Cancelled
Line 4 De Uithof – Zoetermeer Javalaan	6	Line 4a: De Uithof – Brouwersgracht Line 4b: Central Station – Zoetermeer Javalaan
Line 4k Monstersestraat – Zoetermeer Javalaan	6	Line 4k: Central Station – Zoetemeer Javalaan
Line 6 Leyenburg – Leidschendam Noord	6	Line 6a: Leyenburg – city centre – Central Station Line 6b: Laan van NOI – Leidschendam Noord

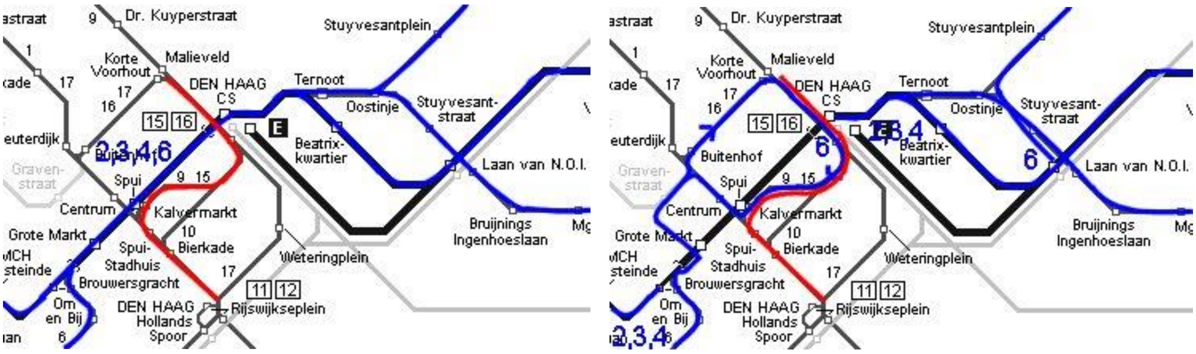

Figure 4.1: Overview of routes of tram lines 2, 3, 4 and 6 in case of no disturbance (left) and in case of a disturbance in the current situation when no measures are taken (right). The red line shows a part of the route of tram lines 9, 15 and 16, which can remain unchanged because of an event in the TTGM (Urbanrail.net, 2014)

In The Hague, there is infrastructure available to connect both sides of the tram tunnel via ground level. Tracks via the Prinsegracht, Jan Hendrikstraat, Gravenstraat, Hofweg and Kalvermarkt and first-floor level of Central Station are already constructed. This shows that there is potential to use these tracks as detour route for tram lines 2, 3, 4 and 6 in case of a major discrete event in the TTGM, since then these lines do not have to be split. This means that passengers will experience a slightly longer in-vehicle time, but that in general most people do not have to make an additional transfer to reach their destination. However, currently this detour route cannot be used directly for two reasons:

- The tracks located in the Jan Hendrikstraat and located on a part of the Buitenhof are located that close to each other, that only the smaller one-directional trams of line 6 can pass each other. The wider bi-directional trams of tram lines 2, 3 and 4 cannot pass each other, since there is overlap in the clearance profile of those trams in both directions.
- The tram connection between the Kalvermarkt and first-floor level of Central Station is physically available, but there is no working signalling system available. Since the location where this connection intersects with the trams driving via the Kalvermarkt and Lage Zand is in a tunnel, this intersection needs to be protected by a signalling system. Because the current system is not in operation anymore, this means that the tram lines currently driving on the Kalvermarkt (tram lines 9, 15 and 16: see Figure 4.1) cannot use the Kalvermarkt together with the diverted trams of lines 2, 3, 4 and 6. This means that – in case of a major discrete event where tram lines 2, 3, 4 and 6 would be diverted over the Kalvermarkt – the route of tram lines 9, 15 and 16 has to be slightly diverted via the Schedeldoekshaven, thereby skipping the tram stop Kalvermarkt-Stadhuis (see Figure 4.4).

In order to allow all four tram lines to use this bypass, it should be guaranteed that no collisions between the wider tram types of line 2, 3 and 4 can occur in the Jan Hendrikstraat and on the Buitenhof. A structural solution for this would be a replacement and reconstruction of the tram tracks. However, since these tracks are only used in case of a disturbance, this is expected to be very expensive compared to the benefits which are realized only during disturbances. Therefore, in this study the design and construction of a signalling system is proposed which checks whether a tram can enter the small part of the Jan Hendrikstraat and Buitenhof. In fact, this means that those two parts of the detour route are operated as single-track. The aspects of this robustness measure can be summarized as follows:

- Design, construction and maintenance of a signalling system (including detection loops) on the Jan Hendrikstraat for a length of 250 meter. Because of the length of 250 meter and the slight curve in the Jan Hendrikstraat (see Figure 4.2), protection by a signalling system is required instead of visual inspection by the driver.
- Design and construction of a signalling system (including detection loops) on the curved part of the Buitenhof for a length of 130 meter. Because of the S-curve on the Buitenhof (see Figure 4.3), it is not sufficient to rely on visual inspection by the tram driver only.
- Rerouting tram lines 9, 15 and 16 via the Schedeldoekshaven, thereby skipping the stop Kalvermarkt-Stadhuis, only in case tram lines 2, 3, 4 and 6 are diverted via the Kalvermarkt to Central Station (see Figure 4.4).

Table 4.3 shows the adapted PT network in case of a major discrete event in the tram tunnel in case this robustness measure is applied. Figure 4.4 shows geographically how the PT services are adjusted in case of an event when this measure would be applied. On the two parts of the detour route where most trams cannot pass each other, the capacity of the track is lower than normal because trams in both directions have to wait for each other. To prevent queuing of trams during peak hours given the high total frequency of these lines, the peak hour lines 3k and 4k in the south-western part of The Hague are coupled to each other. At the Monstersestraat, passengers of these lines can transfer to the rerouted tram lines 2 and 4 which go to the city centre and Central Station. Peak hour tram line 4k on the Zoetermeer side is shortened to station Laan van NOI to prevent queuing at Central Station. At Laan van NOI, switches are available which allow the turning of bi-directional light rail vehicles.

Figure 4.2: Overview of Jan Hendrikstraat in The Hague (note that there is no physical single-track operation in reality, but only a functional single-track operation)

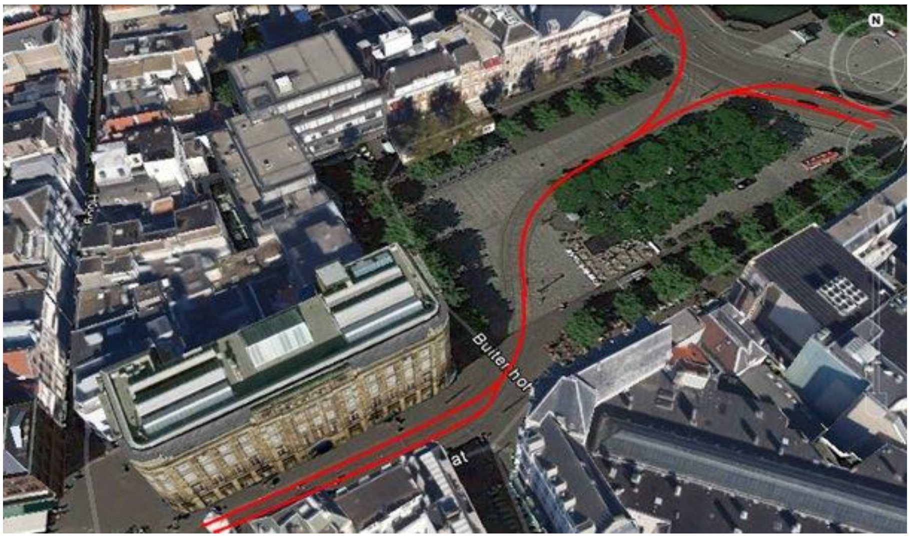

Figure 4.3: **Overview of S-curved tram track on the Buitenhof in The Hague (note that there is no physical single-track operation in reality, but only a functional single-track operation)**

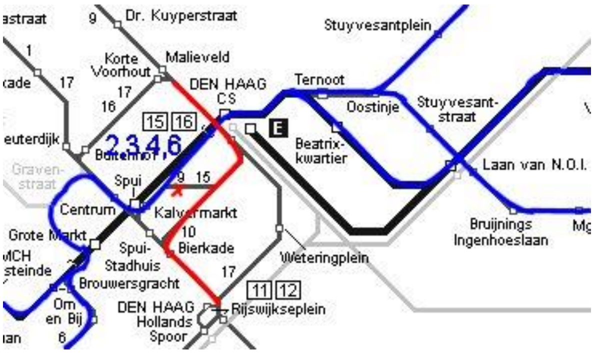

Figure 4.4: Overview of routes of tram lines 2, 3, 4 and 6 in case of a disturbance when tram lines are diverted. The red line shows a part of the route of tram lines 9, 15 and 16, which is diverted via the Schedeldoekshaven instead of the Kalvermarkt because of an event in the TTGM (Urbanrail.net, 2014)

Table 4.3: Overview of adjusted PT services in case of a major discrete event in the TTGM when all tram lines are diverted around the tram tunnel

PT line	Frequency peak (veh/hr/direction)	Disturbed situation
Line 2 Kraayenstein – Leidschendam Leidsenhage	6	Line 2: Kraayenstein – Brouwersgracht – city centre – Central Station – Leidschendam Leidsenhage
Line 3 Loosduinen – Zoetermeer Centrum West	6	Line 3: Loosduinen – Brouwersgracht – city centre – Central Station – Zoetermeer Centrum West
Line 3k Sav. Lohmanplein – Central Station	6	Line 3k: Sav Lohmanplein - Monstersestraat
Line 4 De Uithof – Zoetermeer Javalaan	6	Line 4: De Uithof – Brouwersgracht – city centre – Central Station – Zoetermeer Javalaan
Line 4k Monstersestraat – Zoetermeer Javalaan	6	Line 4ka: Monstersestraat – Sav. Lohmanplein Line 4kb: Laan van NOI – Zoetermeer Javalaan
Line 6 Leyenburg – Leidschendam Noord	6	Line 6: Leyenburg – Brouwersgracht – city centre – Central Station – Leidschendam Noord

Compared to the undisturbed situation, the effect of the diverted tram lines via the city centre on ground level on travel time is as follows:

- The bypass of the TTGM leads to 2 minutes additional driving time;

- Because of the functional single-track operation some waiting time before a single-track can be expected as well. In case each single-track part of the route is modelled as an M/M/1 queuing system, the average waiting time can be calculated. For the Jan Hendrikstraat, the arrival rate λ equals 48 trams per hour (for both directions together), whereas the service rate μ is set equal to 60 trams per hour (the service time is calculated by dividing the single-track length of 250m by the average speed of trams in The Hague of 19 km/h, rounded up to 60 seconds to correct for the influence of the signalized intersection Prinsegracht / Jan Hendrikstraat) (Gemeente Den Haag, 2013). For the single-track at the Buitenhof, λ equals 64 trams per hour during peak hours and 60 trams per hour in the remainder of the day. This is because this part of the route is shared with tram line 17. Based on the calculated service time of 30 seconds, μ equals 120 trams per hour. The average waiting time in queue w_q when this system is modelled as a M/M/1 system can be calculated by using formula (4.1):

$$w_q = \frac{\lambda}{\mu(\mu-\lambda)} \qquad (4.1)$$

  This means that the average waiting time equals 4 minutes for the Jan Hendrikstraat, and 37 seconds and 30 seconds for the Buitenhof during peak hours and non-peak hours, respectively. This waiting time is added to the additional driving time required for this detour route. This leads to a total additional time of 427 sec and 420 sec during peak and non-peak hours for this detour route.

For the calculation of waiting time, random arrival and service patterns are assumed in this study. Also, service on a first-come-first-served base is assumed. It is likely that waiting time can be reduced slightly in case a smarter service discipline is used. If for example all vehicles waiting on one side of the single-track are served simultaneously first before all vehicles waiting on the other side are served simultaneously, total waiting times can be reduced. Because more space is physically available for possible queuing at the side of the Prinsegracht, serving vehicles coming from the Kerkplein side with priority can be an option.

4.2.2 Effect on passenger streams

Method

It is analyzed what the effect is of a disturbance on the distribution of passenger streams over the multi-level PT network. In the used model, it is not possible to construct the exact route choice distribution for each OD-pair of the model within reasonable time. Therefore, the next procedure is used to determine the effects of an event on route choice:

- First, the total number of passengers which are affected by a major discrete event on a certain link segment is calculated. This number can be calculated by summing the passengers of all OD-pairs which are affected by the event. Figure 4.5 illustrates this calculation. B, C, and D represent PT stops which are connected by links BC and CD. Block A represents all PT stops which function as origin on the left hand side of PT stop B, whereas block E represents all PT stops functioning as destination on the right hand side of PT stop D. Only passenger flows from left to right are considered in this example, because this calculation should be done for each direction separately.

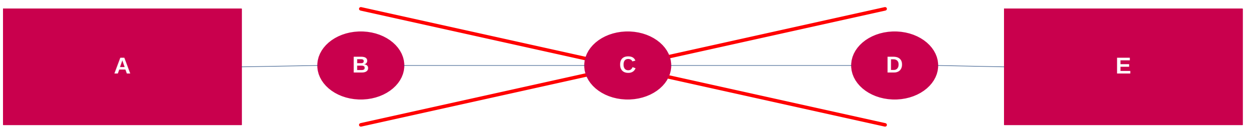

Figure 4.5: Schematic overview of major discrete event on link segment BC-CD

  In case the link segment BC-CD in the direction from A to E is blocked because of an event, the following OD-pairs are affected: AC, AD, AE, BC, BD, BE, CD and CE. The OD-pairs AB and DE are not affected by this event (if PT services remain unchanged between A and B and between D and E). When summing the flows on link BC and CD together, there is a risk on double counts. Therefore, to capture all passengers of the indicated OD-pairs without double counts, the following aspects should be summed:

- Link flow BC (from B to C only): this value captures the passengers on OD-pairs AC, AD, AE, BC, BD and BE;
- Number of boardings at stop C: this value captures the passengers on OD-pairs CD and CE.

By applying this method, the total number of affected passengers $D_{affected}$ can be determined without double counts. Given this example, this approach can be generalized using formula (4.2) given a major discrete event between PT stops s_1 and s_n:

$$D_{affected} = q_{s_1 s_2} + \sum_{s_2}^{s_{n-1}} b_s \qquad (4.2)$$

With parameters:		
	$D_{affected}$	$number\ of\ passengers\ affected\ by\ event$
	$q_{s_n s_{n+1}}$	$passenger\ flow\ on\ link\ s_n s_{n+1}$
	b_s	$number\ of\ boardings\ at\ stop\ s$

- Second, it is tried to identify which route alternatives might be used by these affected passengers. Therefore, based on the PT services supplied on the multi-level PT network after the occurrence of an event, a selection of feasible route alternatives $R_1 \dots R_n$ is made manually with each route alternative R_i consisting of links $i_{R_i,1}, i_{R_i,2} \dots i_{R_i,n}$.
- Third, to identify which percentage of the affected passengers are using each identified route alternative, for each route alternative R_i a link $i \in R_i \cap i \notin R_{j \dots n}$ is selected which is only part of one of the feasible route alternatives (if possible).
- Fourth, for each of these selected links the number of passengers q_i is compared between the undisturbed situation u and the disturbed situation d. If $q_{i,d} - q_{i,u} > 0$, then R_i functions as route alternative for $\left(\frac{q_{i,d} - q_{i,u}}{D_{affected}}\right) * 100$ percent of the passengers which are affected by the major discrete event.
- Fifth, based on the differences in number of passengers on each of the selected links it is aimed to reconstruct the route alternatives chosen by the affected passengers. To find the route alternatives used by all affected passengers, the sum of the passenger increase $\sum_{i=1}^{n}(q_{i,d} - q_{i,u})$ on all selected links i should be equal to the total number of affected passengers $D_{affected}$. In general it is not possible to reconstruct the route alternatives of all affected passengers exactly, since some passengers might use unexpected route alternatives given their specific OD-combination. In this analysis it is aimed to reconstruct the most important route alternatives in case of a disturbance. Route alternatives R_i with $\frac{q_{i,d} - q_{i,u}}{D_{affected}} < 0.01$ are not considered.

Results

The second column of Table 4.4 and Figure 4.6 illustrate the effect of an event on passenger streams in the current situation when no measures are taken. The third column of Table 4.4 and Figure 4.7 show similar results in case the detour measure is applied. As can be seen, after the applied measure most passengers keep using the diverted tram lines 2, 3, 4 and 6 via the city centre. 81% of all passengers affected by the major discrete event keep using these lines, compared to only 44% of the passengers which use the diverted tram line 6 in the situation when no measures are taken. In general, it can be concluded that in case this measure is implemented, fewer other route alternatives are chosen by passengers. For example, fewer passengers start or end their PT trip at Central Station instead of the original stop, fewer passengers use tram line 6 between Leyenburg and the city centre or tram line 17 between the Waldeck Pyrmontkade and the city centre. In general, this measure leads to more concentration of passenger streams via the diverted tram lines 2, 3, 4 and

6. This indicates that less additional transfers have to be made compared to the disturbed situation when no measures are applied, which reduces the negative effect of an event.

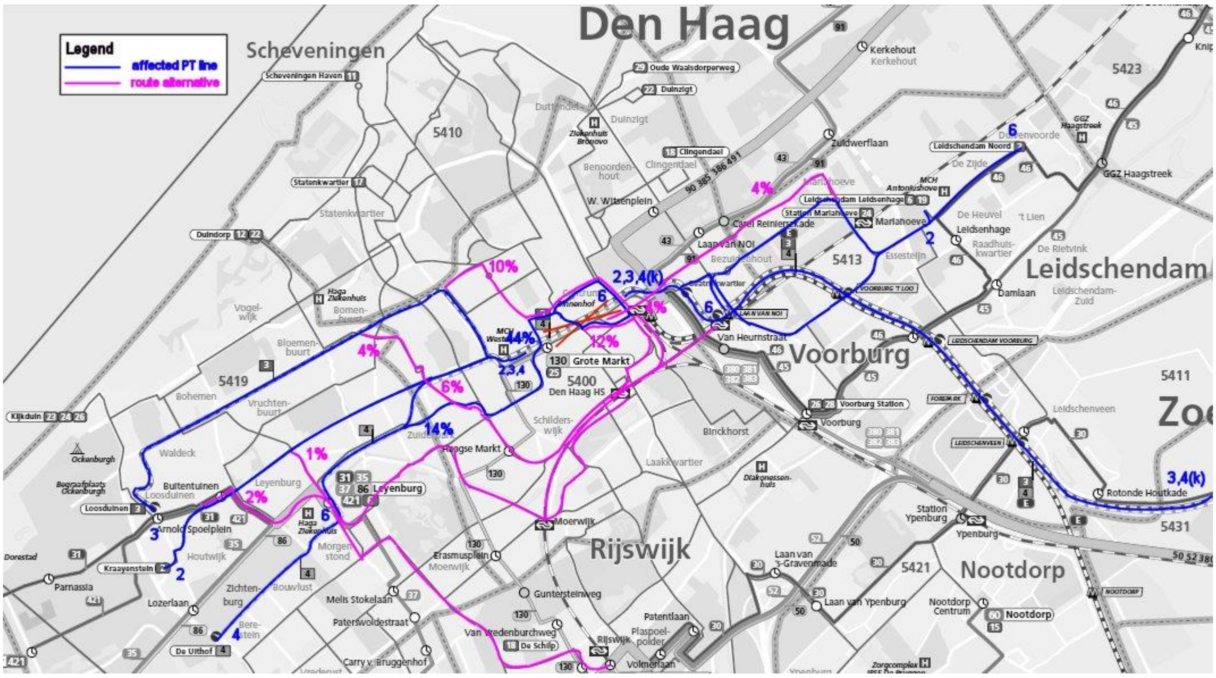

Figure 4.6: Overview of route alternatives chosen by passengers affected by a major discrete event in the TTGM – no measures taken

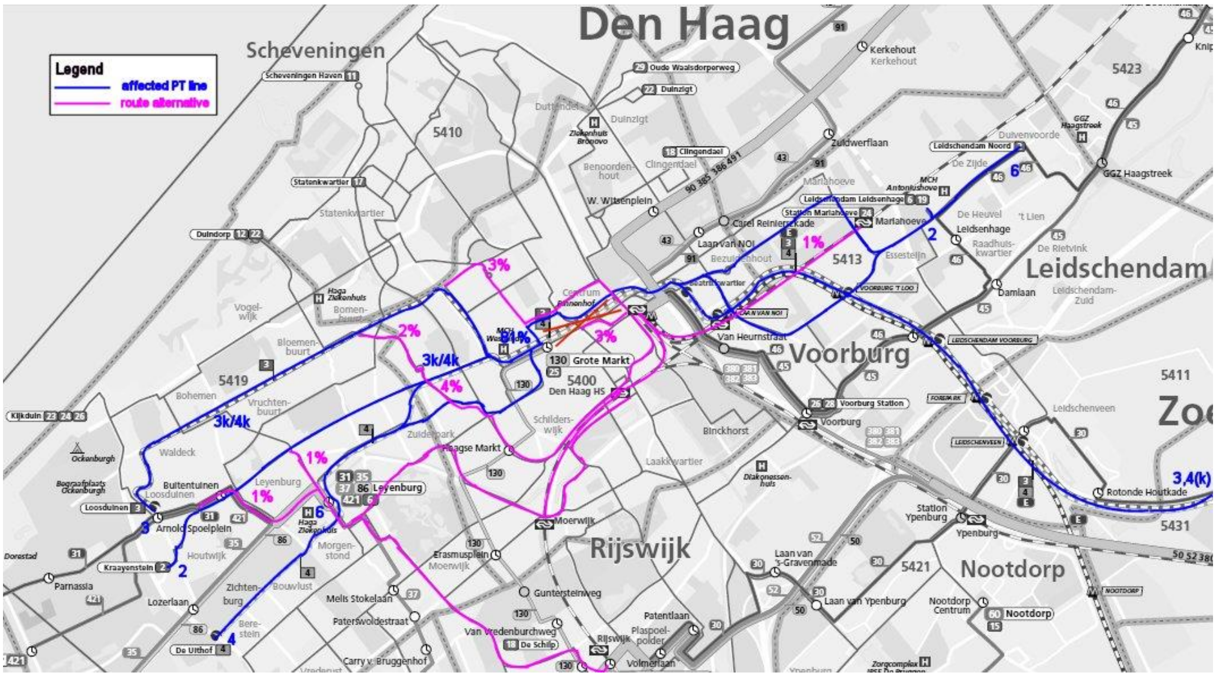

Figure 4.7: Overview of route alternatives chosen by passengers affected by a major discrete event in the TTGM – diverted tram lines 2 / 3 / 4 / 6 around the tram tunnel

Table 4.4: Route alternatives chosen by a percentage of all passengers affected by a major discrete event in the TTGM when no measures are taken (2nd column) and after the detour measure is applied (3rd column)

Route alternative	No measure	Detour measure
Diverted tram line 6 / 2+3+4+6 through city centre	44%	81%
Tram line 6 Leyenburg - city centre	14%	-
Other tram / bus lines on ground level Central Station - Kalvermarkt-Stadhuis	12%	3%
Tram line 17 Waldeck Pyrmontkade - city centre / Central Station	10%	3%
Boarding / alighting PT trip at Central Station instead of affected stop	4%	-
Tram line 12 Goudenregenstraat - city centre	4%	2%
Tram line 12 Loosduinseweg - city centre	2%	2%
Bus line 24 Mariahoeve - Central Station / city centre	2%	-
Bus line 26 Burg. Hovylaan - station The Hague Moerwijk / The Hague HS	2%	1%
Bus line 23 Volendamlaan - station Rijswijk	1%	1%
Station The Hague Mariahoeve - The Hague Central Station	-	1%

4.2.3 Effect on I/C ratio

It is expected that especially on route alternatives which are selected by a relatively large percentage of affected passengers also the load factor (also indicated as intensity/capacity (I/C) ratio) can increase substantially. Figure 4.8 shows the calculated I/C ratio during the evening peak. For each link, the number of passengers travelling on that link is taken as ratio to the total supplied PT capacity. In fact, the I/C ratio indicates the average load factor on each link. In case al seats are taken, this load factor equals 1. It should be mentioned that this I/C ratio or load factor is shown per link. In case different PT lines are operated on that link, it is possible that there are individual differences in I/C ratio between different lines. The values shown in Figure 4.8 should therefore be interpreted as average values for a certain link.

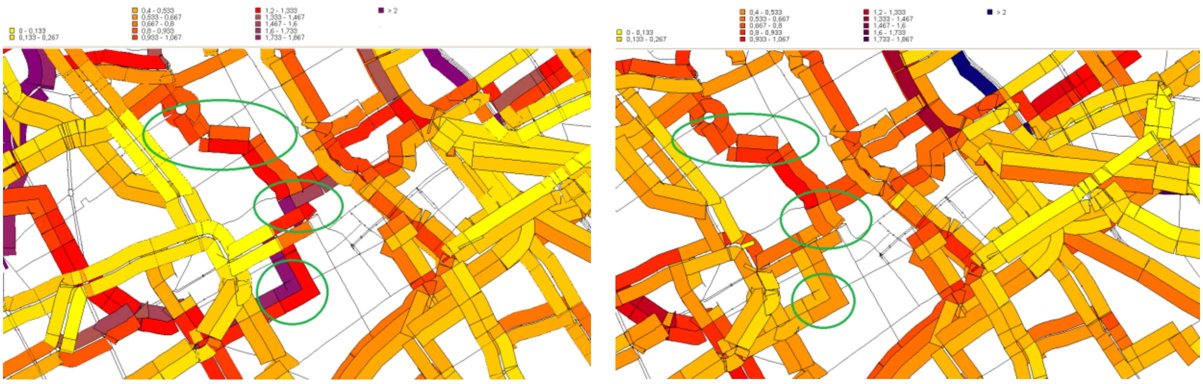

Figure 4.8: I/C ratio during evening peak in case of major discrete event on link segment Brouwersgracht – Central Station when no measures are taken (left) and when the detour measure is applied (right)

Table 4.5 shows the range of I/C ratios found during the evening peak on the links of route alternatives which are chosen relatively often by passengers who are affected by the event. These links are also indicated in Figure 4.8 by the green circles. From Table 4.5 and Figure 4.8 can be concluded that crowding effects occur when no measures are taken. Especially on the links of tram line 6 between Kerkplein, Prinsegracht, Brouwersgracht and Vaillantlaan, load factors are high, up to almost 2.0. Also on the links of tram line 17 between the Waldeck Pyrmontkade and Kerkplein load factors increase, because this route is used by 10% of all affected passengers when no measures are taken.

When the detour measure is applied, it can clearly be seen that I/C values are reduced. On all considered links, the I/C ratio drops. Especially on PT lines between Kerkplein and Vaillant a large drop in I/C ratio is observed. This can be explained because in de detour measure all four tram lines 2, 3, 4 and 6 use the bypass via the Jan

Hendrikstraat. Although the fraction of the total number of affected passengers which use this bypass increases, the I/C ratio drops because of the larger increase in supplied capacity (4 tram lines instead of 1 tram line). Also for tram line 17 I/C values are somewhat reduced, because a lower fraction of all passengers affected by the disturbance uses this route as alternative.

Table 4.5: Overview of I/C ratios during evening peak on selected links in case of event in TTGM

Link	Range I/C ratios – No measure	Range I/C ratios – Detour measure
Vaillantlaan – Brouwersgracht (tram line 6)	1.2 – 1.3	0.5 – 0.7
Brouwersgracht – Vaillantlaan (tram line 6)	1.7 – 1.9	0.4 – 0.5
Prinsegracht – Kerkplein (diverted tram line 6)	1.2 – 1.3	0.5 – 0.7
Kerkplein – Prinsegracht (diverted tram line 6)	1.7 – 1.9	0.7 – 0.8
Van Speykstraat – Kerkplein (tram line 17)	0.9 – 1.3	0.7 – 1.1
Kerkplein – Van Speykstraat (tram line 17)	0.8 – 0.9	0.7 – 0.8

4.3 Temporary extra intercity stops at Zoetermeer and The Hague Ypenburg

4.3.1 Description of measure

This measure aims to improve the robustness of the metro / light rail link segment between station The Hague Laan van NOI and Forepark by increasing flexibility in case of an event, by improving transfers between different network levels. In case of a major discrete event on this track, all PT services are cancelled currently, regardless the type of event or the impact of an event on link availability. However, the metro / light rail services between Laan van NOI and Forepark form an important connection between the area of Zoetermeer / Rotterdam / Pijnacker and The Hague. In case of a major discrete event, this means that this connection is not available anymore for passengers. Table 4.6 shows how the PT services are adjusted in case a major discrete event occurs in the current situation, when no measures are taken. Tram services of line 3a, 4a and 4ka use the turning facility near station Laan van NOI on ground level. This means that these tram services are diverted from Ternoot via the route of tram line 2 to Laan van NOI, instead of using their own tracks to the first-floor level of Laan van NOI.

Table 4.6: Overview of adjusted PT services in case of a major discrete event on the link segment Laan van NOI – Forepark – no measure taken

PT line	Frequency peak (veh/hr/direction)	Disturbed situation
Line 3 Loosduinen – Zoetermeer Centrum West	6	Line 3a: Loosduinen – Laan van NOI Line 3b: Forepark – Zoetermeer Centrum West
Line 3k Sav. Lohmanplein – Central Station	6	Unaffected
Line 4 De Uithof – Zoetermeer Javalaan	6	Line 4a: De Uithof – Laan van NOI Line 4b: Forepark – Zoetermeer Javalaan
Line 4k Monstersestraat – Zoetermeer Javalaan	6	Line 4ka: Monstersestraat – Laan van NOI Line 4kb: Forepark – Zoetemeer Javalaan
Metro line E The Hague Central Station - Slinge	6	Line E: Forepark - Slinge

The proposed measure aims to improve the attractiveness of a parallel route alternative in case of a major discrete event on this link segment. Currently, there are 8 train services per hour per direction operated between Zoetermeer and The Hague. Four of these services are intercity trains which do not stop between Gouda and The Hague. The other four Sprinter services stop at the stations Zoetermeer Oost, Zoetermeer, The

Hague Ypenburg and Voorburg, before reaching The Hague Central Station. This network design measure proposes to add the stations Zoetermeer and The Hague Ypenburg as additional stops for the four intercity services, *only* in case of a disturbance on the track between Laan van NOI and Forepark. By applying this measure, the attractiveness of the train network between Zoetermeer and The Hague as back-up route alternative for the light rail track Laan van NOI – Forepark is improved. The train station Zoetermeer can be reached directly from RandstadRail line 3. Train station The Hague Ypenburg can be reached from the light rail stop Leidschenveen after transferring to tram line 19 or bus line 30 to station Ypenburg.
This measure can be classified as a temporary service network design measure. In case no major discrete event occurs on the link segment Laan van NOI – Forepark, intercity services do not stop between Gouda and The Hague. The additional stops are only made in case of a disturbance on this metro/light rail link segment, since only then the (societal) benefits are expected to outweigh the costs. This means that the travel time for through passengers in these intercity services slightly increases during a disturbance. On the other hand, the frequency of the parallel route alternative between Zoetermeer / The Hague Ypenburg and The Hague is doubled from 4 to 8 trains per hour per direction. This reduces the transfer waiting time. Therefore, it is expected that the attractiveness of this relatively short route alternative is improved.
The additional travel time for intercity services because of the extra stops is assumed to be 5 minutes for each direction. The travel time of the sprinter train service is used as starting point, which would imply 260 seconds additional travel time according to the OmniTRANS model used. This value is rounded up to 5 minutes, given the lower acceleration rate of intercity trains. Although a frequency-based assignment is performed (see chapter 3.2.2), it is checked whether this additional running time of 5 minutes can be inserted in a conflict free way in the current timetable (NS, 2013a). In the direction of The Hague, all intercity services have The Hague Central as final destination. Here, sufficient turnaround time is available to prevent knock-on delays to the next trip. In the other direction towards Enschede / Amersfoort / Utrecht, sufficient turnaround time is also available if the delay cannot be compensated by using available running time supplements during the trip. In both directions, the scheduled buffer time between an intercity service and the next train after the two additional stops are made is at least 7 minutes. This implies that a delay of 5 minutes is not expected to cause knock-on delays to other trains, assuming that other train services operate according to schedule.

4.3.2 Effect on passenger streams

The second column of Table 4.10 (p.80) and Figure 4.9 show the route alternatives chosen by passengers which are affected by the disturbance in case no measures are taken. The third column of Table 4.8 and Figure 4.10 show similar results for the situation in case additional IC stops are temporarily added to the train services between Gouda and The Hague.
It can be concluded that the train connection between Zoetermeer / The Hague Ypenburg and The Hague indeed becomes considerably more attractive as route alternative because of the higher frequency supplied by train services at Zoetermeer and The Hague Ypenburg. After the measure is applied 43% of all affected passengers use this connection as route alternative, compared to 24% in case of a disturbance when no measures are taken. Regarding the other route alternatives in the multi-level PT network used by affected passengers, the differences between the situation without measures and the situation when applying this measure are limited. In both situations, the train connection between Rotterdam and The Hague is quite often used as alternative, as well as the bus connection between Zoetermeer and Leiden. Besides, in both situation 7% of the affected passengers use tram line 19 as alternative connection between Leidschenveen and Leidsenhage, where can be transferred to tram line 2 going to the stations Voorburg ‘t Loo, Laan van NOI and The Hague Central Station. Between Laan van NOI and Voorburg ‘t Loo, tram line 2 functions as back-up network for the blocked light rail/metro line for 6-7% of the passengers. In both the situation without taking any measure and the situation when applying this measure, a small fraction of the affected travellers use different regional and urban bus lines as route alternative in the multi-level network to reach their destination.

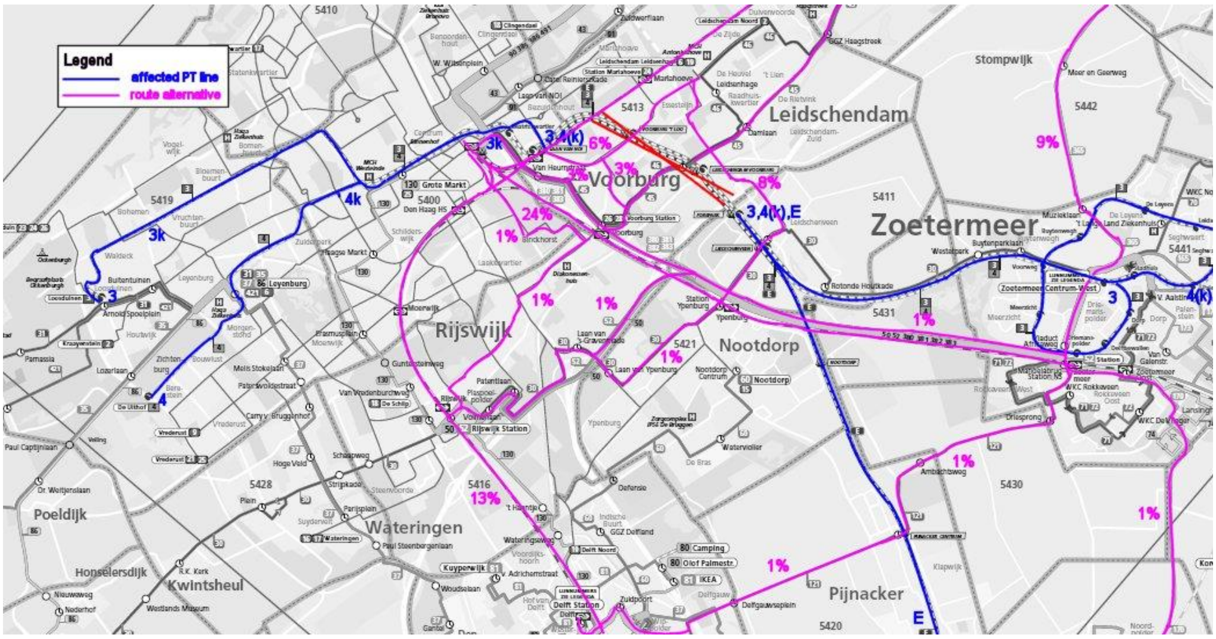

Figure 4.9: Overview of route alternatives chosen by passengers affected by a major discrete event between Laan van NOI and Forepark – no measures taken

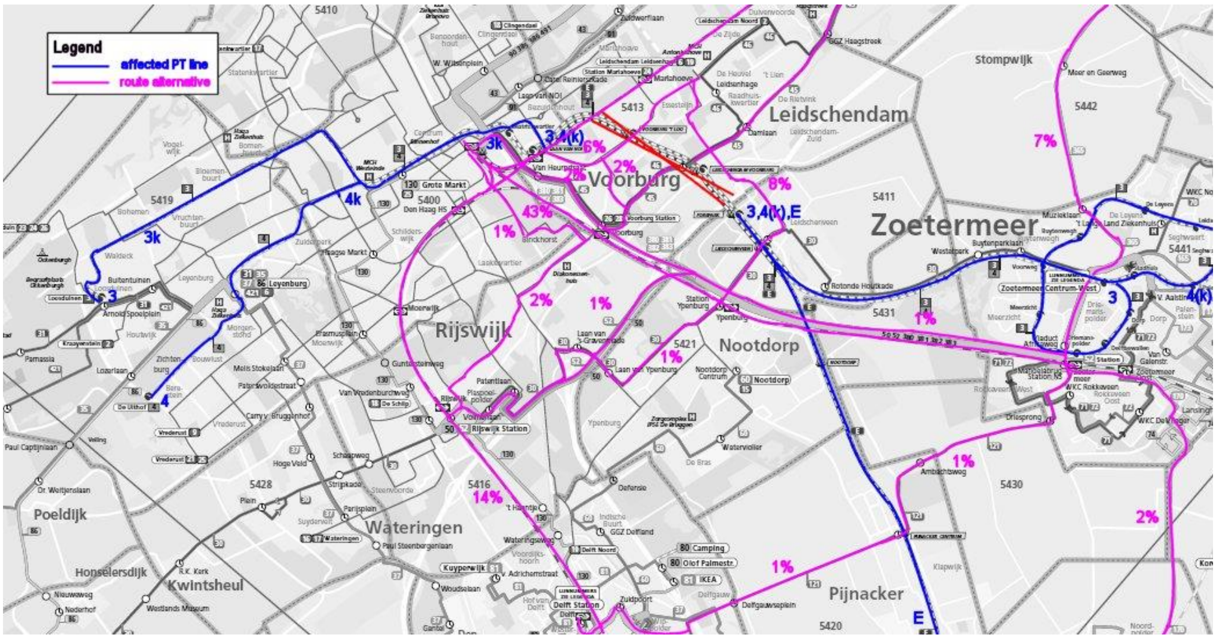

Figure 4.10: Overview of route alternatives chosen by passengers affected by a major discrete event between Laan van NOI and Forepark – extra temporary IC stops Zoetermeer and The Hague Ypenburg

4.3.3 Effect on I/C ratio

The most important effect of the measure of temporarily adding Zoetermeer and The Hague Ypenburg as intercity station is a shift of passengers towards the train link Zoetermeer / The Hague Ypenburg – The Hague in case the light rail / metro track Laan van NOI – Forepark is blocked. A possible disadvantage of this measure is that this sudden increase of passengers travelling by train between Zoetermeer / Ypenburg and The Hague can decrease the comfort level on this track, because the load factor increases. Therefore, for the train links The Hague Central Station – Voorburg, Voorburg – The Hague Ypenburg and The Hague Ypenburg – Zoetermeer (indicated by the green arrows in Figure 4.11), the I/C ratio is compared between the situation without measures and situation with extra IC stops.

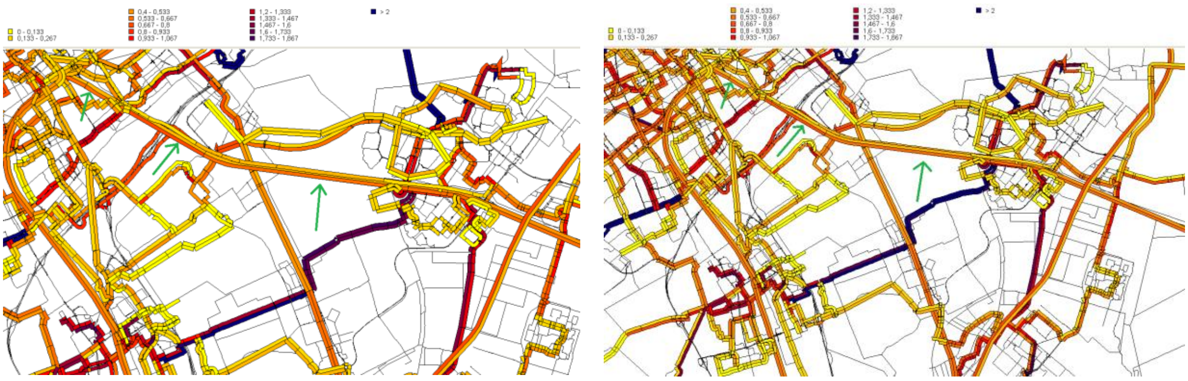

Figure 4.11: I/C ratio during evening peak in case of major discrete event on link segment Laan van NOI - Forepark when no measures are taken (left) and when extra IC stops are temporarily added (right)

Table 4.7 and Figure 4.11 indicate the I/C ratios for these three train links in both directions during the evening peak. On the train link between Voorburg and The Hague Ypenburg and between The Hague Ypenburg and Zoetermeer the I/C ratio increases after this measure is applied. In general this can be considered as a perverse effect of this measure, because comfort level is expected to decrease slightly on those links. However, the mentioned (average) I/C ratios all stay well below 1.0, even after the measure is applied. This indicates that the decrease in comfort level is expected to remain limited.

Table 4.7: Overview of I/C ratios during evening peak on selected train links in case of event between Laan van NOI and Forepark

Link	I/C ratio – No measure	I/C ratio – IC stops
The Hague Central Station – Voorburg (train)	0.7	0.6
Voorburg – The Hague Central Station (train)	0.4	0.3
Voorburg – The Hague Ypenburg (train)	0.6	0.7
The Hague Ypenburg – Voorburg (train)	0.3	0.4
The Hague Ypenburg – Zoetermeer (train)	0.5	0.5
Zoetermeer – The Hague Ypenburg (train)	0.3	0.4

4.4 Extra switches near station Leidschendam-Voorburg

4.4.1 Description of measure

This measure also aims to improve the robustness of the metro / light rail link segment between Laan van NOI and Forepark, by means of compartmentalization. Currently, there are no switches between Laan van NOI and Forepark. This means that in case of a major discrete event somewhere on that link segment, all PT services are cancelled. In case additional switches are realized near one of the stops between Laan van NOI and Forepark, (Voorburg 't Loo or Leidschendam-Voorburg) the second-order effect of major discrete events on the blocked time of the link segment reduces. In this study Leidschendam-Voorburg is chosen as location for the switches. This means that in case of a disturbance between Laan van NOI and Leidschendam-Voorburg, unaffected PT services can be operated between Zoetermeer / Slinge and Leidschendam-Voorburg. In that way, a connection between Zoetermeer / Rotterdam / Pijnacker and The Hague is maintained. Passengers can transfer at Leidschendam-Voorburg to bus services of Veolia Transport going to The Hague. In case of a major discrete event between Leidschendam-Voorburg and Forepark, PT services can remain unaffected between The Hague and Leidschendam-Voorburg. This prevents an additional transfer for passengers travelling between Voorburg 't Loo or Leidschendam-Voorburg and The Hague.

Leidschendam-Voorburg is selected as location for the switches, because maintaining the connection between Forepark (- Zoetermeer / Pijnacker / Rotterdam) on the one hand and Leidschendam-Voorburg (- The Hague) on the other hand is deemed most important. Especially because of the limited route alternatives available between Forepark and Leidschendam-Voorburg in case an event occurs on this metro/light rail link, this link segment is categorized as most vulnerable in the last step of the methodology as explained in chapter 3 (see Table 3.4). Between Leidschendam-Voorburg / Voorburg 't Loo and The Hague, some PT alternatives are available in the multi-level network. In case the switches would be constructed near Voorburg 't Loo, the metro/light rail connection between Leidschendam-Voorburg and Forepark would be cancelled in case an event occurs somewhere on the metro/light rail network between Voorburg 't Loo and Forepark. In case the switches are constructed near Leidschendam-Voorburg, PT services between Leidschendam-Voorburg and Forepark are only cancelled in case an event occurs on this link between Leidschendam-Voorburg and Forepark itself. Selecting Leidschendam-Voorburg as location for the switches therefore means that the connection Leidschendam-Voorburg – Forepark can be maintained more often than when using Voorburg 't Loo as location to construct the switches.

In total, 4 new switches have to be constructed near Leidschendam-Voorburg. On both sides of the station, two switches need to be constructed and connected to each other in order to allow metro/light rail vehicles to change track and turn back in the original direction. By constructing a pair of switches on both sides of the station, Leidschendam-Voorburg can be used as turning point regardless if an event takes place between Voorburg 't Loo and Leidschendam-Voorburg or between Leidschendam-Voorburg and Forepark. In this measure, the construction of switches is not the only aspect which has to be changed in infrastructure layout. Overhead wire also needs to be constructed above both pairs of switches. Besides, on both sides of the station an additional block needs to be added to the signalling system to prevent too large capacity reductions when the switches are used. This means that also two additional signals need to be constructed and incorporated in the signalling system. Figure 4.12 shows the proposed changes in infrastructure near station Leidschendam-Voorburg in detail, with two pairs of switches (a/b and c/d) to be realized.

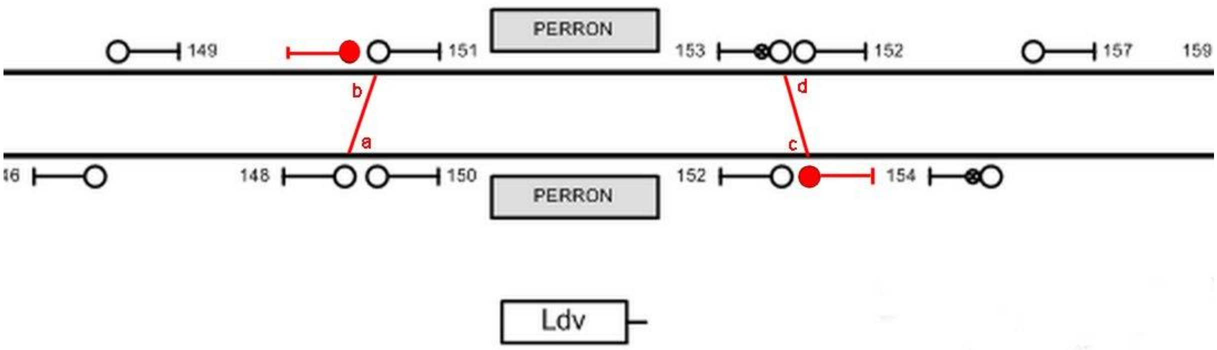

Figure 4.12: Detailed overview of proposed infrastructure near station Leidschendam-Voorburg (Ldv) (Sporenplan, 2013c; adapted)

Table 4.6 in chapter 4.3.1 (p.74) already described the current measures taken by the HTM and RET in case an event occurs between Laan van NOI and Forepark. On the side of The Hague, the turning facility near station Laan van NOI on ground level is used. On the side of Zoetermeer / Rotterdam, trams and metros use Forepark as tail track. Via the interlocking area Pijlkruidveld vehicles can use one of the two tracks of Forepark as turning facility, which in fact means that a double crossover turning configuration is used here. Because of the capacity of double crossovers at Forepark, all metro/light rail services can turn at Forepark according to the measures taken by HTM and RET in reality (maximum combined frequency of turning vehicles during peak hours equals 24 vehicles / hour).

In case of an event on the link Laan van NOI – Leidschendam-Voorburg or on the link Leidschendam-Voorburg – Forepark, the proposed switches near Leidschendam-Voorburg can be considered as a single tail track for each

direction. This means that the capacity of this single tail track is lower than the capacity of the double crossovers used at Forepark (Van Oort & Van Nes, 2010). HTM indicates in their measures ('versperringsmaatregelen') that the capacity of other single tail tracks on the light rail network equals 18 vehicles / hour. This value is therefore also assumed as capacity for the switches near Leidschendam-Voorburg.
Table 4.8 shows how the supplied PT services are adjusted in case of an event between Laan van NOI and Leidschendam-Voorburg when these switches near Leidschendam-Voorburg are constructed. On the side of The Hague, light rail lines 3 and 4(k) use the turning facility near Laan van NOI. As can be seen, it is assumed that metro line E is cancelled between The Hague and Laan van NOI. On the side of Forepark the combined frequency of these services equals 24 vehicles per hour during peak hours and 18 vehicles per hour during non-peak hours. Given the single tail track configuration it is not possible for all 24 vehicles per hour during peak hours to use the switches at Leidschendam-Voorburg without causing substantial knock-on delays. Therefore, during peak hours it is assumed that tram line 4 uses the double crossover configuration Pijlkruidveld to turn back towards Zoetermeer. Line 4 is therefore shortened to the stop Leidschenveen. The other three lines (line 3, 4k and metro E) can use the switches at Leidschendam-Voorburg for turning. Since their combined frequency equals 18 vehicles per hour, the capacity of the switches near Leidschendam-Voorburg is sufficient to accommodate this demand of PT vehicles.

Table 4.8: Overview of adjusted PT services during major discrete event on link Laan van NOI – Leidschendam-Voorburg – switches near Leidschendam-Voorburg

PT line	Frequency peak hours (veh/hr/direction)	Disturbed situation
Line 3 Loosduinen – Zoetermeer Centrum West	6	Line 3a: Loosduinen – Laan van NOI Line 3b: Leidschendam-Voorburg – Zoetermeer Centrum West
Line 3k Sav. Lohmanplein – Central Station	6	Unaffected
Line 4 De Uithof – Zoetermeer Javalaan	6	Line 4a: De Uithof – Laan van NOI Line 4b: Leidschendam-Voorburg – Zoetermeer Javalaan Line 4b: Leidschenveen – Zoetermeer Javalaan (peak)
Line 4k Monstersestraat – Zoetermeer Javalaan	6	Line 4ka: Monstersestraat – Laan van NOI Line 4kb: Leidschendam-Voorburg – Zoetermeer Javalaan
Metro line E The Hague Central Station - Slinge	6	Line E: Leidschendam-Voorburg - Slinge

Table 4.9 shows how the supplied PT services are changed in case an event occurs between Leidschendam-Voorburg and Forepark when these switches are constructed. During non-peak hours, the combined frequency of the lines 3, 4 and metro E (18 vehicles per hour) does not exceed the indicated capacity of a single tail track. Therefore, on the side of The Hague all these three lines can turn at Leidschendam-Voorburg. During peak hours, the combined frequency of the services (24 vehicles per hour) exceeds the capacity of the switches. Therefore, it is proposed that line 4k keeps turning near station Laan van NOI instead of turning at Leidschendam-Voorburg. On the side of Forepark there is sufficient capacity to accommodate the turning of all 24 services per hour because of the double crossover configuration which is available over there. All four affected PT lines are therefore shortened to Forepark in case of an event between Leidschendam-Voorburg and Forepark.

Table 4.9: Overview of adjusted PT services during major discrete event on link Leidschendam-Voorburg – Forepark - switches near Leidschendam-Voorburg

PT line	Frequency peak hours (veh/hr/direction)	Disturbed situation
Line 3 Loosduinen – Zoetermeer Centrum West	6	Line 3a: Loosduinen – Leidschendam-Voorburg Line 3b: Forepark – Zoetermeer Centrum West
Line 3k Sav. Lohmanplein – Central Station	6	Unaffected
Line 4 De Uithof – Zoetermeer Javalaan	6	Line 4a: De Uithof – Leidschendam-Voorburg Line 4b: Forepark – Zoetermeer Javalaan
Line 4k Monstersestraat – Zoetermeer Javalaan	6	Line 4ka: Monstersestraat – Laan van NOI Line 4kb: Forepark – Zoetemeer Javalaan
Metro line E The Hague Central Station - Slinge	6	Line Ea: The Hague Central Station – Leidschendam-Voorburg Line Eb: Forepark - Slinge

4.4.2 Effect on passenger streams

The fourth column of Table 4.10 and Figure 4.13 show the effect of this measure on route choice by affected passengers in case of a major discrete event between Laan van NOI and Leidschendam-Voorburg.

Table 4.10: Route alternatives chosen by a percentage of all passengers affected by a major discrete event between Laan van NOI and Forepark when no measures are taken (2nd column), when extra IC stops are added (3rd column) and when switches are constructed (4th and 5th column)

Route alternative	No measure	IC stops	Switch Leidschendam-Voorburg *LvNOI – LV*	*LV - Forepark*
Light rail line 3 / 4 / metro E Leidschendam-Voorburg - Forepark	-	-	30%	-
Light rail line 3 / 4 / metro E Laan van NOI - Leidschendam-Voorburg	-	-	-	33%
Train Zoetermeer / The Hague Ypenburg - The Hague	24%	43%	14%	27%
Train Rotterdam - The Hague	12%	13%	7%	12%
Bus line 365 Zoetermeer –Leiden; train Leiden - The Hague	9%	7%	8%	9%
Tram line 19 Leidschenveen – Leidsenhage; tram line 2 Leidsenhage - ’t Loo / Laan van NOI / Central Station	8%	8%	1%	7%
Tram line 2 station Laan van NOI - Voorburg ‘t Loo	7%	6%	9%	-
Change boarding / alighting to station Laan van NOI	4%	4%	4%	-
Train Zoetermeer / The Hague Ypenburg – Voorburg; bus line 23 Voorburg - Laan van NOI	3%	2%	4%	-
Bus lines 45 and 46 The Hague Central Station - Leidschendam-Voorburg	3%	2%	3%	1%
Bus line 46 Leidsenhage - Leidschendam-Voorburg	-	-	2%	-
Bus 170 Zoetermeer - Rodenrijs	1%	2%	1%	1%
Train Zoetermeer / The Hague Ypenburg – Voorburg; bus line 23 Voorburg – Rijswijk	1%	-	1%	1%
Train Zoetermeer / The Hague Ypenburg – Voorburg; bus line 26 / 28 Voorburg - The Hague HS / CS	1%	-	-	-
Bus line 30 Leidschenveen - Rijswijk	1%	1%	1%	1%
Bus lines 50 and 52 Zoetermeer - Rijswijk	1%	1%	1%	1%
Q-liner busses Zoetermeer - The Hague CS	1%	1%		1%
Bus line 121 Zoetermeer - Delft	1%	1%	-	1%
Bus line 121 Pijnacker - Delft	-	-	1%	-

From Table 4.10 can be seen that because of the extension of PT services from Forepark to Leidschendam-Voorburg 30% of all affected passengers do not suffer from the disturbance anymore. These passengers can now use these extended services without performing any change in route choice compared to the undisturbed situation. This shows that the extension of PT services between Zoetermeer / Pijnacker / Rotterdam and Leidschendam-Voorburg instead of Forepark is important to connect a substantial amount of passengers in a faster way, with less resistance because of route changes, additional transfers and extra in-vehicle time.
Additionally, it can be seen that the function of tram line 19 between Leidschenveen and Leidschendam as back-up for the blocked metro / light rail services decreases substantially when the metro/light rail services are supplied from/to Leidschendam-Voorburg instead of Forepark. Also the function of the train connection between Zoetermeer / The Hague Ypenburg and The Hague as back-up network for the blocked metro/light rail link segment decreases substantially: 14% instead of 24% of all affected passengers use the train network as route alternative when this measure is applied.

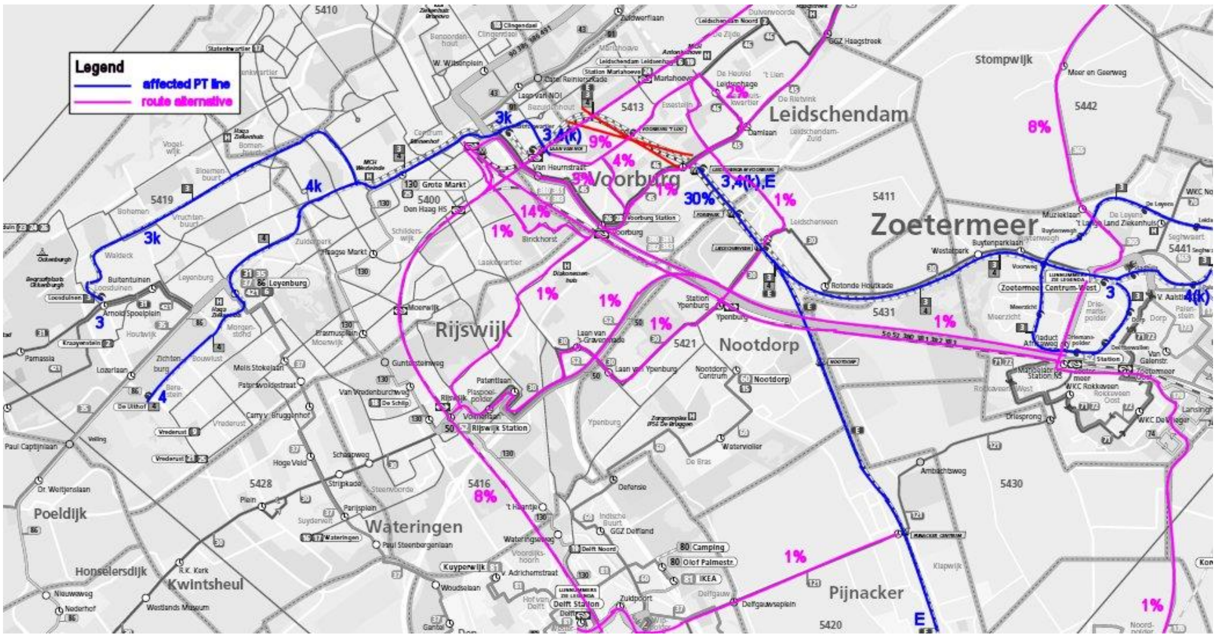

Figure 4.13: Overview of route alternatives chosen by passengers affected by a major discrete event between Laan van NOI and Leidschendam-Voorburg – switches near Leidschendam-Voorburg

On the other hand, in case of a major discrete event between Leidschendam-Voorburg and Forepark the metro / light rail services between Laan van NOI and Leidschendam-Voorburg remain intact to a large extent. The last column of Table 4.10 and Figure 4.14 show that 33% of all affected passengers can now use these extended services between The Hague and Voorburg 't Loo / Leidschendam-Voorburg. Because of the extended PT services these passengers are not hampered by the disturbance anymore.
In case the event takes place between Leidschendam-Voorburg and Forepark, it can be seen that the train connection between Zoetermeer / The Hague Ypenburg and The Hague still functions as an important back-up system for the blocked metro / light rail services, since the metro/light rail connection between Zoetermeer / Pijnacker / Rotterdam and The Hague is blocked. 27% of all affected passengers use the train network as route alternative. Besides, tram line 19 also functions as route alternative between Leidschenveen and Leidsenhage for 7% of the affected passengers in the absence of the metro/light rail connection between Forepark and Leidschendam-Voorburg.
At last, it can be seen that the function of tram line 2 as back-up for the blocked track between The Hague Central Station / Laan van NOI and Voorburg 't Loo is not of relevance anymore when this measure is applied. Also bus line 23 has no back-up function anymore between Voorburg and Laan van NOI. Because of the construction of switches near Leidschendam-Voorburg, the metro/light rail services can still provide services on this part of the network.

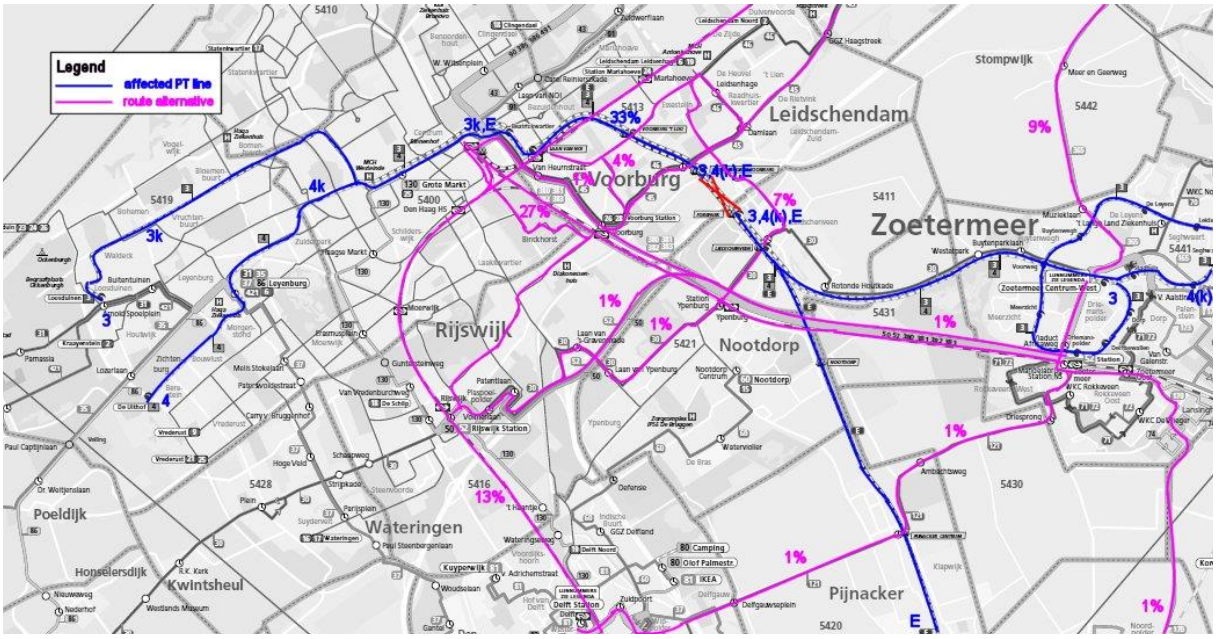

Figure 4.14: Overview of route alternatives chosen by passengers affected by a major discrete event between Leidschendam-Voorburg and Forepark – switches near Leidschendam-Voorburg

4.4.3 Effect on I/C ratio

In case an event occurs between Laan van NOI and Leidschendam-Voorburg, the largest differences in route choice proportions between the situation without measures and the situation with switches are found on tram line 19 and the train line Zoetermeer / Ypenburg – The Hague. In case the metro/light rail services are extended from Forepark to Leidschendam-Voorburg, the function of these two lines as route alternative decreases considerably. Therefore it is expected that the comfort level - represented by the load factor or I/C ratio - on these lines increases in case switches are constructed. Figure 4.15 and Table 4.11 show the results of the comparison of the I/C ratio on 1 link on the route of tram line 19 (Sijtwende tunnel) and for the three train links The Hague – Voorburg, Voorburg – Ypenburg and Ypenburg – Zoetermeer (indicated by the green arrows in Figure 4.15) during the evening peak.

Figure 4.15: I/C ratio during evening peak in case of major discrete event on link segment Laan van NOI – Leidschendam-Voorburg when no measures are taken (left) and when switches are constructed (right)

From Figure 4.15 and Table 4.11 can be concluded that the measure has a limited impact on the load factor on the train links between The Hague and Ypenburg / Zoetermeer. The reduction of the proportion of passengers using the train between Zoetermeer / Ypenburg and The Hague Central Station can be seen in Table 4.11 and Figure 4.15 by the slight reduction of the I/C ratio on the train link between The Hague and Voorburg. On train links between Voorburg and Zoetermeer the I/C ratio remains equal or increases slightly when this measure is applied. Although fewer affected passengers use the train connection from/to The Hague Central Station as route alternative, Table 4.10 shows that there is a small increase in the proportion of affected passengers who travel by train between Zoetermeer / Ypenburg and Voorburg, and then take different urban or regional bus lines as route alternative. For example, a slight increase can be found in passengers using bus line 23 between Voorburg and Rijswijk. These increases are expected to explain the slight increase in I/C ratio on the train links Voorburg – Ypenburg – Zoetermeer.

It can also be concluded that the I/C ratio of tram line 19 decreases substantially when this measure is applied. When no measure is taken, a substantial part of the affected passengers uses tram line 19 as route alternative. Because of the low frequency of tram line 19 (3 trams per hour per direction during peak and non-peak hours: see appendix B3), these additional passengers increase the I/C ratio substantially. When switches are constructed, tram line 19 is not an important back-up route alternative anymore. In case this measure is applied, this leads to a large improvement of the comfort level on this tram line therefore.

Table 4.11: Overview of I/C ratios during evening peak on selected links in case of event between Laan van NOI and Leidschendam-Voorburg

Link	I/C ratio – No measure	I/C ratio – Switches
The Hague Central Station – Voorburg (train)	0.7	0.6
Voorburg – The Hague Central Station (train)	0.4	0.3
Voorburg – The Hague Ypenburg (train)	0.6	0.7
The Hague Ypenburg – Voorburg (train)	0.3	0.3
The Hague Ypenburg – Zoetermeer (train)	0.5	0.6
Zoetermeer – The Hague Ypenburg (train)	0.3	0.3
Sijtwende tunnel to Leidsenhage (tram line 19)	0.6	0.1
Sijtwende tunnel towards Delft Noord (tram line 19)	1.3	0.2

In case an event occurs on the metro/light rail link between Leidschendam-Voorburg and Forepark, Table 4.10 shows that the largest differences in route choice proportions between the situation without measures and situation with switches can be found on tram line 2 (The Hague Central Station / Laan van NOI - Voorburg 't Loo) and on bus line 23 (Laan van NOI – Voorburg Station). In case of switches, the metro/light rail services between Laan van NOI and Leidschendam-Forepark are hardly affected by an event between Leidschendam-Voorburg and Forepark. Therefore, the back-up function of tram line 2 and bus 23 decreases considerably after this measure. It is therefore expected that the load factor on these lines decreases when this measure is applied, thereby improving the comfort level experienced by passengers. Figure 4.16 and Table 4.12 show the results of the comparison of the I/C ratio on 1 link on the route of tram line 2 (between Laan van NOI and Voorburg 't Loo) and on 1 link on the route of bus line 23 (between Laan van NOI and Voorburg Station). These links are indicated by the green arrows in Figure 4.16.

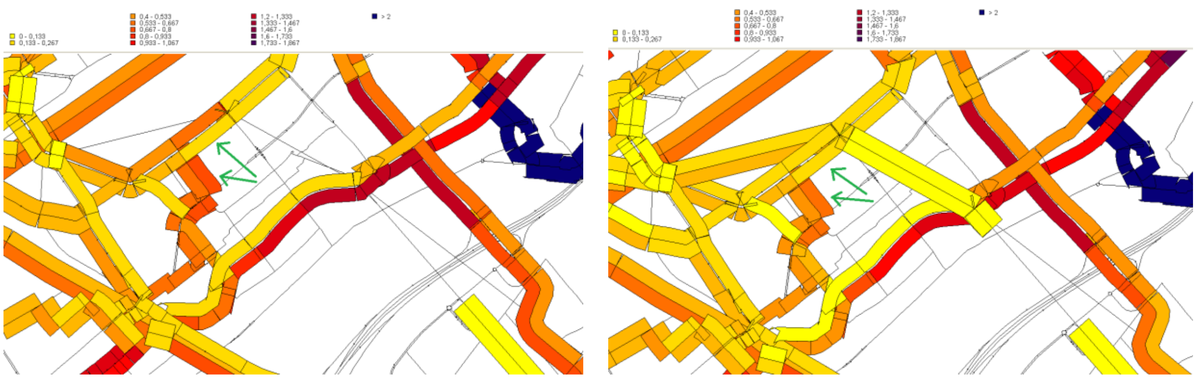

Figure 4.16: I/C ratio during evening peak in case of major discrete event on link segment Leidschendam-Voorburg - Forepark when no measures are taken (left) and when switches are constructed (right)

From Figure 4.16 and Table 4.12 can be concluded that the load factor on the considered links decreases substantially. Therefore, except travel time benefits also comfort benefits are expected on routes which were originally used as alternatives by passengers affected by a disturbance between Leidschendam-Voorburg and Forepark.

Table 4.12: Overview of I/C ratios during evening peak on selected links in case of event between Leidschendam-Voorburg and Forepark

Link	I/C ratio – No measure	I/C ratio – Switches
Laan van NOI – Voorburg 't Loo (tram line 2)	0.2	0.2
Voorburg 't Loo – Laan van NOI (tram line 2)	0.6	0.1
Laan van NOI – Voorburg Station (bus line 23)	0.6	0.4
Voorburg Station – Laan van NOI (bus line 23)	0.8	0.6

4.5 Conclusions

The next conclusions are formulated regarding feasible measure types to improve robustness of PT networks:

- Prevention-focused measures which can reduce the frequency of vehicle breakdowns on all network levels or the frequency of suicide events on the train network are deemed promising measure types.
- Infrastructure design measures focusing on compartmentalization, like the realization of extra turning facilities, or focusing on flexibility, like the realization of an emergency bypass, might be promising in case they can be applied on long link segments with limited major infrastructure constructions.
- Temporary service network design measures which improve redundancy, like a temporary extension of a transit line as back-up during disturbances, or which improve flexibility, like a temporary increase of transfer possibilities between different network levels, seem to be promising types of measures.
- Large infrastructure design measures (like doubling the number of tracks on a link), structural service network design measures (like a structural increase of the frequency of a transit line which can function as back-up for a vulnerable link segment) and measures focusing on reducing the frequency of blockages (like realizing more separated / own right of way on the BTM network) are expected to have limited (societal) robustness benefits compared to the costs.

Regarding the effects of the three proposed measures in this study on passenger streams in the PT network, the following conclusions are formulated:

- The measure 'detour of tram lines around the tram tunnel The Hague' concentrates passengers on the diverted tram lines: 81% of the affected passengers are expected to use these diverted tram lines, compared to 44% of the affected passengers which are currently using the diverted tram line 6.
- This measure reduces the number of additional transfers substantially. Also, the comfort level on the diverted tram route clearly increases because of the additional capacity supplied relative to the additional demand on this route.
- The measure 'temporary extra intercity stops Zoetermeer and The Hague Ypenburg' in case of a disturbance on the link Laan van NOI – Forepark concentrates passengers on the train route alternative between Zoetermeer / Ypenburg and The Hague: 43% compared to the current 24% of the affected passengers use this alternative if this measure is applied.
- A disadvantage of this measure is the slight increase in average I/C ratio on these train links.
- The measure 'switches near Leidschendam-Voorburg' enables 30% and 33% of the originally affected passengers to remain on their original route in case of a disturbance between Laan van NOI and Leidschendam-Voorburg and between Leidschendam-Voorburg and Forepark, respectively.
- This measure especially reduces the I/C ratio on tram lines 2 and 19 and on bus line 23 during events.

5

Societal evaluation and implementation of robustness measures

In this chapter, the measures proposed in chapter 4 to improve the robustness of the multi-level public transport (PT) network of the case study are evaluated by performing a societal cost benefit analysis. This chapter shows how such evaluation can be performed. Information about the frequency, duration and impact of different major discrete event types on infrastructure availability and PT demand as discussed in chapter 2 is used as input for the societal cost benefit analysis. Chapter 5.1 discusses the method used to evaluate robustness measures. In chapter 5.2, the results of the societal evaluation of the three proposed measures are shown. Chapter 5.3 discusses the results of the performed sensitivity analysis. Then, chapter 5.4 shortly discusses the implementation of promising measures. At last, conclusions are formulated in chapter 5.5
In this chapter both the societal effects of robustness measures and the societal costs of non-robustness in the current situation without taking measures are evaluated.

5.1 Method to evaluate robustness measures

5.1.1 Monte Carlo simulation

In chapter 2, different major discrete event types which occur on different network levels of the multi-level PT network are characterized based on their frequency and duration. For different event types, different parameter values are estimated for the probability distributions used to model the frequency and duration. In order to evaluate the societal effects of a robustness measure or to evaluate the societal costs of major discrete events within a certain time period, first it should be known how long a certain link segment r is blocked because of a certain major discrete event type m within this time period. Given the stochasticity related to both the frequency and duration of different major discrete event types, Monte Carlo simulation is used to calculate how often a certain event type occurs and what duration is related to each event. Below the procedure is described how Monte Carlo simulation is used to determine the total time a link segment r is blocked. Results of the Monte Carlo simulation can be found in appendix C1.

- Step 0: initialization.
    - Set a time horizon T which represents the number of operation hours on link segment r per year;
    - Set for each distinguished time period of the day p (morning peak, evening peak etc.) $T_p \in T$;

- Set for each distinguished period of the year s (spring, summer, heavy snow etc.) $T_s \in T$;
- Set for each distinguished time period of the day p within each period of the year s $T_{p,s} \in T$;
- Set for each major discrete event type m on link segment r $\lambda_{m,s}$ which represents the average frequency of occurrence per time period (Poisson parameter) on link segment r in period of the year s;
- Set for each major discrete event type m the parameter values $\mu_{m,s}$ and $\sigma_{m,s}$ of the (log)normal distribution which represent the distribution of the duration of event type m on link segment r in period of the year s;
- Categorize each major discrete event type m in a category C based on the effect on infrastructure availability (0% or 50% infrastructure availability) and based on the effect on PT demand reduction (low level of predictability: no effect on PT demand reduction, or high level of predictability: effect on demand reduction);
- Set $i = 0$;
- Set time $t = 0$;
- Set $F(x) = 1 - e^{-\lambda x}$: in case the frequency of an event can be modelled by a Poisson distribution with parameter λ, then the interarrival time between two events can be modelled by an exponential distribution with this same parameter value λ. $F(x)$ reflects the exponential distribution function for $x \geq 0$;

For each time period of the day p;
For each major discrete event category C;
For each major discrete event type $m \in C$;
For each period of the year s;

- Step 1: $i = i + 1$;
- Step 2: Draw a value U_i from a uniform distribution $U[0,1]$ generated by a pseudo-random generator;
- Step 3: Solve $F(x) = U_i[0,1]$ to calculate the interarrival time x_i between two major discrete events;
- Step 4: Calculate $\sum_{i=1}^{i} x_i$ to determine at which time t from $t = 0$ an event starts:
If $\sum_{i=1}^{i} x_i < T_{p,s}$: then go to step 5; else go to step 7;
- Step 5: Draw a value D_i from a (log)normal distribution $D[\mu, \sigma]$ generated by a pseudo-random generator to determine the duration d of event i;
- Step 6: Repeat from step 1;
- Step 7: Calculate $\sum_{i=1}^{i-1} d_i$ to determine the total time a link segment r is blocked because of major discrete event type m in period of the year s;

Step 8: Calculate $\sum_m \sum_{i=1}^{i-1} d_i$ to determine the total time a link segment r is blocked in period of the year s because of all major discrete event types $m \subseteq C$ occurring on that link segment r.

The distinction between (at most) four functional categories C is required because the societal effects of a major discrete event can differ in each category. A public transport operator (PTO) can take different measures in case of 0% or 50% infrastructure availability, which influences the societal effects. Also, the passenger effects (and therefore societal effects) can be different in case PT demand reduction occurs because of an event with a high level of predictability, compared to the situation where no PT demand reduction occurs.
In this study a pseudo-random generator is used to generate values for the total duration a certain link segment is blocked in a certain time horizon during each period of the day. This means that these values are exactly the same in the situation without measures taken and the situation in which a certain measure is applied. This enables a fair comparison between the situation with and without a measure taken in order to investigate the pure effect of a robustness measure. In this study, Matlab is used to generate pseudo-random values from a uniform and (log) normal distribution.

5.1.2 Aspects of societal cost benefit analysis

This part of the chapter explains the aspects which are considered when performing a societal cost benefit analysis to evaluate different robustness measures. Appendix C2 shows input values and parameter values used for the cost benefit analysis in this study for the parameters mentioned in the formulas below.

Infrastructure effects

In case an infrastructure design measure is proposed, there are costs related to this measure which are represented by the aspect 'infrastructure effects'. Formula (5.1) shows how the infrastructure effects $C_{i,t}$ are calculated for each year t considered in the cost benefit analysis. The infrastructure effects equal the residual value of infrastructure $C_{i,r}$ minus the infrastructure construction cost $C_{i,c}$ and infrastructure maintenance costs $C_{i,m}$. The benefits from the residual value of infrastructure are only relevant in case the economic lifespan of the infrastructure exceeds the time horizon used in the cost benefit analysis; else $C_{i,r}$ equals zero.

$$C_{i,t} = -C_{i,c,t} - C_{i,m,t} + C_{i,r,t} \tag{5.1}$$

Operation effects

In case a service network design measure is proposed, the measure can influence the number of timetable hours (in Dutch: 'dienstregeling uren' (DRU's)). This value only relates to the time PT vehicles are scheduled to transport passengers, thereby excluding empty trips to/from the depot or turnaround time at the final destination of a line. The extra operation costs $C_{o,t}$ in year t equal the product of the additional number of timetable hours operated by PT vehicles O_h and the average costs $C_{o,h}$ related to the operation of one additional timetable hour for a certain PT mode. For a multi-level PT network, formula (5.2) shows how the additional operation costs can be calculated.

$$C_{o,t} = O_{h,train,t} * C_{o,h,train} + O_{h,metro,t} * C_{o,h,metro} + O_{h,tram,t} * C_{o,h,tram} + O_{h,bus,t} * C_{o,h,bus} \tag{5.2}$$

Travel time effects

When determining the travel time effects of a measure, there is focused on the monetized travel time effects as perceived by passengers. This means that all considered travel time components are weighted according to the perception of passengers. The perceived total travel time is monetized by using the value of time (VoT). The total monetized perceived travel time effects $C_{t,t}$ of a measure for each year t can be calculated by using formula (5.3). The travel time effects are summed over all OD-pairs (the model used in this study consists of 5791 zones: see Table 3.2 in chapter 3.3).

$$C_{t,t} = \sum_{o=1}^{5791} \sum_{d=1}^{5791} \left(\alpha_a t_{a,t} + \alpha_w \sum_{x=1}^{n_t+1} t_{w,x,t} + \alpha_{in} \sum_{y=1}^{n_t+1} t_{in,y,t} + \alpha_{n_t} n_{t,t} + \alpha_t \sum_{z=1}^{n_t} t_{t,z,t} + \alpha_e t_{e,t}\right) * VoT \tag{5.3}$$

With parameters:

	C_t	*generalized travel costs*
	VoT	*value of time*
	t_a	*access time from origin to PT service*
	t_w	*waiting time for boarding PT service*
	t_{in}	*in − vehicle time in PT service*
	n_t	*number of transfers between PT services*
	t_t	*transfer walking time to PT service*
	t_e	*egress time from PT service to destination*
	α_x	*corresponding weight for travel time components*

Travel cost effects

A measure can influence the total passenger-distance travelled in the multi-level PT network. This in turn influences the travel costs of a PT trip. The costs $C_{c,t}$ for each year t related to the travelled passenger-distance can be expressed by formula (5.4), in which the total passenger-distance S is multiplied by the average fare f per kilometre. This value is an average value over the different fare systems applied by different PTO's on different network levels, and an average value over the different fare types existing within each fare system (for example: student card, discount card, full tariff).

$$C_{c,t} = \sum_{o=1}^{5791} \sum_{d=1}^{5791} S * f \qquad (5.4)$$

Comfort effects

When considering a passenger perspective, especially in case of major discrete events it is of relevance to incorporate comfort effects in the evaluation of measures. As explained in chapter 3.2.2, the comfort effects are not incorporated in the generalized cost function for the assignment. However, comfort effects are evaluated based on the assignment. In the model used, it is difficult to identify which fraction of which OD-pairs is travelling over each link in the network. Therefore, comfort effects are not determined per OD-pair. Instead, the comfort level is assessed on a link level: for each link a in the network the load factor (the passenger flow divided by the supplied seat capacity) can be calculated. Valuation of comfort effects is performed based on this load factor. As explained in chapter 4, in case multiple transit lines are operated on a certain link, the link level load factor implies the average load factor over all transit lines on that link. This means that individual differences in load factor can exist between transit lines, which are not addressed in this study because the assessment of load factors per transit line per link is very time consuming. Also, the value of this load factor assumes implicitly that passengers are distributed uniformly over each distinguished time period in the model (1st hour and 2nd hour morning peak, evening peak, remaining part of the day: see chapter 3.2.2).

Formula (5.5) expresses the valuation of comfort costs $C_{comf,t,seat}$ in the network for each year t for seated passengers. Formula (5.6) expresses $C_{comf,t,stand}$ for standing passengers. In these functions, the in-vehicle time t_{in} is multiplied by a continuously increasing factor with an increasing load factor LF. However, in practice it might be possible that passengers experience a PT vehicle with a very low load factor in a negative way as well, because of (perceived) unsafety. It is suggested that in reality this function might follow a more parabolic pattern instead of a linear piecewise increasing pattern. Because no quantitative evidence could be found in literature for a parabolic function, in this study a linear piecewise increasing function is used. The 'minus 1' in both expressions is used to deduce the *additional* perceived travel time because of a high load factor only. Without this 'minus 1', the in-vehicle time without comfort problems is added as well to the costs, while this value is already incorporated in formula (5.3).

$$C_{comf,t,seat} = \sum_{a=1}^{n} VoT * t_{in} * \begin{cases} (0.73 + LF * 0.004) - 1, & 67.5 < LF < 75 \\ (0.70 + LF * 0.0044) - 1, & 75 < LF < 125 \\ (0.60 + LF * 0.0052) - 1, & 125 < LF < 150 \\ (0.54 + LF * 0.0056) - 1, & 150 < LF < 175 \\ (0.40 + LF * 0.0064) - 1, & 175 < LF < 200 \end{cases} \qquad (5.5)$$

$$C_{comf,t,stand} = \sum_{a=1}^{n} VoT * t_{in} * \begin{cases} (0.99 + LF * 0.0076) - 1, & 100 < LF < 125 \\ (0.89 + LF * 0.0084) - 1, & 125 < LF < 150 \\ (0.77 + LF * 0.0092) - 1, & 150 < LF < 175 \\ (0.56 + LF * 0.0104) - 1, & 175 < LF < 200 \end{cases} \qquad (5.6)$$

In the cost benefit analysis the comfort costs are marginally calculated only for links a on which an effect in load factor is expected because of a disturbance or measure. For each of the two link segments for which the robustness is aimed to improve in this study, this selection of links is made based on the route alternatives used by affected passengers as shown in chapter 4.

Non-facilitated demand

After the assignment is performed, for a selection of links it is checked whether non-facilitated demand occurs. Based on the I/C plots shown in chapter 4, a selection of links is made on which high load factors occur because of a disturbance. For these links a it is checked whether the passenger flow on that link exceeds the total supplied crush capacity. Again, this check is performed on a link level, which indicates that in case of multiple transit lines it is checked whether demand on a link can be accommodated on average over the different transit lines. In case PT demand q_a exceeds the crush capacity CC_a on a link, it is assumed that passengers have to skip a PT service and wait for a next service. Therefore, the average waiting time based on the combined frequency f_t of transit lines on a link is added to the travel time and monetized to determine the costs of non-facilitated demand $C_{non-f,t}$ for each year t (see formula (5.7)).

$$C_{non-f,t} = \sum_{a=1}^{n} VoT * \alpha_w * \begin{cases} \frac{1}{2*f_t}, & q_a > CC_a \\ 0 & q_a \leq CC_a \end{cases} \qquad (5.7)$$

Reliability effects

In general, service reliability assesses the extent to which realized and scheduled times of a PT vehicle correspond to each other (Van Oort, 2011). The effects of service reliability can be quantified and incorporated in a societal cost benefit analysis: see for example Goudappel Coffeng (2011). Reliability in relation to major discrete events has a different meaning. In this context, it is more focused on long term reliability over a certain time period, in which passengers incorporate both the situation in which no disturbances occur and the situation in which a disturbance occurs in their perception of reliability. Reliability in this context reflects the extent to which reliable PT services are supplied to passengers on the long term. This type of reliability reflects reliability on a more aggregate level, instead of on the level of individual PT vehicles.

On a very aggregate level, it is expected that the costs of long term unreliability are limited. Despite the impact a major discrete event can have, the frequency of major discrete events as calculated in Table 2.6, Table 2.9 and Table 2.10 in chapter 2.2 indicate that most of the time no disturbances occur on a certain link. This means that passengers can make their PT trip most of the time in an undisturbed way. It should be noted that – despite the expectation of quite good long term reliability – passengers can experience reliability in case of a major discrete event in a different, more negative way. It might be possible that passengers give more weight to the few times a disturbance occurs, compared to the many times they can make their PT trip without disturbances. It is possible to quantify long term reliability effects, although this requires extensive calculations. Given time limitations and the expected limited objective effect of measures on long term reliability, this quantification is not part of this study. In the evaluation of measures, a slight improvement of long term reliability because of the proposed measures is indicated qualitatively.

Trip cancellation effects

Trip cancellation costs $C_{cancel,t}$ are only relevant for passengers who cancel their PT trip because of a major discrete event. As explained in chapter 2.5, this effect is only assumed to occur in case of major discrete events with a high level of predictability. For these event types, a PT demand reduction of 14% on affected OD-pairs is assumed in this study (see chapter 2.5 and chapter 3.2.2). The rule of half is applied to determine trip cancellation costs based on the total generalized costs of an affected OD-pair. In theory, the generalized costs on each OD-pair are the sum of the monetized travel time effects, travel costs, comfort effects and reliability effects. However, in this study reliability is considered only qualitatively. Comfort effects are assessed on a link level, and not per OD-pair. Also the travel costs are assessed on an aggregate level in this study: the total passenger-distance travelled over all OD-pairs is monetized without making a distinction between the passenger-distance travelled per OD-pair. This means that the generalized costs on the level of each OD-pair only consist of monetized travel time effects in this study. The rule of half to calculate trip cancellation costs is therefore based on this aspect only, as expressed by formula (5.8).

$$C_{cancel,t} = \sum_{o=1}^{5791} \sum_{d=1}^{5791} 0.5 * ((\alpha_a t_{a,t} + \alpha_w \sum_{x=1}^{n_t+1} t_{w,x,t} + \alpha_{in} \sum_{y=1}^{n_t+1} t_{in,y,t} + \alpha_{n_t} n_{t,t} + \alpha_t \sum_{z=1}^{n_t} t_{t,z,t} + \alpha_e t_{e,t}) * VoT) \quad (5.8)$$

5.2 Evaluation of robustness measures

5.2.1 Societal cost benefit analysis

Time horizon

In this study, a time horizon of 10 years is used to evaluate the effects of the measures. In this study, as simplification PT demand and PT supply are assumed constant in the undisturbed situation during the whole considered time period. If a time horizon longer than 10 years would be chosen, the assumption of constant supply and demand would be violated heavily. If a time horizon much shorter than 10 years would be chosen, there is not sufficient time to incorporate the stochastisticy around the frequency and duration of events in a representative way. This time horizon of 10 years is chosen for all measures which are evaluated in this study, in order to get comparable values for the societal costs of non-robustness for the different link segments considered. In case the economic lifespan of a certain measure exceeds the chosen time period of 10 years, the residual value of the investment for this measure is added as benefit to the infrastructure effects in the last year considered in the cost benefit analysis by assuming straight line depreciation (see formula (5.1)).

Discount rate

In this study a discount rate of 5.5% is used. This is in line with the value indicated by the Kennisinstituut voor Mobiliteit (2012). The value of 5.5% consists of an interest rate of 2.5% which is specified by the government, plus 3.0% macro-economic risk which should be applied over all costs and benefits.

Operation hours

In this study it is assumed that PT services operate 18 hours per day. In reality, there can be small differences between the exact number of operation hours on parts of the multi-level PT network, but on an aggregate level this assumption seems reasonable.

Incorporation of weekends and holidays

In the OmniTRANS transit model used for this study, results are shown for an average working day. To generalize these results to yearly results as input for a cost benefit analysis, a correction for weekend days and holidays needs to be applied. For this correction, the steps as specified by Rijkswaterstaat (2010) are used in order to calculate the costs/benefits for a weekend day based on the costs/benefits of an average working day:

- Use the calculated costs/benefits for the remaining part of a working day as starting point;
- Correct for the fact that the number of trips made on a weekend day for each trip purpose is a fraction of the number of trips made on a week day (note however that on a weekend day more leisure trips are made compared to a working day);
- Correct for the fact that the remaining part of a working day is used as starting point to calculate costs/benefits for a whole weekend day, by considering the ratio in vehicle-hours between the remaining part of a working day and the total weekend day.

As can be seen, this correction is related to the distribution of trip purposes. Using the trip purpose distribution as explained in appendix C2 (4th column of Table C8), the calculated costs/benefits for the remaining part of a working day need to be multiplied by factor (0.59/0.56) in order to get the estimated costs/benefits for a weekend day.

Categorization of total duration of events in time horizon

As explained in chapter 5.1, for each distinguished functional category C the total time a link segment is blocked per year is determined based on Monte Carlo simulation. Given the two dimensions used for this categorization (impact on infrastructure availability and impact on PT demand), in theory four different categories can be distinguished. For the two specific link segments for which measures are evaluated, the measures PTO's take in response to a disturbance are equal in case of 0% and 50% link availability. This means that only two categories are left in this case: the total blocked time of a link segment because of major discrete events with a high level of predictability (PT demand reduction occurs) and the total blocked time of a link segment because of major discrete events with a low level of predictability (no PT demand reduction occurs). This total blocked time is determined for each of the time periods distinguished in the analysis: the four time periods used in the transit model (1st hour morning peak, 2nd hour morning peak, evening peak and remaining part of the working day) and an average weekend day / holiday based on the correction as explained above.

Appendix C1 shows the exact results of the performed Monte Carlo simulation regarding the total time each link segment is blocked because of major discrete events. In general, by using a pseudo-random generator the total time a link segment is blocked is exactly the same for the situation without measures and the situation when a measure is applied. The only exception is the measure where extra switches near Leidschendam-Voorburg are constructed. Extra switches lead to both more flexibility and to more switch failures. Therefore, the frequency of switch failures is increased in this measure. Based on the track layout can be concluded that in the current situation 10 switches can cause failures on the link segment Laan van NOI – Forepark (8 switches on the main tracks and 2 switches on the work shop Leidschendam because of flank protection) (Sporenplan, 2013c). After this measure would be applied, there are 14 switches on this link segment. Therefore, the frequency of switch failures on this link segment is increased by factor 1.4 after this measure is applied.

Table 5.1 summarizes the results of the performed Monte Carlo simulation. For each link segment, the total number of hours that a link segment is blocked because of major discrete events over a period of 10 years is shown. When the measure 'switches near Leidschendam-Voorburg' is applied, the blocked time is calculated separately for the link segment part Laan van NOI – Leidschendam-Voorburg and Leidschendam-Voorburg – Forepark. From this table can be concluded that link segments are blocked because of major discrete events during 1-2% of the operation hours. Adding new switches increases the blocked time of the link segment Laan van NOI – Forepark in total with 139 hours (14% increase in total), when the blocked time of the link segment Laan van NOI – Leidschendam-Voorburg and Leidschendam-Voorburg – Forepark are summed.

Table 5.1: Simulation output of total blocked time of different link segments for a period of 10 years

Link segment	Total blocked time in 10 years (hour)	Relative blocked time
Brouwersgracht – Central Station	715	1.1%
Laan van NOI – Forepark	964	1.5%
Laan van NOI – Leidschendam-Voorburg	765	1.2%
Leidschendam-Voorburg - Forepark	338	0.5%

Results

Based on the assumptions mentioned above, the results of the societal cost benefit analysis are shown in Table 5.2. Appendix C2 shortly explains how the infrastructure effects and operation effects of each measure are calculated. In Table 5.2 the next information is presented:

- The 'Δ' column shows the difference between the value of a certain aspect in case of disturbances when no measures are taken and the value in case of the same disturbances when a certain measure is applied. These values therefore show the difference between the societal costs of major discrete events in case no measures are taken and the societal costs of major discrete events after a measure is applied.

- The ‘present value’ column shows the monetized and discounted value of the difference as shown in the ‘Δ’ column. For all travel time components, the values of the ‘Δ’ column are first multiplied by their corresponding weight factors (see Table C5 in appendix C2).
- The total benefits of a measure equal the sum of the present values of the travel time effects, travel cost effects, comfort effects, capacity effects and trip cancellation effects.
- The total costs of a measure equal the sum of the present values of infrastructure and operation effects.

Table 5.2: Results of societal cost benefit analysis

Link	Tram tunnel		Station Laan van NOI - Forepark			
Measure	Detour tram tunnel		Extra IC stops		Switches	
	Δ	Present value (€*10^4)	Δ	Present value (€*10^4)	Δ	Present value (€*10^4)
Direct effects						
Infrastructure effects						
Infrastructure construction		-12				-350
Infrastructure maintenance		-1.6				-22
Residual value infrastructure		3.4				130
Total		**-10**				**-243**
Operation effects						
Operation hours (DRU)			-634	-13		
Total			**-634**	**-13**		
Travel time effects						
Access time (hour*10^4)	1.6	17	0.0	0.4	0.6	6.5
Waiting time (hour*10^4) (access + transfer waiting time)	3.2	47	6.9	101	2.6	37
In-vehicle time (hour*10^4)	-7.0	-47	-6.0	-39	0.7	4.5
Transfer walking time (hour*10^4)	2.6	33	-0.9	-12	0.5	6.4
Number of transfers (*10^4)	25	32	5.1	6.4	13	16
Egress time (hour*10^4)	1.1	12	-0.0	-0.9	1.0	10
Perceived total (hour*10^4)	**14**	**94**	**8.4**	**55**	**12**	**80**
Travel cost effects						
Passenger kilometres (km*10^4)	184	13	-9.8	-0.7	454	32
Total (km*10^4)	**184**	**13**	**-9.8**	**-0.7**	**454**	**32**
Capacity effects						
Comfort		27		-8.3		-19
Non-facilitated demand		0.0		0.0		0.0
Total		**27**		**-8.3**		**-19**
Reliability effects		+		+		+
Trip cancellation effects		**0.0**		**-0.0**		0.0
Total benefits (€*10^4)		**135**		**46**		**94**
Total costs (€*10^4)		**10**		**13**		**243**
Net Present Value (€*10^4)		**124**		**34**		**-149**

The second column of Table 5.2 shows the total results of the cost benefit analysis for the measure 'detour trams around tram tunnel The Hague'. The following conclusions can be formulated about the results regarding this measure:

- The benefits regarding in-vehicle time compared to the current disturbed situation when no measures are applied are negative. This indicates that after the measure is applied, the total in-vehicle time increases. This is consistent with the effect of this measure on passenger streams as discussed in chapter 4.2. Because of this measure, the largest part of passengers affected by the disturbance now chooses to use the diverted tram lines 2, 3, 4 or 6. Compared to the current situation in which more passengers transfer to other route alternatives or walk the last part of their trip, it is plausible that in-vehicle time increases.
- In line with the reasoning above, the effect of this measure on all other travel time components is positive. This shows that passengers mainly choose to use a route which has a slightly longer in-vehicle time, compared to other route alternatives with shorter in-vehicle times where transfers are required. Because in-vehicle time is perceived less negative compared to other travel time components, the net effect of this measure on travel time is clearly positive.
- The total passenger-distance travelled decreases as well because of this measure, which increases the benefits of this measure. This means that the detour passengers have to make because of an event (measured in distance) becomes smaller after this measure is applied.
- The comfort level increases as well because of this measure. In the situation when no measure is taken, chapter 4.2.3 shows that especially the route of the diverted tram line 6 and the route of tram line 17 suffer from a high load factor. When this measure is applied, except tram line 6 also the other 3 tram lines 2, 3 and 4 can drive via the city centre. The supplied capacity therefore increases more than the demand, leading to a higher level of comfort.

The third column of Table 5.2 shows the total results of the societal evaluation of the measure 'temporary extra intercity stops at Zoetermeer and The Hague Ypenburg'. The next conclusions can be formulated:

- The largest benefit of this measure is the reduction in waiting time. Because the frequency of trains stopping at Ypenburg and Zoetermeer is doubled, the average waiting time decreases.
- The largest societal cost of this measure is the extra in-vehicle time. This increase in in-vehicle time is especially caused because through passengers on the intercity services between Gouda and The Hague now suffer from additional travel time because of the extra stops. This shows the design dilemma between longer in-vehicle time and shorter waiting times: the additional costs because of longer in-vehicle times do not outweigh the additional benefits because of shorter waiting times here.
- A small increase in total travelled passenger-kilometres can be found because of this measure. This can be explained because a larger fraction of passengers affected by the disturbance chooses the train link Zoetermeer / Ypenburg – The Hague as route alternative because of the measure. Although the travel time of this alternative is relatively short because of the high average speed on the train link and because of reduced average waiting time, measured in kilometres this route alternative is often longer than route alternatives which were initially used.
- This measure has a slightly negative effect on the comfort level. As discussed in chapter 4.3.3, because of this measure affected passengers are more concentrated to the train link Zoetermeer / Ypenburg – The Hague as route alternative. This has as disadvantage that the comfort level on this train link decreases. However, the monetized effect is limited compared to the benefits gained from shorter waiting times.

In the fourth column of Table 5.2 the results of the evaluation of the measure 'switches near Leidschendam-Voorburg' are shown. The following conclusions are formulated:

- In general, this measure creates benefits for all travel time components. This means that all travel time components are reduced when this measure is applied, compared to the situation without this measure taken. Also less passenger-kilometres have to be made when this measure would be implemented, leading to benefits on this aspect as well. These effects can be explained because a part of the passengers is not affected by a disturbance anymore, because PT services can still be supplied on a part of the link segment in case of switches near Leidschendam-Voorburg. For these passengers no alternative route is required anymore, which decreases travel time and travel distance.

- The largest cost component of this measure is clearly related to infrastructure. Especially the construction of the switches leads to high costs. The results show that all travel time benefits do not outweigh the high infrastructure costs of this measure.
- At last, it can be concluded that the comfort level slightly decreases. This can be explained because in the current situation affected passengers use a quite large number of route alternatives. This indicates that the increase of passengers per route alternative is limited. After this measure is applied, about 30-33% of the initially affected travellers can keep using the metro/light rail services on a part of the link segment Laan van NOI – Forepark. This means that a substantial part of the affected passengers are concentrated on the part of the link segment Laan van NOI – Forepark which is not blocked anymore, leading to higher load factors. This can explain the reduction in comfort level.

5.2.2 Societal costs of non-robustness

The societal costs of major discrete events on a link segment can be calculated by comparing the societal costs between the situation when major discrete events occur and the situation when no major discrete events would occur at all (maximum robustness). These societal costs of major discrete events are in fact the costs of non-robustness of a certain link segment in the multi-level PT network. For both the situation without measures and the situation when a measure is applied, the costs of non-robustness (the difference between societal costs when major discrete events occur and societal costs when there are no disturbances) can be calculated.

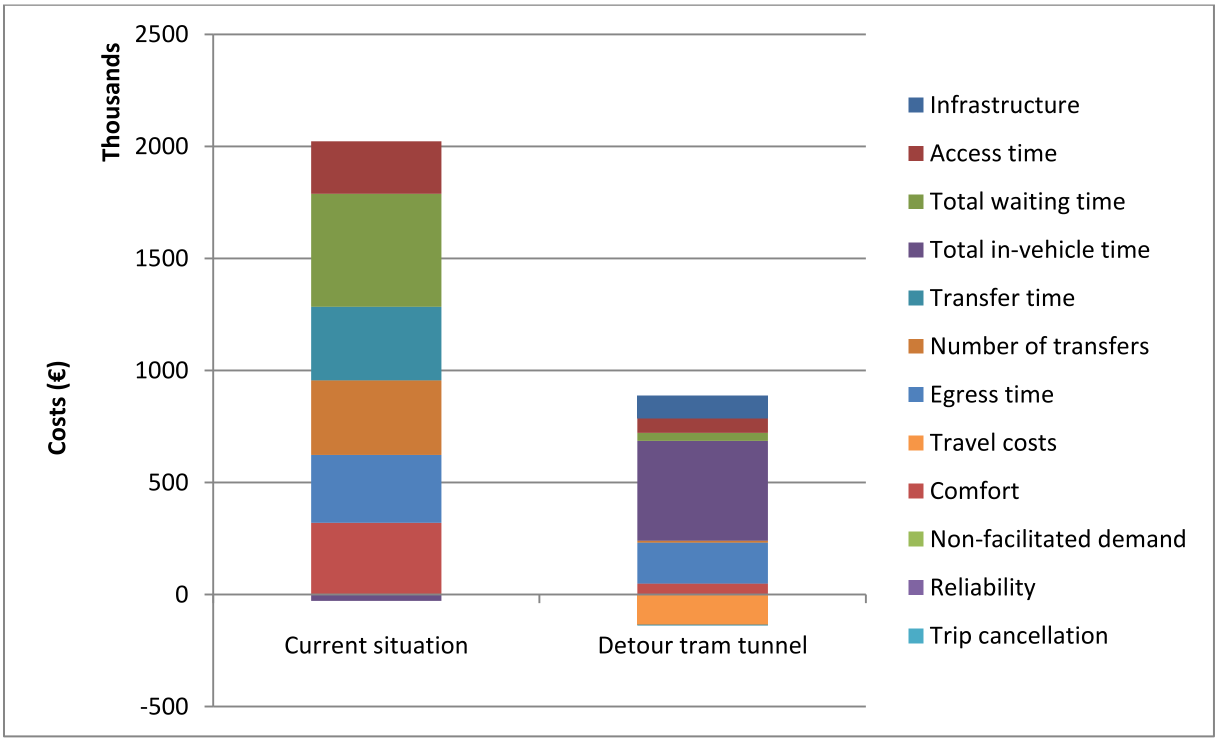

Figure 5.1: Societal costs of non-robustness in current situation without measures (left) and when the detour measure would be applied (right)

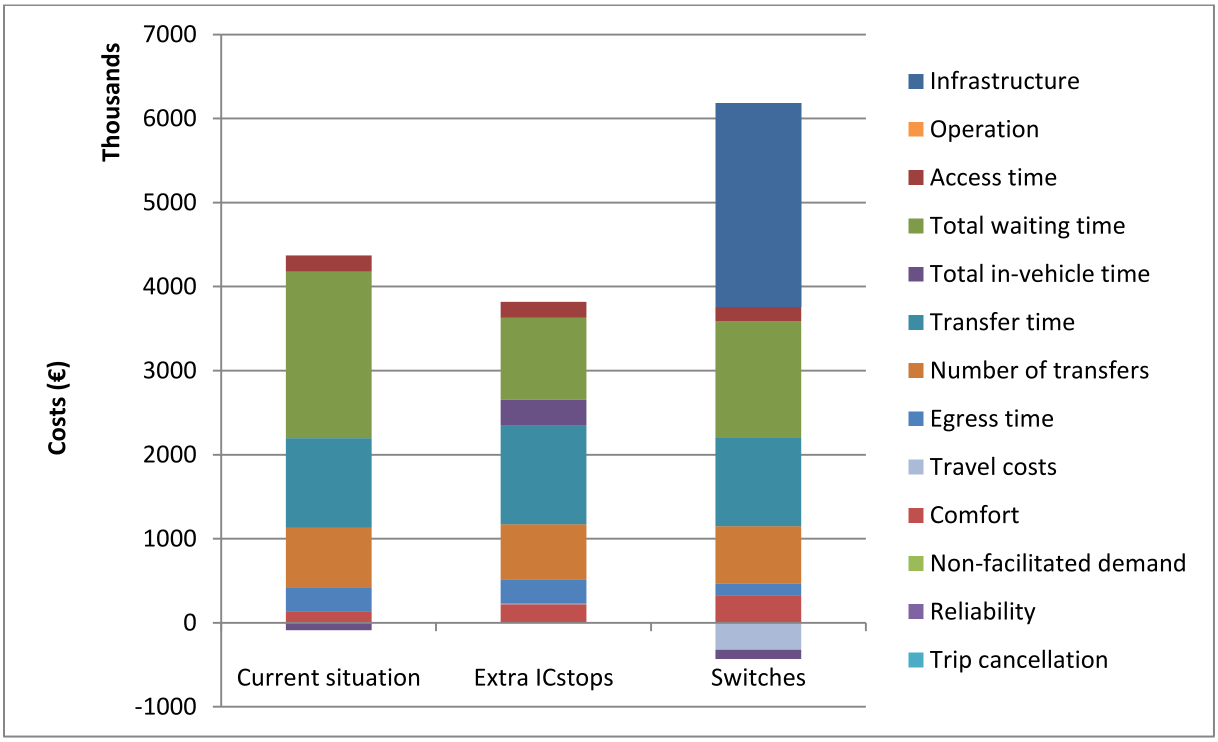

Figure 5.2: Societal costs of non-robustness in current situation without measures (left), when the measure 'extra IC stops' would be applied (middle) and when the measure 'extra switches' would be applied (right)

Figure 5.1 shows the societal costs of disturbances on the link Brouwersgracht – Central Station. In this figure, the additional societal costs because of major discrete events are calculated for the time period of 10 years. It can be seen that disturbances increase all travel time components and reduce travel comfort substantially, thereby increasing the societal costs. The largest part of the societal costs of events on this link segment can be attributed to the additional waiting time required for extra transfers needed to reach a destination. It should be noted that for the travel cost aspect, only the relative effect between the current situation and the situation after a measure is applied is known from the used transit model. Therefore, the travel costs are only shown as costs or benefit in the column of the measure.

Figure 5.1 also shows the societal costs of major discrete events in case the detour measure is applied. It can clearly be seen that the costs of non-robustness are substantially reduced by this measure. Especially the societal costs because of extra waiting time, transfer time and number of transfers are reduced. In total, this measure reduces the societal costs of non-robustness by 62%.

Figure 5.2 shows the costs of non-robustness – the societal costs of disturbances – for the link Laan van NOI – Forepark. When comparing the current situation with disturbances with the 'ideal' situation with maximum robustness (no disturbances at all), it can be seen that the societal costs of events are mainly caused by additional waiting time and transfer time.

When the measure 'extra IC stops at Zoetermeer and Ypenburg' would be applied, the total societal costs because of non-robustness are slightly reduced by 8%. This reduction is mainly caused by a reduction in waiting time, although at costs of some extra in-vehicle time.

From Figure 5.2 can clearly be seen that the societal costs of disturbances increase when the measure 'extra switches near Leidschendam-Voorburg' would be implemented, compared to the current situation. Although the societal costs because of travel time and travel cost effects are reduced by this measure, the societal costs increase substantially because of the high infrastructure costs. Also comfort costs increase slightly. In total, when infrastructure costs are incorporated, this measure increases the costs of non-robustness by 35%.

Table 5.3 summarizes the societal costs of non-robustness for the two considered link segments. These costs are calculated for the current situation, and for the situation in which a specific measure is applied. Except the total costs of non-robustness over the time period of 10 year, an estimation of the average societal costs of one major discrete event is performed. This is done by using the total time a link segment is blocked in this time period of 10 years (based on the results of the Monte Carlo simulation: see appendix C1) and the average duration of major discrete events on each link segment (see Table 2.14 in chapter 2.3).
It can be seen that the societal costs of disturbances on the link Laan van NOI – Forepark are higher than the societal costs of disturbances on the link Brouwersgracht – Central Station. This indicates that from a societal perspective the link Laan van NOI – Forepark suffers from a higher vulnerability than the link Brouwersgracht – Central Station. The measures 'detour trams around the tram tunnel' and 'temporary extra IC stops Zoetermeer and The Hague Ypenburg' reduce the societal costs per major discrete event.
It can also be seen that the average number of events in 10 years increases when the measure 'extra switches' is applied because of the higher frequency of switch failures. Overall, the (average) societal costs of an event become highest when the measure 'extra switches' would be applied.

Table 5.3: Total and average societal costs of major discrete events per link segment

Link / measure	Costs of non-robustness in 10 years (€*10^4)	Average number of events in 10 years	Average societal costs per event (€*10^3)
Brouwersgracht – Central Station – no measures	199	670	3.0
Brouwersgracht – Central Station – detour	75	670	1.1
Laan van NOI – Forepark – no measures	428	787	5.4
Laan van NOI – Forepark – extra IC stops	394	787	5.0
Laan van NOI – Forepark – switches	577	933	6.2

5.3 Sensitivity analysis

A sensitivity analysis is performed to analyze the effect of different values for uncertain input parameters on the results of the cost benefit analysis. When performing a sensitivity analysis, it is checked for which input data the largest uncertainty is expected.

Sensitivity to total blocked time of link segment

For this study, one of the most uncertain aspects is related to the frequency and duration of events on the BTM network. For the train network, quite detailed data from a longer time period are available. However, the databases used to estimate parameter values for frequency and duration of BTM events are remarkably smaller. Therefore, not all values used to characterize major discrete events on the BTM network could be tested statistically. In this chapter is therefore analyzed how sensitive the results of the societal cost benefit analysis are for different values of the input data regarding frequency and duration of events. Therefore, the total duration per year a link is blocked (which is the product of the frequency and duration of events on that link) is decreased by 20% and increased by 20%. The robustness measures are evaluated again. The results as shown in Table 5.4 indicate a bandwidth in which the real Net Present Value is expected to be.

From this table can be concluded that the Net Present Value of the measure 'detour trams around tram tunnel' and measure 'extra IC stops at Zoetermeer and The Hague Ypenburg' is quite sensitive for the total duration of major discrete events as input value. This can be explained because the costs of these measures, which are independent of the total blocked time, are relatively small compared to the benefits of these measures, which are directly dependent of the blocked time. However, despite this sensitivity, the Net Present Value for both measures remains clearly positive from a societal perspective.

For the measure 'extra switches near Leidschendam-Voorburg', the relative difference in Net Present Value indicates that the results of this measure are relatively insensitive to different total blocked times as input values. This can be explained because the costs of this measure – which are independent of the total blocked time – contribute substantially to the societal effects of this measure. The travel time benefits, which are dependent of the total blocked time, have a relatively small influence on the final NPV. Changing the total blockage time does not influence the infrastructure effects of this measure, which leads to a more stable output. This means that the Net Present Value of this measure remains convincingly negative.

Table 5.4: Results of sensitivity analysis to event duration: absolute and relative change in Net Present Value

Measure	Event duration -20%		Event duration +- 0%		Event duration +20%	
	NPV(€*10^4)	%	NPV(€*10^4)	%	NPV(€*10^4)	%
Detour tram tunnel	98	-22%	124	0%	151	+22%
Extra intercity stops	27	-20%	34	0%	41	+20%
Switches Leidschendam-Voorburg	-168	+13%	-149	0%	-126	-15%

Sensitivity to Value of Time

The Value of Time (VoT) used in the evaluation of measures is not directly derived from literature. In literature, the VoT is indicated for train and BTM separately. Therefore, based on the ratio between the average time spent per day in train and in BTM, a weighted average VoT is calculated (see appendix C2 for a more detailed explanation). This means that the assumed VoT of € 8.28 / hour is relatively uncertain: therefore a sensitivity analysis is performed to this value. The VoT is decreased and increased by 20%, based on which measures are evaluated again. Table 5.5 shows the absolute and relative effect on the Net Present Value after performing this sensitivity analysis.

From this table can be concluded that the results of the measure 'extra IC stops' are especially sensitive to different values of time, followed by the results of the measure 'detour around tram tunnel'. Again, the results of the measure 'switches near Leidschendam-Voorburg' are most robust against different values of time as input. Although the results of the first two measures are more sensitive for different VoT's, the NPV remains clearly positive even in case the VoT is reduced substantially. In reality, it is not expected that the VoT will deviate more than 20% from the assumed value. Therefore, the whole bandwidth of possible NPV's remains positive for the measures 'detour around tram tunnel' and 'extra IC stops'.

Table 5.5: Results of sensitivity analysis to VoT: absolute and relative change in Net Present Value

Measure	VoT -20% (€6.62/hr)		VoT +-0% (€8.28/hr)		VoT +20% (€9.94/hr)	
	NPV(€*10^4)	%	NPV(€*10^4)	%	NPV(€*10^4)	%
Detour tram tunnel	100	-19%	124	0%	149	+19%
Extra intercity stops	24	-28%	34	0%	43	+28%
Switches Leidschendam-Voorburg	-165	+11%	-149	0%	-133	-11%

Sensitivity to travel information and network knowledge

During all assignments barrier-free travelling is assumed, thereby assuming that passengers have full information about the occurrence of a major discrete event and about route alternatives available in the multi-level PT network (see chapter 3.2.2). This shows the potential of the remaining part of the PT network to accommodate passengers which are affected by a disturbance. This means that effects as calculated in all cost benefit analyses can be considered as upper bounds. This evaluation of measures shows what NPV *can* be realized in case passengers are provided with full information. Although in reality full information is not realistic, it is expected that travel information will be improved further the upcoming years, given the increasing use of smart phones which can give a lot of information about disturbances and route alternatives.

However, when these measures would be applied currently without improving travel information, for all measures a lower NPV is expected. For the measure 'detour trams around tram tunnel', the effect of less information on the NPV is expected to be limited. Because the largest part of the affected passengers stays in the diverted tram lines, a quite similar route choice pattern is expected even if passengers are not aware of an event on beforehand. During the trip, these passengers will just be confronted by the detour made on these lines. For the measure 'extra IC stops' less information can reduce the NPV more heavily. This is because passengers need to be aware of the fact that extra transfer possibilities at Zoetermeer and The Hague Ypenburg are supplied, before they will change their route choice to the train route alternative. Therefore it is especially important for this measure that PTO's provide passengers with sufficient information regarding the extra IC stops, in order to keep the NPV of this measure positive.

5.4 Implementation of measures

Based on the calculated Net Present Value and the performed sensitivity analyses the following conclusions can be formulated:

- The measure 'detour trams around tram tunnel The Hague' has a high Net Present Value, indicating that societal benefits substantially outweigh the costs of the measure.
- The Net Present Value of the measure 'detour trams around tram tunnel The Hague' is quite sensitive for different durations of the total time the link segment Brouwersgracht – Central Station is blocked, and for different VoT's. However, despite these sensitivities, the bandwidth for the Net Present Value still remains very positive from a societal point of view.
- The measure 'temporary extra IC stops at Zoetermeer and The Hague Ypenburg' has a positive Net Present Value. The societal benefits of this measure also clearly outweigh the costs, although the benefits are not that large as realized by the measure 'detour trams around tram tunnel'.
- The Net Present Value of this measure 'extra IC stops' is relatively sensitive to different input values used for total blocked time and VoT. The NPV is especially sensitive to different VOT's. Also qualitatively it can be stated that the NPV of this measure is sensitive to the amount of travel information provided to passengers.
- The measure 'extra switches near Leidschendam-Voorburg' has a clear negative Net Present Value, indicating that costs outweigh the societal benefits. Besides, the NPV of this measure is relatively insensitive to different durations of blocked time of the link segment and different values of time.

Based on these conclusions, recommendations can be formulated regarding the implementation of measures to improve the robustness of the case study PT network:

- The measure 'detour trams around tram tunnel The Hague' is recommended to implement, especially because of the very positive NPV, which is expected to remain positive even in case of some fluctuations in values of input parameters.
- The measure 'temporary extra IC stops at Zoetermeer and The Hague Ypenburg' is recommended to implement, especially because this measure offers an alternative which can be implemented easily. No infrastructure needs to be constructed for this measure. However, providing passengers with sufficient information about the improved transfer possibilities during disturbances is a requirement for a successful implementation.
- The measure 'extra switches near Leidschendam-Voorburg' is *not* recommended to implement, especially because of the stable, clearly negative Net Present Value.

Table 5.6 shows how the costs and benefits related to each measure are distributed over different stakeholders in the multi-level PT network. As explained in chapter 3.2.2, given the passenger perspective in this study a barrier-less travelling is assumed in case of disturbances. This means that additional travel costs because passengers have to make a detour are assumed to be fully compensated by the PTO's. Therefore, travel cost effects are not shown for passengers. In case fewer passenger-kilometres can be travelled during a disturbance because of a measure, the reduction in additional travel costs which PTO's have to compensate is presented as benefit for the PTO in Table 5.6.

From this table it can be seen that passengers benefit most from the effects of the measures. The implementation of the measure 'detour trams around tram tunnel' leads to both a positive financial and societal effect. Because of the financial benefits, a relatively smooth implementation process is expected for this measure. To create support and to ease the implementation process of this measure further, it might be an option that the HTM takes (partial) responsibility for the infrastructure costs of this measure, which normally have to be paid by the municipality. This can be assumed reasonable given the fact that the disturbances also occur on the PT network of HTM. Because this measure leads to financial benefits for the HTM which are larger than the financial costs the municipality should make, financial benefits are still left for HTM even when the HTM would take full responsibility for the investment costs.
For the measure 'extra IC stops at Zoetermeer and The Hague Ypenburg' it can be seen that the largest part of the financial costs comes at formal responsibility of the NS, because of the additional timetable hours the NS needs to make. In order to increase the willingness of NS to cooperate in the implementation of this measure, it seems reasonable to compensate NS for the additional costs they have to make. Clearly, the NS have to make financial costs because of a disturbance on the network of HTM and RET. Compensation of these costs could be done by the HTM, RET or the Stadsgewest Haaglanden, or by a combination of these stakeholders. These stakeholders should negotiate which amount of money they want to contribute for the realization of societal benefits for passengers on the link between Laan van NOI and Forepark. Note that the financial effects of this measure are negative. This means that the implementation of this measure will cost money from a financial perspective. Implementation is therefore only realistic if one or more stakeholders are willing to contribute financially to realize societal robustness benefits.

Table 5.6: Distribution of societal / financial costs and benefits over stakeholders involved in the multi-level PT network

Link	**Tram tunnel**		**Station Laan van NOI - Forepark**			
Measure	**Detour tram tunnel**		**Extra IC stops**		**Switches**	
Costs / benefits	Financial ($€*10^4$)	Societal ($€*10^4$)	Financial ($€*10^4$)	Societal ($€*10^4$)	Financial ($€*10^4$)	Societal ($€*10^4$)
PT passengers		+121		+47		+62
Stadsgewest Haaglanden					-220	
Municipality of The Hague	-10					
HTM	+13				-22	
HTM / RET			-0.7		+32	
Dutch Railways (NS)			-13			
Total ($€*10^4$)	+3.4	+121	-13	+47	-210	+62
NPV total ($€*10^4$)	*+124*		*+34*		*-149*	

5.5 Conclusions

In this chapter is shown how measures proposed to improve the robustness of a multi-level PT network against major discrete events can be evaluated. Because of the stochasticity related to the duration and frequency of different major discrete event types, Monte Carlo simulation is used to generate values for the frequency and duration from a Poisson and (log) normal distribution, respectively. Based on the performed Monte Carlo simulation the total time a link segment is blocked per year can be determined. This total blocked time can be used as input for the societal cost benefit analysis.

The following conclusions can be formulated based on the analyses performed in this chapter:

- On average, major discrete events block 1-2% of all scheduled PT operations on the two considered link segments Brouwersgracht – Central Station and Laan van NOI – Forepark.

- When no measures are applied, the average societal costs of one major discrete event equal €3.0*10^3 and €5.4*10^3 for the link segment Brouwersgracht – Central Station and Laan van NOI – Forepark, respectively.
- The measure 'detour trams around tram tunnel' can reduce the average societal costs of a disturbance on the link Brouwersgracht – Central Station by 62%: when this measure would be implemented, the average societal costs of one event on this link segment equal €1.1*10^3.
- The measure 'temporary extra IC stops at Zoetermeer and The Hague Ypenburg' can reduce the average societal costs of a disturbance on the link Laan van NOI – Forepark by 8% to €5.0*10^3.

The Net Present Value of the measures 'detour tram around tram tunnel' and 'temporary extra IC stop at Zoetermeer and The Hague Ypenburg' are both positive. This indicates that from a societal point of view, there is still room to improve the robustness of multi-level PT networks. Because disturbances occur only during 1-2% of the PT operations on average, there should be looked for relatively small, 'smart' measures to improve the robustness of links in the multi-level network. Large infrastructure design measures, like the construction of switches, lead to high costs which outweigh the robustness benefits. The results of Table 5.7 support this conclusion. This study shows that smaller infrastructure design measures and temporary service network design measures are able to improve the robustness of the multi-level PT network from a societal perspective. Note that especially a successful implementation of a temporary service network design measure requires more flexibility of PTO's and more cooperation between PTO's during disturbances.

Table 5.7: Relation between financial costs of measure and realized Net Present Value

	Detour tram tunnel	Extra IC stops	Switches Leidsch-V
Financial costs (€*10^4)	10	13	243
Net Present Value (€*10^4)	124	34	-149

6

Conclusions and recommendations

In this chapter, the main conclusions of the performed study are formulated first (chapter 6.1). Second, recommendations for further improvements of the proposed methodology are formulated in chapter 6.2. Chapter 6.3 shows recommendations for further research.

6.1 Conclusions

For this study, the following main research question is formulated:

> **What methodology can be developed to evaluate the robustness of multi-level public transport networks and to evaluate robustness effects of measures for the case study network between Rotterdam and The Hague?**

The methodology developed in this study to evaluate the robustness of multi-level public transport networks and to evaluate robustness measures is shown in Figure 6.1. The developed methodology consists of four phases. The most important conclusions for the steps in each phase are discussed below. The multi-level public transport network between Rotterdam and The Hague is used as case study for illustrative purposes.

Phase A: Characterization of different major discrete event types on the multi-level public transport network based on frequency, duration, impact on infrastructure availability and impact on public transport demand

In this first phase, different major discrete event types on different network levels are identified and characterized based on the frequency with which they occur, the duration and the impact on infrastructure availability and public transport demand. All this information is calculated as much as possible based on empirical, real-world data in this study. Besides, to our best knowledge this is the first study in which major discrete events on a certain network level are characterized relative to other public transport network levels. The next conclusions can be formulated based on empirical data:

- On the Dutch train network, the major discrete event types ‘vehicle breakdown’, ‘switch failure’, ‘suicide’ and ‘signal failure’ occur with the highest frequency per time period: together these four event types are responsible for 63% of all events occurring on the train network.

- The major discrete event type 'vehicle breakdown' occurs with the highest frequency on train, metro/light rail and tram networks. Vehicle breakdowns are responsible for 61%, 46% and 18% of all major discrete events on the tram network, metro/light rail network and train network, respectively.
- The expected number of vehicle breakdowns per million vehicle-kilometres equals 2.11 on train networks, 57.7 on bus network, 61.4 on metro/light rail networks and 120 on tram networks. The expected number of major incidents per million vehicle-kilometres equals 0.37 on train networks, 3.31 on metro/light rail networks, 11.0 on bus networks and 12.9 on tram networks. Also after correcting for differences in average speed between different modes, it can be concluded that train networks are more robust against vehicle breakdowns and major incidents in terms of frequency, compared to metro/light rail, tram and bus networks. Especially tram networks seem to be relatively vulnerable to vehicle breakdowns and major incidents.
- The average duration of major discrete events on the bus/tram/metro network is slightly larger than one hour, whereas the average duration of events on the train network varies between one and four hours for different event types. Both the average duration and variance of the duration of major discrete events on the train network are larger compared to these values for major discrete events on the bus/tram/metro network.
- In case of major discrete events with a high level of predictability – like large maintenance works which are announced on beforehand – based on Chipcard data a public transport demand reduction of 14% is empirically found on affected trips on a working day on an urban public transport network.
- Empirical data suggests that public transport demand reduction is larger in case the share of leisure trips is larger, compared to days when commuting and business are the most dominant trip purposes. A public transport demand reduction because of maintenance works between 50% and 56% as empirically found can be considered as upper bound on a weekend day.

Phase B: Identification of the most vulnerable links in the multi-level public transport network

In this study a methodology is developed to identify the most vulnerable links in a multi-level public transport network, which is shown in Figure 6.1. The average frequency, average duration and impact of events on infrastructure availability as determined in phase A are used as input for this methodology. The following conclusions are formulated:

- The identified most vulnerable link segments are from different network levels. This indicates that there is not one network level which is clearly most vulnerable or most robust.
- Links on the train network are especially vulnerable because many passengers experience hindrance in case of a disturbance. The expected blocked time of train links is relatively low.
- Compared to train links, metro/light rail and tram links suffer more often from disturbances. Especially busy metro and tram links are therefore vulnerable in the multi-level network.

Phase C: Development of robustness measures for the identified vulnerable links and evaluation of measures

When the most vulnerable links in a multi-level public transport network are identified, measures can be developed to improve the robustness of these links. In general, the next types of measures might be promising, given the characteristics of disturbances on different network levels:

- Prevention-focused measures which can reduce the frequency of vehicle breakdowns (can be applied on all network levels) or can reduce the frequency of suicide events on the train network;
- Small infrastructure design measures which can realize extra turning facilities or an emergency bypass;
- Temporary service network design measures which improve network redundancy or flexibility.

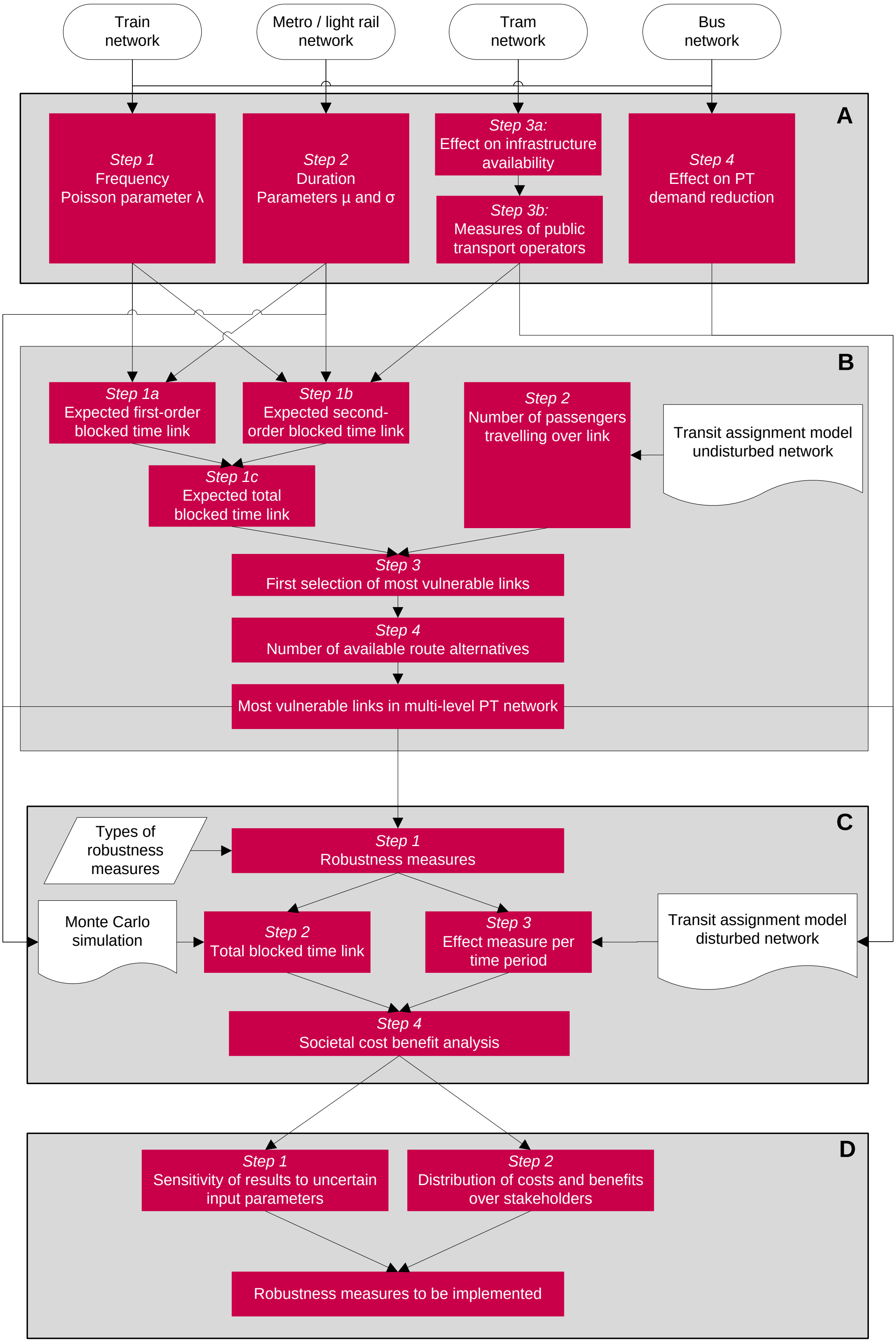

Figure 6.1: Schematic overview of developed methodology to evaluate robustness and robustness measures in multi-level public transport networks

After measures are developed, a method is developed to evaluate the effects of these measures:

- Use Monte Carlo simulation to determine the total time a link segment is blocked per year, differentiated to each time period (morning peak, evening peak etc.) distinguished in the used transit assignment model. Because of the stochasticity related to the duration and frequency of different major discrete event types as identified in phase A, Monte Carlo simulation is used to generate values for the frequency and duration from a Poisson and (log) normal distribution, respectively.
- When the total blocked time for a link segment is known, the difference in societal costs of disturbances between the situation without measure and the situation when a measure is applied can be calculated for a certain time period by using a societal cost benefit analysis.

Robustness measures are evaluated for two vulnerable link segments of the case study network. For the link segment Brouwersgracht – Central Station, a measure is proposed in which an emergency bypass is realized to divert transit lines in case of an event on this link segment. For the link segment Laan van NOI – Forepark, the measures 'temporary extra intercity stops at Zoetermeer and The Hague Ypenburg' and 'construction of switches near Leidschendam-Voorburg' are evaluated. The following conclusions can be formulated:

- On average, major discrete events block 1-2% of all scheduled PT operations on the two considered link segments Brouwersgracht – Central Station and Laan van NOI – Forepark.
- For a period of 10 years, the simulated time that the link segment Brouwersgracht – Central Station and Laan van NOI – Forepark are blocked by major discrete events equals 715 hours and 964 hours, respectively.
- When no measures are applied, the average societal costs of one major discrete event equal €3.0*10^3 and €5.4*10^3 for the link segment Brouwersgracht – Central Station and Laan van NOI – Forepark, respectively. These values indicate the costs of non-robustness per event. From a societal perspective, the last link therefore suffers from a higher level of vulnerability compared to the first link.
- The measure 'detour trams around tram tunnel' can reduce the average societal costs of a disturbance on the link Brouwersgracht – Central Station by 62%: when this measure would be implemented, the average societal costs of one event on this link segment equal €1.1*10^3.
- The measure 'temporary extra intercity stops at Zoetermeer and The Hague Ypenburg' can reduce the average societal costs of a disturbance on the link Laan van NOI – Forepark by 8% to €5.0*10^3.

The Net Present Value of the measures 'detour tram around tram tunnel' and 'temporary extra intercity stop at Zoetermeer and The Hague Ypenburg' is in both cases positive. This indicates that from a societal point of view, there is still room to improve the robustness of multi-level public transport networks. The Net Present Value of the measure 'extra switches near Leidschendam-Voorburg' is negative. Because disturbances occur only during 1-2% of the PT operations on average, there should be looked for relatively small, smart measures to improve the robustness of links in the multi-level network.

Phase D: Implementation of measures

In this phase, it is analyzed which measures can be implemented:

- Perform a sensitivity analysis to investigate for which measures the Net Present Value remains quite stable and positive, in case the values of uncertain input parameters are changed.
- Investigate how the financial and societal costs and benefits of a robustness measure are distributed over different stakeholders involved in the multi-level public transport network.
- Sufficient travel information, flexibility of public transport operators and more cooperation between public transport operators are requirements for a successful implementation of especially temporary service network design measures, for which the network of another public transport operator temporarily functions as back-up for a blocked network part of a certain operator.

6.2 Recommendations for further improvements of the proposed methodology

This chapter formulates recommendations for further improvements of the proposed methodology to evaluate the robustness of multi-level public transport networks. The recommendations are based on a reflection on assumptions made in this study.

First, the methodology could be improved further if the (probability function of the) frequency and duration of major discrete events on the bus/tram/metro network are estimated and statistically tested for more categories. In this study, a functional categorization is used when estimating a Poisson parameter for the frequency of events on the bus/tram/metro network. For the duration, only one distribution function is estimated which represents the duration of all event types together for each mode of the bus/tram/metro network.
This allows a more in-depth analysis to the frequency and duration of events. For example, if the frequency of switch failures increases (as is the case for the measure 'switches near Leidschendam-Voorburg'), the additional blocked time could be determined based on duration values specified for switch failures. In this study however, the average duration over all event types on the metro/light rail network is used. Although differences are expected to be limited because of the relatively low frequency of switch failures, specifying frequency and duration for more event categories can give more information and insight about the effects of major discrete event types.

Second, the applied methodology could be improved further when multiple, location-specific predictors would be used to estimate the frequency of events on a certain link. In this study, for each major discrete event type one predictor is assumed which is used to translate general parameter values to values for a specific link. It is however expected that the frequency of an event can better be predicted by considering multiple predictors and their interactions. Therefore, the methodology can be improved if different link characteristics are used simultaneously to estimate the frequency of a certain major discrete event type on that link.
In this set of predictors, also location-specific influences should be incorporated. In this study, only general link characteristics like link length, vehicle-kilometres and track length are used as predictors. However, the occurrence of major discrete events can also depend strongly on the specific location of a link. For example, the presence of mental hospitals near a train track is a location-specific predictor which can strongly influence the frequency of suicide events on a certain link.

Third, the methodology used to identify vulnerable links can be improved further by developing an algorithm to assess the number of available routes in the multi-level network for each link and for each origin-destination pair (step 4 of phase B in Figure 6.1). In this study, the number of available route alternatives is assessed qualitatively based on the specific network layout. This is done because the number of available route alternatives differs per origin-destination pair. Quantifying these alternatives is therefore very time consuming. However, the methodology developed in this study can be improved further if an algorithm can be designed to calculate this number of route alternatives given a certain network layout. For example, for each origin-destination pair which is affected by a major discrete event on a certain link, the number of feasible route alternatives could be calculated by applying route choice set criteria as formulated by Fiorenzo-Catalano (2007). Given time considerations, such method is not applied in this study yet. Applying such method however contributes to objectify all steps of the developed methodology. This increases the extent to which this methodology can be reproduced and generalized to other networks as well.

Fourth, the methodology developed to identify vulnerable links could be improved further when the link-based focus is extended. The methodology developed in this study only focuses on the identification of vulnerable links in a network. The nodes connecting different links are therefore only implicitly considered. However, especially nodes where many links come together can be vulnerable. Therefore, extending the developed link-based methodology to a methodology which can incorporate the vulnerability of large interlockings and junctions in an explicit way can be valuable.

Fifth, the method applied in chapter 4 to identify route alternatives chosen by passengers in case of disturbances can be improved further when a more advanced algorithm would be used. In this study, the exact routes travelled by all passengers per origin-destination pair are hard to reproduce. Therefore, as explained in chapter 4.2, feasible route alternatives are selected manually. For each route alternative a unique link is selected, for which differences in passenger flow are analyzed. However, in order to formalize this procedure, it would be better if an objective algorithm would be used to generate feasible routes. Also for this step in the methodology, criteria as formulated by Fiorenzo-Catalano (2007) might be useful in order to find feasible routes.

Sixth, the assignment procedure used in this study can be improved when en-route route choice is incorporated in the transit assignment model. In this study only pre-trip route choice is incorporated in the assignment, given the limitations of the model used. Using pre-trip route choice only gives an upper bound of the effects of measures, because it assumes that all passengers have full information about the disturbance and route alternatives available in the multi-level network. This upper bound is certainly of value, because it shows the potential of the multi-level public transport network to function as back-up for passengers in case of a disturbances when no information or knowledge barriers exist. However, the incorporation of en-route route choice is valuable to get insight in the dynamics which occur during the transition phase between an undisturbed and a disturbed situation. Without en-route route choice, a stepwise transition is implicitly assumed.
In addition, the methodology can be improved further as well in case a capacity constrained assignment is performed. Because it is not possible yet to specify a convergence criterion for transit assignment in OmniTRANS, in this study capacity is checked independent from the model after the assignment. Incorporating a capacity constraint in the assignment might be especially of relevance during large disturbances, in order to prevent the assignment of passengers to routes where no capacity is left anymore.

Seventh, the impact of events during heavy snow can be modelled in a more realistic way. In this study, events are only simulated on identified vulnerable links separately. Given the relatively low frequency of major discrete events, it seems reasonable during regular circumstances not to consider the interaction effect if two major discrete events would occur simultaneously at locations close to each other, which would strengthen the total negative effect for passengers. However, during heavy snow the frequency of especially switch failures, signal failures and vehicle breakdowns increases considerably. In this case, it becomes quite realistic that events occur simultaneously on the network, and that there is overlap in the influence area of these events. Therefore, during heavy snow it is recommended not to model events on the selected vulnerable link only, but to model events on different links simultaneously.

Finally, the performed societal cost benefit analysis can be improved in case public transport demand and supply are not assumed fixed during the whole considering time horizon of 10 years. In this study demand and supply are assumed fixed as simplification. However, in order to evaluate measures over a longer time period in a more realistic way, demand and supply scenarios should be used instead of assuming a constant demand and supply.
At last, the societal cost benefit analysis can be improved further when long term reliability effects are incorporated quantitatively. Although the effect of measures on long term reliability is expected to be limited (see chapter 5.1.2), it is recommended to quantify this in order to underpin this assumption.

6.3 Recommendations for further research

This chapter formulates recommendations for further research, based on the results found in this study.

First, it is recommended to perform more research to the seasonal influences on the frequency of major discrete events on the bus/tram/metro network. The database used for this study only contains data from the summer and spring. Therefore, seasonal influences could not be tested statistically. In this study, the frequency of events during spring and winter is estimated based on the seasonal patterns found for events on the train network. It is recommended to use a larger database which contains data of major discrete events of all seasons of the year, in order to get more reliable information about events occurring on the bus/tram/metro network in different seasons.
Besides, the use of data from different public transport operators is recommended, since this reduces the risk that the used data is not representative for the frequency and duration of events on the bus/tram/metro networks in The Netherlands in general, if the values of this operator are for example atypical.

Second, it is recommended to get more insight in the effects of different major discrete event types on public transport demand reduction. In this study, a limited amount of Chipcard data is used to illustrate the effect of predictable major discrete events on public transport demand reduction. However, a part of this data does not show the whole public transport trip made by passengers. Some data only show information about one trip leg made, whereas other data show the total trip made on the network of one public transport operator. However, full information about the effects of major discrete events on public transport demand reduction can only be gained if the total multi-level or even multimodal trip through the network can be reconstructed. Chipcard data – which are only recently available – are very promising in order to investigate the route choice effects of passengers because of predictable major discrete events.
Besides, in this study no public transport demand reduction is assumed for major discrete events with a low level of predictability. However, when events with a low level of predictability occur relatively often on a certain link, there can be a long term effect on demand because of these event as well. Insight in this long term effect can certainly be of value in order to calculate the costs of disturbances and to evaluate proposed measures to improve robustness in a complete and adequate manner.
Additionally, the Chipcard data used is coming from two urban public transport operators. It is therefore recommended to investigate the effect of for example large maintenance works on the train network on public transport demand.

Third, it is recommended to gain more knowledge about behaviour of passengers during major discrete events. Currently, there is hardly information about the exact behaviour when passengers are confronted with major discrete events. The use of Chipcard data in combination with GPS tracking might be an interesting option to gain more insight around this issue. When more information about this type of behaviour is known, the chosen transit (assignment) models can be consistent with the model requirements coming from such empirical research.
Additionally, it is recommended to perform research to the modelling of passenger behaviour during major discrete events in relation to crowding. In case of crowding during major discrete events, a fraction of the passengers is expected to change route choice. However, another fraction is expected to remain on the same route, while skipping a crowded vehicle. Research to what fraction of passengers performs what kind of behaviour, is certainly of relevance.

Fourth, it is recommended to validate the developed methodology to identify vulnerable links in a multi-level public transport network. For a small test network, the links which are indicated as most vulnerable based on this methodology should then be compared to the list of most vulnerable links when a disturbance is simulated on each link of the network separately.

Finally, it is recommended to extend the topic of this study of robustness of multi-level public transport networks to robustness of real multimodal networks. In that way, the total network – both public and private – can be considered when determining which route alternatives can be used by passengers. Research to the extent that travellers are willing to perform multimodal transfers in case of events can certainly be of value.

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Appendix A1

Seasonal differences between frequencies of major discrete events on train network

This appendix shows the method and results of testing whether seasonal differences exist in frequency of different major discrete event types occurring on the Dutch train network. Table A1 shows the resulting 10 event types of the 15 major discrete event types as identified in chapter 2.1 for which it is deemed relevant to test if seasonal differences exist. To test for seasonal differences, it is tested if the average frequency per time period with which a certain event type occurs differs significantly between different seasons. This testing consists of two steps:

- Check if a parametric ANOVA-test can be performed to test whether the average number of events per time period differs between the seasons (De Vocht, 2006):
    - Check if events occurring in different seasons are independent from each other.
    - Test if no significant differences in variance exist between the four groups by performing Levene's Test of Homogeneity of Variances. In case the p-value related to Levene's statistic is smaller than the significance level $\alpha=0.05$, the null hypothesis that no significant differences in variance exist between the groups is rejected.
    - Test if the dependent variable – the average number of events per time period – for each season follows a normal distribution. This is done by visual inspection of the histogram and Q-Q plot, by analyzing skewness and kurtosis of the curve (in a perfect normal distribution skewness and kurtosis are equal to zero) and by performing a Kolmogorov-Smirnov (K-S) test (with Lilliefors correction) and Shapiro-Wilk (S-W) test.
- If all three conditions are satisfied, perform a parametric ANOVA-test. If one or more conditions as mentioned above are not satisfied, perform a non-parametric Kruskal-Wallis test to test if significant differences in average frequency exist between different seasons.

For all event types, it can be assumed that the occurrence of events in different seasons is independent from each other. Table A1 shows the results of testing on homogeneity of variances. Tables A2 – A5 show the results of testing the normality of the distribution of average number of events per time period for each season. From tables A1 – A5 can be concluded that no major discrete event type satisfies all conditions to perform a parametric ANOVA test: for all event types either the variances of different seasons are not statistically equal, or values of the dependent variable do not follow a normal distribution (or both). Therefore, for all major discrete event types on the train network a non-parametric Kruskal-Wallis test is performed to test for seasonal differences in average number of events per time period.

Table A1: Results of testing the homogeneity of variances for major discrete event types

Major discrete event type	Levene's statistic	p-value
Vehicle breakdown	1.97	.121
Switch failure	2.55	.059
Blockage	1.82	.147
Defect / damaged bridge	3.41	.019
Power failure	3.20	.025
Defect track	3.79	.012
Defect overhead wire	1.76	.158
Signal failure	0.22	.803
Suicide	0.24	.867
Level crossing failure	0.85	.471

Table A2: Results of testing the normality of average number of events per time period during spring

Major discrete event type	Skewness	Kurtosis	K-S statistic	p-value	S-W statistic	p-value
Vehicle breakdown	0.29	0.11	0.14	.065	0.96	.216
Switch failure	0.67	0.01	0.15	.029	0.94	.047
Blockage	2.04	5.77	0.33	.000	0.68	.000
Defect / damaged bridge	0.85	-0.14	0.25	.000	0.81	.000
Power failure	1.52	2.10	0.30	.000	0.78	.000
Defect track	3.03	7.84	0.53	.000	0.35	.000
Defect overhead wire	0.61	0.70	0.26	.000	0.82	.000
Signal failure	2.14	8.46	0.17	.004	0.81	.000
Suicide	0.40	-0.20	0.16	.010	0.95	.088
Level crossing failure	0.74	1.43	0.18	.003	0.92	.008

Table A3: Results of testing the normality of average number of events per time period during summer

Major discrete event type	Skewness	Kurtosis	K-S statistic	p-value	S-W statistic	p-value
Vehicle breakdown	0.88	2.40	0.15	.024	0.94	.046
Switch failure	1.00	0.78	0.20	.000	0.91	.005
Blockage	1.40	1.92	0.27	.000	0.81	.000
Defect / damaged bridge	1.93	4.47	0.28	.000	0.76	.000
Power failure	1.96	6.04	0.24	.000	0.82	.000
Defect track	1.58	2.18	0.38	.000	0.68	.000
Defect overhead wire	1.54	3.23	0.22	.000	0.81	.000
Signal failure	0.47	0.00	0.13	.109	0.97	.309
Suicide	1.29	2.70	0.17	.007	0.90	.002
Level crossing failure	0.09	-0.73	0.17	.109	0.95	.061

Table A4: Results of testing the normality of average number of events per time period during autumn

Major discrete event type	Skewness	Kurtosis	K-S statistic	p-value	S-W statistic	p-value
Vehicle breakdown	0.46	0.70	0.14	.200	0.97	.504
Switch failure	0.43	0.73	0.18	.037	0.96	.320
Blockage	1.66	3.10	0.24	.000	0.78	.000
Defect / damaged bridge	2.17	6.10	0.38	.000	0.62	.000
Power failure	1.31	2.26	0.22	.003	0.83	.001
Defect track	2.17	6.10	0.38	.000	0.62	.000
Defect overhead wire	2.24	7.15	0.27	.000	0.67	.000
Signal failure	-0.18	-0.88	0.15	.165	0.93	.083
Suicide	0.90	1.08	0.18	.031	0.94	.104
Level crossing failure	1.28	2.26	0.23	.165	0.87	.003

Table A5: Results of testing the normality of average number of events per time period during winter

Major discrete event type	Skewness	Kurtosis	K-S statistic	p-value	S-W statistic	p-value
Vehicle breakdown	0.48	0.08	0.14	.077	0.95	.110
Switch failure	0.16	-0.69	0.13	.191	0.96	.276
Blockage	2.58	7.13	0.35	.000	0.59	.000
Defect / damaged bridge	0.66	-0.54	0.25	.000	0.83	.000
Power failure	1.24	1.08	0.28	.000	0.80	.000
Defect track	2.68	9.45	0.36	.000	0.60	.000
Defect overhead wire	0.71	0.30	0.18	.006	0.86	.000
Signal failure	1.49	4.11	0.15	.060	0.88	.002
Suicide	0.36	0.43	0.21	.001	0.93	.038
Level crossing failure	0.58	0.47	0.22	.060	0.92	.012

Table A6 shows the results of the performed Kruskal-Wallis test. For the event types 'switch failure', 'defect overhead wire', 'defect track', 'defect / damaged bridge' and 'suicide' no significant difference in average number of events could statistically be shown. For the event types 'vehicle breakdown', 'signal failure', 'level crossing failure', 'power failure' and 'blockage' the Kruskal-Wallis test gives significant results, indicating that significant differences exist between seasons. In that case, the average number of events per time period is checked empirically for each season to get an indication which seasons are expected to differ significantly from each other. After this categorization is made, a Kruskal-Wallis test (if one category consists of three seasons and one category of one season) or Mann-Whitney U test (if both categories consist of two seasons) is performed again to check whether significant differences between seasons per category still exist. Within all categories, no significant differences between seasons are found in this second step. Therefore, the categorization as shown in Table A6 is used in this study. In case seasonal differences exist, a Poisson parameter is estimated for each category of a major discrete event type separately.

Table A6: Results of Kruskal-Wallis test

Event type	Kruskal-Wallis X^2	p-value	Category 1	Category 2
Switch failure	.594	.898		
Vehicle breakdown	12.5	.006	Spring / summer / winter	Autumn
Signal failure	12.7	.005	Spring	Summer / autumn / winter
Level crossing failure	14.1	.003	Autumn / winter	Spring / summer
Power failure	11.6	.009	Spring / autumn / winter	Summer
Defect overhead wire	6.01	.111		
Defect track	7.73	.052		
Defect bridge	7.31	.063		
Suicide	4.32	.229		
Blockage	8.00	.046	Spring / winter	Summer / autumn

Appendix A2

Frequencies of major discrete events on the train network

In this appendix, the results of statistical testing which parameters can approximate the frequency with which different major discrete event types occur on the train network are described. As explained in chapter 2.2, from a theoretical perspective it is expected that the frequency with which an event type occurs per time period can be described by a Poisson distribution. Therefore, it is statistically tested if the empirical distribution fits a Poisson distribution. Tables A7 – A11 show the results of this distribution fitting for each major discrete event type on the Dutch train network separately. These tables indicate the estimated Poisson parameter ƛ, which equals the average number of events per time period. The empirical frequencies are compared with the expected frequencies based on this estimated Poisson parameter. These tables also show the X^2 value calculated based on the empirical and expected frequencies. This X^2 value is compared to the critical X^2 value for *n-1* degrees of freedom (with *n* being the number of different values for the frequency of an event per time period found in the empirical distribution) (Universiteit Twente, 2013). In case the X^2 value > the critical X^2 value when using a significance level α=0.05, the hypothesis that the empirical distribution follows a Poisson distribution is rejected. Two conditions have to be satisfied when performing a Chi-square test (De Vocht, 2006):

- 80% of all expected cell frequencies ≥ 5;
- 100% of all expected cell frequencies ≥ 1.

In case those conditions are not satisfied directly, different frequencies found in the empirical distribution are clustered into a larger category in order to increase the expected cell frequency of this cluster.

In appendix A1 it is tested if seasonal differences in average frequency of event types exist. It is statistically shown that for some event types seasonal differences exist in the average frequency with which an event occurs per time period. For these events the Poisson parameter ƛ is estimated for each season separately. Therefore, tables A7 – A10 show the estimated Poisson parameters and resulting X^2 values for all major discrete event types on the Dutch train network as a whole for each season. In case no seasonal influences are relevant for the frequency of a certain event type, the estimated Poisson parameter is equal for all seasons.
As explained in chapter 2.2 a special snow scenario is developed representing heavy snowfall, which can only occur during the winter season. In this snow scenario, the Poisson parameters representing the frequency of vehicle breakdowns, switch failures and signal failures are different from the parameters used during regular periods in the winter. Therefore, Table A11 shows the estimated Poisson parameters and distribution fitting process for all major discrete event types during heavy snow.

Table A7: Parameter estimation of frequency of major discrete events on the whole Dutch train network during spring

Major discrete event type	Poisson parameter	X^2 value	Critical X^2 value
Vehicle breakdown	λ = 5.0 / week	6.1	14
Major incident	λ = 1.0 / week	9.0	9.5
Switch failure	λ = 4.7 / week	10.8	18.3
Blockage	λ = 0.6 / week	0.9	6.0
Restrictions by emergency services	λ = 2.1 / week	3.1	11.1
Defect / damaged rail bridge	λ = 0.9 / week	3.7	9.5
Power failure	λ = 1.1 / week	8.1	9.5
Defect track	λ = 0.4 / week	2.3	6.0
Defect overhead wire	λ = 1.0 / week	5.7	9.5
Signal failure	λ = 3.0 / week	6.6	9.5
Suicide	λ = 4.5 / week	16.9	16.9
Level crossing failure	λ = 2.8 / week	9.0	11.1
Damaged train viaduct	λ = 0.3 / week	0.0	6.0
Copper theft	λ = 0.3 / week	0.0	6.0
Large maintenance works	λ = 1.3 / month	5.3	6.0

Table A8: Parameter estimation of frequency of major discrete events on the whole Dutch train network during summer

Major discrete event type	Poisson parameter	X^2 value	Critical X^2 value
Vehicle breakdown	λ = 5.0 / week	6.1	14
Major incident	λ = 1.0 / week	9.0	9.5
Switch failure	λ = 4.7 / week	10.8	18.3
Blockage	λ = 1.1 / week	5.6	9.5
Restrictions by emergency services	λ = 2.1 / week	3.1	11.1
Defect / damaged rail bridge	λ = 0.9 / week	3.7	9.5
Power failure	λ = 2.2 / week	6.3	9.5
Defect track	λ = 0.4 / week	2.3	6.0
Defect overhead wire	λ = 1.0 / week	5.7	9.5
Signal failure	λ = 4.4 / week	18.4	15.5 (α = 0.05) 20.1 (α = 0.01)
Suicide	λ = 4.5 / week	16.9	16.9
Level crossing failure	λ = 2.8 / week	9.0	11.1
Damaged train viaduct	λ = 0.3 / week	0.0	6.0
Copper theft	λ = 0.3 / week	0.0	6.0
Large maintenance works	λ = 1.3 / month	5.3	6.0

Table A9: Parameter estimation of frequency of major discrete events on the whole Dutch train network during autumn

Major discrete event type	Poisson parameter	X^2 value	Critical X^2 value
Vehicle breakdown	ƛ = 6.9 / week	1.2	6.0
Major incident	ƛ = 1.0 / week	9.0	9.5
Switch failure	ƛ = 4.7 / week	10.8	18.3
Blockage	ƛ = 1.1 / week	5.6	9.5
Restrictions by emergency services	ƛ = 2.1 / week	3.1	11.1
Defect / damaged rail bridge	ƛ = 0.9 / week	3.7	9.5
Power failure	ƛ = 1.1 / week	8.1	9.5
Defect track	ƛ = 0.4 / week	2.3	6.0
Defect overhead wire	ƛ = 1.0 / week	5.7	9.5
Signal failure	ƛ = 4.4 / week	18.4	15.5 (α = 0.05) 20.1 (α = 0.01)
Suicide	ƛ = 4.5 / week	16.9	16.9
Level crossing failure	ƛ = 1.9 / week	5.6	9.5
Damaged train viaduct	ƛ = 0.3 / week	0.0	6.0
Copper theft	ƛ = 0.3 / week	0.0	6.0
Large maintenance works	ƛ = 1.3 / month	5.3	6.0

Table A10: Parameter estimation of frequency of major discrete events on the whole Dutch train network during winter – regular scenario

Major discrete event type	Poisson parameter	X^2 value	Critical X^2 value
Vehicle breakdown	ƛ = 5.0 / week	6.1	14
Major incident	ƛ = 1.0 / week	9.0	9.5
Switch failure	ƛ = 4.7 / week	10.8	18.3
Blockage	ƛ = 0.6 / week	0.9	6.0
Restrictions by emergency services	ƛ = 2.1 / week	3.1	11.1
Defect / damaged rail bridge	ƛ = 0.9 / week	3.7	9.5
Power failure	ƛ = 1.1 / week	8.1	9.5
Defect track	ƛ = 0.4 / week	2.3	6.0
Defect overhead wire	ƛ = 1.0 / week	5.7	9.5
Signal failure	ƛ = 4.4 / week	18.4	15.5 (α = 0.05) 20.1 (α = 0.01)
Suicide	ƛ = 4.5 / week	16.9	16.9
Level crossing failure	ƛ = 1.9 / week	5.6	9.5
Damaged train viaduct	ƛ = 0.3 / week	0.0	6.0
Copper theft	ƛ = 0.3 / week	0.0	6.0
Large maintenance works	ƛ = 1.3 / month	5.3	6.0

Table A11: Parameter estimation of frequency of major discrete events on the whole Dutch train network during winter – snow scenario

Major discrete event type	Poisson parameter	X^2 value	Critical X^2 value
Vehicle breakdown	ƛ = 1.5 / day	0.3	7.8
Major incident	ƛ = 1.0 / week	9.0	9.5
Switch failure	ƛ = 6.6 / day	5.5	6.0
Blockage	ƛ = 0.6 / week	0.9	6.0
Restrictions by emergency services	ƛ = 2.1 / week	3.1	11.1
Defect / collided rail bridge	ƛ = 0.9 / week	3.7	9.5
Power failure	ƛ = 1.1 / week	8.1	9.5
Defect track	ƛ = 0.4 / week	2.3	6.0
Defect overhead wire	ƛ = 1.0 / week	5.7	9.5
Signal failure	ƛ = 1.6 / day	2.1	7.8
Suicide	ƛ = 4.5 / week	16.9	16.9
Level crossing failure	ƛ = 1.9 / week	5.6	9.5
Damaged / collided train viaduct	ƛ = 0.3 / week	0.0	6.0
Copper theft	ƛ = 0.3 / week	0.0	6.0
Large maintenance works	ƛ = 1.3 / month	5.3	6.0

From tables A7 – A11 it can be concluded that the calculated X^2 value for almost all event types does not exceed the critical X^2 value when using a significance level α=0.05. This indicates that a Poisson distribution can be assumed to describe the frequencies with which all these event types occur in all seasons. Regarding the frequency of suicide events per week, it can be seen from Table A7 – A11 that the X^2 value is similar to the critical X^2 value, indicating that the hypothesis that the empirical distribution follows a Poisson distribution is almost rejected for this event type. However, since this value does not exceed the critical value, a Poisson distribution can still be assumed.

Table A8 – A10 show that the frequency with which signal failures occur per week during summer, autumn and regular winter circumstances is the only exception where the X^2 value exceeds the critical X^2 value when using a significance level α=0.05. However, when applying a significance level α=0.01, also for this event type the X^2 value $<$ the critical X^2 value. Given the theoretical expectations and given statistical evidence found for other event types, a Poisson distribution is also used to represent the frequency of signal failures per time period during these seasons.

Appendix A3

Seasonal differences between frequencies of major discrete events on BTM network

In this appendix, it is explained how the frequency with which different event types on the BTM network occur is determined for different seasons. As explained in chapter 2.2, only historic data of major discrete events on the BTM network of one urban public transport operator (PTO) from the summer and autumn of 2013 is available for this study. No data is available regarding the frequency of BTM events during spring and winter. Therefore, the Poisson parameters for the frequencies during these seasons are derived based on the frequencies found for the summer and autumn and based on seasonal differences as found empirically for major discrete events on the train network. In chapter 2.2.2 the six steps to estimate the Poisson parameters for events on the BTM network are explained. This appendix elaborates on the sixth step of this procedure.

Seasonal differences between frequencies of major discrete events on the metro/light rail network

Table A12 shows the frequency of different major discrete event types on the whole Dutch train network and the frequency on the metro/light rail network considered in the case study. In this table, the functional categorization of event types as explained in chapter 2.1 and chapter 2.4 is used. The frequencies of train events in all time periods and the frequencies of metro/light rail events in summer and autumn are empirically derived. Parameter values for metro/light rail events during spring and winter are derived as follows:

- The resulting parameter values for the train network show that the frequency of vehicle breakdowns does not differ significantly between spring, summer and winter (regular scenario). Only during autumn the frequency of vehicle breakdowns is higher because of the influence of leaves on the track. 78% of the considered metro network of the RET, and 100% of the considered light rail network of the HTM is operated over ground (OV in Nederland, 2013b). In total, 82% of the considered metro/light rail network in the case study area is operated over ground. Therefore, the pattern of frequencies of vehicle breakdowns on the metro/light rail network over the year is expected to be similar to the pattern found for the train network over the year. This means that the frequency of metro/light rail vehicle breakdowns during summer is also applied as frequency for spring and winter (regular scenario). The effect of heavy snow on vehicle breakdowns is expected to be similar for the part of the metro/light rail network which is operated over ground. Heavy snow is not expected to influence the frequency of metro/light rail vehicle breakdowns on underground track parts. Therefore, to determine a value for the frequency of vehicle breakdowns during heavy snow, the ratio between the frequencies during heavy snow and regular winter circumstances on the train network (11/5.0) is multiplied by 0.82. This adjusted ratio is multiplied with the frequency of 11 metro/light rail vehicle breakdowns per week during regular winter circumstances, leading to an expected frequency of 20 vehicle breakdowns per week on the metro/light rail network during heavy snow.

- The frequency of major incidents on train networks is not sensitive to seasonal influences. The analysis of the frequency of major incidents on the metro/light rail network shows a slightly higher frequency during autumn (0.7 events per week) compared to the summer (0.6 events per week). This difference might be explained by the fact that during summer holidays the frequencies of different metro lines are reduced. Since the number of vehicle-kilometres is assumed as predictor for the frequency of major incidents (see Table 2.4 in chapter 2.2), a lower number of vehicle-kilometres during summer can slightly reduce the frequency of major incidents in this season. In line with the pattern found on the train network, the frequency of major incidents on the metro/light rail network during spring and winter is expected to be equal to the frequency found during autumn.
- The event category 'blockage + other' represents different event types which all can be predicted based on link length and all lead to 0% infrastructure availability. For the metro/light rail network, the event types 'blockage', 'power failure', 'signal failure' and 'restrictions by emergency services' are functionally combined in this category. For the train network, the estimated parameters of these categories (Table 2.3) are summed in order to get comparable values. Given the similarities between the train network and metro/light rail network, the ratio between the frequencies of major incidents in spring and summer, and the ratio between the frequencies in autumn and winter (regular scenario) on the train network are also applied to the metro/light rail network. To determine the frequency of this event category during heavy snow, the ratio found on the train network between the frequency during heavy snow and during regular winter circumstances (16/9.1) is multiplied by 0.82, given the assumption that heavy snow only influences the part of the metro/light rail network which is operated over ground.
- No seasonal differences could statistically be shown regarding the frequency of switch failures on the train network between spring, summer, autumn and winter (regular scenario). Therefore, this assumption is also applied for the frequencies on the metro/light rail network. To determine the frequency of switch failures on the metro/light rail network during heavy snow, the ratio found for the train network (46/4.7) is again multiplied by 0.82.
- As explained in chapter 2.2, the frequency of large maintenance works is determined based on the work of Tahmasseby (2009). For this value, no empirical data is used. Therefore, this event type is not considered in this appendix.

Table A12: Frequency of major discrete events per week for each season on the whole Dutch train network and on the whole metro/light rail network of the RET and HTM within the case study area

Time period of the year	Vehicle breakdown		Major incident		Blockage + other		Switch failure	
	Train	Metro	Train	Metro	Train	Metro	Train	Metro
Spring	5.0	11	1.0	0.7	7.7	10	4.7	1.0
Summer	5.0	11	1.0	0.6	11	14	4.7	1.0
Autumn	6.9	16	1.0	0.7	9.6	13	4.7	1.0
Winter – regular	5.0	11	1.0	0.7	9.1	13	4.7	1.0
Winter – heavy snow	11	20	1.0	0.7	16	18	46	11

Seasonal differences between frequencies of major discrete events on the tram network

Table A13 shows the frequency of different major discrete event types on the whole Dutch train network and the frequencies on the total tram network considered in the case study area. In this table, again the functional categorization of event types as explained in chapter 2.1 and chapter 2.4 is used. The frequencies of train events in all time periods and the frequencies of events on the tram network during summer and autumn are empirically derived. Parameter values for the frequency of events on the tram network during spring and winter are derived as follows:

- Because both the tram network and the train network are operated over ground for (almost) 100%, it is expected that seasonal influences on the frequency of different major discrete event types are comparable for these two networks. Therefore, the patterns in frequency as observed on the train network over the year are also applied to the tram network. This means that it is assumed that the frequency of tram breakdowns during spring and winter is equal to the frequency of tram breakdowns during summer. Again, the frequency of tram breakdowns during autumn is expected to be higher because of slippery tracks. The ratio between the frequency of train breakdowns during heavy snow and regular winter circumstances is also applied to determine the frequency of tram breakdowns during heavy snowfall.
- Consistent with the pattern found regarding the frequency of major incidents on the train network, no seasonal differences are assumed for the frequency of major incidents on the tram network as well.
- The functional category 'blockage + other' for the tram network consists of the event types 'blockage', 'power failure', 'open bridge' and 'restrictions by emergency services'. Compared to the train and metro/light rail network, no signal failures occur on a tram network. The ratio between the frequency of this event category during spring and summer and the ratio between the frequency during autumn and winter as found for the train network are also applied to determine parameter values for this event category on the tram network during spring and winter.
- In line with empirical findings on the train network, no seasonal influences are expected regarding the frequency of switch failures during regular circumstances. Only during heavy snow, the frequency of switch failures is expected to increase substantially, in line with the factor found on the train network.
- The frequency of large maintenance works is determined based on literature (Tahmasseby, 2009) and is therefore not included in Table A13.

Table A13: Frequency of major discrete events per week for each season on the whole Dutch train network and on the whole tram network of the RET and HTM within the case study area

Time period of the year	Vehicle breakdown		Major incident		Blockage + other		Switch failure	
	Train	Tram	Train	Tram	Train	Tram	Train	Tram
Spring	5.0	32	1.0	4.0	7.7	15	4.7	1.0
Summer	5.0	32	1.0	4.0	11	21	4.7	1.0
Autumn	6.9	49	1.0	4.0	9.6	24	4.7	1.0
Winter – regular	5.0	32	1.0	4.0	9.1	15	4.7	1.0
Winter – heavy snow	11	68	1.0	4.0	16	15	46	11

Seasonal differences between frequencies of major discrete events on the bus network

As explained in chapter 2.2, it was not possible to determine parameter values for the frequency of different event types occurring on the total bus network considered in this case study because of time and information constraints. Because the data provided by an urban PTO regarding frequency of events occurring on her bus network is confidential, this data cannot be used to show the seasonal influences on the frequency of events on the bus network quantitatively. These effects are however quantified to determine the values in Table 2.11 in chapter 2.2. In this appendix however, the derivation of the frequency of events on the bus network during spring and winter is explained qualitatively.

- It is not expected that the frequency of bus breakdowns is higher during autumn compared to other seasons. However, from the empirical data it can be concluded that the frequency of bus breakdowns during summer is higher than the frequency during autumn. This might be explained because busses are more sensitive to overheating during summer. Therefore, the frequency of bus breakdowns during summer is considered to be higher than during other seasons. This means that the frequency of bus breakdowns which is empirically found for autumn is also used as frequency during spring and winter.

- In line with the patterns found for the train, metro/light rail and tram networks, no seasonal influences are expected on the frequency of major incidents on bus networks. Therefore, the frequencies of major incidents derived for summer and autumn are also applied as frequency during spring and winter.
- For bus networks, the functional event category of events which can be predicted by link length and lead to 0% infrastructure availability is mainly related to blockages. Since both train and bus networks are operated over ground for (almost) 100%, it is expected that seasonal influences on the frequency of blockages found for the train network are comparable for the bus network. Therefore, the ratio between the frequency of blockages during spring and summer and the ratio between the frequency during autumn and winter as found for the train network are also applied to determine the Poisson parameters reflecting the frequency of this event type on bus networks during spring and winter. Note that in an absolute way it is expected that busses suffer more from blockages than trains, given the fact that busses mainly have a shared right of way with other traffic, compared to trains having own right of way. Despite the expected differences in absolute frequency per time period between the train and bus network, the seasonal influence on these frequencies is however not expected to be different.

Appendix A4

Distribution fitting of the duration of major discrete events

In chapter 2.3 the results of the statistical testing whether the duration of different major discrete event types can be described by a normal or lognormal distribution are shown. In this appendix, the distribution fitting process is explained in more detail for each major discrete event type separately. For all major discrete event types identified on the train network (see Table 2.1 in chapter 2.1) it is statistically tested whether the empirical distribution of durations follows a normal or lognormal distribution. These distribution types are tested, since Tahmasseby (2009) indicates these types as possible distributions to describe the duration of events. Only the duration of the event type 'large maintenance works' is not tested statistically. For this event type a Bernoulli distribution is assumed to describe the duration, based on theoretical considerations (the reader is referred to chapter 2.3 for a more detailed explanation). For all other event types the empirical distribution of the duration of events from the taken sample (see chapter 2.3) is analyzed. The histogram and Q-Q plot are visually inspected. Also, skewness and kurtosis of this empirical distribution are checked. In a perfect normal distribution skewness and kurtosis are equal to zero. In case of a perfect lognormal distribution, skewness and kurtosis are equal to zero when a histogram of the log transformed data is used. At last, by performing a Kolmogorov-Smirnov (K-S) test (with Lilliefors correction) and a Shapiro-Wilk (S-W) test it is tested whether the empirical data statistically fit a normal distribution. To test whether the empirical data can be approximated by a lognormal distribution, a logarithmic transformation is applied to the empirical dataset. By performing a Kolmogorov-Smirnov test and Shapiro-Wilk test to analyze if the log transformed data fits a normal distribution, it can be statistically tested if the non-transformed data follows a lognormal distribution. Table A14 shows the results of these performed analyses for event types occurring on the train network.

Table A14: Results of testing the (log)normality of the duration of major discrete events on the train network

Major discrete event type	Distribution	Skewness	Kurtosis	K-S statistic	p-value	S-W statistic	p-value
Vehicle breakdown	Normal	2.26	5.38	0.25	.000	0.73	.000
	Lognormal	-0.17	0.80	0.11	.200	0.96	.274
Major incident	Normal	1.02	0.90	0.13	.197	0.92	.015
	Lognormal	-0.44	-0.44	0.10	.200	0.97	.426
Switch failure	Normal	1.94	2.98	0.28	.000	0.72	.000
	Lognormal	0.58	0.21	0.14	.146	0.94	.098
Blockage	Normal	1.24	1.34	0.15	.066	0.89	.003
	Lognormal	-0.49	-0.23	0.10	.200	0.97	.541
Restrictions by emergency services	Normal	1.64	2.82	0.25	.000	0.79	.000
	Lognormal	-0.07	-0.90	0.10	.200	0.96	.277
Defect rail bridge	Normal	1.92	2.97	0.32	.000	0.73	.000
	Lognormal	0.22	0.59	0.18	.011	0.95	.104
Power failure	Normal	1.37	2.46	0.12	.200	0.89	.003
	Lognormal	-1.28	2.18	0.17	.024	0.91	.009
Defect track	Normal	1.28	1.10	0.20	.002	0.86	.001
	Lognormal	-0.56	0.44	0.08	.200	0.97	.471
Defect overhead wire	Normal	0.93	0.12	0.15	.073	0.91	.009
	Lognormal	-0.50	-0.37	0.12	.200	0.97	.392
Signal failure	Normal	0.62	-0.62	0.21	.001	0.92	.025
	Lognormal	-0.82	0.37	0.13	.200	0.93	.047
Suicide	Normal	-0.47	0.38	0.13	.200	0.97	.365
	Lognormal	-1.77	4.70	0.20	.002	0.85	.000
Level crossing failure	Normal	1.49	2.45	0.15	.079	0.87	.001
	Lognormal	-0.65	-0.07	0.15	.066	0.95	.155
Damaged train viaduct	Normal	0.25	-0.45	0.09	.200	0.97	.455
	Lognormal	-1.14	0.46	0.23	.000	0.87	.001
Copper theft	Normal	1.05	0.30	0.20	.002	0.89	.003
	Lognormal	-0.48	0.50	0.13	.181	0.96	.339

For the event types ‘vehicle breakdown’, ‘switch failure’, ‘restrictions by emergency services’, ‘defect track’, ‘signal failure’ and ‘copper theft’ on the train network the p-value related to the performed K-S test is only significant when testing the fit to a normal distribution. For these event types the p-value is larger than 0.05 when testing the fit to a lognormal distribution. This indicates – in line with literature – that the duration of these event types can be modelled by a lognormal distribution. A similar conclusion can be drawn from Table A14 when analyzing the p-value of the performed S-W test for these event types. The only difference is that the p-value for the event ‘signal failure’ is slightly smaller than 0.05. This can be explained because the S-W test has more power than a K-S test, thereby leading to p-values which are earlier significant (Nornadiah & Yap, 2011).
For the event types ‘major incident’, ‘blockage’, ‘defect overhead wire’ and ‘level crossing failure’ on the train network, the p-value of the performed K-S test is not significant when fitting the empirical data to both a normal and lognormal distribution. In that case, from a theoretical perspective a lognormal distribution is favoured, because in a lognormal distribution only nonnegative values can occur. This prevents the probability on unrealistic negative values for the duration of an event, as is possible when modelling the duration by using a normal distribution. Additionally, when a more powerful S-W test is performed the p-values become smaller than 0.05 when testing the fit to a normal distribution for all these four event types. The p-values of these events when testing the fit to a lognormal distribution remain larger than 0.05 when using an S-W test. A lognormal distribution is therefore considered as more robust over different tests on (log)normality. For these event types a lognormal distribution is therefore assumed.
For the event type ‘defect / damaged rail bridge’ the p-value is only larger than 0.05 when performing an S-W test on log normality: all other p-values of this event type are smaller than 0.05. Therefore, a lognormal distribution is assumed for this event type as well. For the events ‘power failure’, ‘damaged train viaduct’ and

'suicide' the p-value of the K-S test (and for the last two event types also the p-value of the S-W test) is only larger than 0.05 when fitting the empirical data to a normal distribution. The p-values of the K-S and S-W tests are significant when it is tested whether the data fit a lognormal distribution. This means that there is empirical evidence to prefer the use of a normal distribution when modelling the duration of these event types compared to the use of a lognormal distribution. However, the mentioned disadvantage of the normal distribution is that there is a certain probability on negative values, which is unrealistic when considering the duration of events. The probability on negative values is calculated for these three event types based on average and standard deviation as shown in Table 2.12 in chapter 2.3, which results in probabilities on negative values of 0.09 (power failure), 0.04 (damaged train viaduct) and 0.0001 (suicide). Only the probability on negative values as calculated for suicide events is considered acceptable in this study, because this probability can almost be neglected. Therefore, a normal distribution is used to model the duration of suicide events. The probability on negative values for power failures and damaged train viaducts are considered too high, since a substantial part of duration values drawn from these distributions can possibly be negative. Therefore, despite the empirical evidence, a lognormal distribution is used to model the duration of these event types given the theoretical advantage of this distribution type.

As explained in chapter 2.3, for events on the BTM network the duration is determined for all event types together. Based on the available data, for all event types together occurring on the metro/light rail, tram or bus network the duration is statistically tested. Similar analyses are performed as described above regarding the duration of events occurring on the train network. Table A15 shows the results of the performed analyses for events on the BTM network.

Table A15: Results of testing the (log)normality of the duration of major discrete events on the BTM network

Mode	Distribution	Skewness	Kurtosis	K-S statistic	p-value	S-W statistic	p-value
Metro / light rail network	Normal	4.97	29.1	0.27	.000	0.48	.000
	Lognormal	0.43	0.82	0.10	.200	0.98	.524
Tram network	Normal	1.31	1.37	0.18	.000	0.88	.000
	Lognormal	-0.27	-0.20	0.08	.200	0.98	.617
Bus network	Normal	2.38	6.15	0.22	.000	0.73	.000
	Lognormal	0.16	0.49	0.08	.160	0.97	.029

A lognormal distribution is used to model the duration of events occurring on the metro/light rail, tram and bus network. From Table A15 can clearly be concluded that p-values of both the K-S and S-W test are significant when testing the fit to a normal distribution, whereas p-values for the duration of events on the metro/light rail and tram network are larger than 0.05 in both tests when the fit to a lognormal distribution is tested. For the duration of events on the bus network, only the p-value related to the K-S test is larger than 0.05 when testing the fit to a lognormal distribution. Given both the theoretical and empirical evidence a lognormal distribution is used to describe the duration of events on all three network levels. In chapter 2.3, parameter values are calculated for the selected distribution function for each major discrete event type to describe the duration of that event type.

Appendix A5

Qualitative assessment of impact of events on infrastructure availability

In chapter 2.4 the impact of different major discrete event types on infrastructure availability is discussed. As explained in that chapter, in a first step a qualitative assessment of the effects of different event types on infrastructure availability is performed. This assessment is based on expert judgment after an interview held with a dispatcher of the NS working at the Operation Control Centre Rail (OCCR) in Utrecht (Van der Reest, 2013). Table A16 summarizes the results of this qualitative assessment. Based on this assessment and a quantitative assessment for some event types in a second step, different major discrete event types are categorized into three categories: events leading to 0% link infrastructure availability, events leading to partial link unavailability (50% link infrastructure availability assumed) and events leading to the blockage of one track of a link. This last category can be similar to the second category in case a link consists of one track per direction.

Table A16: Qualitative assessment of the effects of different major discrete event types on infrastructure availability based on Van der Reest (2013)

Major discrete event type	Qualitative assessment based on expert judgment
Vehicle breakdown	In general: 1 track of a link is unavailable. In special cases more tracks can become unavailable: - If a train breaks down on switches in an interlocking or junction area; - If repair works need to be performed to the train, an additional track can become unavailable because of safety reasons.
Major incident (e.g. car collision, train collision, derailment)	In general: all track of a link are unavailable. In special cases tracks can partly become available: - In case of a four-track link (not relevant for level crossing collisions), in a second phase a part of the tracks might become available again, depending on the track on which the incident took place; - If the incident takes place at an interlocking or junction area with many tracks, it might be possible to operate a part of the train services via other tracks on that link.
Switch failure	Mostly: part of tracks of a link are unavailable. Sometimes: all tracks of a link are unavailable.

Major discrete event type	Qualitative assessment based on expert judgment
Blockage (e.g. tree on track, car on track, dismantle bomb WWII)	In general: all tracks of a link are unavailable. Sometimes (especially in case of a four-track link): part of tracks of a link can remain available (for example in case of a tree blocking a part of the tracks).
Restrictions by orders of emergency services	All tracks of a link are unavailable.
Defect / damaged rail bridge	All tracks of a link are unavailable.
Power failure	All tracks of a link are unavailable.
Defect track	In general: 1 track of a link is unavailable. Sometimes: all tracks of a link are available, with reduced allowed maximum speed.
Defect overhead wire	Mostly: all tracks of a link are unavailable. Once in a while: a part of tracks of a link is unavailable.
Signal failure	Sometimes: all tracks of a link are available with delayed operations (for example, if only 1 signal malfunctions, it can often be passed after briefing). Sometimes: part of tracks of a link is unavailable. Sometimes: all tracks of a link are unavailable.
Suicide	In general: all track of a link are unavailable. In special cases tracks can partly become available: - In case of a four-track link, in a second phase a part of the tracks might become available again, depending on the track on which the suicide took place.
Level crossing failure	Sometimes: all tracks of a link are available with delayed operations (depends on train intensity). Sometimes: a part of tracks of a link is unavailable. Sometimes: all tracks of a link are unavailable.
Damaged train viaduct	All tracks of a link are unavailable.
Copper theft	Sometimes: all tracks of a link are available if only one signal or level crossing is affected. Sometimes: a part of tracks of a link is unavailable. Sometimes: all tracks of a link are unavailable.
Large maintenance work	All tracks of a link are unavailable.

Appendix A6

Route alternatives during maintenance on tram network Rotterdam

In chapter 2.5 the effect of large maintenance works on the tram link between Rotterdam Central Station and Kruisplein on public transport (PT) passenger demand is calculated. Almost all tram lines in Rotterdam are usually operated via the link Central Station – Kruisplein. This means that the routes of almost all tram lines need to be adjusted. The adjustments can be summarized as follows (see also Figure 2.4 in chapter 2.5):

- Tram line 2/20: rerouted via Beurs – Stadhuis instead of Vasteland – Eendrachtsplein – Kruisplein;
- Tram line 4: split in two parts (Marconiplein – Lijnbaan and Central Station – Bergweg);
- Tram line 7: rerouted via Lijnbaan – Beurs – Stadhuis instead of Kruisplein – Central Station – Stadhuis;
- Tram line 8: split in two parts (Spangen – Lijnbaan and Central Station – Bergweg);
- Tram lines 21/23/24: rerouted via Eendrachtsplein - Lijnbaan instead of Kruisplein – Central Station.

To determine the effect of these maintenance works on PT demand, for all stop pairs of each tram line which is affected by the maintenance works it is constructed what the most likely route alternative would be for passengers in the adjusted network (the reader is referred to chapter 2.5 for more explanation). This is done manually. In this construction, the most likely route alternative for each affected trip which could be made without transfer in the original network is selected. In reality, different route alternatives for each stop pair of a tram line might be available. However, for each affected stop pair only one route alternative is constructed based on an expert judgment. Table A17 gives an exact overview of the affected stop pairs per tram line and the assumed route alternative in the adjusted network. This table also indicates how many additional transfers are required in this route alternative, and which PT stops are possible transfer locations for these transfers. Based on the last column of Table A17 it can be seen at which PT stops the additional transfers, and therefore the additional check-ins of passengers because of these maintenance works, are to be expected.

Table A17: Overview of constructed route alternative for all affected stop pairs on a tram line

From/to stop(s)	To/from stop(s)	Nr of extra transfers	Possible PT transfer stops
Line 21 / 23 / 24			
Woudhoek / Marconiplein / Holy - Kruisplein	CS	0	(walk Kruisplein – CS)
Woudhoek / Marconiplein / Holy - Kruisplein	Weena / Stadhuis	1	Beurs
Kruisplein	CS	-1	(walk Kruisplein – CS)
Kruisplein	Weena	1	Beurs
Kruisplein	Stadhuis	1	Beurs
CS / Weena / Stadhuis	Weena / Stadhuis / Beurs	0	(other PT lines)
CS / Weena / Stadhuis	Keizerstraat	0	(other PT lines; walk Beurs – Keizerstraat)
CS / Weena / Stadhuis	Blaak - De Esch	1	Beurs
CS / Weena / Stadhuis	Leuvehaven / Wilhelminaplein	0	(metro D/E; tram 2/20)
CS / Weena / Stadhuis	L. Pincoffsweg - Varkenoordseviaduct	0	(tram 2/20)
CS / Weena / Stadhuis	Stadion Feyenoord - Limbrichthoek	1	Beurs / Leuvehaven / Wilhelminaplein / L. Pincoffsweg / Vuurplaat
Line 4			
Marconiplein - Eendrachtsplein	Kruisplein	1	Lijnbaan
Marconiplein - Eendrachtsplein	CS	1	Beurs
Marconiplein - Eendrachtsplein	Weena	1	Lijnbaan / Beurs
Marconiplein - Eendrachtsplein	Heer Bokelweg - Bergweg	2	Lijnbaan / Beurs - Stadhuis / Weena / Pompenburg
Kruisplein	CS	-1	(walk Kruisplein – CS)
Kruisplein	Weena - Bergweg	0	(walk Kruisplein – CS)
Line 8			
Spangen - Beurs	Kruisplein	1	Vasteland / Leuvehaven / Beurs / Lijnbaan
Spangen - Beurs	CS	1	Leuvehaven / Beurs
Spangen - Beurs	Weena / Pompenburg	1	Vasteland / Leuvehaven / Beurs
Spangen - Beurs	Meent - Zwaanshals	1	Vasteland
Spangen - Beurs	Benthuizerstraat	2	Vasteland / Leuvehaven / Beurs - Stadhuis / Weena / Pompenburg / Meent / Noorderbrug / Zaagmolenbrug
Lijnbaan	Kruisplein	0	(walk Lijnbaan – Beurs)
Lijnbaan	CS	0	(walk Lijnbaan – Beurs)
Lijnbaan	Weena - Zwaanshals	0	(tram 7)
Lijnbaan	Benthuizerstraat	1	Pompenburg / Meent / Noorderbrug / Zaagmolenbrug
Kruisplein	CS	-1	(walk Kruisplein – CS)
Kruisplein	Weena - Bergweg	0	(walk Kruisplein – CS)

From/to stop(s)	To/from stop(s)	Nr of extra transfers	Possible PT transfer stops
Line 7			
Willemsplein - Eendrachtsplein	Kruisplein	1	Lijnbaan
Willemsplein - Eendrachtsplein	CS	1	Stadhuis
Willemsplein - Eendrachtsplein	Weena	0	(walk Stadhuis / Pompenburg – Weena)
Kruisplein	CS	-1	(walk Kruisplein – CS)
Kruisplein	Weena - Zaagmolenbrug	0	(walk Kruisplein - CS; tram 8)
Kruisplein	Crooswijksestraat - Woudestein	1	Lijnbaan
CS	Weena / Pompenburg	0	(other PT lines)
CS	Meent - Zaagmolenbrug	0	(tram 8)
CS	Crooswijksestraat - Woudestein	1	Weena / Stadhuis / Pompenburg / Meent / Noorderbrug / Zaagmolenbrug
Line 2/20			
Lombardijen - Beijerlandselaan	Vasteland	1	Leuvehaven
Lombardijen - Beijerlandselaan	Museumpark	1	Stadhuis
Lombardijen - Beijerlandselaan	Eendrachtsplein	1	Stadhuis (tram 7) / Beurs (metro ABC)
Lombardijen - Beijerlandselaan	Kruisplein	1	Vuurplaat / L. Pincoffsweg / Wilhelminaplein / Leuvehaven / Beurs
Vuurplaat - Wilhelminaplein	Vasteland	1	Leuvehaven
Vuurplaat - Wilhelminaplein	Museumpark	1	Lijnbaan
Vuurplaat - Wilhelminaplein	Eendrachtsplein	1	Lijnbaan (tram 23 / tram 7) / Beurs (metro ABC)
Vuurplaat - Wilhelminaplein	Kruisplein	0	(tram 23)
Vasteland / Museumpark	Museumpark / Eendrachtsplein	0	(tram 7)
Vasteland / Museumpark	Kruisplein	1	Lijnbaan
Vasteland / Museumpark	CS	1	Stadhuis
Eendrachtsplein	Kruisplein	-1	(walk Eendrachtsplein – Kruisplein)
Eendrachtsplein	CS	1	Beurs (metro ABC / metro DE) / Stadhuis (tram 7)
Kruisplein	CS	-1	(walk Kruisplein – CS)
Line 25			
Schiebroek - Weena	Kruisplein	0	(walk Kruisplein – CS)
Schiebroek - Weena	Lijnbaan	0	(walk Lijnbaan – Beurs)
CS	Kruisplein	-1	(walk Kruisplein – CS)
CS	Lijnbaan	0	(walk Lijnbaan – Beurs)
Kruisplein	Lijnbaan	0	(tram 21/23/24)
Kruisplein	Beurs - Carnisselande	1	Beurs / Leuvehaven / Wilhelminaplein / L. Pincoffsweg / Vuurplaat
Lijnbaan	Beurs - Carnisselande	0	(walk Lijnbaan – Beurs)

Appendix B1

Sensitivity of assignment results

In this appendix the sensitivity of assignment results to different logit scale parameter values and the sensitivity when performing a capacity constrained assignment are investigated. This is done by repeatedly simulating a certain major discrete event on a certain location for different scenarios. In this appendix, a major discrete event on the train link between Rijswijk and Delft is simulated. This event leads to 0% infrastructure availability on this train link. The supplied PT services are adjusted based on measures the NS would take in that case in reality.

Sensitivity of assignment results to logit scale parameter values

In the Zenith algorithm the scale parameter is reflected by the logit access stop choice parameter. This value reflects how many passengers favour the route alternative with the lowest generalized costs. Therefore, this value reflects the knowledge passengers have about the network. A higher value of the scale parameter indicates that people have more knowledge about the network, which leads to a larger proportion of passengers choosing the alternative with the lowest generalized costs. This means that theoretically, PT demand between a certain OD-pair is expected to be more concentrated on a limited number of route alternatives in case the scale parameter value increases.

As explained in chapter 3.2, in this study is assumed that passengers have full information and knowledge about the disturbance and route alternatives available in the adjusted multi-level PT network when an event occurs. This means that during the assignment in case of an event the value of the scale parameter remains unchanged, in order to determine the pure effects of the event itself on the assignment results.

However, in practice passengers do not always have full information or knowledge to base their route choice on. One the one hand, a lower scale parameter value might be expected during the occurrence of major discrete events, which reflects the reduced knowledge of passengers during disturbances. One the other hand, it might be expected that passengers – when confronted with a certain disturbance – choose for a familiar route alternative. This can mean that passenger flows are concentrated on some route alternatives which are relatively familiar to passengers, whereas more unknown route alternatives are not considered. Such concentration of demand on certain route alternatives indicates a higher scale parameter value. Therefore, from a theoretical perspective it is not clear how the scale parameter changes in reality when a major discrete event occurs. Table B1 shows how the passenger flow on possible route alternatives for the blocked train link Rijswijk – Delft changes when using different values for the logit scale parameter ϕ.

Table B1: Relative change in passenger flow on different links in case of a major discrete event compared to the undisturbed situation when ϕ = 0.5 is used

Link	ϕ = 0.3	ϕ = 0.4	ϕ = 0.5	ϕ = 0.6	ϕ = 0.7
The Hague Moerwijk – Rijswijk (train)	-100	-100	-100	-100	-100
Rijswijk – The Hague Moerwijk (train)	-100	-100	-100	-100	-100
Rijswijk – Delft (train)	-100	-100	-100	-100	-100
Delft – Rijswijk (train)	-100	-100	-100	-100	-100
Delft - Delft Zuid (train)	-68	-68	-68	-68	-68
Delft Zuid – Delft (train)	-65	-65	-65	-65	-65
Delft Zuid - Schiedam Centrum (train)	-67	-67	-67	-66	-66
Schiedam Centrum - Delft Zuid (train)	-63	-62	-62	-62	-62
Berkel Westpolder - Pijnacker Zuid (RET metro E)	204	203	203	203	203
Pijnacker Zuid - Berkel Westpolder (RET metro E)	225	224	223	222	222
Brasserskade – Verffabriek (HTM tram line 1)	398	397	395	393	392
Verffabriek – Brasserskade (HTM tram line 1)	708	712	715	715	716
Lange Kleiweg direction The Hague (Veolia bus line 130)	518	520	522	522	523
Lange Kleiweg direction Delft (Veolia bus line 130)	558	563	568	568	568
Parijsplein direction Leyenburg (Veolia bus line 37)	496	491	490	488	487
Parijsplein direction Delft (Veolia bus line 37)	461	470	474	479	482
Schiphol – Rotterdam Central Station (high speed line)	30	30	30	30	30
Rotterdam Central Station – Schiphol (high speed line)	73	73	73	73	73
Nieuwerkerk a/d IJssel – Gouda (train)	5	5	5	6	6
Gouda – Nieuwerkerk a/d IJssel (train)	6	6	6	6	6
Gouda – Zoetermeer Oost (train)	1	1	1	1	1
Zoetermeer Oost – Gouda (train)	3	3	3	3	3
Geldermalsen – Culemborg (train)	2	2	2	2	2
Culemborg – Geldermalsen (train)	4	4	4	4	4
Gouveneurlaan direction Moerwijk (HTM tram line 16)	22	25	25	26	26
Gouveneurlaan direction station HS (HTM tram line 16)	14	19	20	20	21
Burg. Elsenlaan direction Rijswijk (HTM tram line 17)	138	137	137	137	137
Burg. Elsenlaan direction station HS (HTM tram line 17)	125	124	123	122	121
Calandplein direction Rijswijk (HTMBuzz bus line 18)	31	32	33	33	34
Calandplein direction station HS (HTMBuzz bus line 18)	29	31	34	40	43
Neherkade direction Moerwijk (HTMBuzz bus line 26)	-7	-11	-11	-11	-10
Neherkade direction station HS (HTMBuzz bus line 26)	-13	-16	-19	-22	-22
Delftsestraatweg direction Zoetermeer (Veolia bus line 121)	61	61	61	61	61
Delftsestraatweg direction Delft (Veolia bus line 121)	99	99	99	99	99

From Table B1 can be concluded that in general the assignment results are quite insensitive for different values of the scale parameter. On most links considered in this table, the passenger flow is hardly changed when the scale parameter value is changed. From this table can be concluded that the passenger flow on tram line 1, tram line 16 and bus lines 18 and 130 are slightly sensitive for the value of the scale parameter: in case this value increases, the flow over this routes also increases. This indicates that in case knowledge about these route alternatives increases, (slightly) more passengers are expected to choose these routes. However, in general the effects of using different scale parameter values are limited.

Sensitivity of assignment results to a capacity constrained assignment

In chapter 3.2.2 is explained why comfort and capacity effects are not incorporated in the generalized cost function when performing an assignment. In this part of the appendix, the sensitivity of assignment results to the use of a capacity constrained assignment is investigated. To this end, for all relevant transit lines a crush capacity is added to the model. In this capacity constrained assignment it is tried to prevent the assignment of passengers to a PT service when the demand is larger than the crush capacity of this service. The crowding function in the OmniTRANS model is specified in such way that the costs of a certain route are multiplied by a very large factor (e.g. factor 10.000) in case passenger flow exceeds crush capacity. Route alternatives with no capacity left become very unattractive because of this multiplication, which prevents that more passengers will choose this route. Based on the simulated major discrete event, four scenarios are tested to investigate the effect of a capacity constrained assignment (see Figure B1). Table B2 shows the relative change in passenger flow on different links for these four scenarios. When comparing the loads between scenario A and C, and when comparing the loads between scenario B and D, the pure effect of the capacity constraint on the assignment results can be investigated. For all scenarios a logit scale parameter value of 0.5 is used. As explained in chapter 3.2.2, it is not possible in OmniTRANS yet to specify a convergence criterion when performing an iterative transit assignment. Therefore, the iterative procedure does not stop automatically: a fixed number of iterations need to be specified a priori. Therefore, it cannot be checked whether convergence has been reached. When a capacity constrained assignment is performed, 5 iterations are performed in this sensitivity analysis. Because in fact a stochastic user equilibrium assignment is performed, it is expected that the number of iterations required to reach convergence is limited (compared to a deterministic user equilibrium assignment, for example).

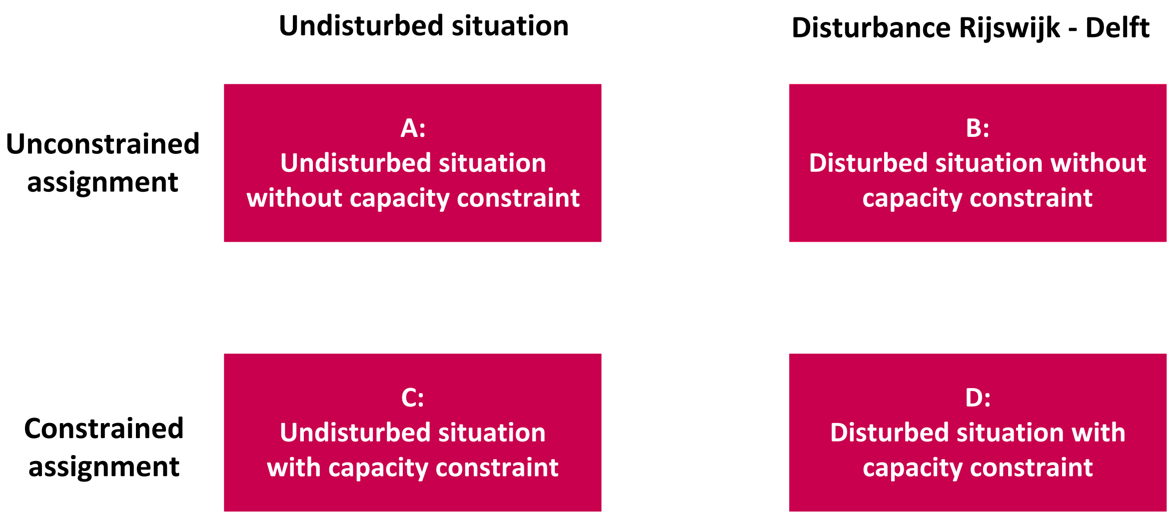

Figure B1: Overview of four possible scenarios to test the sensitivity of assignment results to a capacity constrained assignment

From Table B2 can be concluded that the assignment results are sensitive to the incorporation of a capacity constraint in the assignment procedure. When comparing scenario C and A, it can be seen that a shift takes place from different train route alternatives (with a high load factor) to different bus alternatives (which have a lower load factor). When comparing scenario D and B in case of a major discrete event, especially a shift from metro line E and tram line 1 to different train alternatives can be noticed. This can be explained because metro line E offers a fast route alternative between Rotterdam and The Hague, whereas tram line 1 offers an quite fast route alternative between Delft and The Hague in case the train network is blocked. However, the capacity of these lines is not sufficient to accommodate the extra demand of all passengers from the train network. Therefore, because of the capacity constraint incorporated in the assignment, the use of the longer train route alternative between Rotterdam and The Hague via Gouda increases. This prevents the assignment of passengers to the metro and tram line which exceeds the crush capacity of these lines.
As explained in chapter 3.2.2, it is expected that real passenger behaviour during major discrete events lies somewhere between the extremes sketched by scenarios B and D. The assignment results of scenario B and

scenario D can therefore be considered as lower and upper bound for the assignment results as expected in reality.

Table B2: Relative change in passenger flow on different links in scenarios C, B and D compared to scenario A (the undisturbed situation without capacity constraint)

Link	C	B	D
The Hague Moerwijk – Rijswijk (train)	-13	-100	-100
Rijswijk – The Hague Moerwijk (train)	-18	-100	-100
Rijswijk – Delft (train)	-10	-100	-100
Delft – Rijswijk (train)	-12	-100	-100
Delft - Delft Zuid (train)	-11	-68	-59
Delft Zuid – Delft (train)	-10	-65	-46
Delft Zuid - Schiedam Centrum (train)	-11	-67	-57
Schiedam Centrum - Delft Zuid (train)	-10	-62	-43
Berkel Westpolder - Pijnacker Zuid (RET metro E)	-11	203	49
Pijnacker Zuid - Berkel Westpolder (RET metro E)	-15	223	68
Brasserskade – Verffabriek (HTM tram line 1)	127	395	162
Verffabriek – Brasserskade (HTM tram line 1)	174	715	230
Lange Kleiweg direction The Hague (Veolia bus line 130)	137	522	160
Lange Kleiweg direction Delft (Veolia bus line 130)	369	568	144
Parijsplein direction Leyenburg (Veolia bus line 37)	139	490	105
Parijsplein direction Delft (Veolia bus line 37)	260	474	83
Schiphol – Rotterdam Central Station (high speed line)	-20	30	18
Rotterdam Central Station – Schiphol (high speed line)	-31	73	87
Nieuwerkerk a/d IJssel – Gouda (train)	-28	5	63
Gouda – Nieuwerkerk a/d IJssel (train)	-24	6	80
Gouda – Zoetermeer Oost (train)	-21	1	60
Zoetermeer Oost – Gouda (train)	-35	3	75
Geldermalsen – Culemborg (train)	-47	2	6
Culemborg – Geldermalsen (train)	-47	4	8
Gouveneurlaan direction Moerwijk (HTM tram line 16)	20	25	13
Gouveneurlaan direction station HS (HTM tram line 16)	49	20	12
Burg. Elsenlaan direction Rijswijk (HTM tram line 17)	-4	137	174
Burg. Elsenlaan direction station HS (HTM tram line 17)	-12	123	130
Calandplein direction Rijswijk (HTMBuzz bus line 18)	58	33	21
Calandplein direction station HS (HTMBuzz bus line 18)	30	34	24
Neherkade direction Moerwijk (HTMBuzz bus line 26)	14	-11	13
Neherkade direction station HS (HTMBuzz bus line 26)	38	-19	-14
Delftsestraatweg direction Zoetermeer (Veolia bus line 121)	-17	61	71
Delftsestraatweg direction Delft (Veolia bus line 121)	-7	99	28

Appendix B2

Overview of link segments of case study network

Table B3 of this appendix gives an overview of all link segments, with corresponding number, identified on the train, metro/light rail and tram network of the case study network to identify the most vulnerable links.

Table B3: Overview of identified link segments on train, metro/light rail and tram network of case study

Nr	Link segment	Mode	Nr	Link segment	Mode
1	The Hague Central - The Hague Laan van NOI	Train	28	Hoek van Holland Haven - Hoek van Holland Strand	Train
2	The Hague Laan van NOI - The Hague Central	Train	29	Hoek van Holland Haven - Maassluis West	Train
3	The Hague Laan van NOI - The Hague HS	Train	30	Maassluis West - Hoek van Holland Haven	Train
4	The Hague HS - The Hague Laan van NOI	Train	31	Maassluis West - Maassluis	Train
5	The Hague Central - The Hague HS	Train	32	Maassluis - Maassluis West	Train
6	The Hague HS - The Hague Central	Train	33	Maassluis - Vlaardingen West	Train
7	The Hague HS - The Hague Moerwijk	Train	34	Vlaardingen West - Maassluis	Train
8	The Hague Moerwijk - The Hague HS	Train	35	Vlaardingen West - Vlaardingen Centrum	Train
9	The Hague Moerwijk - Rijswijk	Train	36	Vlaardingen Centrum - Vlaardingen West	Train
10	Rijswijk - The Hague Moerwijk	Train	37	Vlaardingen Centrum - Vlaardingen Oost	Train
11	Rijswijk - Delft	Train	38	Vlaardingen Oost - Vlaardingen Centrum	Train
12	Delft - Rijswijk	Train	39	Vlaardingen Oost - Schiedam Nieuwland	Train
13	Delft - Delft Zuid	Train	40	Schiedam Nieuwland - Vlaardingen Oost	Train
14	Delft Zuid - Delft	Train	41	Schiedam Nieuwland - Schiedam Centrum	Train
15	Delft Zuid - Schiedam Centrum	Train	42	Schiedam Centrum - Schiedam Nieuwland	Train
16	Schiedam Centrum - Delft Zuid	Train	43	Rotterdam Central - Rotterdam Noord	Train
17	Schiedam Centrum - Rotterdam Central	Train	44	Rotterdam Noord - Rotterdam Central	Train
18	Rotterdam Central - Schiedam Centrum	Train	45	Rotterdam Noord - Rotterdam Alexander	Train
19	Rotterdam Central - Rotterdam Blaak	Train	46	Rotterdam Alexander - Rotterdam Noord	Train
20	Rotterdam Blaak - Rotterdam Central	Train	47	The Hague Central - Voorburg	Train
21	Rotterdam Blaak - Rotterdam Zuid	Train	48	Voorburg - The Hague Central	Train
22	Rotterdam Zuid - Rotterdam Blaak	Train	49	Voorburg - The Hague Ypenburg	Train
23	Rotterdam Zuid - Rotterdam Lombardijen	Train	50	The Hague Ypenburg - Voorburg	Train
24	Rotterdam Lombardijen - Rotterdam Zuid	Train	51	The Hague Ypenburg - Zoetermeer	Train
25	Rotterdam Lombardijen - Barendrecht (conventional tracks)	Train	52	Zoetermeer - The Hague Ypenburg	Train
26	Barendrecht - Rotterdam Lombardijen (conventional tracks)	Train	53	Zoetermeer - Zoetermeer Oost	Train
27	Hoek van Holland Strand - Hoek van Holland Haven	Train	54	Zoetermeer Oost - Zoetermeer	Train

Nr	Link segment	Mode	Nr	Link segment	Mode
55	Zwarte Pad - Harstenhoekstraat	Tram	109	Noordwest Buitensingel - Monstersestraat	Tram
56	Harstenhoekstraat - Zwarte Pad	Tram	110	Monstersestraat - Noordwest Buitensingel	Tram
57	Harstenhoekstraat - Circustheater	Tram	111	Monstersestraat - Delftselaan	Tram
58	Circustheater - Harstenhoekstraat	Tram	112	Delftselaan - Monstersestraat	Tram
59	Circustheater - Nieuwe Duinweg	Tram	113	Delftselaan - Hobbemaplein	Tram
60	Nieuwe Duinweg - Circustheater	Tram	114	Hobbemaplein - Delftselaan	Tram
61	Nieuwe Duinweg - Madurodam	Tram	115	Delftselaan - Paul Krugerplein	Tram
62	Madurodam - Nieuwe Duinweg	Tram	116	Paul Krugerplein - Delftselaan	Tram
63	Madurodam - Korte Voorhout	Tram	117	Paul Krugerplein - Loosduinseweg	Tram
64	Korte Voorhout - Madurodam	Tram	118	Loosduinseweg - Paul Krugerplein	Tram
65	Korte Voorhout - Lange Voorhout	Tram	119	Paul Krugerplein - Apeldoornselaan	Tram
66	Lange Voorhout - Korte Voorhout	Tram	120	Apeldoornselaan - Paul Krugerplein	Tram
67	Lange Voorhout - Buitenhof	Tram	121	Dierenselaan - Zevensprong	Tram
68	Buitenhof - Lange Voorhout	Tram	122	Zevensprong - Dierenselaan	Tram
69	Buitenhof - Plein 1813	Tram	123	Zevensprong - Monstersestraat	Tram
70	Plein 1813 - Buitenhof	Tram	124	Monstersestraat - Zevensprong	Tram
71	Plein 1813 - Rooseveltplantsoen	Tram	125	Zevensprong - Fahrenheitstraat	Tram
72	Rooseveltplantsoen - Plein 1813	Tram	126	Fahrenheitstraat - Zevensprong	Tram
73	Rooseveltplantsoen - Kanaalweg	Tram	127	Fahrenheitstraat - Van Speykstraat	Tram
74	Kanaalweg - Rooseveltplantsoen	Tram	128	Van Speykstraat - Fahrenheitstraat	Tram
75	Kanaalweg - Duinstraat	Tram	129	Fahrenheitstraat - Goudenregenstraat	Tram
76	Duinstraat - Kanaalweg	Tram	130	Goudenregenstraat - Fahrenheitstraat	Tram
77	Duinstraat - Circustheater	Tram	131	Goudenregenstraat - Markenseplein	Tram
78	Circustheater - Duinstraat	Tram	132	Markenseplein - Goudenregenstraat	Tram
79	Strandweg - Duinstraat	Tram	133	Goudenregenstraat - depot Lijsterbesstr.	Tram
80	Duinstraat - Strandweg	Tram	134	Depot Lijsterbesstr. - Goudenregenstraat	Tram
81	Duinstraat - Statenlaan	Tram	135	Depot Lijsterbesstr. - Savornin Lohmanplein	Tram
82	Statenlaan - Duinstraat	Tram	136	Savorning Lohmanplein - depot Lijsterbesstr.	Tram
83	Statenlaan - Loosduinseweg	Tram	137	Savornin Lohmanplein - Arnold Spoelplein	Tram
84	Loosduinseweg - Statenlaan	Tram	138	Arnold Spoelplein - Savornin Lohmanplein	Tram
85	Van Boetzelaerlaan - Frederik Hendriklaan	Tram	139	Zevensprong - Volendamlaan	Tram
86	Frederik Hendriklaan - Van Boetzelaerlaan	Tram	140	Volendamlaan - Zevensprong	Tram
87	Frederik Hendriklaan - Statenplein	Tram	141	Volendamlaan - Kraayensteinlaan	Tram
88	Statenplein - Frederik Hendriklaan	Tram	142	Kraayensteinlaan - Volendamlaan	Tram
89	Statenplein - Rooseveltplantsoen	Tram	143	Apeldoornselaan - Leyenburg	Tram
90	Rooseveltplantsoen - Statenplein	Tram	144	Leyenburg - Apeldoornselaan	Tram
91	Statenplein - Laan van Meerdervoort	Tram	145	Leyenburg - Dedemsvaartweg	Tram
92	Laan van Meerdervoort - Statenplein	Tram	146	Dedemsvaartweg - Leyenburg	Tram
93	Laan van Meerdervoort - Jan Hendrikplein	Tram	147	Dedemsvaartweg - Zichtenburg	Tram
94	Jan Hendrikplein - Laan van Meerdervoort	Tram	148	Zichtenburg - Dedemsvaartweg	Tram
95	Jan Hendrikplein - Grote Kerk	Tram	149	Zichtenburg - De Uithof	Tram
96	Grote Kerk - Jan Hendrikplein	Tram	150	De Uithof - Zichtenburg	Tram
97	Grote Kerk - Buitenhof	Tram	151	De Dreef - Dedemsvaartweg	Tram
98	Buitenhof - Grote Kerk	Tram	152	Dedemsvaartweg - De Dreef	Tram
99	Grote Kerk - Brouwersgracht	Tram	153	Melis Stokelaan - Parijsplein	Tram
100	Brouwersgracht - Grote Kerk	Tram	154	Parijsplein - Melis Stokelaan	Tram
101	Brouwersgracht - Central Station (tram tunnel The Hague)	Tram	155	Parijsplein - Dorpskade	Tram
102	Central Station (hoog) – Brouwersgracht (tram tunnel The Hague)	Tram	156	Dorpskade - Parijsplein	Tram
103	Brouwersgracht - Hobbemaplein	Tram	157	Dedemsvaartweg - Loevesteinlaan	Tram
104	Hobbemaplein - Brouwersgracht	Tram	158	Loevesteinlaan - Dedemsvaartweg	Tram
105	Brouwersgracht - Noordwest Buitensingel	Tram	159	Loevesteinlaan - Zuiderpark	Tram
106	Noordwest Buitensingel - Brouwersgracht	Tram	160	Zuiderpark - Loevesteinlaan	Tram
107	Noordwest Buitensingel - Laan van Meerdervoort	Tram	161	Zuiderpark - Wouwermanstraat	Tram
108	Laan van Meerdervoort - Noordwest Buitensingel	Tram	162	Wouwermanstraat - Zuiderpark	Tram

Nr	Link segment	Mode	Nr	Link segment	Mode
163	Loevesteinlaan - Cannenburglaan	Tram	217	Gruttosingel - Heuvelweg	Tram
164	Cannenburglaan - Loevesteinlaan	Tram	218	Heuvelweg - Gruttosingel	Tram
165	Cannenburglaan - Jonckbloetplein	Tram	219	Weigelia - Leisenhage	Tram
166	Jonckbloetplein - Cannenburglaan	Tram	220	Leidsenhage - Weigelia	Tram
167	Parijsplein - Volmerlaan	Tram	221	Leidsenhage - MCH Antoniushove	Tram
168	Volmerlaan - Parijsplein	Tram	222	MCH Antoniushove - Leidsenhage	Tram
169	Volmerlaan - Jonckbloetplein	Tram	223	Leidsenhage - Dillenburgsingel	Tram
170	Jonckbloetplein - Volmerlaan	Tram	224	Dillenburgsingel - Leidsenhage	Tram
171	Jonckbloetplein - Lorentzplein	Tram	225	Weigelia - Essensteyn	Tram
172	Lorentzplein - Jonckbloetplein	Tram	226	Essensteyn - Weigelia	Tram
173	Lorentzplein - Broeksloot	Tram	227	Essensteyn - Laan van NOI	Tram
174	Broeksloot - Lorentzplein	Tram	228	Laan van NOI - Essensteyn	Tram
175	Lorentzplein - Laakkade	Tram	229	Laan van NOI - Oostinje	Tram
176	Laakkade - Lorentzplein	Tram	230	Oostinje - Laan van NOI	Tram
177	Oudemansstraat - Rijswijkseweg	Tram	231	Essensteyn - Mariahoeve	Tram
178	Rijswijkseweg - Oudemansstraat	Tram	232	Mariahoeve - Essensteyn	Tram
179	Laakkade – tunnel HS	Tram	233	Mariahoeve - Oostinje	Tram
180	Tunnel HS - Laakkade	Tram	234	Oostinje - Mariahoeve	Tram
181	Hobbemaplein - Wouwermanstraat	Tram	235	Oostinje - Ternoot	Tram
182	Wouwermanstraat - Hobbemaplein	Tram	236	Ternoot - Oostinje	Tram
183	Wouwermanstraat - tunnel HS	Tram	237	Ternoot - Central Station	Tram
184	Tunnel HS - Wouwermanstraat	Tram	238	Central Station - Ternoot	Tram
185	Tunnel HS - Station HS	Tram	239	Central Station - Korte Voorhout	Tram
186	Tunnel HS - Station HS	Tram	240	Korte Voorhout - Central Station	Tram
187	Station HS - Tunnel HS	Tram	241	Central Station - Rijswijkseplein	Tram
188	Station HS - Rijswijkseplein	Tram	242	Rijswijkseplein - Central Station	Tram
189	Rijswijkseplein - Station HS	Tram	243	Central Station - Lage Zand	Tram
190	Oranjelaan - Stationsplein	Tram	244	Lage Zand - Central Station	Tram
191	Rijswijkseplein - Laakkade	Tram	245	Kalvermarkt - Lage Zand	Tram
192	Laakkade - Rijswijkseplein	Tram	246	Lage Zand - Kalvermarkt	Tram
193	Laakkade - Broeksloot	Tram	247	Bierkade - Rijswijkseplein	Tram
194	Broeksloot - Laakkade	Tram	248	Rijswijkseplein - Bierkade	Tram
195	Broeksloot - Herenstraat	Tram	249	Bierkade - Kalvermarkt	Tram
196	Herenstraat - Broeksloot	Tram	250	Kalvermarkt - Bierkade	Tram
197	Herenstraat - Broekpolder	Tram	251	Kalvermarkt - Buitenhof	Tram
198	Broekpolder - Herenstraat	Tram	252	Buitenhof - Kalvermarkt	Tram
199	Broekpolder - Nootdorpse Landingslaan	Tram	253	Buitenhof - Lange Vijverberg	Tram
200	Nootdorpse Landingslaan - Broekpolder	Tram	254	Lange Vijverberg - Buitenhof	Tram
201	Broekpolder - 's-Gravenmade	Tram	255	The Hague Central - Laan van NOI (RET)	Metro
202	s-Gravenmade - Broekpolder	Tram	256	Laan van NOI - The Hague Central (RET)	Metro
203	s-Gravenmade - Brasserskade	Tram	257	Ternoot - Laan van NOI	Tram
204	Brasserskade - 's-Gravenmade	Tram	258	Laan van NOI - Ternoot	Tram
205	Brasserskade - Nieuwe Plantage	Tram	259	Laan van NOI - Forepark	Light rail
206	Nieuwe Plantage - Brasserskade	Tram	260	Forepark - Laan van NOI	Light rail
207	Nieuwe Plantage - Krakeelpolderweg	Tram	261	Forepark - Leidschenveen	Light rail
208	Krakeelpolderweg - Nieuwe Plantage	Tram	262	Leidschenveen - Forepark	Light rail
209	Krakeelpolderweg - Abtswoudsepark	Tram	263	Leidschenveen - switches Leidschenveen/Voorweg Laag	Light rail
210	Abtswoudsepark - Krakeelpolderweg	Tram	264	Switches Leidschenveen/Voorweg Laag - Leidschenveen	Light rail
211	Brasserskade - Plesmanlaan	Tram	265	Switches Leidschenveen/ Voorweg Laag - Centrum West	Light rail
212	Plesmanlaan - Brasserskade	Tram	266	Centrum West - switches Leidschenveen / Voorweg Laag	Light rail
213	Plesmanlaan - Gruttosingel	Tram	267	Centrum West - Voorweg Hoog - Segwaert	Light rail
214	Gruttosingel - Plesmanlaan	Tram	268	Segwaert - Voorweg Hoog - Centrum West	Light rail
215	Gruttosingel - Nootdorp Centrum	Tram	269	Segwaert - Centrum West	Light rail
216	Nootdorp Centrum - Gruttosingel	Tram	270	Centrum West - Segwaert	Light rail

Nr	Link segment	Mode	Nr	Link segment	Mode
271	Segwaert - Javalaan	Light rail	321	Marconiplein - Delfshaven	Metro
272	Javalaan - Segwaert	Light rail	322	Delfshaven - Marconiplein	Metro
273	Javalaan - Van Tuyllpark	Light rail	323	Delfshaven - Coolhaven	Metro
274	Van Tuyllpark - Javalaan	Light rail	324	Coolhaven - Delfshaven	Metro
276	Bleizo - Van Tuyllpark	Light rail	325	Coolhaven - Eendrachtsplein	Metro
277	Leidschenveen - Pijnacker Zuid	Metro	326	Eendrachtsplein - Coolhaven	Metro
278	Pijnacker Zuid - Leidschenveen	Metro	327	Eendrachtsplein - Blaak	Metro
279	Pijnacker Zuid - Melanchtonweg	Metro	328	Blaak - Eendrachtsplein	Metro
280	Melanchtonweg - Pijnacker Zuid	Metro	329	Blaak - switches Gerdesiaweg / Voorschoterlaan	Metro
281	Melanchtonweg - Central Station	Metro	330	Switches Gerdesiaweg / Voorschoterlaan - Blaak	Metro
282	Central Station - Melanchtonweg	Metro	331	Switches Gerdesiaweg / Voorschoterlaan - Kralingse Zoom	Metro
283	Central Station - Beurs	Metro	332	Kralingse Zoom - switches Gerdesiaweg / Voorschoterlaan	Metro
284	Beurs - Central Station	Metro	333	Kralingse Zoom - Capelsebrug	Metro
285	Beurs - Leuvehaven	Metro	334	Capelsebrug - Kralingse Zoom	Metro
286	Leuvehaven - Beurs	Metro	335	Capelsebrug - Slotlaan	Metro
287	Leuvehaven - Wilhelminaplein	Metro	336	Slotlaan - Capelsebrug	Metro
288	Wilhelminaplein - Leuvehaven	Metro	337	Slotlaan - De Terp	Metro
289	Wilhelminaplein - Rijnhaven	Metro	338	De Terp - Slotlaan	Metro
290	Rijnhaven - Wilhelminaplein	Metro	339	Capelsebrug - Prinsenlaan	Metro
291	Rijnhaven - Zuidplein	Metro	340	Prinsenlaan - Capelsebrug	Metro
292	Zuidplein - Rijnhaven	Metro	341	Prinsenlaan - Alexander	Metro
293	Zuidplein - Slinge	Metro	342	Alexander - Prinsenlaan	Metro
294	Slinge - Zuidplein	Metro	343	Alexander - Graskruid	Metro
295	Slinge - Rhoon	Metro	344	Graskruid - Alexander	Metro
296	Rhoon - Slinge	Metro	345	Graskruid - Binnenhof	Metro
297	Rhoon - Portugaal	Metro	346	Binnenhof - Graskruid	Metro
298	Portugaal - Rhoon	Metro	347	Graskruid - switches Hesseplaats / Nieuw Verlaat	Metro
299	Portugaal - Tussenwater	Metro	348	Switches Hesseplaats / Nieuw Verlaat - Graskruid	Metro
300	Tussenwater - Portugaal	Metro	349	Switches Hesseplaats / Nieuw Verlaat - De Tochten	Metro
301	Tussenwater - switches Hoogvliet/Zalmplaat	Metro	350	De Tochten - switches Hesseplaats / Nieuw Verlaat	Metro
302	Switches Hoogvliet/Zalmplaat - Tussenwater	Metro	351	De Tochten - Nesselande	Metro
303	Switches Hoogvliet/Zalmplaat - Spijkenisse Centrum	Metro	352	Nesselande - De Tochten	Metro
304	Spijkenisse Centrum - switches Hoogvliet/Zalmplaat	Metro	353	Holysingel - Bachsingel	Tram
305	Spijkenisse Centrum - Heemraadlaan	Metro	354	Bachsingel - Holysingel	Tram
306	Heemraadlaan - Spijkenisse Centrum	Metro	355	Bachplein - Harreweg	Tram
307	Heemraadlaan - De Akkers	Metro	356	Harreweg - Bachplein	Tram
308	De Akkers - Heemraadlaan	Metro	357	Bachplein - Prinses Beatrixlaan	Tram
309	Tussenwater - Pernis	Metro	358	Prinses Beatrixlaan - Bachplein	Tram
310	Pernis - Tussenwater	Metro	359	Prinses Beatrixlaan - 's-Gravenlandseweg	Tram
311	Pernis - Vijfsluizen	Metro	360	s-Gravenlandseweg - Prinses Beatrixlaan	Tram
312	Vijfsluizen - Pernis	Metro	361	s-Gravenlandseweg - Broersvest	Tram
313	Vijfsluizen - Troelstralaan	Metro	362	Broersvest - 's-Gravenlandseweg	Tram
314	Troelstralaan - Vijfsluizen	Metro	363	Broersvest - Marconiplein	Tram
315	Troelstralaan - Parkweg	Metro	364	Marconiplein - Broersvest	Tram
316	Parkweg - Troelstralaan	Metro	365	Marconiplein - P.C. Hooftplein	Tram
317	Parkweg - Schiedam Centrum	Metro	366	P.C. Hooftplein - Marconiplein	Tram
318	Schiedam Centrum - Parkweg	Metro	367	P.C. Hooftplein - Spartastraat	Tram
319	Schiedam Centrum - Marconiplein	Metro	368	Spartastraat - P.C. Hooftplein	Tram
320	Marconiplein - Schiedam Centrum	Metro	369	P.C. Hooftplein - Mathenesseplein	Tram

Nr	Link segment	Mode	Nr	Link segment	Mode
370	Mathenesseplein - P.C. Hooftplein	Tram	424	Switches Weena / Schiekade - Eudokiaplein	Tram
371	Mathenesseplein - 1e Middellandstraat	Tram	425	Eudokiaplein - switches Weena / Schiekade	Tram
372	1e Middellandstraat - Mathenesseplein	Tram	426	Eudokiaplein - Van der Hoonaardstraat	Tram
373	1e Middellandstraat - Kruisplein	Tram	427	Van der Hoonaardstraat - Eudokiaplein	Tram
374	Kruisplein - 1e Middellandstraat	Tram	428	Van der Hoonaardstraat - Kootsekade	Tram
375	Marconiplein - Delfshaven	Tram	429	Kootsekade - Van der Hoonaardstraat	Tram
376	Delfshaven - Marconiplein	Tram	430	Kootsekade - Kleiweg	Tram
377	Delfshaven - Heemraadsingel	Tram	431	Kleiweg - Kootsekade	Tram
378	Heemraadsingel - Delfshaven	Tram	432	Kootsekade - depot Hillegersberg / Lommerrijk	Tram
379	Heemraadsingel - Mathenesserlaan	Tram	433	Depot Hillegersberg / Lommerrijk - Kootsekade	Tram
380	Mathenesserlaan - Heemraadsingel	Tram	434	Depot Hillegersberg / Lommerrijk - Molenlaan	Tram
381	Mathenesserlaan - Eendrachtsplein	Tram	435	Molenlaan - depot Hillegersberg / Lommerrijk	Tram
382	Eendrachtsplein - Mathenesserlaan	Tram	436	Pompenburg - Meent	Tram
383	Delfshaven - Schiemond	Tram	437	Meent - Pompenburg	Tram
384	Schiemond - Delfshaven	Tram	438	Meent - Zaagmolenbrug	Tram
385	Schiemond - Pieter de Hooghweg	Tram	439	Zaagmolenbrug - Meent	Tram
386	Pieter de Hooghweg - Schiemond	Tram	440	Zaagmolenbrug - Van der Hoonaardstraat	Tram
387	Pieter de Hooghweg - Euromast	Tram	441	Van der Hoonaardstraat - Zaagmolenbrug	Tram
388	Euromast - Pieter de Hooghweg	Tram	442	Zaagmolenbrug - Boezemsingel	Tram
389	Euromast - Vasteland	Tram	443	Boezemsingel - Zaagmolenbrug	Tram
390	Vasteland - Euromast	Tram	444	Meent - Oostplein	Tram
391	Vasteland - Willemsplein	Tram	445	Oostplein - Meent	Tram
392	Willemsplein - Vasteland	Tram	446	Boezemsingel - Woudestein	Tram
393	Vasteland - Eendrachtsplein	Tram	447	Woudestein - Boezemsingel	Tram
394	Eendrachtsplein - Vasteland	Tram	448	De Esch - Oude Plantage	Tram
395	Eendrachtsplein - Lijnbaan	Tram	449	Oude Plantage - De Esch	Tram
396	Lijnbaan - Eendrachtsplein	Tram	450	Oude Plantage - depot Kralingen	Tram
397	Lijnbaan - Kruisplein	Tram	451	Depot Kralingen - Oude Plantage	Tram
398	Kruisplein - Lijnbaan	Tram	452	Depot Kralingen - Oostplein	Tram
399	Kruisplein - Central Station	Tram	453	Oostplein - depot Kralingen	Tram
400	Central Station - Kruisplein	Tram	454	Oostplein - Churchillplein	Tram
401	Central Station - Weena	Tram	455	Churchillplein - Oostplein	Tram
402	Weena - Central Station	Tram	456	Leuvehaven - Wilhelminaplein	Tram
403	Stadhuis - Beurs	Tram	457	Wilhelminaplein - Leuvehaven	Tram
404	Beurs - Stadhuis	Tram	458	Wilhelminaplein - Varkenoordseviaduct	Tram
405	Beurs - Lijnbaan	Tram	459	Varkenoordseviaduct - Wilhelminaplein	Tram
406	Lijnbaan - Beurs	Tram	460	Varkenoordseviaduct - Beijerlandselaan	Tram
407	Beurs - Churchillplein	Tram	461	Beijerlandselaan - Varkenoordseviaduct	Tram
408	Churchillplein - Beurs	Tram	462	Beijerlandselaan - Hilledijk	Tram
409	Churchillplein - Leuvehaven	Tram	463	Hilledijk - Beijerlandselaan	Tram
410	Leuvehaven - Churchillplein	Tram	464	Hilledijk - Afrikaanderplein	Tram
411	Leuvehaven - Vasteland	Tram	465	Afrikaanderplein - Hilledijk	Tram
412	Vasteland - Leuvehaven	Tram	466	Afrikaanderplein - Maashaven	Tram
413	Weena - switches Weena / Schiekade	Tram	467	Maashaven - Afrikaanderplein	Tram
414	Switches Weena / Schiekade - Weena	Tram	468	Maashaven - Charlois	Tram
415	Switches Weena / Schiekade - Schiekade	Tram	469	Charlois - Maashaven	Tram
416	Schiekade - switches Weena / Schiekade	Tram	470	Hilledijk - Breeplein	Tram
417	Schiekade - Walenburgweg	Tram	471	Breeplein - Hilledijk	Tram
418	Walenburgweg - Schiekade	Tram	472	Breeplein - Carnisselande	Tram
419	Walenburgweg - Abraham Kuyperstraat	Tram	473	Carnisselande - Breeplein	Tram
420	Abraham Kuyperstraat - Walenburgweg	Tram	474	Breeplein - Smeetslandsdijk	Tram
421	Abraham Kuyperstraat - Wilgenplaslaan	Tram	475	Smeetslandsdijk - Breeplein	Tram
422	Wilgenplaslaan - Abraham Kuyperstraat	Tram	476	Smeetslandsdijk - Kreekhuizenlaan	Tram
423	Wilgenplaslaan - Peppelweg - Wilgenplaslaan	Tram	477	Kreekhuizenlaan - Smeetslandsdijk	Tram

Nr	Link segment	Mode	Nr	Link segment	Mode
478	Kreekhuizenlaan - Akkeroord	Tram	484	Stadion Feijenoord - Varkenoordseviaduct	Tram
479	Akkeroord - Kreekhuizenlaan	Tram	485	Varkenoordseviaduct - Stadion Feijenoord	Tram
480	Groene Tuin - Akkeroord	Tram	486	Akkeroord - P&R Beverwaard	Tram
481	Akkeroord - Groene Tuin	Tram	487	P&R Beverwaard - Akkeroord	Tram
482	Groene Tuin - Stadion Feijenoord	Tram	488	P&R Beverwaard - Limbrichthoek	Tram
483	Stadion Feijenoord - Groene Tuin	Tram	489	Limbrichthoek - P&R Beverwaard	Tram

Appendix B3

Frequency and capacity of modelled transit lines

This appendix gives an overview of the frequency and capacity of most relevant transit lines as used in the OmniTRANS model. For these transit lines, the frequency per hour during the morning peak, evening peak and remaining part of an average working day are shown in the next tables. Note that the frequency used for the remaining part of the day is an average value over the different time intervals considered in this period. Therefore, the frequency during the remaining part of an average working day is often not an integer value. For transit lines not mentioned in this table, default values of the Rotterdam regional model of OmniTRANS are used. Also the seat capacity and crush capacity as assumed for each transit line are shown in this appendix.

Tram network The Hague

Table B4: Overview of frequencies of relevant transit lines used in the OmniTRANS model for tram network The Hague

Transit line	Route	Freq remainder day	Freq morning	Freq evening
HTM tram 1	Scheveningen – Delft Tanthof	4.70	6	6
HTM tram 2	Kraayenstein – Leidsenhage	4.80	6	6
HTM RR 3	Loosduinen – Zoetermeer Centrum West	4.80	6	6
HTM RR 3k	Sav. Lohmanplein – Central Station	0	6	6
HTM RR 4	De Uithof – Zoetermeer Javalaan	4.80	6	6
HTM RR 4k	Monstersestraat – Zoetermeer Javalaan	0	6	6
HTM tram 6	Leyenburg – Leidschendam Noord	4.80	6	6
HTM tram 9	Scheveningen – Vrederust	5.20	6	6
HTM tram 9k	Madurodam - Vrederust	0	6	6
HTM tram 11	Scheveningen – Station HS	4.30	5	5
HTM tram 12	Duindorp – Station HS	4.90	8	6
HTM tram 15	Central Station – Nootdorp	4.70	6	6
HTM tram 16	Central Station – Wateringen	4.70	6	6
HTM tram 17	Statenkwartier – Wateringen	4.70	8	8
HTM tram 19	Leidsenhage – Delft Noord	3	3	3

Table B5 shows the seat capacity and crush capacity (sum of seat capacity and standees capacity) per vehicle on each tram line of the network of The Hague. This table indicates which vehicle types operate on each line. The seat capacity and crush capacity of each vehicle type are derived from Haagsetrams (2013). For the vehicle type 'GTL-8' the capacity is a weighted average over the two different types (GTL-8 I: 71 seats and 118 standees; GTL-8 II: 76 seats and 112 standees).

Table B5: Overview of seat capacity and crush capacity on different tram lines of the tram network of The Hague

Tram lines The Hague	Vehicle type peak	Seat peak	Crush peak	Vehicle type non-peak	Seat non-peak	Crush non-peak
2, 3, 3k, 4, 19	1xRegioCitadis	86	216	1xRegioCitadis	86	216
4k	2xRegioCitadis	172	432	-	-	-
1, 6, 9, 11, 12, 15, 16, 17	1xGTL-8	73	189	1xGTL-8	73	189

Urban bus network The Hague

Table B6: Overview of frequencies of relevant transit lines used in the OmniTRANS model for urban bus network The Hague

Transit line	Route	Freq remainder day	Freq morning	Freq evening
HTMBuzz bus 18	Rijswijk De Schilp – Clingendael	3.50	4	4
HTMBuzz bus 18	Rijswijk De Schilp – Central Station	0	4/0	0/4
HTMBuzz bus 21	Scheveningen – Vrederust	3.50	6	4
HTMBuzz bus 22	Duindorp – Duinzigt	3.50	4	4
HTMBuzz bus 22	Central Station – Oude Waalsdorperweg	0	4	4
HTMBuzz bus 23	Scheveningen – Kijkduin	4.70	8	8
HTMBuzz bus 24	Kijkduin – Station Mariahoeve	4.50	8	8
HTMBuzz bus 25	Vrederust – Grote Markt	4.80	8/6	6/8
HTMBuzz bus 26	Kijkduin – Voorburg Station	1.40	6	4
HTMBuzz bus 26	Leyenburg – Voorburg Station	0	6	4
HTMBuzz bus 26	Kijkduin – Station HS	1.90	0	0
HTMBuzz bus 28	Central Station – Voorburg Station	0	4	4

For all busses operated by HTMBuzz on the urban lines of The Hague a seat capacity of 30 and a crush capacity of 90 passengers are assumed, based on observations of the MAN Lion's City busses operated by HTMBuzz.

Metro network Rotterdam

Table B7: Overview of frequencies of relevant transit lines used in the OmniTRANS model for metro network Rotterdam

Transit line	Route	Freq remainder day	Freq morning	Freq evening
RET metro A	Binnenhof – Schiedam Centrum	2.20/2.40	6	6
RET metro A	Binnenhof – Kralingse Zoom	0.40/0.45	0.50	0
RET metro B	Nesselande – Schiedam Centrum	4.05	6	6
RET metro C	De Terp – Spijkenisse De Akkers	4.05	6	6
RET metro D	Rotterdam Central – Spijkenisse De Akkers	4.05	6	6
RET metro D	Rotterdam Central - Slinge	0	6/0	0
RET metro E	The Hague Central - Slinge	3.80	6	6

Table B8 shows the seat capacity and crush capacity for the different metro vehicle types used on the metro network of Rotterdam (RET, 2013d). In Table B9 is shown which composition of vehicle types is used on each metro line during peak and non-peak hours and the related seat and crush capacity per PT service. For metro lines A and B the seat and crush capacity during peak hours are the averages of the seat / crush capacity of 3x5400 and 2x5600 metro series as vehicle composition.

Table B8: Overview of seat capacity and crush capacity of different metro series used on the metro network of Rotterdam

Metro vehicle type	Seat capacity	Crush capacity
Series 5300	72	225
Series 5400	64	217
Series 5500	104	271
Series 5600	104	271

Table B9: Overview of seat capacity and crush capacity on different metro lines of the metro network of Rotterdam

Metro lines Rotterdam	Vehicle type peak	Seat peak	Crush peak	Vehicle type non-peak	Seat non-peak	Crush non-peak
A, B	3x5400/ 2x5600	200	597	1x5600	104	271
C	2x5600	208	542	1x5600	104	271
D	3x5300	216	675	2x5300	144	450
E	2x5500	208	542	1x5500	104	271

Tram network Rotterdam

Table B10: Overview of frequencies of relevant transit lines used in the OmniTRANS model for tram network Rotterdam

Transit line	Route	Freq remainder day	Freq morning	Freq evening
RET tram 2	Charlois – Groene Tuin	3.40	6	6
RET tram 4	Molenlaan – Marconiplein	3.40	6	6
RET tram 7	Woudestein – Willemsplein	3.30/3.35	6	6
RET tram 8	Kleiweg – Spangen	3.50	6	6
RET tram 20	Central Station - Lombardijen	8	8	2
RET tram 21	De Esch – Woudhoek	2	4	4
RET tram 23	Beverwaard – Marconiplein	4.40	8	8
RET tram 24	De Esch – Holy	3	4	4
RET tram 25	Schiebroek - Carnisselande	4.85	8	8

Table B11 shows the seat and crush capacity of the two different tram types which are operated by the RET on the tram network of Rotterdam (Citadis I and Citadis II) (RET, 2013e). It is also shown which vehicle type is assumed for each tram line in Rotterdam.

Table B11: Overview of seat capacity and crush capacity on different tram lines of the tram network of Rotterdam

Tram lines Rotterdam	Vehicle type peak	Seat peak	Crush peak	Vehicle type non-peak	Seat non-peak	Crush non-peak
2, 20, 21, 23, 25	1xCitadis I	63	182	1xCitadis I	63	182
4, 7, 8, 24	1xCitadis II	56	181	1xCitadis II	56	181

Urban and regional bus network Rotterdam

The frequencies used in the OmniTRANS model for relevant urban and regional bus lines in the region Rotterdam are shown in Table B12. The seat capacity and crush capacity per bus on both the urban and regional lines are assumed to be 36 and 95, respectively. These values are derived from RET (2013a). These values are weighted average values over the three largest bus types operated by the RET (MAN Lion’s City, Den Oudsten Alliance and Mercedes-Benz Citaro).

Table B12: Overview of frequencies of relevant transit lines used in the OmniTRANS model for urban and regional bus network Rotterdam

Transit line	Route	Freq remainder day	Freq morning	Freq evening
RET bus 30	Station Alexander - Schollevaar	3.30	6	6
RET bus 31	Station Alexander - Oostgaarde	1.20	2	2
RET bus 32	Overschie - Noordereiland	2.30	6	6
RET bus 33	Central Station – Rotterdam Airport	3.70	7	6
RET bus 34	Capelsebrug – Kralingse Veer	1	1	1
RET bus 35	Station Alexander – Station Noord	1.80	3	3
RET bus 36	Station Alexander – Kralingse Zoom	2.35	4	4
RET bus 37	Station Alexander - Capelsebrug	0.70	1	1
RET bus 38	Central Station – station Schiedam	4.50	8	8
RET bus 39	Central Station - Crooswijk	3.15	6	6
RET bus 40	Central Station – Station Delft	1.25	4/3	3
RET bus 42	Marconiplein – Bedrijventerrein N.W.	1.35	8	6
RET bus 44	Central Station - Zuidplein	3.30	7	6
RET bus 46	Charlois - Westblaak	2	3/4	4/3
RET bus 48	Central Station – Station Zuid	3.35	6	6
RET bus 50	Rotterdam Airport - Meijersplein	2	3	3
RET bus 51	Station Schiedam Centrum – Woudhoek	1.20	2	2
RET bus 53	Station Schiedam Centrum – Woudhoek	1	2	2
RET bus 54	Station Schiedam Centrum – De Gorzen	1.40	3	3
RET bus 56	Holy Noord – Station Vlaardingen West	3.35/3.45	7.50	6
RET bus 57	Holy Noord - Westerhoofd	1	2	2
RET bus 66	Zuidplein – Feijenoord	4.05	8	7.50
RET bus 67	Zuidplein - Pendrecht	3.30/3.15	6	6
RET bus 68	Zuidplein - Heijplaat	1.20/1.25	4.50/4	2
RET bus 70	Zuidplein - Keizerswaard	4.15/4.25	9/10	8/7.50
RET bus 71	Zuidplein – RDM Campus	0.30	4/3.50	2.50/3
RET bus 72	Zuidplein - Sluisjesdijk	0.35	4	4
RET bus 73	Zuidplein - Charlois	4.10/4.15	11/10	7.50/8
RET bus 76	Zuidplein - Keizerswaard	3.40	6	6
RET bus 77	Zuidplein - ss Rotterdam - Rijnhaven	2.20/2.25	4	4
RET bus 126	Schiedam - Maassluis	1.15	2	2
RET bus 170	Rodenrijs - Zoetermeer	2.50	6	6
RET bus 173	Rodenrijs – Zoetermeer	1.10	2	2
RET bus 173a	Rodenrijs - Bleiswijk	1.40	4	4
RET bus 174	Station Noord – Station Delft	0.80	2	2
RET bus 174a	Station Noord – Berkel Westpolder	0.70	0	0
RET bus 182	Zuidplein – Barendrecht	0.95	2	2
RET bus 183	Kralingse Zoom - Barendrecht	0.95	2	2
RET bus 184	Zuidplein - Barendrecht	2.25	4	4
RET bus 187	Zuidplein - Barendrecht	0.05	2/0	0/2
RET bus 226a	Maassluis – Schiedam	0	2/0	0

Urban bus networks of Zoetermeer and Delft; regional bus network Haaglanden

Table B13: Overview of frequencies of relevant transit lines used in the OmniTRANS model for urban bus network Zoetermeer

Transit line	Route	Freq remainder day	Freq morning	Freq evening
Veolia bus 70	Zoetermeer Centrum West circle line	2.90	4	4
Veolia bus 71	Zoetermeer Centrum West circle line	1.50	2	2
Veolia bus 72	Zoetermeer Centrum West circle line	1.50	2	2
Veolia bus 74	Zoetermeer Centrum West - Kryptonstraat	0	2	2

Table B14: Overview of frequencies of relevant transit lines used in the OmniTRANS model for urban bus network Delft

Transit line	Route	Freq remainder day	Freq morning	Freq evening
Veolia bus 60	Nootdorp – station Delft – Tanthof	2	2	2
Veolia bus 69	Station Delft – Technopolis	0.70	8	4
Veolia bus 80	Delftsehout/IKEA – station Delft - Tanthof	1	2	2
Veolia bus 81	IKEA – station Delft - Kuyperwijk	2	2	2
Veolia bus 82	Station Delft – Tanthof - Voorhof	0.40	1	1

Table B15: Overview of frequencies of relevant transit lines used in the OmniTRANS model for regional bus network Haaglanden

Transit line	Route	Freq remainder day	Freq morning	Freq evening
Veolia bus 30	Naaldwijk – Zoetermeer Centrum West	2	4	4
Veolia bus 31	Naaldwijk – The Hague Leyenburg	2.70	4	4
Veolia bus 32	Naaldwijk – station Delft	1.60	4	4
Veolia bus 33	Naaldwijk – station Maassluis West	1.50	2	2
Veolia bus 34	Naaldwijk - Monster	0	0/2	2/0
Veolia bus 35	Leyenburg – station Hoek van Holland Haven	1.55	2	2
Veolia bus 37	Leyenburg – Station Delft - Delfgauw	2	2	2
Veolia bus 38	Station Delft - Maasland	1	2	2
Veolia bus 50	Zoetermeer Centrum West - station Rijswijk	0.30	4	2
Veolia bus 52	Station Zoetermeer – station Rijswijk	0	2/0	0/2
Veolia bus 86	Leyenburg – station Schiedam Centrum	2.40	4	4
Veolia bus 86	Leyenburg - Naaldwijk	1	0	0
Veolia bus 121	Station Delft - Zoetermeer	1.70	4	4
Veolia bus 130	The Hague Grote Markt – station Delft	2	2	2
Veolia bus 130	The Hague Grote Markt – station Rijswijk	1.70	2	2

For all busses on these three networks operated by Veolia Transport, a seat capacity and crush capacity of 30 and 90 passengers are assumed, respectively. Because Veolia Transport operates a similar bus type as HTMBuzz (MAN Lion's City), the same values for seat capacity and crush capacity are assumed in this study (OV in Nederland, 2013a).

Train network

Table B16 shows the frequencies used in the OmniTRANS model for relevant train lines. Table B17 shows the seat capacity and crush capacity of different train types. These values are partly derived from literature. Based on the values available, estimations are performed for capacity values of other train types. From the data available can be concluded that in the SLT-trains (sprinter type) seats cover about 50% of the crush capacity, whereas for VIRM intercity trains the seat capacity covers about 70% of the crush capacity (NS, 2013bc). For the SGMm sprinter trains – which in functional terms can be placed between the SLT and VIRM trains – 60% coverage of the crush capacity by seats is therefore assumed. For the ICMm train type also 70% of the crush capacity is assumed to be covered by seats, because of the functional consistency with the VIRM intercity train type. For each unit of the train types ICMm and ICRm the same seat and crush capacity are assumed, given the large similarities between these two train types. Table B18 shows which train types and compositions are assumed for each train line during peak and non-peak hours (Waarisdetrein.nl, 2013). In reality, the exact train composition can be different for consecutive trains of one train series as well. In this study, fixed values for seat and crush capacity are assumed for each train series during peak and non-peak hours.

Table B16: Overview of frequencies of relevant transit lines used in the OmniTRANS model for train network

Transit line	Route	Freq remainder day	Freq morning	Freq evening
NS IC 500	Rotterdam - Groningen	1	1	1
NS IC 700	The Hague Central - Groningen	1	1	1
NS IC 900	Amsterdam Central – Breda	2	2	2
NS IC 1200	The Hague HS – Roosendaal (- Brussels)	1	1	1
NS IC 1700	The Hague Central - Enschede	1	1	1
NS IC 1900	The Hague Central - Venlo	2	2	2
NS IC 2000	The Hague Central – Utrecht Central	2	2	2
NS IC 2100	The Hague Central – Amsterdam Central	2	2	2
NS IC 2200	Amsterdam Central - Dordrecht	2	2	2
NS IC 2600	Lelystad Centrum - Vlissingen	2	2	2
NS IC 2800	Rotterdam Central – Utrecht Central	2	2	2
NS SPR 4000	Rotterdam Central - Uitgeest	2	2	2
NS SPR 4100	Rotterdam Central – Hoek van Holland	2	2	2
NS SPR 4200	Rotterdam Central – Maassluis West	2	2	2
NS SPR 5000	The Hague Central – Breda	1	2	2
NS SPR 5000	The Hague Central – Dordrecht	1	0	0
NS SPR 5100	The Hague Central – Roosendaal	1	2	2
NS SPR 5100	The Hague Central – Dordrecht	1	0	0
NS SPR 5700	The Hague Central – Weesp – Utrecht C	2	2	2
NS SPR 6300	The Hague Central - Harlem	2	2	2
NS SPR 9700	Rotterdam Central – Gouda Goverwelle	0	2	2
NS SPR 9800	The Hague Central – Utrecht Central	2	2	2
NS IC 11700	The Hague Central – Amersfoort Schothorst	1	1	1
NS IC 12500	Rotterdam Central - Leeuwarden	1	1	1
NS IC 12700	The Hague Central - Leeuwarden	1	1	1
NS SPR 14100	Rotterdam Central – Vlaardingen Centrum	0	4	4
NS SPR 19800	The Hague Central – Gouda Goverwelle	2	2	2
Thalys 9300	Amsterdam Central – Brussels – Paris	1	1	1

Table B17: Overview of seat capacity and crush capacity of different train types operated on the train network. Values in bold are derived from NS (2013bc) and Thalys (2013); other values are estimated based on these values

Train type – nr of units	Seat capacity	Crush capacity
SLT-6	**332**	**680**
SLT-4	**222**	**435**
SGMm-3	**222**	370
SGMm-2	**142**	237
VIRM-6	**626**	**904**
VIRM-4	**428**	**616**
ICMm-3	**187**	271
ICMm-4	**252**	363
ICRm-6	374	541
ICRm-7	439	634
Thalys	**373**	**374**

Table B18: Overview of seat capacity and crush capacity on different train series of the train network

Train series	Train type + composition peak	Seat peak	Crush peak	Train type + composition non-peak	Seat non-peak	Crush non-peak
IC 500, 1700, 1900, 11700, 12500	ICM-3+ICM-3 +ICM-4	626	904	ICM-3+ICM-3	374	541
IC 700, 2000, 2800, 12700	VIRM-6	626	904	VIRM-6	626	904
IC 900	ICR-6	374	541	ICR-6	374	541
IC 1200	ICR-7	439	634	ICR-7	439	634
IC 2100, 2200, 2600	VIRM-6+VIRM-4	1054	1520	VIRM-6	626	904
SPR 4000	SGM-3+SGM-3	444	740	SGM-3	222	370
SPR 4100, 4200, 6300, 9700, 9800, 14100, 19800	SLT-6	332	680	SLT-6	332	680
SPR 5000, 5100, 5700	SLT-6+SLT-4	554	1115	SLT-6	332	680
Thalys 9300	Thalys	373	374	Thalys	373	374

Appendix C1

Results Monte Carlo simulation: total blocked time of link segments

This appendix shows the results of the performed Monte Carlo simulation. For the two link segments for which measures are developed – the tram link segment Brouwersgracht – Central Station and the metro/light rail link segment Laan van NOI – Forepark – the total time is simulated that this link segment is blocked because of a major discrete event for each of the 10 years of the cost benefit analysis separately. The simulations are performed in Matlab by using a pseudo-random generator. In general, by using a pseudo-random generator the total time a link segment is blocked is exactly the same for the situation without measures and the situation when a measure is applied. The only exception is the measure where extra switches near Leidschendam-Voorburg are constructed. Extra switches lead to both more flexibility and to more switch failures. Therefore, the frequency of switch failures is increased in this measure. In the current situation there are 10 switches on the link segment Laan van NOI – Forepark which can cause failures: 8 switches on the main tracks and 2 switches on the work shop Leidschendam which can cause disturbances because of flank protection (Sporenplan, 2013c). After this measure would be applied, there are 14 switches on this link segment. Therefore, the frequency of switch failures on this link segment is increased by factor 1.4 after this measure is applied.

Table C1 shows the total duration of blockages on the link segment Brouwersgracht – Central Station per year, measured in hours. Since on average 18 operation hours per day are assumed, it can be calculated that over a period of 10 years (which equals 65.745 operation hours) this link segment is blocked for 715 hours. This means that this link segment is blocked during 1.1% of the operation time, according to these simulation results.

Table C1: Overview of simulated number of hours that the link segment Brouwersgracht – Central Station is blocked per year

Year	0	1	2	3	4	5	6	7	8	9	*total*
vehicle breakdown	68	56	65	50	73	53	40	36	46	22	*510*
major incident	2	6	8	9	4	1	12	6	8	5	*61*
blockage, power failure, other	7	10	10	14	10	12	10	11	9	11	*104*
switch failure	0	2	1	3	1	3	1	1	2	1	*15*
maintenance work	0	11	0	0	0	0	0	0	0	14	*25*
total	*78*	*86*	*83*	*75*	*88*	*68*	*64*	*54*	*65*	*53*	**715**

Table C2 shows the simulated duration that the link segment Laan van NOI – Forepark is blocked by major discrete events for the situation when no measures are applied and the situation when the measure 'temporary extra intercity stops Zoetermeer and The Hague Ypenburg' is applied. In total, PT operations on this link segment are blocked during 1.5% of the time.

Table C2: Overview of simulated number of hours that the link segment Laan van NOI - Forepark is blocked per year

Year	0	1	2	3	4	5	6	7	8	9	*total*
vehicle breakdown	52	62	70	51	60	54	69	52	49	45	*563*
major incident	1	1	0	0	3	1	12	7	0	1	*25*
blockage, power failure, other	26	38	37	32	26	31	26	38	30	37	*320*
switch failure	1	3	7	1	2	5	1	4	4	2	*31*
maintenance work	0	0	0	0	0	25	0	0	0	0	*25*
total	*80*	*104*	*114*	*84*	*91*	*115*	*107*	*101*	*83*	*85*	**964**

When the measure 'switches near Leidschendam-Voorburg is applied, a distinction is made between disturbances on the part between Laan van NOI and Leidschendam-Voorburg, and the part of the link between Leidschendam-Voorburg and Forepark. Table C3 and Table C4 show the simulated duration of disturbances on both parts of the total link segment. To calculate the total duration of blockages on the total link segment, the values of these tables should be summed. From these tables can be seen that in total this link segment is blocked during 1.7% of the operation time. The additional switches increase the total blocked time by 139 hours over the 10 years together, according to the simulation results.

Table C3: Overview of simulated number of hours that the link segment Laan van NOI – Leidschendam-Voorburg is blocked per year

Year	0	1	2	3	4	5	6	7	8	9	*total*
vehicle breakdown	40	45	44	56	40	44	47	35	56	45	*452*
major incident	1	1	1	0	0	2	2	1	13	1	*22*
blockage, power failure, other	19	27	28	26	25	18	19	27	21	21	*232*
switch failure	1	3	7	2	3	5	4	4	2	3	*34*
maintenance work	0	0	0	0	0	0	0	25	0	0	*25*
total	*62*	*77*	*79*	*84*	*68*	*69*	*72*	*90*	*92*	*71*	**765**

Table C4: Overview of simulated number of hours that the link segment Leidschendam-Voorburg - Forepark is blocked per year

Year	0	1	2	3	4	5	6	7	8	9	*total*
vehicle breakdown	9	16	16	13	21	12	16	13	14	26	*155*
major incident	3	5	14	10	9	11	7	17	7	5	*88*
blockage, power failure, other	4	12	5	6	10	12	8	12	8	8	*83*
switch failure	0	1	0	1	1	1	0	2	1	4	*11*
maintenance work	0	0	0	0	0	0	0	0	0	0	*0*
total	*16*	*32*	*35*	*29*	*41*	*35*	*32*	*44*	*30*	*44*	**338**

Appendix C2

Input and parameter values for societal cost benefit analysis

This appendix shows the parameter values which are used in the performed societal cost benefit analyses. Also, input values for infrastructure and operation effects of different measures are shown.

Infrastructure effects

For the measure 'detour of tram lines around tram tunnel The Hague' a general estimation of the infrastructure construction costs and infrastructure maintenance costs is performed based on expert judgment (source is confidential). The following assumptions are used in this estimation:

- The construction costs consist of the costs for the signalling system, including the costs for cables and loops.
- In order to check whether the single-track is used by a tram or not on a regular base, loops should be placed every 50 meters to detect the location of a tram.
- The economic lifetime of cables and loops is expected to be 30 years. Therefore, the residual value of cables and loops is calculated after a period of 10 years based on straight line depreciation.
- The economic lifetime of the signalling system itself is expected to be 8 years. Therefore, after 8 years costs of replacing the signalling system are included in the cost benefit analysis. For this replacement, the residual value after 10 years is calculated based on straight line depreciation.

Based on these assumptions and the length of the two parts of the detour route for which this signalling system is required (Jan Hendrikstraat: 250m and Buitenhof: 130m), the next values are calculated:

- Infrastructure construction costs year t=0: € $1.2*10^5$;
- Infrastructure construction costs year t=8: € $1.6*10^3$;
- Infrastructure maintenance costs per year: € $2.0*10^3$;
- Residual value of infrastructure year t=9: € $5.5*10^4$.

It should be mentioned that the estimated values are based on standard, average values. No location specific influences are considered.

For the measure 'switches near Leidschendam-Voorburg' the infrastructure construction costs and infrastructure maintenance costs are calculated based on an estimation performed by a rail infrastructure construction company (source is confidential). In the calculation of infrastructure construction costs, the following aspects are included:

- Construction of four switches type C (which are frequently used in the straight direction, and limited used in left-turning or right-turning direction);
- Construction of overhead wire above the switches;
- Adapting the blocks of the signalling system;
- Design costs;
- Costs of the temporary closures of the link segment: no PT operations are possible on the link segment during the construction of switches.

Based on these aspects, the next values are used in this study:

- Infrastructure construction costs for each combination of two switches: € $1.5*10^6$ - € $2.0*10^6$. Therefore, in this study an average value of € $1.75*10^6$ is used for the construction of a combination of two switches. Since in total two combinations of two switches are proposed, total infrastructure construction costs in year t=0 equal € $3.5*10^6$;
- Infrastructure maintenance costs per year: € $7.0*10^3$ per switch, which means € $2.8*10^4$ in total per year;
- Infrastructure residual value: the lifetime of an average switch is set equal to 25 years (Warmerdam, 2005). Therefore, based on straight line depreciation the residual value after 10 years equals 60% of the total construction costs.

It should be mentioned that this estimation is based on general, average values. The specific location where the switches should be constructed is not considered in the calculation. Therefore, in reality the total costs can be slightly more or slightly less than estimated in this study.

Operation effects

When the measure 'temporary extra intercity stops at Zoetermeer and The Hague Ypenburg' is applied, the running time of each intercity service increases with 5 minutes (see chapter 4.3). Four intercity services are operated in each direction between The Hague and Gouda. In case a disturbance lasts for 1 hour, this means that for both directions together the additional running time equals 40 minutes. In case the service network design is adjusted for one hour, this means that the number of timetable hours for NS increases with 2/3 hour. In this study, for the average costs of one timetable hour for a train $C_{o,h,train}$ a value of €250 is assumed (Centrum Vernieuwing Openbaar Vervoer, 2005).

Travel time effects

From literature it is shown that different travel time components are perceived differently by passengers. Table C5 shows the different travel time components and their weights as used for the evaluation of measures in this study. These weights are derived from Bovy and Hoogendoorn-Lanser (2005). These weights are verified with weights found in Van der Waard (1988), Wardman (2001) and Arentze and Molin (2013). The values as determined by Bovy and Hoogendoorn-Lanser (2005) are used in this study, since these values are specifically based on preference studies performed in The Netherlands. Since the Dutch sample used by Arentze and Molin (2013) does not contain passengers with a commuting trip purpose, these values are only used as verification. In general it can be concluded from the verification that the weights of different travel time components slightly differ between different studies, although similar patterns can be found.

Table C5: Overview of weights used for different travel time components (Bovy & Hoogendoorn-Lanser, 2005)

Travel time component	Weight
Access time	1.6
Waiting time (access waiting time and transfer waiting time)	2.2
In-vehicle time	1.0
Transfer walking time	1.9
Transfer penalty	11.4 (minutes)
Egress time	1.6

Most recent literature indicates the Value of Time (VoT) for train and bus/tram/metro (BTM) separately (Kennisinstituut voor Mobilteit, 2013). In this study a generalized VoT is used over all modes together, since the share of train or BTM in the total PT trip could not be determined easily. Therefore, the average travel time per person per day (averaged over all Dutch inhabitants) in train and BTM as given in OViN (2013) is used as correction to determine an overall VoT for this study (see Table C6). For this study the VoT therefore equals €8.28 per hour.

Table C6: Overview of calculation of Value of Time averaged over train and BTM

Aspect	Value
Value of Time train (averaged over all purposes)	€ 9.25 per hour (Kennisinstituut voor Mobilteit, 2013)
Value of Time BTM (averaged over all purposes)	€ 6.75 per hour (Kennisinstituut voor Mobilteit, 2013)
Average travel time per person per day in train	4.16 min (OViN, 2013)
Average travel time per person per day in BTM	2.62 min (OViN, 2013)
Value of Time (averaged over train and BTM)	*€ 8.28 per hour*

Travel cost effects

In this study, an average fare of €0.09/km is assumed (Bakker & Zwaneveld, 2009). This value is an average value over the different fare systems applied by different public transport operators (PTO's) on different network levels, and an average value over the different fare types existing within each fare system (for example: student card, discount card, full tariff).

Comfort effects

The valuation of comfort effects in this study is based on a meta-analysis over different studies to the valuation of comfort effects performed by Wardman (2011). In this study by Wardman (2011), for the trip purposes 'commuting' and 'leisure' different multipliers of the in-vehicle time are determined for both seated and standing passengers for different load factors (see 2nd – 5th columns of Table C9). However, in the PT trip matrix used in this study no distinction between different trip purposes is made. Therefore, a general distribution of trip purposes is used in this study. Goudappel Coffeng (2013) shows the average distribution of passengers over trip purposes for train and BTM separately (see 2nd and 3rd column of Table C8). In order to get one general trip purpose distribution over all modes in the multi-level PT network, a correction is applied based on the average number of trips made per day in train and BTM (see Table C7). Table C8 (4th column) shows the trip purpose distribution over all PT modes together as used in this study. In line with the assumption made by Bel (2013) in his research to the incorporation of crowding in transit assignment, for the valuation of comfort effects the trip purpose 'business' is added to the trip purpose 'commuting', whereas the trip purpose 'other' is added to the trip purpose 'leisure'. This assumption allows the calculation of multipliers of the in-vehicle time which represent comfort level for seated and standing passengers over all trip purposes, based on the distribution of trip purposes as shown in the 4th column of Table C8. Table C9 (6th and 7th column) shows the resulting multipliers. As can be seen, a multiplier for standing passengers becomes only relevant in case of a load factor $\geq$ 100%, assuming that each passenger takes a seat when there is one available.

Table C7: Average number of trips per day for train and BTM

Mode	Average number of trips per day
Train	0.06
BTM	0.05

Table C8: Trip purpose distribution on train, BTM and total multi-level PT network (2nd and 3rd column based on Goudappel Coffeng, 2013)

Trip purpose	Train	BTM	Total multi-level PT network
Commuting	53%	56%	55%
Business	6%	3%	4%
Leisure / other	41%	41%	41%

Table C9: Overview of multipliers of in-vehicle time for seated and standing passengers for different trip purposes and load factors to represent comfort effects

Load factor	Commuting (Wardman, 2011)		Leisure (Wardman, 2011)		Total	
	Seated	Standing	Seated	Standing	Seated	Standing
50%	0.86		1.04		0.93	
75%	0.95		1.14		1.03	
100%	1.05	1.62	1.26	1.94	1.14	1.75
125%	1.16	1.79	1.39	2.15	1.25	1.94
150%	1.27	1.99	1.53	2.39	1.38	2.15
175%	1.4	2.2	1.69	2.64	1.52	2.38
200%	1.55	2.44	1.86	2.93	1.68	2.64

Based on linear interpolation of the multipliers for load factors between the mentioned values in Table C9, formulas (5.5) and (5.6) as shown in chapter 5.1.2 are derived. These formulas express the calculation of comfort costs $C_{comf,t,seat}$ in the network for each year t for seated passengers and $C_{comf,t,stand}$ for standing passengers, respectively.