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Disruptions in rail-bound urban public transport

A generic framework for managing disruptions from a passenger perspective



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A generic framework for managing disruptions in rail-bound urban public transport from a passenger perspective

by

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TIL5060 – Master Thesis Project

For the degree of Master of Science in Transport, Infrastructure and Logistics at the Delft University of Technology

Student number: 4098021
Date: December 2, 2016
To be defended on: December 16, 2016

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Preface

This thesis presents the final product of my Master of Science program Transport, Infrastructure and Logistics at the Delft University of Technology. The topic of this graduation project is the management of disruptions in rail-bound urban public transport networks. Although it is conducted at the public transport operator of The Hague, HTM, a generally applicable framework is presented to be used in the management of disruptions in rail-bound urban public transport systems.

I would like to thank HTM for providing me with the opportunity of conducting this research, as well as the warm welcome I received. I was always free to ask, wherever in the organisation, and almost always provided with the information I needed. A special note to my supervisor at HTM, Rien van Leeuwen. Thanks for always helping me make the challenges I faced manageable, as well as helping me find my way in the organisation.

Furthermore, I would like to express my gratitude to my graduation committee. Oded Cats, for your very detailed and constructive feedback, always challenging me and eventually leading to this final result. Niels van Oort, thanks for thinking with me, always showing me even more opportunities making the framework useful and the efforts of coming to the office of HTM. Wijnand Veeneman, for reminding me about the tension between building a model on the one hand and its applicability in reality on the other. Serge Hoogendoorn, for the pleasant official meetings as well as guaranteeing the quality of this research during the process.

Last but not least, I would like to thank my parents and brother, who have always supported me during my time and choices here in Delft, as well as all of my friends, who have made it an unforgettable period of time.

Enjoy reading,

*Dennis Roelofsen
December 2, 2016*

Executive summary

Urban public transport networks are an increasingly vital aspect of contemporary society considering the ongoing worldwide urbanization and increased focus on climate- and congestion issues. A main aspect in the evaluation of users – and thus in the attractiveness of urban public transport to use – is its reliability, and ability to maintain its function in case of disruptions.

In current literature, no systematic and comprehensive framework is found for rail-bound urban public transport operators to use in case of disruptions, and which explicitly takes into account the passenger perspective. The operator perspective on the other hand is not to be neglected, since measures can have different consequences from the operator perspective. For instance, different measures can lead to different delays incurred by the resources on the subsequent activities scheduled for that resource.

Given this knowledge gap, the main research question has been defined as follows:

How can disrupted operations in rail-bound urban public transport systems be managed, in order to minimize total generalized passenger travel time, taking into account operational consequences?

The focus of this research is on rail-bound urban public transport networks. Two measures are considered: detouring vehicles on the disrupted line, and short-turning of vehicles on both ends of the disruption, effectively cutting the line in two.

The research is set up in two parts. First, a conceptual framework is developed, which provides a generally applicable manner for managing disruptions, taking into account the passenger perspective on the one hand and the resource perspective on the other. Second, the developed framework is applied to several (hypothetical) disruption locations as well as one actual disruption. This is done to demonstrate and test its performance, but also to assess currently used disruption management protocols, as well as to find general trends regarding the implementation of considered measures.

Methodology

In order to provide a generally applicable framework, first a model is developed which can provide different alternatives for any given network. Then, the generated alternatives are assessed from the passenger perspective by their resulting total generalized passenger travel time on the disrupted line, and from the resource perspective by their resource delay in case of detouring. In case of short-turning, no quantitative assessment is provided from the resource perspective. Assessing the resource perspective of short-turning by the resource delay is not appropriate, since resources do not arrive at the destination terminal as long as the disruption lasts. Depending on the vehicle- and crew schedules, the effect of short-turning on subsequent activities should be assessed. Figure 0.1 presents the conceptual model representing the developed methodology.

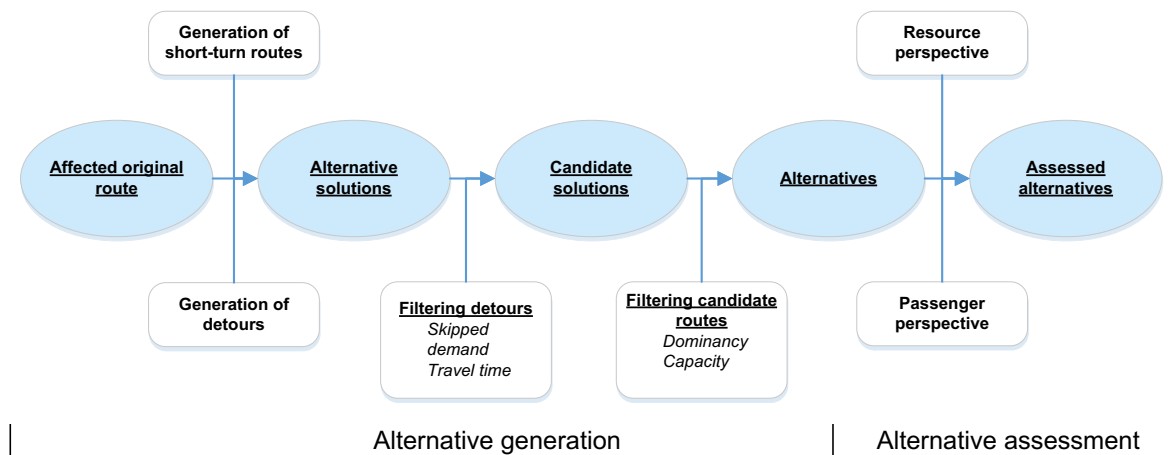


Figure 0.1: Conceptual model of methodology.

For the alternative generation model, the k -shortest path algorithm is used. This finds k routes from an origin node to a destination node, starting with the shortest. This leads to a set of all possible detours. Using the following guidelines this set of detours is being reduced to a set of alternatives, which will be assessed from both discussed perspectives:

- A threshold value excluding detours exceeding a certain extra travel time compared to the original route.
- A threshold value excluding detours directly affecting a certain amount of extra passengers compared to the alternative directly affecting the least amount of passengers.
- Dominancy aspect, excluding detours which skip (at least) the same stops as another detour but have a longer travel time.
- Capacity of the network. The effect of the increased frequency on the detour is assessed. The dominancy aspect and the capacity of the network are taken into account iteratively.

Besides detour alternatives, short-turn alternatives are also taken into account. These alternatives are generated by comparing the short-turn possibilities in the network, which is model input, by the original route of the disrupted line.

After the alternatives are generated, these are assessed from both perspectives. For determining the total generalized passenger time, historical data of passenger flows is used as model input. The passenger impact of the different alternatives is determined using several assumptions regarding passenger route choice when confronted with a disruption:

- Passengers for which their original boarding stop and/or alighting stop is not skipped by the alternative remain using that stop.
- Passengers for which their original boarding stop and/or alighting stop is skipped will either walk directly to their destination, walk to another stop that is being served or will wait until the disruption is over and service is resumed. The choice whether to walk or to wait is represented by a (given) probability distribution function depending on the walking distance.

Taking into account these assumptions, the total passenger travel time for the different alternatives is being determined, distinguished by the corresponding trip elements. The total travel time per trip

element is then weighted using generally accepted weighting factors, representing the different passenger perceptions of the various trip elements.

Case studies

The developed framework is applied to four (hypothetical) disruption locations in the HTM tram network in The Hague. Two main criteria are taken into account in determining the locations:

- No evident alternatives for passenger path choice are available. Since historical passenger flow data is used and this is assumed not to change, passengers should not have an obvious alternative available when confronted with a disruption. Considering this limitation, a disruption duration of one hour is assumed.
- On the other hand, in order to demonstrate the frameworks' face validity, different non-obvious alternatives should be available for the rerouting of vehicles.

To see the effect of different passenger demand levels, for each of the four locations, two different passenger demand levels were taken into account (morning-peak and rest-of-day). To demonstrate the possible effect of the framework in reality, an actual disruption which took place on July 15th 2016 is simulated using the framework. This also gave opportunity to look into the resource perspective in a more thorough manner, by using the actual vehicle- and crew schedules.

For all four locations, 7 to 9 alternatives were generated. These alternatives have been assessed from the passenger perspective (by means of discrete event-based simulation) as well as from the resource perspective, for both morning-peak- and rest-of-day passenger demand levels. Additionally, the assessed alternatives have been compared to the disruption management protocols. Table 0.1 presents the difference between the detour alternative resulting in the lowest TGTT and the short-turn alternative resulting in the lowest TGTT, for all locations. It also shows the difference in extra TGTT incurred by the alternative with the lowest TGTT, as compared to the protocol.

Table 0.1: Results of assessed alternatives, difference between detouring and short-turning, and potential in extra TGTT savings.

	Difference detouring vs. short-turning		Potential savings extra TGTT	
	Morning-peak	Rest-of-day	Morning-peak	Rest-of-day
Location A	- 6%	+ 28%	49%	39%
Location B	+ 15%	- 2%	13%	0%
Location C	- 29%	- 40%	41%	41%
Location D	- 80%	- 64%	85%	73%

The results show that differences in passenger demand levels affect the outcome in terms of the alternative resulting in the lowest TGTT. Furthermore, it shows that current disruption management protocols differ substantially in result compared to the alternative with the lowest TGTT. It should be noted that these potential savings in extra TGTT only occur on the disrupted line, and second-order effects of for instance resource delay on subsequent activities are not represented by it. Further analysis of the current disruption management protocols showed these are mainly driven by the operator perspective, minimizing resource delay.

Assessment of the actual disruption showed that the measure implemented differed from the protocol. A combination of alternatives as provided by the model was implemented, while only one alternative was communicated. This led to a sub-optimal result according to the model, due to a mismatch between actual operations and information provided to passengers.

Considering the different disruption locations, differences in passenger demand levels and the outcome in terms of passenger impact on the disrupted line, three main variables have been identified which are of main importance when considering detouring or short-turning in the management of disruptions. These are the ratio between passengers benefited by detouring versus passengers benefited by short-turning, the distance between the two short-turning stops, and the detour length. Based on the values of these variables, an indication can be provided for the favourable alternative from a passenger perspective (Figure 0.2).

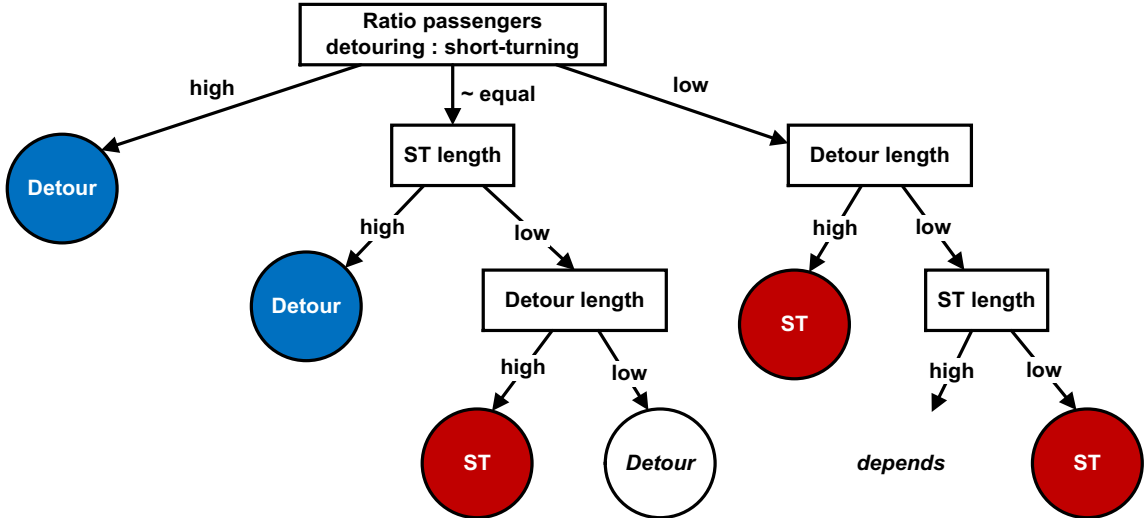


Figure 0.2: Decision-tree indicating favourable alternative (from a passenger perspective).

Looking at Figure 0.3, passengers favoured by detouring are those originating from stops in group 1 and destined for stops in group 4. Passengers favoured by short-turning are destined for stops in group 2 or originating from stops in group 3. For passengers originating from stops in group 2 or passengers destined for stops in group 3, it depends on the walking distance between their stop and the last / first stop served upstream / downstream of the disruption. The longer the distance, the more favourable short-turning is.

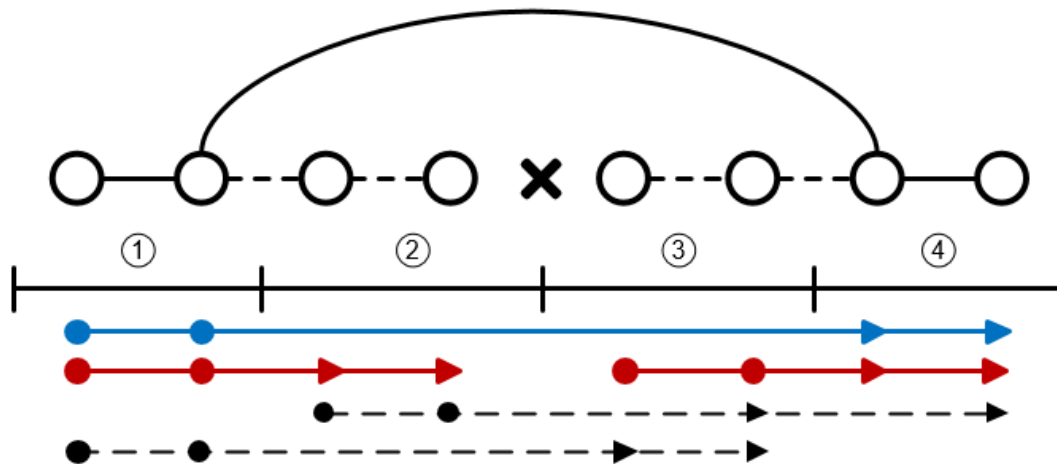


Figure 0.3: Different stops in relation to detouring and short-turning, and the favourable alternative depending on the OD-relation (blue = detour, red = short-turn, black = depending on distance).

Recommendations

This framework is perceived to be mainly suited for usage as support for traffic controllers, either tactical in the construction of disruption management protocols, or real-time as part of a decision support system. Furthermore, it can be used in strategic/tactical planning, for instance to assess (some of) the benefits of adding additional infrastructure (as was also shown in this research), or assessing benefits of additional slack time in the resource schedules.

In its current form, the framework is applicable for a limited amount of locations as well as disruption duration. The main recommendation therefore is extending the provided methodology by incorporating a passenger route choice model, including the different alternatives available for passengers in the network. Then it would be possible to make a network-wide assessment of the different alternatives, making the method suitable for use not only for locations without real alternatives for passengers, but for all other locations as well.

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List of symbols

β^x	Weight factor for trip element x
d	Unavailable edge
d_e	Distance of edge e
D	Subsequence of unavailable edges
e	Edge
E	Set of edges e (tracks)
E_l	Sequence of edges of line l
$E_{l,p}$	Sequence of edges of line l for route p
f_e^c	Capacity of an edge e
f_e^r	Redundant capacity (veh/hour) of edge e
f_e^s	Planned service frequency of edge e
f_l^s	Service frequency of a line l
$f_l^{s,res}$	Residual service frequency of a line l
G	Graph G
$Gt_{i,j}^t$	Generalized travel time between i and j
i	Origin
j	Destination
k	Scheduled activity k
K	Set of activities k
$\pi_{i,j,\tau}$	OD-demand between i and j for time interval τ
P_v	Set of routes with the same skipped stops
p^{dom}	Dominant route
p_l	Route p for a line l
P_l	Set of routes p for a line l
s	Stop
s^t	Stop with short-turn possibility
s_{e^-}	Stop upstream of edge e (origin)
s_{e^+}	Stop downstream of edge e (destination)
$s_{l,1}$	First stop of line l
$s_{l, l }$	Last stop of line l
$s_{l,p,q}$	Stop upstream of disruption
$s_{l,p,q q }$	Last stop before disruption
$s_{l,p,r}$	Stop downstream of disruption
s_{l,p,r_1}	First stop downstream of disruption
$s_{l,p,v}$	Skipped stop
$s_{l,p,u}$	Additional traversed stop
S	Set of nodes s (stops)

S^t	Set of stops with short-turn possibilities
S_l	Sequence of stops of line l
$S_{l,p}$	Sequence of stops of line l for route p
$S_{l,p,q}$	Sequence of stops upstream disruption using route p
$S_{l,p,r}$	Sequence of stops downstream disruption using route p
$S_{l,p,u}$	Sequence of additional traversed stops
$S_{l,p,v}$	Sequence of stops skipped using route p
t_k^b	Buffer time of activity k
t_k^d	Delay for activity k
t_{k+1}^d	Delay for the subsequent activity of k
$t_{l,p}^d$	Delay for a line l caused by a route p
$t_{l,p}^r$	Route time of a line l using route p
$t_{i,j}^v$	Vehicle trip time between stop i and stop j
$t_{i,j,p}^v$	Vehicle trip time between i and j using route p
t_s^{wait}	Waiting time at stop s
t_e^{walk}	Walking time of edge e
$t_{i,j}^{walk}$	Walking time between stop i and stop j
$t_{i,j,p}^{walk}$	Walking time between i and j using route p
τ	Indicator for a time interval
T	Set of time intervals τ

1

Introduction

Urban public transport systems are a vital aspect of nowadays society. The ongoing worldwide urbanization poses challenges for policy makers in providing a suitable transportation system, in which public transport usage can provide benefits in terms of congestion, environment and costs for the society as compared to car usage. The usage of public transport depends on several factors, of which one of the main factors is its reliability (Brons & Rietveld, 2007). Disruptions highly affect the reliability of public transport and the evaluation of it by its passengers. This research aims to improve the management of disruptions in rail-bound urban public transport systems, by approaching it from a passenger perspective.

This chapter gives an introduction into the need and approach of this research. First, the problem will be sketched, leading to the problem definition. Following the problem definition, the research objective and research questions will be presented. Furthermore, the scope of the research will be discussed, giving an overview of aspects incorporated in the research and aspects which are not. Finally, the thesis outline and the relations between the several parts of the research will be given.

1.1 Problem context

The reliability of a public transport system is widely considered as one of the most important service aspects in the evaluating its quality (Brons & Rietveld, 2007; Peek & Van Hagen, 2002; Redman, Friman, Gärling, & Hartig, 2013). Reliability of a public transport system is defined by Van Oort (2011) as “the certainty of service aspects compared to the schedule (such as travel time (including waiting), arrival time and seat availability) as perceived by the user”. Deviations of operations as compared to the planned operations can occur due to a large variety of reasons, such as a failure of infrastructure or material, lack of personnel or external factors such as weather conditions or other road users.

Passengers suffer from deviations from planned operations by late, early or no arrival of vehicles, leading to higher waiting times and thus total travel times, re-routing of vehicles making the trip time longer and stops not being served, or crowding in vehicles making the trip less comfortable as what was planned and expected by the passengers. Besides passengers being impacted by deviations, the operators themselves are also negatively influenced. Typically, public transport operators tend to schedule their resources (such as personnel and rolling stock) as efficiently as possible. This leads to efficient schedules and rosters during regular operations, but makes controlling disruptions a complex

task. Logically, the complexity increases with the severity of the deviation from planned operations. Deviations which cause rescheduling of personnel, rolling stock or infrastructure (rerouting) are referred to as disruptions; deviations which do not cause rescheduling are referred to as disturbances.

Public transport systems in urban areas are more prone to deviations from planned schedule than public transport systems outside urban areas (Yap, 2014), probably due to denser areas in which they operate and the higher number of interactions with their environment. When faced with disturbances or disruptions, public transport operators typically control operations by means of a traffic control centre. These traffic controllers have an overview of the network and can control operations by various measures in order to regain planned operations. This can be a complex task, since the operations are influenced by a lot of factors, of which many cannot be influenced by the traffic control. Traffic control depends for instance upon availability and location of vehicles and personnel, all kinds of external factors and the status of infrastructure (full/partial blockage, possibility for detours). Rail-bound urban public transport is impacted heavier in the latter factor than non-rail bound urban public transport, since it is less flexible when faced with sections which cannot be operated. Measures which can be used by the traffic control are among others detouring (different route between parts of original route), skipping stops, short-turning (reverse somewhere along the route instead of at the destination terminal), holding (stopping longer than necessary, for instance to adhere schedule) and deadheading (not serving the last stops of a route for passengers) (Van Oort, 2011). The actions traffic control conducts in order to provide the best service for passengers and to regain planned operations are referred to as disruption management.

Naturally, the impact of disruptions for the passengers varies. Besides the fact that this depends on the severance of the disruptions itself, it depends on location in the network and time of day as well, and the associated affected passengers. With the implementation of smartcard payment systems, public transport operators have a detailed overview of the regular traffic volumes over the network and over time. Based on this information, they should be able to assess the impact of the disruption for its passengers. Also, if passengers are informed regarding the network state and know that operations are heavily disrupted, passengers might make a different mode and/or route choice.

Disruption management currently practiced by public transport operators is mainly focused on the operator perspective. Carrel, Mishalani, Wilson & Attanucci (2013) have for instance provided a framework to systematically evaluate disruption management in an urban context, and applied it to the metro system of the London Underground. It showed current practice of disruption management techniques are mainly focused on the management of personnel rather than the impact it has for its passengers. An extension of this study is provided by Babany (2015). He provides a framework which is also applied to the London Underground metro system, providing support in the decision making process during the management of disruptions. It takes into account crew constraints, infrastructure constraints, and aims for providing a good service for its passengers and coming back to schedule. However, the framework is only applicable in restoring the schedule; that is when the origin of the disruption has been solved again but operations are still disrupted.

Both of the previously discussed examples are applied to a metro system. Literature regarding disruption management regarding tram operations is limited. Tram systems differ from metro by being less constraint by the supply side of the network, since less stringent safety regulations apply. Literature focusing on the tram network is provided by Carnaghi (2014). He presents a decision support system, taking into account the passenger perspective by aiming to improve the service quality (reliability + comfort level). It does not take into account the operator perspective of the implemented measures.

Based on the potential of data available and the current literature, a knowledge gap has been found in the disruption management for rail-bound urban public transport systems. No comprehensive framework is available which explicitly takes into account the passenger impact of disruptions and implemented measures, but on the other hand also takes into account the operator perspective, in order to support in making a well-informed decision. Therefore, the following problem definition has been set:

No generic framework is available for rail-bound urban public transport systems, making use of the available data to systematically assess possible measures in managing disruptions, from both passenger perspective as well as the resource perspective.

1.2 Research objective and research questions

1.2.1 Research objective

Following this problem definition, the research objective is to provide urban public transport operators with a framework to systematically improve the management of disruptions for its passengers, using available smartcard data. With a framework, a set of coherent tools is meant, including a model to generate alternatives and a simulation model to assess these alternatives from a passenger perspective and a resource perspective. Jointly, they should support the decision making process.

The focus of the research is the passenger perspective, but operational consequences are also considered (operator perspective). Operational constraints which will be taken into account are derived from material, personnel and infrastructure.

In order to capture the perspective of the passenger, solutions will be sought by minimizing the generalized total passenger travel time. By generalizing the travel time of passengers, the lower valuation for time being spent waiting, walking and transferring as compared to regular in-vehicle travel time can be taken into account.

1.2.2 Research questions

Based on the problem definition and research objective, the following main research question and sub research questions have been defined as follows:

How can disrupted operations in rail-bound urban public transport systems be managed, in order to minimize total generalized passenger travel time, taking into account operational consequences?

- What are the characteristics of the proposed measures, for various aspects of the problem? (passengers, personnel, rolling stock, infrastructure)
- How can different alternatives for the proposed measures be generated, in a generic, universally applicable manner?
- What is the passenger perspective and the operator perspective respectively of the generated alternatives, and how can these be assessed?
- What are factors to be taken into account in the management of disruptions, considering the two proposed measures?

1.3 Scientific and societal relevance

1.3.1 Scientific relevance

In current practice as well as currently available literature, the management of disruptions is usually considered from one perspective only. This research aims to provide a comprehensive approach, focused on minimizing total passenger travel time, but taking into account the operational consequences as well. Operational consequences occur due to the scheduling of resources, and by disruptions and its countermeasures these schedules cannot be adhered to anymore. Such a comprehensive approach has not been seen in currently available literature regarding the management of disruptions in rail-bound urban public transport systems.

Furthermore, this research is looking into the factors influencing the effect of the two proposed measures, short-turning and detouring. It is expected that the effect of alternatives can vary along with differences in passenger flows. This effect has also not been seen explicitly in currently available research.

1.3.2 Societal relevance

Firstly, this research focuses on minimizing total passenger travel time. Passengers might benefit from this, by being provided a better service during disrupted operation of public transport, leading to lower (perceived) travel times in the case of disruptions. Increased service reliability positively influences the evaluation of public transport by its passengers and the attraction public transport has for passengers in their mode choice.

Secondly, public transport operators benefit by gaining insights of systematically managing disruption from a passenger perspective, instead of a personnel or material perspective. It will provide insights in the consequences interventions have for the operational constraints, allowing traffic controllers making

better informed decisions. By increasing the service reliability passengers' evaluation can rise, which is typically one of the key performance indicator used in evaluating the performance of public transport operators by concession grantors.

1.4 Scope

The research focuses on rail-bound urban public transport. This is characterised by low flexibility when faced with disruptions due to its dependence on infrastructure as compared to road-bound urban public transport, while it is less regulated due to safety regulations compared to heavy rail.

Disruptions in the context of this research are defined as an unexpected event, which fully affects the availability of a part of the infrastructure for a limited period of time. It is assumed that this is not a long-term blockage; i.e. passengers are assumed not to make different choices prior to their trip because of the disruption. However, disruptions will take long enough so measures need to be implemented. For simplicity reasons, only the lines directly affected by the unavailable infrastructure will be taken into account.

Not all possible measures of the traffic controllers will be taken into account. Due to a limitation in time of the research, only detouring and short-turning will be incorporated as a measure for traffic controllers. Detouring is currently used as the main measure by traffic controllers when faced a blockage in infrastructure, whereas short-turning is used by a measure by traffic controllers when no detour is not possible. Figure 1.1 schematically illustrates the different alternatives, with the short-turning alternatives being represented by the white circles on both sides of the disruption.

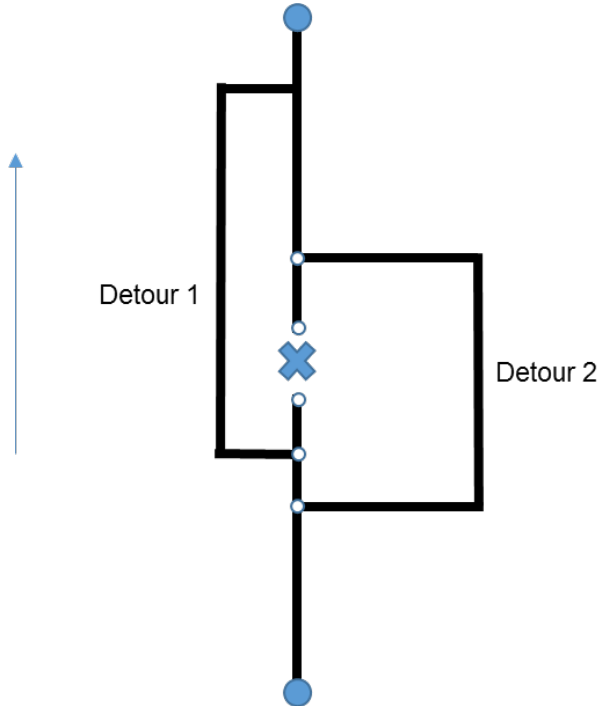


Figure 1.1: Schematic overview of considered alternatives, with short-turning alternatives being represented by the white circles.

It is assumed that the pre-trip choices of passengers, such as pre-trip route choice, departure time choice and mode choice, are not affected by the disruption. This assumption is partially true, since passengers might not have full information regarding the state of the network and the disruptions. However, if it is known that operations are disrupted, some passengers might choose not to make the trip, or make different choices regarding mode and/or route. Therefore, the framework is more suited for disruptions where passengers do not have obvious route alternatives available, and less suited for locations with alternative passenger routes.

Due to different exploitation than was planned caused by a disruption, passengers might make different route choices. For instance, if stops are skipped due to rerouting, passengers might alight at a different stop than was planned. It is assumed that passengers have full information regarding measures being taken. However, as mentioned before network effects are not considered. This means that different routing choices take place along the disrupted line, and other service lines are not considered by the passenger.

1.5 Case study

To test and demonstrate the generic framework, it will be applied in a case study. This will be (a part of) the tram network of The Hague, operated by HTM. The case study will be conducted by means of simulation. By using simulation, several scenarios can be tested for a certain unavailability of infrastructure in the The Hague tram network. Scenarios for instance vary on location in the network or various passenger demand levels (for instance peak/off-peak). Based on the simulation of various scenarios, derivation of some basic guidelines are sought for. Guidelines could be case-specific, but might also be generic and applicable in other cases as well.

In order to evaluate the workings of the developed framework, a case study of an actual disruption will be conducted, where the actual practice will be compared with the outcomes of this research. This will be done by simulating a previously occurred disruption as well as the implemented measure, and comparing this with a simulation making use of the developed framework. In this manner, it can be assessed if the implemented solution was optimal on the considered aspects, according to the framework.

1.6 Thesis outline

This thesis will start with presenting some background information regarding disruption management in rail-bound urban public transport systems in chapter 2. The context of in which this research operates will be discussed, by discussing rail-bound urban public transport systems, disruptions and resilience of public transport systems and the management of disruptions with its objectives, constraints and measures. Chapter 2 will be concluded with a literature review, giving an overview of the state-of-the-art research regarding disruption management on various aspects, both in heavy-rail as well as rail-bound urban public transport systems. It will be concluded with the knowledge gap which has been defined for this research.

Chapter 3 presents the methodology used in this research, to generate and assess different alternatives. First, the route generation methods used will be discussed, which leads to a set of alternative solutions with all different detour and short-turning possibilities. Using several filter rules, these alternative solutions will be reduced to a set of candidate solutions first and ultimately to viable alternatives. Secondly, a method to assess the generated alternatives will be presented, from a passenger perspective as well as the resource perspective.

In chapter 4, a description of the case study will be presented. An introduction to HTM (public transport operator in The Hague) will be provided, as well as to the case study conducted by means of simulation. Different scenarios will be evaluated for the case study, which will be illustrated in the scenario design section. Also, a description of a previously occurred disruption will be given, which will be simulated and used to assess the added-value of the developed framework.

Chapter 5 presents a description of the model implementation. The used model input will be discussed, consisting of network data, passenger demand data, used thresholds in the alternative generation model and the values for the different model variables. Furthermore, the model implementation in respectively MATLAB and Simio will be elaborated on, finishing with the model replications, verification and validation.

Chapter 6 presents the results of the case study for the different scenarios. It also presents the analysis of a previously occurred disruption, where the current practice will be compared with the outcomes of the developed framework. Also, an overall analysis will be presented, looking at the general trends found in the results.

Finally, chapter 7 presents the conclusions and recommendations of this research. The main research question will be answered as well as the practical implications of the framework. Recommendations towards HTM will be provided, the research contribution will be discussed and based on the limitations recommendations for further research will be provided.

Figure 1.2 presents the thesis flowchart.

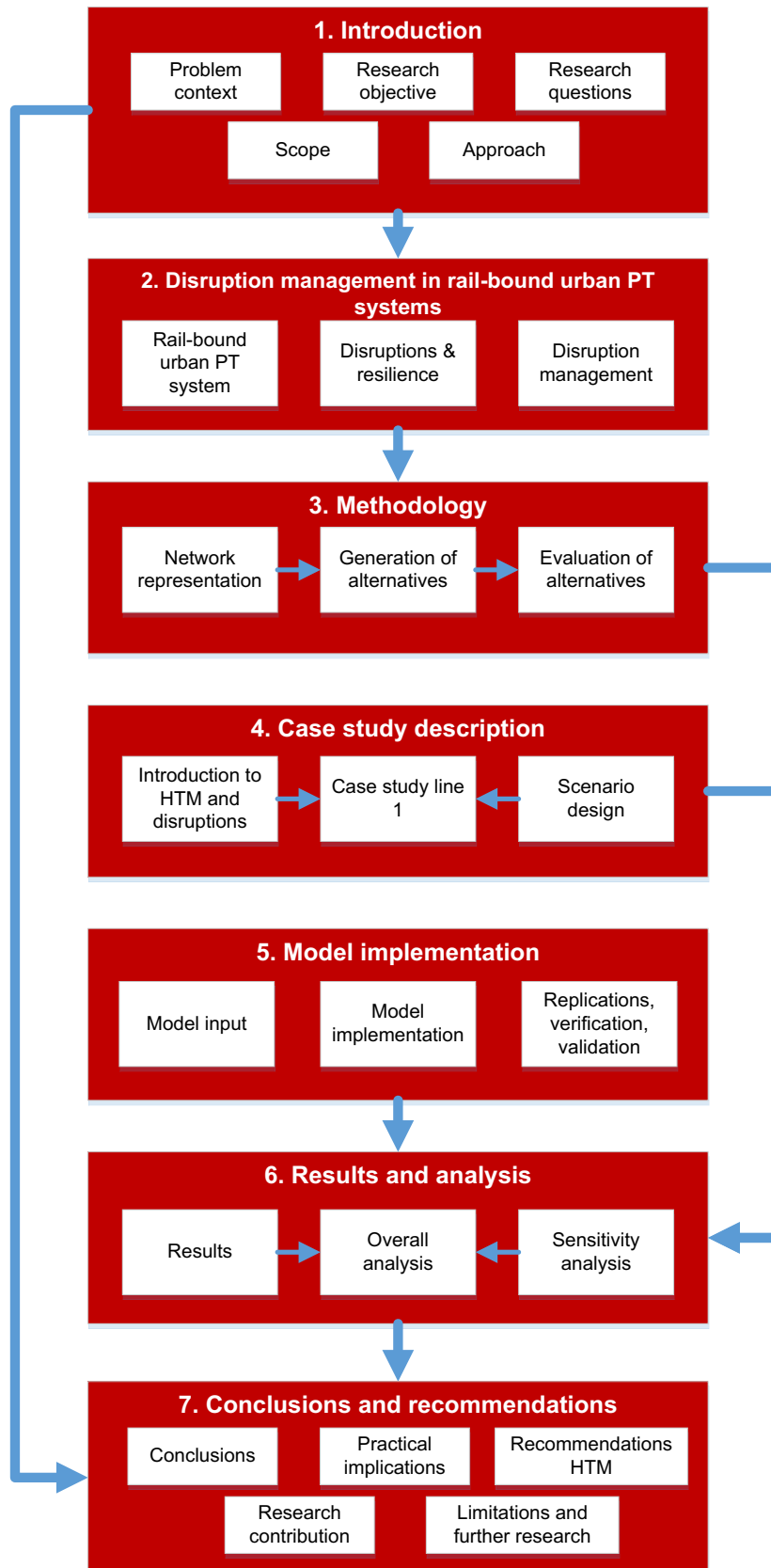


Figure 1.2: Thesis flowchart.

2

Disruption management in rail-bound urban public transport

This chapter provides a description of the context in which this research operates, as well as a literature review. First, the characteristics of a rail-bound urban public transport system (PT) will be described, including the planning process associated with it. Then disruptions in as well as the resilience of a public transport system will be discussed, followed by the management of disruptions and the objectives, constraints and measures used in this research. Finally, a literature review will be presented of studies conducted in the field of disruption management in public transport systems in general as well as disruption management rail-bound urban public transport.

2.1 Rail-bound urban public transport

Rail-bound urban PT systems are the main focus of this research, specifically tram networks. Urban PT systems are characterized as public transport systems operating mostly throughout cities, usually being denser areas with a lot of interaction between various transport modes as compared to systems operating interurban services. This leads to a higher possibility of services being operated other than was planned, for instance due to an unavailable section of infrastructure, and can ultimately lead to disruptions. Furthermore, journeys in urban areas are typically shorter than journeys outside of urban areas, making the impact of disruptions relatively large. Line spacing as well as stop spacing is typically short, which is why walking parts of the journey will be considered explicitly.

Rail-bound PT systems are characterized as PT systems which are operating on rails and guided by its flanges. By using steel wheels on steel rails, there is less friction as compared to road-bound PT, which uses rubber-tires on concrete/asphalt, leading to more energy efficient operation. Often, rail-bound PT systems are using electric motors for their propulsion. Electricity is typically supplied using overhead wires or a third rail in the case of metro systems.

Tram networks are operating using a dedicated infrastructure (rails and overhead wires), but do not have full exclusive right of way, which for instance heavy-rail and metro systems do. They can be partially separated from other traffic (typically along segments but not at crossings) or operating on streets with mixed traffic. This also leads to the fact that tram systems are typically manually controlled based on the visual inspection of the driver (Vuchic, 1981), and less likely to become automated as

compared to metro systems. Based on current traffic conditions, tram drivers are responsible for controlling the vehicle. Since no stringent safety regulations are in place compared with metro and heavy-rail, it is less constraint from the supply side (infrastructure) of the network.

Compared to road-bound urban PT systems, such as urban buses, tram systems have similar characteristics in terms of maximum speed, operational speed and stop spacing (Van Nes, 2002). The main distinction between tram and bus characteristics from a passenger point of view is the higher capacity of tramlines, which can be up to 5 times as high as the capacity of bus lines (Cats, 2015). However, due to its dependency on the infrastructure and the limited amount of infrastructure available compared with road-bound urban PT, this makes it very limited in flexibility when faced with an unavailable section of infrastructure. Whereas bus services can fairly easily reroute (even though this can be limited as well since buses cannot use all roads available, for instance due to its geometry) and/or use other road lanes, tram services have limited options to reroute. This also implies that when faced with an unavailable section of infrastructure, tram services are generally impacted more severely by it than bus services (Tahmasseby, 2009).

2.1.1 Planning

Rail-bound public transport are generally operating according to a predefined plan. Typically, two levels comprise the design of the processes to be operated, specifying the timetable and schedules. The output of these two levels is used for the transportation of passengers on the operational level (the actual operations) (Van Oort, 2011). Besides the fact that the output of a higher level is used as input for the lower level, feedback from lower levels can also be used in the higher levels (see Figure 2.1) (Tahmasseby, 2009).

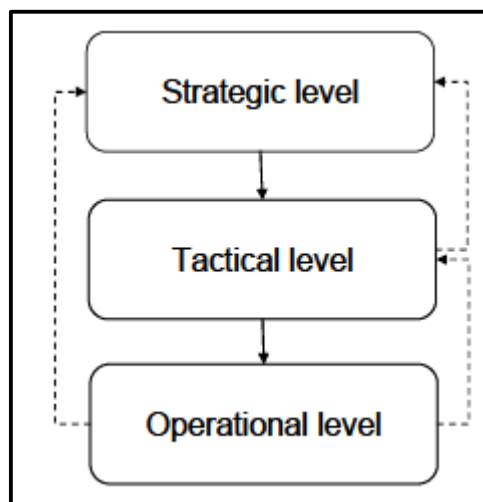


Figure 2.1: Planning levels, operations and associated feedback loops (Tahmasseby, 2009).

First, on the strategic level the network is designed. This defines the lines layout and operational characteristics such as main frequencies, based on expected ridership, budget, service standards and geographical characteristics (Ibarra-Rojas, Delgado, Giesen, & Munoz, 2015; Van Oort, 2011). The design of the physical infrastructure network can also be part of the strategic planning level. This stage is typically referred to as the network route design (A. Ceder, 2015).

Based on the line layout with the associated stops and main frequencies, the service frequency, fleet size requirement and departure and arrival times for each vehicle on each route can be derived on the tactical planning level. This stage is referred to as the timetable development in literature (A. Ceder, 2015). Both these two steps, route selection and frequency setting, are a function of the available network and the passenger demand. If the public transport is operated under a concession, these are typically part of the contract (Heerikhuisen - Ouweland, 2016). From the timetables for all routes and all vehicles, the vehicles can be scheduled and driver schedules and driver rosters are computed at the tactical planning level as well (Ibarra-Rojas et al., 2015; Van Oort, 2011). These two stages are referred to in literature as the vehicle scheduling problem and the crew scheduling problem respectively (A. Ceder, 2015). The vehicle schedules and the rosters for the personnel are the main input for the operational level (actual operations) (Ibarra-Rojas et al., 2015; Van Oort, 2011).

Since operations do not always go as planned, Ibarra-Rojas et al. (2015) provide a fourth level, which is the control level. Based on the actual situation, (real-time) control strategies can be used to better match actual operations with the planned operations. See Figure 2.2 for the interaction between the various levels in the planning process and real-time control.

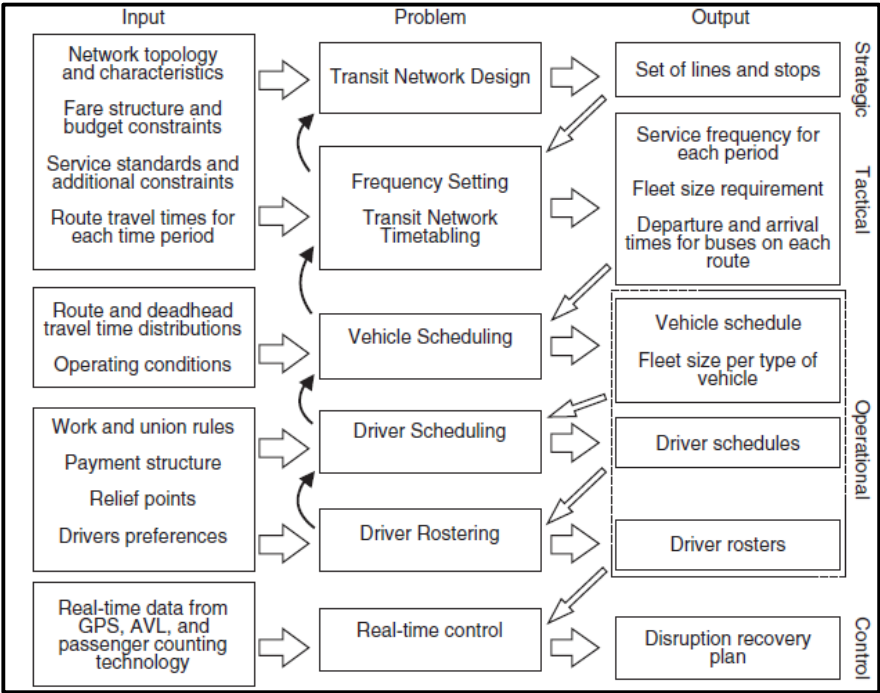


Figure 2.2: Interaction between planning, operations and real-time control strategies (Ibarra-Rojas et al., 2015).

This research is mainly focused on controlling when actual operations are not matching the planned operations. However, since the operational planning level should provide feedback to the tactical- and strategic planning level (see Figure 2.1), recommendations regarding the tactical- or strategic planning level are not excluded from the research per se.

2.2 Disruptions and resilience

Disrupted operations are referred to in this research as operations which differ from planned operations, and which cause the need to reschedule routes, crew and/or rolling stock (Cacchiani et al., 2014). Disruptions can occur due to a range of incidents, both internal and external. Internal causes for disruptions are for instance vehicle breakdown, unavailability of personnel or a switch failure, whereas external causes can be wrong parked vehicles, accidents occurring on the track or adverse weather conditions (Mattsson & Jenelius, 2015).

In managing disruptions, three phases can typically be distinguished. First, the state of the system diminishes, for instance due to an unavailability of infrastructure. Secondly, a general measure is taken, providing some service while the infrastructure is still unavailable. An example of a general measure in this context is providing a detour. Thirdly, when the infrastructure has become available again, the system state is being recovered in order to regain planned operations. The ability of a public transport system to cope with disruptions is referred to as its resilience (Mattsson & Jenelius, 2015). Faced with an incident causing a disruption, for instance an accident causing a junction to become unavailable, the state of the system quickly deteriorates since no vehicles can pass the junction anymore. Usually, it takes some time to resolve the incident. The severity in which the system deteriorates depends on the reaction of the operator. A short detour might be available, limiting the consequences for passengers, or there could be no detour available, leading to no more services available between both sides of the unavailable infrastructure. During this time, the system operates a steady-state operation, for instance by operators using a pre-defined contingency plan. When the incident has been solved, operations are regained until they are as planned again.

Two key aspects of the resilience of a public transport system are its robustness and its rapidity. Its robustness depicts the severity of impact an incident has on the system function. The time it takes for the system to recover, from the start of the incident up to full recovery, is referred to as its rapidity.

To illustrate these three phases, the resilience, the robustness and the rapidity of a system, the so-called bathtub model can be used. The vertical distance of the system function as compared to its planned operations depicts the robustness of the system; the horizontal distance between the incident and regained planned operations depicts the rapidity. Phase one is the transition state from the moment the disruption occurs until the steady-state operation. Phase two depicts the steady-state operation itself and phase three shows the transition state from steady-state operation until operations are as planned again. Figure 2.3 illustrates the bathtub model.

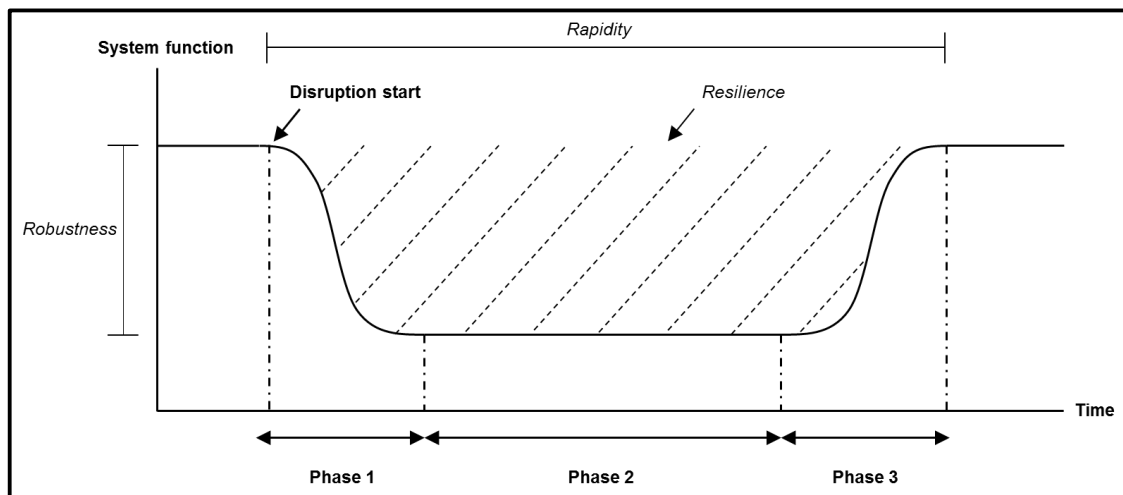


Figure 2.3: Bathtub model used to study disruptions (adapted from (Louwerse & Huisman, 2014)).

2.3 Disruption management

When an incident is being reported to the traffic controllers, first the severity of the incident is evaluated. Incidents can be reported by a driver of a vehicle, but can also be by supporting personnel on the ground or emergency services. The incident is evaluated by the traffic controllers, which can be supported by personnel at location. Based on the severity of the incident, disruption programs can be implemented by traffic controllers (Chu & Oetting, 2013; Maas, 2016).

The disruption program is being implemented upon which the operations reach a steady state (phase 2 bathtub model). Disruption programs are pre-defined programs used by public transport operators, specifying the operations when certain incidents occur. For instance, if part of the infrastructure is unavailable, a disruption program typically contains the to be operated detour (if available) and/or cancellation of services (van Delft, 2016). By using pre-defined disruption programs, traffic controllers can implement these faster and communicate these to the passengers than computing ad-hoc dispatching measures every time an incident occurs (Chu & Oetting, 2013).

However, these disruption programs do not provide a comprehensive solution in handling disrupted operations. They provide the basic operations to be conducted, for instance a different route to be taken by the vehicles for certain lines, but do not provide a solution in terms of detailed timetables for all vehicles including drivers operating them. No incident is the same, depending on its kind and the current operational situation, making it impossible to provide pre-define disruption programs for possible incidents and situations.

As said before, the disruption programs form the basis for managing disruptions. These programs are usually set up following some basic rules. Examples of rules being followed at operators in developing disruption programs (when detours are available) is to minimize the amount of skipped stops (Den Elzen, 2016). While such a rule implicitly take into account the passenger impact, but by making use of passenger flows derived from smartcard data this could be taken into account in a more explicit manner.

The ad-hoc management of disruptions can also vary per operator. This usually has to do with the information that is available for the traffic controllers. At some operators, traffic controllers have no information available regarding vehicle schedules and personnel rosters. Therefore, they do not take this into account their decision making process, making it their main job to implement the disruption program, resolve operational issues such as bunching by taking individual measures and try to regain planned operations as soon as the incident has been solved (Traffic control - HTM, 2016). At other operators (for instance RET Rotterdam), traffic controllers have (some) information regarding personnel rosters. For instance, on the overview of the current locations of vehicle, it can also be shown which driver is operating that vehicle and whether or not it his is last shift of the day / on that vehicle. This makes it possible for traffic controllers to take this into account in their decision making process (Durand, 2016). It is also possible that a dedicated traffic controller is responsible for rescheduling personnel in case of disruptions, which is the case at the public transport operator of Amsterdam, GVB (De Goede, 2016).

2.3.1 Objectives of disruption management

Passenger perspective

The main task of public transport operators is the transportation of passengers. Based on the various alternatives available for passengers, they make a choice regarding their mode of use, based on the expected utility of various alternatives. A commonly used representation of quality factors of public transport, which thus affects the mode choice of passengers, is the “pyramid of Maslow for Public Transport” provided by Peek & van Hagen (2002), shown in Appendix A (p. II).

In order to capture the evaluation of public transport by passengers, the total generalized passenger travel time (TGTT) will be used as one of the key performance indicators in this research. By using the total passenger travel time, it is able to take into account various elements of the travel time, such as total waiting time, total in-vehicle time and total walking time. These trip elements are perceived differently by passengers, for instance, waiting is usually perceived worse than in-vehicle trip time, and transferring is negatively evaluated by passengers, above the extra journey time it brings with it. By using the TGTT, the different perceptions of passengers regarding the various trip elements can be taken into account.

Usage of resources

Providing the best possible service for its passengers is one of the goals of public transport operators. However, this is a goal that should not be achieved against all costs. During planned operations, the vehicle schedules and the crew rosters are planned as efficiently as possible, in order to make exploitation as cost-efficient as possible. One way of doing this is for instance the so called “slippende bemanning”, or slipping personnel. This entails that drivers are not fixed to one vehicle during their dayshift, but they change vehicles. Vehicles on their turn are not fixed to one line only, but can change lines over the day. By doing so the vehicles and personnel are used in a more efficient manner than when drivers and vehicles were coupled as well as vehicles and lines (Heerikhuizen - Ouwehand, 2016).

Also during disrupted operations, minimizing the impact on passengers is not a goal to be achieved against all costs. This could for instance be done by having many spare vehicles and spare drivers spread out over the network, which can be used when faced with a disruption, or by having a lot of redundant infrastructure in the network. Since this is not the case for most public transport operators, solutions are also to be evaluated on the usage of resources, which can for instance be constraint by a number of available drivers or vehicles.

2.3.2 Constraints in managing disruptions

Besides the demand side of the network being input in the planning process, the supply side of the network logically is also incorporated in the planning process. Several aspects from the supply side can be distinguished which can be defined as constraints in the planning as well as the operational and the control process. Various constraints will be discussed hereafter, and how they will be dealt with during this research.

Infrastructure

The infrastructural aspect of the network obviously serves as a constraint. For all public transport services, infrastructure should be available upon which vehicles can operate. In an urban context, rail-bound public transport is generally constraint in a more extensive manner than road-bound public transport due to the limited availability of rail-bound infrastructure, which is more expensive and more space consuming than roads. Besides the limited availability of rail-bound infrastructure, also the nature of rail-bound public transport poses constraints for the operation. Since rail-bound public transport is guided by rails, additional infrastructure needs to be available for seemingly ordinary processes. For instance, in order to change tracks, switches need to be available. The same accounts for turning around in the opposite direction, where dependent on the material used, either a loop should be available for unidirectional material, or a switch should be available in order to get on the right track again after changing direction for bidirectional material.

Also, not all infrastructure is suitable for all types of material. Material can differ in terms of weight and minimum curve radius. Therefore, certain parts of the network are only suited to be operated by certain types of vehicles.

Vehicles

As has been mentioned before, vehicles also pose constraints in the planning as well as the operational and control process. Various amounts of vehicle types yield various amount of characteristics. One major aspect is if the material is unidirectional or bidirectional. As mentioned before, unidirectional material needs additional infrastructure as compared to bidirectional material. Bidirectional material is therefore more flexible in operation. Also, as discussed before, not all material is necessarily suitable for the entire infrastructure network.

Material can also differ in terms of operational speed, capacity or comfort level. A different operational speed yields different trip running times between stops. If this difference is significant, it needs to be taken into account in the planning process. The capacity of vehicles can also differ, both in total capacity as well as seating/standing capacity. If the capacity of the vehicle cannot serve the demand pattern,

increasing the capacity can be considered if possible or frequencies can be increased. The comfort level of vehicles influences the evaluation of the trip. A whole range of factors affect the comfort level of the vehicles, for instance its tidiness, its seat as well as standing spacing or its interior design.

Of course, the availability of vehicles is also a major constraint in the planning as well as the control process. There is a limited amount of vehicles available, which is minimized during the planning process, and thus poses constraints in the control stage. In order to minimize the number of used vehicles in the planning process, vehicles are not fixed to one specific line. Vehicles can be planned over various lines throughout the day, with various drivers operating them (C. Ceder, 2016).

Personnel

Just as the vehicles, the personnel and its amount is also limited and minimized during the planning process in order to operate as efficiently as possible. Whereas vehicles are for instance constraint by the infrastructure network, the personnel scheduling and operational process is constraint by legal regulations as well as company specific regulations, which can be stricter than the legal requirements.

Examples of rules being used in the scheduling process of personnel are a maximum duty time, the right for personnel to have a break after a certain period of time, the right to have a meal break at a certain moment in time or to have a minimum amount of resting time between the end of the shift on the first day and the beginning of the shift on the second day. These rules can also differ per person, for instance based on their age or function.

In order to minimize the number of vehicles, the concept of slipping personnel is used. This means that drivers and vehicles are scheduled separate from each other. This stems from the base of maximizing the utilization of vehicles and personnel. Where the personnel are entitled to breaks and a maximum length of duty, the utilization of vehicles is less stringent constraint. Therefore, vehicles can be taken over by a driver which is just (re)starting his duty when the previous driver is going on a break. By using the concept of slipping personnel the utilization of the vehicles is higher than if every driver were to have its "own" vehicle. However, this poses difficulties when operations are disrupted, since a disruption on the one line can easily spread to another line.

2.3.3 Considered measures

As previously discussed, two measures will be incorporated into this research. Faced with an unavailability of infrastructure, detours will be considered as well as short-turning. Both measures are basically the rerouting of vehicles, where they both can be part of a disruption program.

Detouring is a measure often taken by traffic controllers when faced with an unavailability of infrastructure in rail-bound urban public transport operations. Important in this notion is that to be able to conduct this measure, redundant infrastructure must be available (Tahmasseby, 2009; Van Oort, 2011). It should be physically present but it should also be suitable for the vehicles that are being operated.

An advantage of detouring as compared to short-turning is that passengers as well as vehicle and personnel is able to arrive at the planned terminus of the line. This can save passengers a possible transfer, and vehicles and personnel is able to go to the planned end stop which can prove to be beneficial. However, a detour usually means that certain stops are skipped as opposed to the planned operations. Some passengers might not be able to alight at their preferred stop, making their egress time higher and thus their total travel time, or they could need an additional transfer. Passengers who planned boarding the vehicle at the skipped stop might be faced with additional access time or an additional transfer as well. On the other hand, when applying a detour, vehicles might stop at stops which are not planned, which could be beneficial for alighting and boarding passengers as well, decreasing their access/egress time or number of transfers. Applying a detour usually means that the trip times of the entire line are not as they were planned. This can have implications for the vehicle schedules and personnel rosters. This is especially problematic when detours take longer than the planned trip times, which is usually the case. When the detour is longer than the planned trip times, vehicles as well as personnel might miss their next shift. Figure 2.4 illustrates the detouring measure.

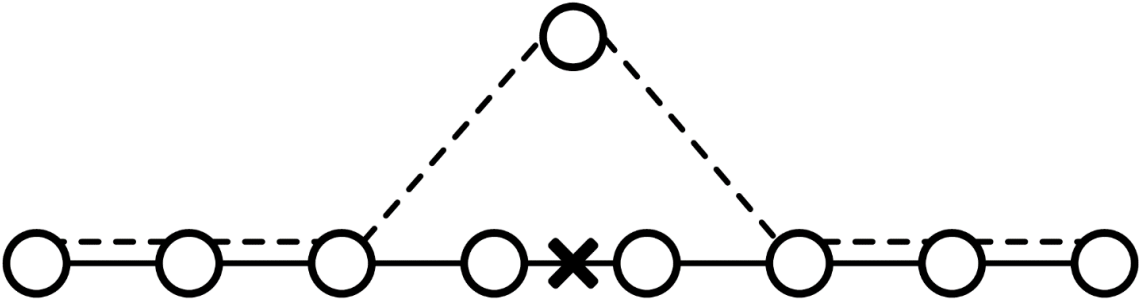


Figure 2.4: Illustration of detouring principle, with the original route (solid) and detour (dotted).

Short-turning is often applied when no detour is available. If this is the case, the line is cut in two pieces at the location of the unavailable infrastructure. As is the case with detouring, short-turning should be possible from an infrastructural perspective (Van Oort, 2011). Depending on the available infrastructure, the location where the vehicles short-turn varies. Therefore, it could be that vehicles skip more stops than strictly necessary. The vehicles switches direction upstream of the unavailable infrastructure on both sides. For the passengers and personnel, short-turning means that they cannot reach the other side of the unavailable infrastructure, without transferring or using another mode (such as walking). Depending if the vehicles are unidirectional or bidirectional, a loop/wye is necessary for short-turning, or a crossover switch will suffice, respectively. Figure 2.5 illustrates the short-turning principle.



Figure 2.5: Illustration of the short-turning principle.

Depending on the situation, public transport operators can choose to provide passengers with a replacement service between the two short-turn ends. This replacement service is usually provided using a (shuttle-)bus. Factors influencing operators whether or not to implement a replacement service are for instance the passenger demand between the two ends, expected duration of the disruption,

availability of alternative routes for passenger and the ease with which replacement services can be implemented (availability of material and personnel).

The latter factor in combination with the often limited duration of an unplanned disruption makes that replacement services are not often implemented in unplanned disruptions as compared to planned disruptions. Since this research focuses on the management of unplanned disruptions, it is assumed no replacing services will be implemented. In case of implementing short-turning, passengers traveling from the one side of the disruption to the other side, this means that they will have to walk from the short-turning stop on the one side to the other side.

2.4 Literature review

Extensive research has been done regarding the management of disruptions in public transport systems. Public transport services are characterized by the fact that they can be used by anyone and that they usually operate following a pre-defined timetable. This timetable can be defined up until months before actual operation, and consists of three steps: timetable development, vehicle scheduling, and crew rostering (see §2.1.1). Faced with a disruption, traffic controllers have to reschedule current operations by performing these three steps again. Cacchiani et al. (2014) provide an overview of literature available regarding the research on rescheduling of timetable, vehicle and crew in a heavy-railway context.

Most of the literature available regarding disruption management of rail-bound public transport systems is focused on the heavy-railway context. Pender, Currie, Delbosc, & Shiwakoti (2012) provide an overview of worldwide applied disruption management when faced with unplanned service disruptions. Although it describes the current practice of rail operators facing a disruption, it does not provide a systematic evaluation of the performed service disruption management.

Corman, D'Ariano, Pacciarelli, & Pranzo (2010) provide a rerouting and rescheduling algorithm for a heavy-railway system and apply this in a case study on the Dutch railway network. It is focused on infrastructural constraints, adjusting the timings of trips and the tracks of routes, but it has no consideration for passengers. Other research focusing on the infrastructural constraints is conducted by Pellegrini, Marlière and Rodriguez (2014) who developed a model minimizing delays taking into account detailed infrastructure constraints.

Veelenturf, Kidd, Cacchiani, Kroon, & Toth (2015) provide a railway timetable rescheduling approach for handling large scale disruptions. It takes into account the timetable rescheduling of passenger trains, including rolling stock and infrastructure constraints, but not incorporating crew constraints. It takes into account the possibility to reroute trains with the objective to minimize delays and cancellations. It focuses on all stages of a disruption, that is, the first transition stage from regular operations to steady state operations when an incident occurs, the steady state operations itself, and the transition stage to regain planned operations again. Another research which takes into account the rolling stock constraints is provided by Nielsen, Kroon, & Maróti (2012). They provide a generic framework for dealing with

disruptions of railway rolling stock schedules, and taking into account the train stock balance at the different parts of the lines at the end of the day.

Besides literature being available regarding timetable rescheduling or rolling stock rescheduling, research regarding crew rescheduling has been conducted as well. Huisman (2007) provides a column generation based algorithm to solve the crew rescheduling problem for expected unavailability of infrastructure, for instance due to planned maintenance. Rezanova & Ryan (2010) provide a solution to the crew rescheduling problem for major (unplanned) disruptions.

As can be seen above, current literature majorly focuses on optimizing either timetable rescheduling, rolling stock rescheduling or personnel rescheduling. It does not provide a comprehensive approach which can help in the management of disruptions, nor is the impact on the demand side of the system (passenger perspective) explicitly taken into account. This can partly be explained due to the nature of heavy-railway systems. There is a significant difference between disruption management in urban public transport and heavy rail. The management of disruptions in heavy rail is highly dependent on availability of infrastructure and safety regulations, whereas this is less the case for (rail-bound) urban public transport. Disruption management in heavy rail operations is therefore more driven by the supply-side of the network, whereas in urban public transport a more demand-driven approach can be used, due to less strict constraints imposed by the infrastructure and safety regulations. Metro systems in this context resemble heavy-rail operations, since they are also more constraint to infrastructure and safety regulations than tram systems. Detouring for instance is a commonly practiced measure in the disruption management process of tram networks, whereas this is far less the case for metro networks.

However, some literature is available taking into account the passenger perspective in a heavy-rail context. Puong & Wilson (2008) provide a model that includes denied boarding, longer dwell times due to overcrowding and an objective function accounting for waiting times as well as in-vehicle times. The model includes short-turning strategies as well as holding strategies on high-frequency services (metro). Louwerse & Huisman (2014) have developed a timetable rescheduling model which takes into account passenger service, being defined as minimizing the number of cancelled trains as well as the delays of the operated trains. Even headways over time and direction are taken into account as well. However, rolling stock constraints and crew constraints are not modelled explicitly.

Literature that covers a systematic evaluation of currently used disruption management in an urban context is provided by Carrel, Mishalani, Wilson, & Attanucci (2013). It provides a framework to empirically evaluate metro line operations to identify limitations of currently deployed control strategies, by making use of automatically collected train and passenger movement data. It applies the framework to the metro system of the London underground, and shows that its current practice of disruption management is focused more on the management of personnel rather than the impact it has on passengers. Babany (2015) provides a framework for providing decision support during the recovering phase of the management of disruptions (phase 3 bathtub model), taking into account crew constraints as well as infrastructure constraints, with the aim of providing a good service for its passengers and coming back to schedule. This framework is also applied to the London metro system.

Canca, Barrena, Laporte, & Ortega (2014) provide a short-turning policy for the management of demand disruptions in rapid transit systems. They propose an optimization model which selects the most suitable zone to short-turn vehicles when faced with an increase of demand, either expected or unexpected, and apply this on the C5 line of the Madrid commuter railway system.

Literature that focuses on tram networks is provided by Carnaghi (2014). He presents a decision support system to be used for disrupted tram operations. It takes into account the passenger perspective by aiming to improve the service reliability, being defined as the travel time reliability and the level of comfort. It provides a system which supports dispatchers in choosing an intervention, with the objective to maximise the service reliability, but did not take into account the effect interventions had on the resource schedules.

Koppenol (2016) has recently looked into the robustness of rail-bound urban public transport networks, including tram networks. He assessed how certain link attributes influenced the relationship between a capacity reduction on that link and the performance of the network as a whole. Even though he did not look into the management of disruptions itself, part of his methodology can be followed in the generation of different alternatives, since he also focused on detouring and short-turning.

2.5 Conclusions disruption management in rail-bound PT systems

In this chapter, the context of rail-bound urban public transport has been discussed, being far more constraint by the infrastructure than road-bound urban public transport. Furthermore, the planning process has been discussed, which showed the different cycles in the planning process. Different phases and aspects of disruption management have been elaborated upon by means of the bathtub model.

Based on the existing literature, a knowledge gap has been defined for a comprehensive and systematic approach in evaluating the management of disruptions in rail-bound urban PT systems from a passenger perspective, and taking into account the effects interventions have on the resource aspect as well. This research aims to provide a framework for public transport operators, in generating alternatives in terms of detours and short-turning possibilities based on a given infrastructure network and assessing them from a passenger- and resource perspective. The next chapter will elaborate upon the methodology developed in order to generate and assess different alternatives.

3

Methodology

In this chapter, a methodology will be presented in order to generate alternatives as well as to analyse them. Alternatives in this context are different routing possibilities for the public transport operator to choose from when faced with a disruption, such as detour possibilities as well as the short-turning possibilities. Alternatives can have different characteristics from a passenger perspective as well as resource perspective.

First the representation of an urban public transport network will be discussed using graph theory. The presented terminology will be used in the remainder of the chapter for the generation and assessment of alternatives.

Secondly, a method for the generation of alternatives will be presented. This is a step-wise process, where first all possibilities are generated. Then, based on a set of rules, filtering takes place to ultimately result in the alternatives to be assessed, which can be implemented by a public transport operator.

The alternatives will be assessed from two different perspectives, that is the passenger perspective and the resource perspective. As was shown in the previous chapter, current literature generally underexposes the passenger perspective in the management of disruptions. Passengers are affected by an alternative for instance by a longer in-vehicle travel time or skipped stops. Resources, in this context vehicles and personnel, might be affected by an alternative by a later arrival at their destination terminal than was scheduled, causing other activities to be delayed as well.

Figure 3.1 illustrates the different processes presented in this chapter and the relation between them.

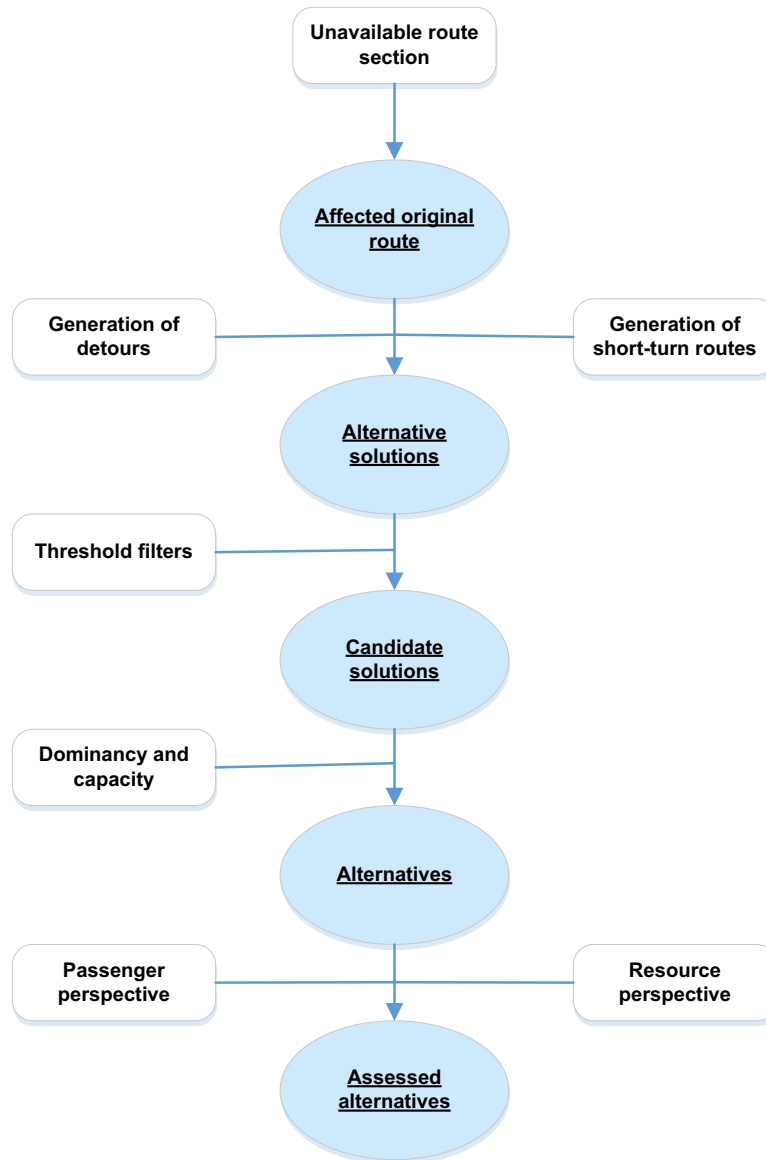


Figure 3.1: Process from generating routes to assessed alternatives.

3.1 Network representation

Before the different alternatives can be generated and analysed, first a generic approach will be discussed for the representation of public transport network. This representation will be used throughout the remainder of this chapter.

A public transport network consists of stops for passengers to board and alight, and tracks which connect the different stops with each other. Such a network can be represented using graph theory, consisting of vertices and edges. A network can be represented by a graph G , with stops and tracks being represented as vertices and edges respectively. The graph G then exists of a set of vertices S and a set of edges E , so $G = (S, E)$. For generating different reroute possibilities, a bi-directed weighted graph will be used. This means that edges can have two directions, have an origin node and a destination node, and that the edges are weighted. Each edge $e \in E$ is defined by an origin node $s_e \in$

S , a destination node $s_{e^+} \in S$. Weights for the edges in this case are the distance d_e , and associated vehicle travel time and walking time, t_e^v and t_e^{walk} respectively.

To illustrate this principle, a fictive example has been set, illustrated in Figure 3.2.

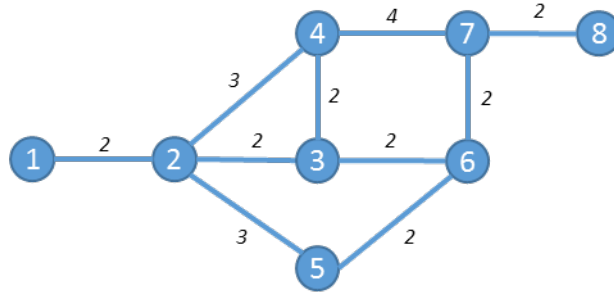


Figure 3.2: Fictive PT network, with edge labels representing vehicle travel time.

The set of vertices in this example is $S = (1,2,3,4,5,6,7,8)$. The set of edges E with the corresponding origin node s_{e^-} and destination node s_{e^+} and the weights, in this example representing the travel time between the nodes, is illustrated in Table 3.1. Since it is a bidirectional graph, edges are represented in both directions. Note that this example represents a symmetric network, which does not have to be the case.

Table 3.1: Set of edges E , origin nodes s_{e^-} , destination nodes s_{e^+} and vehicle travel time t_e^v .

s_{e^-}	s_{e^+}	t_e^v
1	2	2
2	1	2
2	3	2
3	2	2
2	4	3
4	2	3
3	4	2
4	3	2
2	5	3
5	2	3
3	6	2
6	3	2
4	7	4
7	4	4
5	6	2
6	5	2
6	7	2
7	6	2
7	8	2
8	7	2

Public transport operators operate pre-defined service lines, servicing a sequence of different stops $s \in S$ and traversing a sequence of edges $e \in E$. A line l commences at a stop $s_{l,1}$ (origin terminal) and ends at a stop $s_{l,|l|}$ (destination terminal). The total sequence of stops served by a line can be represented as $S_l = (s_{l,1}, s_{l,2}, \dots, s_{l,|l|})$, and $s \in S$. The total sequence of edges traversed by a line l can be denoted in a similar manner, thus $E_l = (e_{l,1}, e_{l,2}, \dots, e_{l,|l|})$, and $e \in E$.

For the given example in Figure 3.2, an example of a line a could be $S_a = (1,2,3,6,7,8)$, and $E_a = ((1,2), (2,3), (3,6), (6,7), (7,8))$. This line has its origin terminal at stop 1 and its destination terminal at stop 8, and serves stops 2, 3, 6 and 7 along its way.

3.2 Generating alternatives

Using the terminology presented before, in this paragraph the generation of alternatives will be discussed. When faced with an unavailability of infrastructure, public transport operators have to find an alternative route if they want to keep operating the disrupted line. The alternatives are the different route possibilities for a public transport operator to implement, which will be assessed from the passenger perspective and the resource perspective in the next section.

For the generation process of the alternatives, first all different route possibilities will be mapped. This is an extensive set of routes, and referred to as the alternative solutions. This set of alternative solutions contains unreasonable routes which can be excluded. Therefore, filtering takes based on a set of rules, leading to a set of candidate solutions. Based on the concept of dominancy as well as the capacity of the network, these candidate solutions are reduced to actual alternatives. Figure 3.3 illustrates this process from route generation to the alternative solutions, candidate solutions and alternatives.

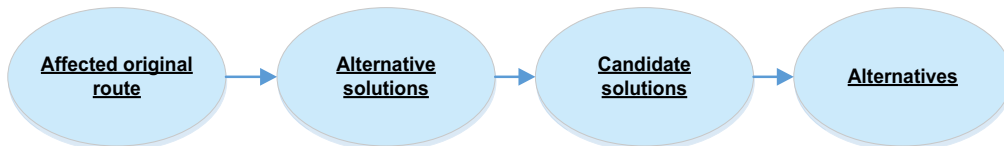


Figure 3.3: Process from the affected original route to alternatives.

3.2.1 Alternative solutions

In the case of an incident leading to an unavailability of infrastructure in the network, the corresponding affected edge $d \in E$, or subsequence of edges $D \subseteq E$ are removed from the set of edges. If the unavailable infrastructure was used by a line l , thus $d \in E_l$, a different route has to be found for that line. The set of alternative solutions contains all routes from an origin terminal to the destination terminal of a line which can theoretically serve as an alternative. Routes in this set of alternative solutions consist of detours and short-turn possibilities, which are generated in a different manner (Figure 3.4). Combinations of detouring and short-turning are not considered in this research, since for the disruption durations considered this is not likely to be implemented (for instance due to complexity of informing passengers and personnel rightly) (Den Elzen, 2016).

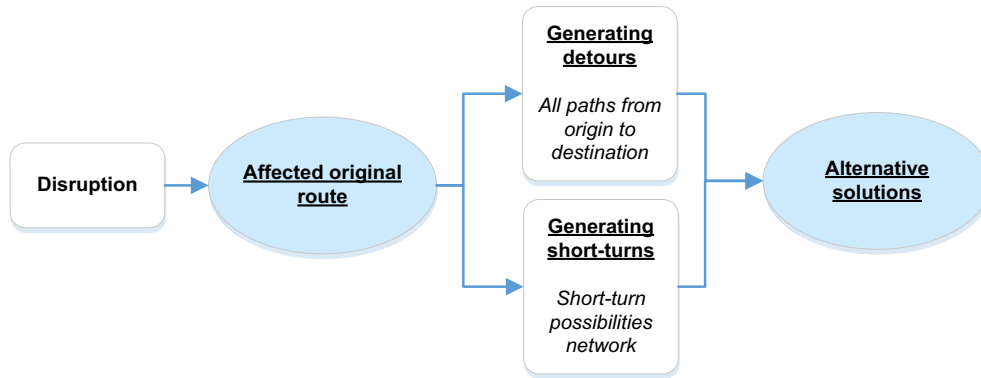


Figure 3.4: Process from affected original route to the alternative solutions.

Detours

In order to find the different detouring routes, the k -shortest paths between the origin terminal and the destination terminal for the disrupted network are sought for. This is conducted using an algorithm presented by Yen (1971), being an extension on Dijkstra's (1959) shortest path algorithm. With Dijkstra's (Dijkstra, 1959) shortest path algorithm, one is able to find the shortest path from a node i to a node j . The extended k -shortest path algorithm then finds all k shortest paths from node i to node j without any loops.

In current literature it is found that the limitation of using the k -shortest path algorithm in route choice modelling is "the possibility of generating over circuitous and extremely similar routes that are highly unattractive to travellers" (Prato, 2009). Due to the nature of rail-bound networks, having a limited infrastructure network available compared to for instance road-bound or pedestrian route choice generation, this limitation is perceived not to be of such effect to opt for another route choice generation method. Alternative options could be to extend the k -shortest path algorithm with "gateway shortest path", constraining routes through different nodes spread over the network, resulting in spatially distributed routes (Lombard & Church, 1993), or a different method such as branch-and-bound, where the branching rule is dependent on certain route choice assumptions other than the minimum cost route, such as discarding routes in the direction of the origin instead of the destination (Prato & Bekhor, 2006). The benefits of using these alternatives are perceived not outweigh the increasing complexity it brings with it. Furthermore, having similar routes available might be of use when considering the capacity of the network, which will be discussed in §3.2.3.

Using the k -shortest path algorithm, all routes can be found from $s_{l,1}$ to $s_{l,|l|}$. Each route p yields a sequence of stops $S_{l,p} \subseteq S$ as well as a sequence of edges $E_{l,p} \subseteq E$. By using this k -shortest path algorithm, the generated routes are without loops. This means that routes containing a loop are not taken into account. Even though it might be possible for a route containing a loop to be more beneficial from a passenger perspective, its application in reality is assumed to be very rare, since it needs redundant infrastructure that needs to be available at the two stops between which the loop exists.

The sequence of stops for a line l using route p $S_{l,p}$ consists of three sub-sequences. First of all, there is the subsequence of stops upstream of the disruption that are still being served. This subset is defined

as $S_{l,p,q}$ with elements $s_{l,p,q}$ where s_{l,p,q_1} denotes the first stop of the sequence (which is equal to $s_{l,1}$), and $s_{l,p,q|q|}$ the last stop upstream of the disruption. Secondly, there is the subsequence of stops which are traversed due to the disruption, but were not originally. This subset is defined as $S_{l,p,u}$, with elements $s_{l,p,u}$. Lastly, there is the subset of stops still being served downstream of the disruption. These stops $s_{l,p,r}$ are collected in subsequence $S_{l,p,r}$. There is another subsequence of importance, which are the skipped stops of a line l for a route p . These stops $s_{l,p,v}$ are collected in subsequence $S_{l,p,v}$.

Short-turning (cutting line)

Besides rerouting a vehicle using a detour, public transport operators sometimes opt (or are forced due to a lack of detour possibilities) to short-turn vehicles on both sides of the unavailable infrastructure. The line l is then basically cut in two new lines, one upstream of the incident and one downstream of the incident. However, as was discussed before, short-turning needs additional infrastructure and is generally not available everywhere throughout the network. In order to account for this, a set $S^t \subseteq S$, where $s^t \in S^t$ represents those stops where short-turn infrastructure is available.

If a part of the network $D \subseteq E$ is not available anymore, and $d \in E_l$, the line is cut in a part upstream of the disruption and a part downstream of the disruption. However, since short-turning is not available everywhere throughout the network, short-turning routes operate to and from short-turning nodes only. The part of the line upstream of the disruption is defined by the sequence $S_{l,q} = (s_{l,q_1}, s_{l,q_2}, \dots, s_{l,q_d^-})$, while the part of the line downstream of the disruption is defined as $S_{l,r} = (s_{l,r_{d^+}}, s_{l,r_{d^++1}}, \dots, s_{l,r|})$. Since short-turns can only take place at some specific nodes, the different routes upstream of the network incorporating short-turning are denoted by $S_{l,p,q} = (s_{l,p,q_1}, s_{l,p,q_2}, \dots, s^t)$, for all $s^t \in S_{l,q}$. Similarly, all different routes downstream of the network incorporating short-turning are denoted by $S_{l,p,r} = (s^t, \dots, s_{l,p,|r|-1}, s_{l,p,|r|})$, for all $s^t \in S_{l,r}$.

3.2.2 Candidate solutions

The set of alternative solutions contains all routes being a theoretic alternative for the public transport operator when faced with a disruption. However, certain routes can be excluded beforehand. These are detour possibilities which do not make sense from a logical point of view, since it is clear that they perform worse than others and are therefore not worth analysing and evaluating any further. In order to exclude these routes for further analysis, the routes are compared to the original route of a line l in terms of stops served and skipped as well as the original route trip time of line l . The route trip time of a line l is defined as the time that is needed between departure at the origin terminal and the arrival at the destination terminal. The total of routes which are not excluded result in the set of candidate solutions (Figure 3.5).

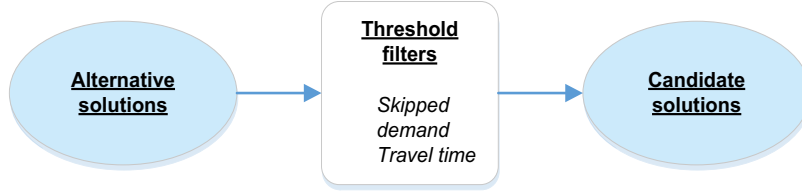


Figure 3.5: Constructing the candidate solutions using threshold filters on the alternative solutions.

Formally, the subsequence of stops which are skipped due to a route p ($S_{l,p,v}$) can be found by subtracting the route-stop matrix of the line using the original route with the route-stop matrix of the line using a route p . The route-stop matrix represents on the y-axis all routes $p \in P_l$, and on the x-axis all stops $s \in S$. For each route (matrix row), a cell equals 1 if the stop is being served by that route (thus $s \in S_{l,p}$) and 0 otherwise. By subtracting the original route-stop row of a line l with that of a path p , the skipped stops $S_{l,p,v}$ are indicated if the cell in the route-stop row of line l still equals 1. Stops that were not being served originally, but are being served due to route p are indicated by a value of -1.

Referring to the previously discussed example, the corresponding route-stop matrix is given in Table 3.2 with (3,6) being the unavailable edge.

Table 3.2: Route-stop matrix for line α and routes 1 to 3.

	1	2	3	4	5	6	7	8
Line α	1	1	1	0	0	1	1	1
Route 1	1	1	0	1	0	0	1	1
Route 2	1	1	1	1	0	0	1	1
Route 3	1	1	0	0	1	1	1	1

The route trip time t_l^r of the original route of a line l can be determined by summing all the vehicle travel times t_e^v of each edge in E_l :

$$t_l^r = \sum_{e \in E_l} t_e^v \quad (3.1)$$

Similarly, the route trip time of a route p for a line l can be determined by summing all the vehicle travel times t_e^v of each edge in $E_{l,p}$:

$$t_{l,p}^r = \sum_{e \in E_{l,p}} t_e^v \quad (3.2)$$

All the routes in the set of alternative solutions are compared to the original route which has the least amount of passengers affected in terms of skipped stops, and a certain threshold will be installed above which routes in the set of alternative solutions will be filtered out. This threshold depends on the network topology and characteristics, and is therefore a parameter depending on the network. An example of a threshold can for instance be that routes in the set of alternative solutions which affect five times as much passengers by skipped stops compared to the alternative solutions which affects the least number of passengers by skipped stop, are disregarded.

It might be possible that an alternative solutions does not affect that many passengers by skipped stops, but that the route trip time increases tremendously, causing it not to be a viable option. Therefore, a similar threshold will be used regarding the route trip time of the alternative solutions. Here, the different routes in the set of alternative solutions are compared to the original route of a line l , instead of the alternative solution having the least route trip time, since it is possible that certain routes have a shorter route trip time than the original line. An example of this threshold is that alternative solutions taking twice as long as the original route are disregarded beforehand. This is a threshold that is also depend on the network topology and characteristics, and is therefore a parameter varying per network.

3.2.3 Alternatives

The set of candidate alternatives now contains detour routes which satisfy certain threshold rules, as well as various short-turn possibilities. The different detour routes are assessed in terms of skipped demand (skipped stops) as well as their route trip time. In order to translate the set of candidate solutions into a viable alternative route set, one last step has to be conducted, which filters out some of the candidate solutions. This filter has to do with the concept of dominance as well as the capacity of the network (Figure 3.6).

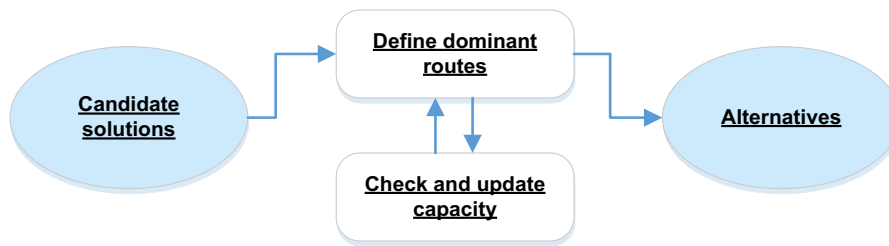


Figure 3.6: Generating alternatives from the set of candidate solutions.

Dominant routes

A route is dominated by another route if it performs worse on at least one aspect without being better on any of the other aspects (Cats, 2011). In economics terminology, dominated routes can be referred to as Pareto non-optimal routes. The underlying assumption of this concept is that a decision-maker will not opt for a Pareto non-optimal route, since this route is always inferior to another dominant route (Pareto optimal), and has been used in transit route choices for instance by Cats (2011), Androutsopoulos and Zografos (2009), and Koppenol (2016).

In relation to the routes which have been generated in this chapter, dominated detouring routes are for instance routes having the same amount of skipped stops as another route, but having a longer route trip time. If the same amount of passengers is affected by skipped stops by a candidate route, it is never beneficial to consider a route which implies longer travel times.

In order to find dominant routes, the skipped stops of each route p for a line l ($S_{l,p,v}$) are compared. All routes p for which $S_{l,p,v}$ are equal, form a set of routes P_v . For each set of routes P_v , the route $p \in P_v$ with the lowest route trip time $t_{l,p}^r$ is determined, which is the dominant route p^{dom} for that set P_v .

Capacity of the network

However, by rerouting a line using a detour, the line traverses different tracks than was planned. Most of the times, these tracks have been planned for usage by other lines as well. In the route generation process up until now, vehicle trip times between stops have been taken regardless of other traffic.

There is no coherent definition of the capacity of a railway network. Citing the International Union of Railways (2004), “railway infrastructure capacity depends on the way it is utilised”. Given an infrastructure network, the capacity of the network is based on the interdependencies of four underpinning parameter, which are the *number of trains*, the *average speed*, the *stability* and the *heterogeneity* (UIC, 2004). The relation can be clearly seen in the ‘capacity balance’, shown in Figure 3.7.

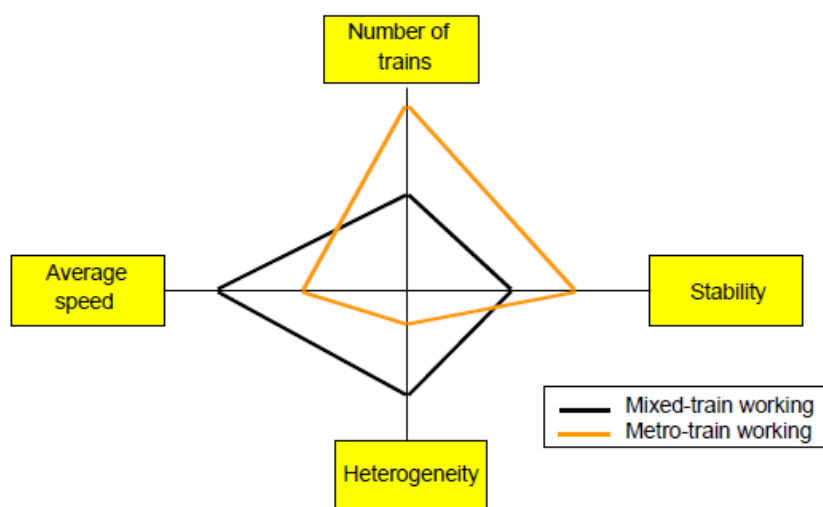


Figure 3.7: UIC capacity balance (UIC, 2004).

From the origin, an axis per parameter has been drawn. The four values for each of the parameters are connected by each other by a cord, of which the length corresponds to the capacity of the network. Looking at rail-bound urban public transport networks from this perspective, its operations are quite homogenous. Running times between stops does not vary significantly between services. Its stability on the other hand is relatively low, due to a high number of interactions with the environment. During a disruption and an implemented detour, the number of trains traversing a track probably increases. Also, services become more heterogeneous because the detoured vehicle does not stop at all stops located along the detour route. Following the capacity balance from the UIC, this influences the stability and/or the average speed.

Going back to the generation of alternatives, the influence of assigning more vehicles onto the same tracks in case of detouring should be taken into account. Looking at the state of the practice, capacity issues and the associated performance reduction (average speed) mostly arises due to limited stopping places at stops and junctions with traffic control systems (*Dutch: Verkeers Regel Installatie*). For instance, if a traffic control system is set for one vehicle, and two vehicles arrive one after another at the

junction, the second vehicle has to wait twice. The same accounts for a stop with a platform for only one vehicle.

However, to take into account all factors influencing the vehicle trip time between stops based on the number of vehicles traversing the track in a generic manner would not be possible in the time and scope of this research. Therefore, a more pragmatic and generally applicable method will be used, derived from traffic flow theory.

In this research, tracks (edges) between stops are considered to have a certain capacity, denoted by f_e^c , in vehicles per hour. Up until this capacity is reached, the vehicle trip time between stops will not be affected. However, if the frequency assigned to the track due to a detour exceeds this threshold, the travel time between the two stops will increase for all vehicles traversing that track during that time period. The factor with which the travel time between stops is affected depends on the exceedance of the capacity and/or the location in the network.

Due to this increase of travel time between stops, the considered route might not be the dominant route anymore. In this case, the dominant route should be filled up until its capacity is fulfilled. The residue of the frequency of the disrupted line will then be assigned to the second best route, skipping the same stops. Based on the capacity of that second best route and the updated route times of the second best route, the (updated) route times of the original dominant route, the updated route time of the second best route and the route time of the third best route are compared. The residual frequency is then assigned to the route with the lowest route time. If the third best route has the lowest route time in this case, then this process of updating the route times and comparing them to the previously updated route times and the next route skipping the same stops needs to be repeated, until all frequency of the disrupted line is assigned. Concluding, the four steps that need to be considered in assigning the frequency are as follows:

1. Assign frequency disrupted line to dominant route.
2. Update dominant route time.
3. Compare updated dominant route time with next best route (and previous dominant routes).
4. If next best route is now dominant, assign capacity of the disrupted line until capacity original dominant route is fulfilled, and repeat process with the residual frequency.

So formally, first it needs to be determined which lines traverse an edge e . These lines are collected in set $L_e = \{l \in L | e \in E_l\}$. Lines which are planned to traverse these tracks have a certain service frequency f_l^s . The planned service frequency of that edge f_e^s can be determined by summing all the service frequencies of the lines traversing that edge.

$$f_e^s = \sum_{l \in L_e} f_l^s \text{ for } e \in E \quad (3.3)$$

By subtracting the sum of service frequencies of lines traversing the track from the capacity of the track, the redundant capacity f_e^r of that track e can be determined:

$$f_e^r = f_e^c - f_e^s \text{ for } e \in E \quad (3.4)$$

As discussed before, a detour route consists of a sequence of edges $E_{l,p}$. For the edges which were not planned to be traversed, thus subset $E_{l,p,u} \not\subset E_{l,p}$, the weakest link has to be determined. The weakest link in this context denotes the edge which has the minimum redundant capacity f_e^r available. If the minimum redundant capacity $f_e^{r,min}$ for $e \in E_{l,p,u}$ available exceeds or is equal to the service frequency of the disrupted line l , thus $f_e^{r,min} \geq f_l^s$ for $e \in E_{l,p,u}$, this detour route is valid and can be used. The redundant capacity of the traversed edges has to be updated by subtracting the service frequency of the disrupted line l from the previous redundant capacity.

If the service frequency of the disrupted line l is higher than the redundant capacity available, thus $f_e^{r,min} < f_l^s$ for $e \in E_{l,p,u}$, the vehicle trip times of all edges $e \in E_{l,p,u}$ for which $f_e^r < f_l^s$ are affected and need to be updated. The updated vehicle trip time between a stop i and a stop j $t_{i,j,p}^r$ can be determined as follows:

$$t_{i,j,p}^{v'} = t_{i,j,p}^v \cdot y_e(f_l^{s,res}) \quad (3.5)$$

The factor with which the travel time for an edge e is affected is represented by the function y of the frequency of the disrupted line that needs to be assigned, the residual frequency $f_l^{s,res}$. Using the updated travel times $t_{i,j,p}^{v'}$ the updated route time $t_{l,p}^{r'}$ can be determined. As discussed, the next step is to compare the updated route time with the next best route. If the next best route is now dominant, $f_e^{r,min}$ is assigned to the originally dominant route and the process is repeated with the new dominant route and the residual service frequency.

In order to limit the complexity of the service, only routes of the same set P_v will be considered. Even though it is possible that combining various (dominant) routes from various sets P_v into one alternative might result in a better outcome, combining different route sets P_v is not considered. By combining different route sets P_v , different stops will be skipped varying per vehicle. This is assumed to be undesirable for public transport operators, since it is confusing for passengers and difficult to inform them properly (Den Elzen, 2016).

Another assumption in this approach is that it is assumed that the services traverse the tracks homogenously spread over time. In case multiple vehicles want to traverse the same track (and thus stops and junctions) at the same time, travel times are likely to increase even if the capacity of the track is not exceeded. However, modelling a more realistic distribution of vehicles would a much more sophisticated approach, which is considered to take too much effort compared to the limited benefits it would have in the context of this research.

Short-turning candidate routes do not have a dominant route, since the short-turning routes are distinguished by the different short-turn possibilities, and therefore per definition differ in terms of skipped stops as well as route trip time. Short-turning routes in the set of candidate solutions are therefore also alternatives.

3.3 Assessing alternatives

Now that the alternatives have been generated, they have to be assessed in order to compare them between each other. Alternatives will be assessed from a passenger perspective, by using their total generalized passenger travel time, as well as from a resource perspective, determining the delay of an alternative causes at the destination terminal and taking into account its subsequent activity (Figure 3.8).

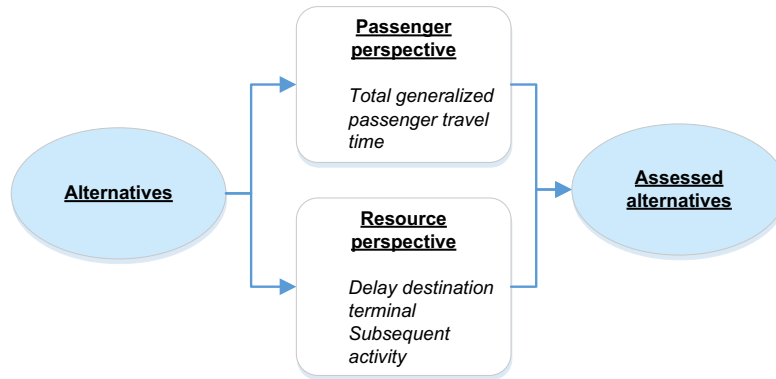


Figure 3.8: Assessing alternatives from a passenger perspective and a resource perspective.

3.3.1 Passenger perspective

Depending on the origin and destination of a passenger, an alternative can have different consequences. Normally, in an undisrupted situation, the passenger travel time t^t between an origin i and a destination j on the same line l is defined as the waiting time t^{wait} at i and the in-vehicle travel time t^v between i and j :

$$t_{i,j}^t = t_i^{wait} + t_{i,j}^v \text{ for } i, j \in S_l \quad (3.6)$$

In determining the passenger path choices as well as the total passenger travel time for different alternatives, several assumptions have been made which are listed below:

- Passengers have no information regarding the disruption prior to the trip, meaning the generation of trips is as in undisrupted situations. This is a realistic assumption for unexpected disruptions such as considered in this research, but less realistic for planned disruptions such as planned maintenance works.
- Network-effects are excluded. Passengers which had planned to travel using the disrupted line will still do so; in other words, no other choices are taken into account, except cancelling their trip when served stops are too far away and the duration of the disruption is too long. In order to fully assess the different alternatives in case of a disruption, all other route choices should be taken into account as well. In this research network effects are not taken into account, since it is considered too complex to present a generic methodology which is on the one hand more realistic by taking into account all other choices passengers have, and is specific enough to be of use for public transport operators on the other hand as well.

- Passengers have information about the closest stop served, as well as knowing how to get there by foot and the travel time by foot.

Passenger path choice

As has been discussed before, the sequence of planned stops S_l of a line l can be divided in three subsequences when faced with an unavailability of infrastructure. $S_{l,p,q}$ represents the stops still being served upstream, $S_{l,p,r}$ represents the stops still being served downstream of the disruption and $S_{l,p,v}$ represents the skipped stops by a route p . For trips for which both the origin and the demand are still being served by a route p , it is logically assumed that passengers board the vehicle at their planned origin stop and alight at their planned destination stop.

For trips which are affected by the rerouting in terms of the origin and/or destination stop being skipped, this assumption does not hold. For these trips, the decision that has to be made by the passenger is choosing between waiting until service is regained, walking to a stop that is being served, walking directly to their destination, or cancelling the trip. Cancelling the trip in this context represents that the passenger makes a different trip choice, mode choice or route choice, and which one is considered irrelevant in the remainder of the analysis of alternatives.

As for the choice between walking, waiting and cancelling, all three choices will be assigned a certain cost. As for walking, the cost depends on the walking distance to the closest stop that is being served by the disrupted line and the cost per distance unit. When the walking distance is converted to walking time, the cost per time unit is the weight factor β^{walk} . This weight factor will be used later on as well when generalizing the travel time, in order to account for different perceptions of trip elements. It is not realistic to assume walking to the closest served stop as a realistic alternative in all situations however. A maximum walking distance t_{max}^{walk} is implemented, above which walking is not considered an option. The cost for walking is therefore defined as:

$$\beta^{walk} \cdot t^{walk} \text{ for } t^{walk} \leq t_{max}^{walk} \quad (3.7)$$

It is also possible that the destination stop is closer than the closest stop being served. In this case, it is assumed passengers walk directly to their destination stop, for which the cost can be determined analogous. Similarly, passengers are assumed to opt for walking directly to their destination as well if the cost of walking directly is lower than the total cost of walking to the closest stop, waiting and the in-vehicle time (and possibly walking again if the destination stop was skipped as well). The cost of the adjusted journey can be determined by generalizing the travel time. By generalizing the travel time, the different perceptions over the different trip elements passengers have can be taken into account. The generalized passenger travel time will be discussed more extensively in the next section.

The cost for waiting is defined in a similar manner as the cost for walking. Waiting has a different wait factor β^{wait} , and the waiting time t^{wait} is derived from the remaining duration of the disruption, for which an estimation is assumed to be known. The cost for waiting is therefore defined as:

$$\beta^{wait} \cdot t^{wait} \quad (3.8)$$

As the waiting time, being defined as the remaining duration of the disruption, changes over time, it can be that passengers first opt to walk to the closest served stop, but as the remaining time of the disruption decreases, passengers opt to wait instead.

The waiting weight factor can vary along with the waiting time. Besides a different perception of passengers regarding different trip elements, passengers can also perceive different waiting times differently. For instance, regular waiting time for a vehicle is perceived differently than waiting for a vehicle which is running late.

Thirdly, the cancellation of the trip by a passenger is also an option. Cancellation has a fixed cost, which is independent of walking time or the remaining time of the disruption. The cancellation cost (basically a penalty) represents that passengers are not assumed to wait unlimitedly, but as the waiting time becomes to large passengers opt for a different choice. This choice must be penalized in order to correctly assess the different alternatives.

For each OD-pair incorporating a skipped origin stop and/or a skipped destination stop, the cost for walking to a served stop, walking to the destination directly and waiting until regained service can be defined, as well as the penalty for cancelling the trip. Then, the passenger path choice for each OD-pair is determined by choosing the option with the lowest costs.

Passenger travel time disrupted operation

Now that the passenger path choices have been determined, passenger perspective of an alternative can be assessed. The passenger perspective is reflected by the (generalized) total passenger travel time of an alternative, which is depending on the total amount of passengers affected and the route of the alternative (and the corresponding skipped stops).

The origin stop i and the destination stop j can be located at three sections of the line; upstream of the disruption ($\in S_{l,p,q}$), at the skipped section of the line due to the disruption ($\in S_{l,p,v}$) or downstream of the disruption ($\in S_{l,p,r}$). Depending on the location of both the origin i and destination j , the passenger travel time for a route p between origin and destination $t_{i,j,p}^t$ can be determined. Figure 3.9 illustrates the terminology used for the location of the stops with respect to the location of the disruption.

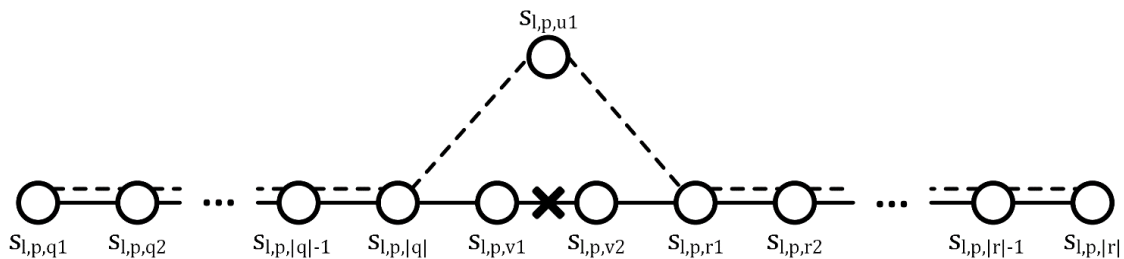


Figure 3.9: Illustration of used terminology for stops in the relation of an original route (solid line) and a detour (dotted line).

The travel time between an origin i and a destination j during a disruption is dependent on several factors. First of all, it depends on the location of origin i in respect to the applied alternative. Dependent

on the location of the origin stop, passengers have to wait at the origin stop or walk to a stop served. For a route p , the origin stop can be located upstream of the disruption ($i \in S_{l,p,q}$), downstream of the disruption ($i \in S_{l,p,r}$) or can be skipped ($i \in S_{l,p,v}$).

Second of all, passenger travel time depends on the location of destination j . Just as for the origin stop, for a route p the destination stop can be located upstream, downstream of the disruptions, or skipped. However, destination stops cannot be located prior to the origin stop; for instance, it is not possible for a destination stop to be located upstream of the disruption if the origin is located downstream of the disruption.

Third of all, passenger travel time can be dependent on the measure incorporated in the alternative. Whether short-turning or detouring is considered, can affect the passenger travel time elements. For instance, for detouring it is possible to board upstream of the disruption and alight downstream of the disruption, whereas for short-turning some distance should be crossed by foot.

Finally, passenger travel time depends on the previously discussed passenger path choice. Depending on the path choice, the passenger travel time consists for instance of directly walking from the origin to the destination, walking to the last stop upstream ($S_{l,p,lq1}$) and boarding a vehicle there, or walking to the first stop served downstream of the disruption ($S_{l,p,r1}$) and boarding a vehicle there.

Figure 3.10 presents a flowchart defining the passenger travel time elements, depending on the discussed factors, while Appendix B (p. IIII) presents all corresponding equations.

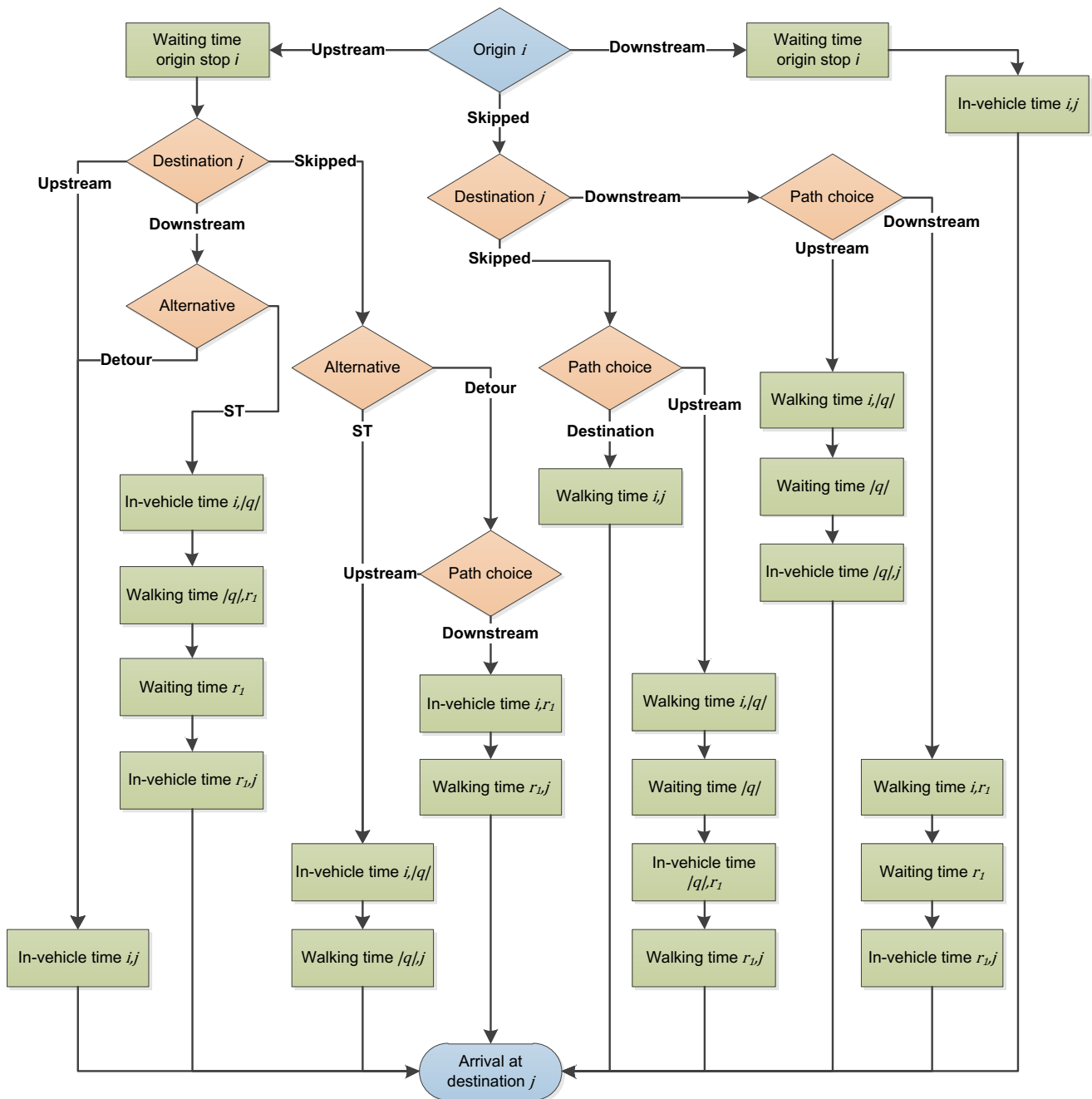


Figure 3.10: Flowchart for determining the passenger travel time, depending on origin, destination, alternative, and path choice.

As one might have noticed already, not all trip components of a journey are considered. Figure 3.11 presents an overview of the passenger travel time components of a journey (Van Oort, 2011).

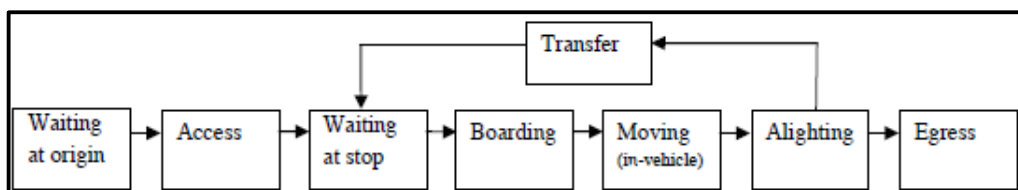


Figure 3.11: Passenger travel time components (Van Oort, 2011).

Due to the high frequency that is typical for rail-bound urban public transport, it is assumed that passengers arrive randomly at the stop. Therefore, no time is spent waiting at their origin. The access time as well as the egress time are not influenced by the incident, since origin stop i and destination stop j are assumed unchanged. Therefore, access and egress time is not taken into account. The boarding time and alighting time are assumed to be incorporated in the in-vehicle travel time and therefore not taken into account explicitly. This does not represent reality entirely, since boarding times and alighting times depend on the amount of passengers alighting/boarding, but for simplicity reasons it is assumed to be fixed and incorporated in the in-vehicle time between stops.

As has been briefly discussed before, these different passenger trip components are perceived differently by passengers. Therefore, each element is assigned a corresponding weight, in order to capture the difference in perception. Transfers are penalized by a fixed penalty, since *ceteris paribus* direct trips are preferred over trips with a transfer.

So, each trip element has its corresponding weight. An example of the generalized travel time (Gt^t) between on origin downstream of the disruption and a destination upstream of the disruption with no detour available is then:

$$Gt_{i,j,p}^t = \beta^{wait} \cdot t_{i,p}^{wait} + \beta^{ivt} \cdot t_{i,|q|,p}^{ivt} + \beta^{walk} \cdot t_{|q|,r_1,p}^{walk} + \beta^{wait} \cdot t_{r_1,p}^{wait} + \beta^v \cdot t_{r_1,j,p}^{ivt} + \beta^t \cdot \#_{transfers} \quad (3.9)$$

The different weight factors for the different trip elements are denoted by β . A transfer occurs when there are multiple legs in a trip. This is for instance the case when a passenger boards a vehicle between i and $|q|$, and then walks from $|q|$ to j . An additional transfer would be made if he walks from $|q|$ to r_1 and boards a second vehicle there.

The different alternative routes will be ranked from a passenger perspective based on their total generalized passenger travel time. In order to calculate the total generalized passenger travel time for a route p $Gt_p^{t,tot}$ during a time interval τ , being element of a set of time intervals T , the travel time between each i and each j is multiplied with the corresponding demand for that time interval $\pi_{i,j,\tau}$, and summed over all $i, j \in S_l$.

$$Gt_{p,\tau}^{t,tot} = \sum_{i \in S_l} \sum_{j \in S_l} Gt_{i,j,p}^t \cdot \pi_{i,j,\tau} \text{ for } \tau \in T, p \in P_l \quad (3.10)$$

Probably the amount of passengers willing to travel from i to j differs over time. The travel time between i to j probably also differs over time, but it is assumed that variations are not significantly large enough and the travel time is therefore assumed fixed. The total generalized passenger travel time over the whole set of time intervals T is then:

$$Gt_p^{t,tot} = \sum_{\tau \in T} \sum_{i \in S_l} \sum_{j \in S_l} Gt_{i,j,p}^t \cdot \pi_{i,j,\tau} \text{ for } p \in P_l \quad (3.11)$$

An important aspect in the evaluation of passengers of public transport is the issue of crowding. In-vehicle crowding has not been taken into account in this research, because only effects on the disrupted line are taken into account. Effects on other lines are excluded, and by taking in-vehicle boarding into account on the disrupted line only could lead to alternatives being underestimated which do not cause in-vehicle crowding on the disrupted line, but do so on other lines; in other words, in order to take into account in-vehicle crowding explicitly, a network-wide assessment is necessary. However, denied boarding on the disrupted line are taken into account. Denied boarding are perceived very badly by passengers. In order to take this into account modelling wise, an extra penalty is assigned to the waiting time from the denied boarding. So until arrival of the first vehicle the regular waiting time weight factor is applied, and if denied boarding occurs the waiting time from the arrival of the first vehicle until arrival of the second vehicle, the weight factor is multiplied with the denied boarding factor (Börjesson & Eliasson, 2014).

Passengers on-board during disruption

The previously discussed travel times during disrupted operations are valid for passengers starting their journey during the disruption. Passengers who are already aboard of the vehicle when the disruption occurs are also affected by it, for instance due to their stop not being served anymore, or a longer in-vehicle travel time due to a detour. Since the trip elements prior to the start of the disruption are not affected by the possible alternatives, these are not taken into account while analysing the alternatives from the passenger perspective. In other words, for passengers already aboard of the vehicle, the waiting time at the origin i is neglected, as well as the in-vehicle time up to the start of the disruption. From the start of the disruption the different trip element travel times are calculated in the same manner as has been discussed before, since these can be affected by the chosen alternative.

3.3.2 Resource perspective

Disruptions do not only affect the demand side of the network (passengers) by leading to different travel times and routes than expected, but they also affect the supply side (resources) of the network. As discussed previously, resources are planned minutely, defining their activity and location for all times. The goal in the planning process is, given a certain timetable, to minimize the number of resources used.

The resource perspective of the different alternatives are given here without intervention in the schedules, i.e. rescheduling personnel and vehicles. The possibilities to reschedule by switching driver shift, changing vehicles, or the usage of spare drivers/vehicles are so extensive and dependent on the actual situations, that providing a generic rescheduling approach for resources for the different alternatives is considered out of the scope. Therefore, the consequences from a resource perspective of the different alternatives without rescheduling will be assessed here.

For the alternatives incorporating a detour, the resource schedule and timetable is likely to be affected. The effect of the detour on the timetable has been discussed when assessing the alternatives from a passenger perspective.

The resource schedule is significantly affected if the delay caused by a detour propagates onto the next scheduled activity, which is the case if it arrives delayed at the destination terminal and the delay cannot be compensated for by any buffer times. Buffer times can be incorporated in the schedule when the time scheduled for an activity is longer than the actual time needed. If it arrives earlier than planned at the destination terminal, i.e. the detour was effectively a shortcut, the planned activities can follow through as was planned for the remainder of the duty. The same accounts for a detour arriving at the destination terminal at the same time as was planned.

A delay arises on a disrupted line if the route trip time due to a detour is longer than the route trip time of the original line. The amount of delay of a route p on a line l $t_{l,p}^d$ is the difference between the scheduled route trip time and the route trip time of the detour. Or formally:

$$t_{l,p}^d = t_{l,p}^r - t_l^r \quad (3.12)$$

Note that the delay can have a negative value as well, which indicates that the detour is actually a shortcut. Only delays caused by the different routes p are taken into account.

With the amount of delay $t_{l,p}^d$, the delayed arrival time at the destination terminal of the resource can be determined. In order to assess the effective delay for the subsequent activity it needs to be compensated with the buffer time. For any delay of an activity $k \in K$ (set of all activities scheduled), the delay of the subsequent activity $k + 1$ can be determined by subtracting the original delay with the buffer time t_k^b , assuming the duration of the activity is as was planned. Formally, this can be denoted as follows:

$$t_{k+1}^d = t_k^d - t_k^b \text{ for } k \in K \quad (3.13)$$

Subsequent planned activities can be of all kind, such as the return trip for both driver as well as vehicle, a shift on another line for just the driver or vehicle, a break for the driver, end-of-shift for the driver, scheduled maintenance for a vehicle, etc. Please note that a driver is not necessarily coupled to a vehicle, and they should thus be seen as two separate resources.

The consequences of the delay can range in severity based on the subsequent activity scheduled. For instance, if it is the last shift, the consequence is a later end-time of the shift. The delay is cleared and other than a longer shift time there are no consequences. The longer shift time can have consequences, such as violation of legal regulations, overtime, or the later end-time of the shift shortening the time in-between shifts. Delays can also propagate onto next shifts, which can among other vary in terms of passenger demand.

In order to take into account that the effect of a delay can range in severity based on the activity, the delays will be weighted. The weights will be assigned a low value if the severity of the delayed activity is relatively low, such as end of duty time or a shift on a line with low passenger demand, and will be assigned a high value if the severity is high, such as a line with high passenger demand. Formally, this is denoted as follows, with β_k indicating the weight factor and Gt_k^d indicating the weighted delay of an activity k :

$$Gt_k^d = t_k^d \cdot \beta_k \text{ for } k \in K \quad (3.14)$$

The total of weighted delays Gt^d for all activities k is then represented by:

$$Gt^d = \sum_{k \in K} t_k^d \cdot \beta_k \quad (3.15)$$

3.4 Conclusions methodology

In this chapter, the methodology developed in this research has been presented. The framework consists of two models, the first one to generate alternatives and the second one to assess these generated alternatives.

For the generation of detouring alternatives, the k -shortest path algorithm is used. The found routes from origin node to destination node are then being reduced to alternatives to be assessed, taking into account the following aspects:

- A threshold value excluding detours exceeding a certain extra travel time compared to the original route.
- A threshold value excluding detours directly affecting a certain amount of extra passengers compared to the alternative directly affecting the least.
- Dominancy aspect, excluding detours which skip (at least) the same stops as another detour, but having a longer travel time.
- Capacity of the network. The effect of the increased frequency on the detour is assessed. The dominancy aspect and the capacity of the network are taken into account iteratively.

The generated alternatives are then being assessed from the passenger perspective as well as a resource perspective. For the passenger perspective, the following assumptions have been made:

- Passengers for which their original boarding stop and/or alighting stop is not skipped by the alternative, remain using that stop.
- Passengers for which their original boarding stop and/or alighting stop is skipped, will either walk directly to their destination, walk to another stop that is being served, or will wait until the disruption is over and service is resumed. The choice whether to walk or to wait is represented by a (given) probability distribution function depending on the walking distance.

Using these assumptions, the total passenger travel time for the different trip elements can be determined. Taking into account the difference in passenger perception of these elements, the total generalized passenger travel time on the disrupted line can be determined. As for the resource perspective, the resource delay in minutes per vehicle at the destination terminal is used to account for the resource perspective. For short-turning alternatives, no quantitative assessment from the resource perspective has been made.

4

Case study description

In order to demonstrate the previously discussed methodology, the framework will be applied to several (fictive) unplanned disruptions in the tram-network of HTM in The Hague. Furthermore, an actual disruption which took place on July 15th 2016, will be simulated. The implemented strategy of the traffic control centre will be assessed in relation to strategies being outcome of the developed framework. Besides demonstrating the developed framework, the case study is also used to assess the disruption management protocols currently used by HTM in a systematic manner.

First an introduction to the tram network of The Hague will be provided, containing general information regarding the network, the environment in which it operates and the problem of unplanned disruptions. Secondly, a motivation will be provided regarding the choice of the different disruption locations. Lastly, different scenarios used in the assessment of alternatives will be discussed.

4.1 Rail-bound urban public transport in The Hague

The city of The Hague is the political centre of the Netherlands and with approximately 515,000 inhabitants it is ranked as the third city of the Netherlands according to the population. Its agglomeration formerly known as Haaglanden yields to a population over 1,000,000 inhabitants. The rail-bound urban public transport system is operated by HTM, which operates in The Hague and its surroundings, geographically speaking from Scheveningen in the north to Delft in the south, and from Loosduinen / Wateringen in the west to Zoetermeer in the east. Besides rail-bound urban public transport, HTM also operates local bus services in The Hague. HTM operates on three network levels, namely light-rail, tram and bus. Table 4.1 shows the main characteristics of HTM, while Figure 4.1 shows the geographical location of the different rail-bound urban public transport lines, with lines 3 & 4 being the light-rail lines.

Table 4.1: Main characteristics HTM for the year 2015 (HTM Personenvervoer N.V., 2015)

Average number of passengers per day	257,000
Revenues [€]	296 million
Network length [km]	336
Fleet size	
- Light-rail vehicles	- 71
- Trams	- 148
- Buses	- 115
Employees [FTE]	1,714

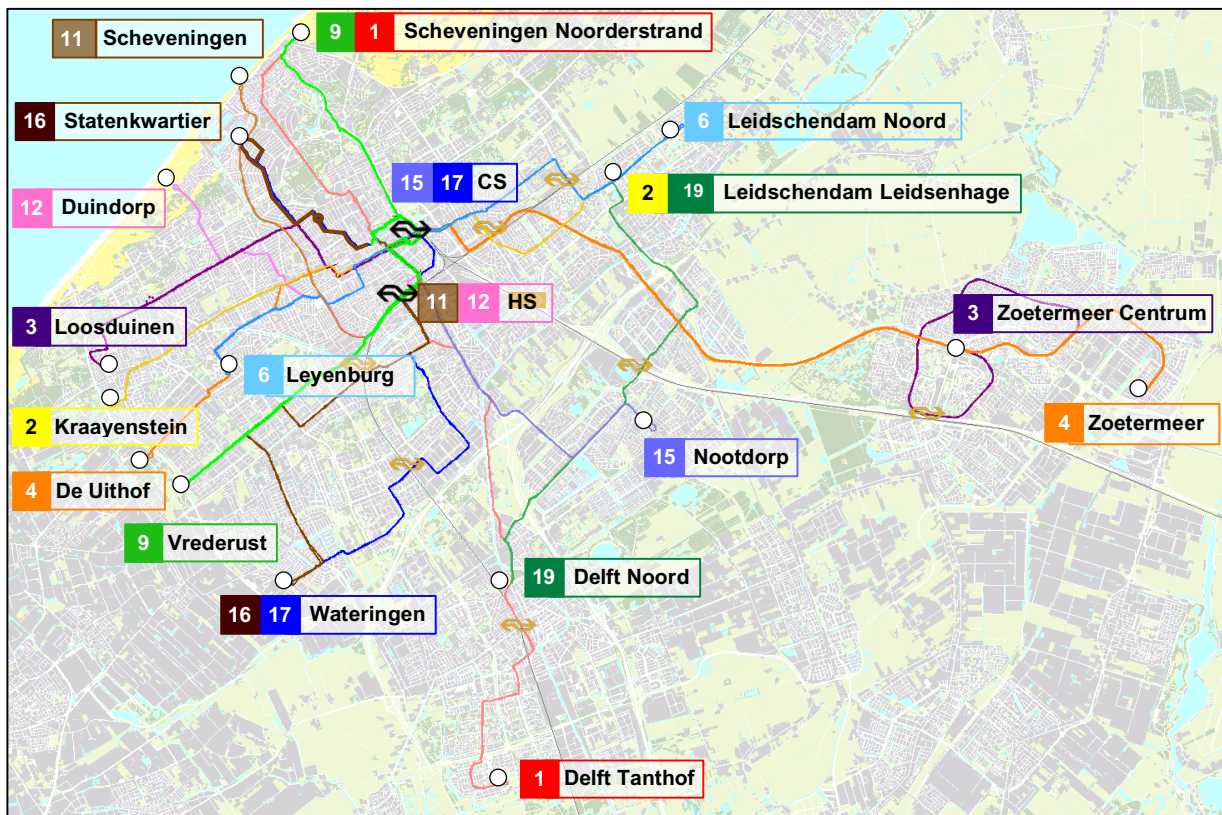


Figure 4.1: Rail-bound urban public transport lines operated by HTM. (Hoogvliet, 2016).

4.2 Disturbances and disruptions at HTM

4.2.1 Frequency and duration

As has been discussed earlier, disturbances are referred to as irregularities compared to the schedule which do not cause the rescheduling of vehicles, crew or infra (rerouting), whereas irregularities which do cause rescheduling are referred to as disruptions. Note that this definition does not say anything regarding the severity of the irregularity directly, since it only refers to the reaction of the operator. However, generally speaking disturbances in this context represent (smaller) delays, whereas disruptions occur due to a blockage of infrastructure. Therefore, disturbances logically occur on a much

more frequent basis than disruptions. Table 4.2 shows some information regarding the frequency of disturbances / disruptions and the duration of disruptions on rail-bound services operated by HTM in 2015 and for the time period from January 2016 until and including August 2016. It can be seen that 246 disruptions have been recorded in 2016, which equals about one disruption per day, stressing the urgency of handling disruptions in a systematic manner. Compared to statistics of the previous year (2015), the number of disruptions is about equal, whereas the number of disturbances has dropped. This is due to a different method in registering disturbances.

Table 4.2: Characteristics of disturbances and disruptions at HTM (rail-bound) (Janssen, 2016).

	2015	Jan 2016 – Aug 2016
Registered irregularities	1216	694
- Disturbances	- 865 (71%)	- 448 (65%)
- Disruptions	- 351 (29%)	- 246 (35%)
Duration of disruption		
- Average	- <i>missing data</i>	- 61 minutes
- Percentage within 1 hour	- <i>missing data</i>	- 74%
Number of disruptions per line – top 3:	Line 12 – 63 times Line 1 – 62 times Line 17 – 60 times	Line 1 - 42 times Line 6 - 40 times Line 12 - 32 times

4.2.2 HTM disruption management

Disruptions in the HTM network are managed from a central traffic control centre. Here the traffic controllers have an overview of the actual locations of the vehicles in the network, along with their current status compared to the schedule. The traffic control centre can communicate with every driver and vice versa, and in case of a disruption the traffic control centre decides upon the strategy in continuing operations. Traffic controllers do so using disruption management protocols (*Dutch: bijsturingsprotocollen*). This is a detailed map of the network representing each track and switch, and provides a strategy for all track sections and major junctions in case of disruptions. However, depending on the situation, the traffic controller always decides upon the actual strategy to be used.

The management of operations process is part of the greater management of passenger transportation process, which in its turn is part of the overarching business process of transporting passengers. The management of operations process is schematically illustrated in Figure 4.2, while the latter two can be found in Appendix C (p. IV).

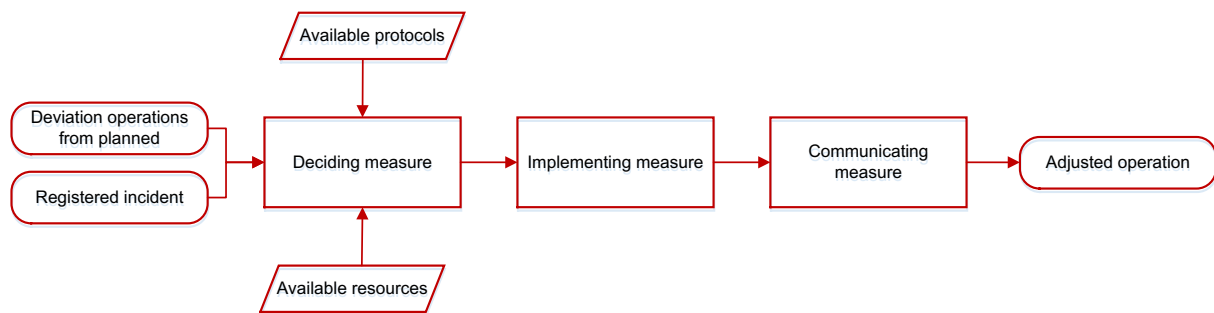


Figure 4.2: Management of operations process (Maas, 2016).

The disruption management protocols are constructed based on common sense, using skipping the least number of stops as a rule of thumb. However, if the route with the least number of skipped stops is considerably longer than another alternative, another alternative might be chosen. Considerably longer in this context is not further specified and up to the employee constructing the disruption management protocols to decide upon. The protocols are being updated a few times per year, due to changes in service and feedback from traffic controllers, when they stumbled upon an illogical protocol when managing a disruption. Passenger flows are not taken into account explicitly in constructing the protocols, however this can be taken into account by the traffic controller based on experience when handling a disruption. In general, detouring is always applied when possible.

4.3 Case study line 1

To demonstrate the framework developed to systematically generate and assess alternatives, the framework will be used to manage several (fictive) disruptions in the HTM network, using discrete event-based simulation. In order to make efficient use of the time available, it is decided to simulate the several disruptions on one and the same line. In choosing this line and the disruptions on the line, two main criteria are perceived to be of importance:

- No evident substitutes available for passenger route choice in case of disruption. Since the framework uses historical passenger demand data and assumes this not to change, disruptions must be located at places with no obvious alternative passenger routes. If there is an obvious other passenger route available, passengers are most likely to choose that route and the historical passenger demand data is not suited for assessing different alternatives.
- Different (non-obvious) alternatives available regarding rerouting of vehicles. In order to demonstrate the developed framework, disruptions considered should take place on locations where there are multiple alternatives available, in order to assess and compare the different alternatives.

Using these two main criteria, it was decided to model and simulate disruptions occurring on the northern part of line 1, in and between the centre of The Hague and Scheveningen. Stops 'Kneuterdijk' up until stop 'Scheveningse Slag' are only served by line 1. Passengers having stop 'Kurhaus' in Scheveningen as their destination can use line 9 located east of line 1, but this line is located at a 15 minutes' walk for the greater majority of the stops on line 1. On the western side of line 1 operates line 16; however, this

line is also located at around 15 minutes' walk and does not serve stops usually served by line 1 (see Figure 4.3).

Besides the fact that the northern part of line 1 does not have obvious alternative passenger routes available, the line also crosses the city centre, which is a highly dense area with a lot of traffic and events, making the occurrence of disruptions more likely as compared to lines operating in less dense areas (see also Table 4.2). Again, from a time and modelling perspective, it is decided to model one-way operations only.

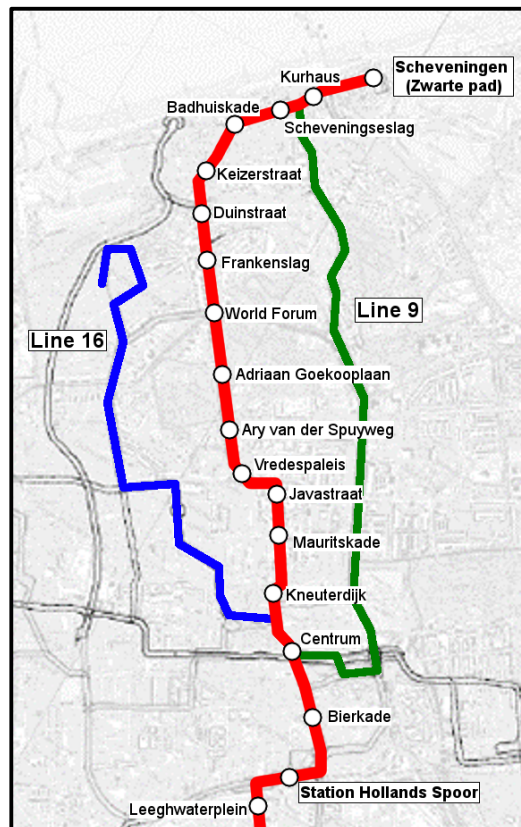


Figure 4.3: Northern part of line 1 versus line 9 and line 16.

4.4 Scenario design

Since the goal of this research is not only to develop and demonstrate a framework to handle unplanned disruptions, but also to provide some general guidelines, several scenarios will be used to see what different characteristics of for instance disruption location or passenger flows have on the generation and assessment of alternatives.

4.4.1 Different disruption locations on line 1

As has been discussed, disruptions on different locations on the northern part of line 1 will be simulated. The chosen locations are the following (Figure 4.4):

- A Centre of The Hague, Centrum – Gravenstraat / Kneuterdijk (99)
- B Centre of The Hague, Centrum – Gravenstraat – Kneuterdijk (207)

- C Kneuterdijk – Mauritskade (8)
- D HS – Centrum (97, 98, 99)

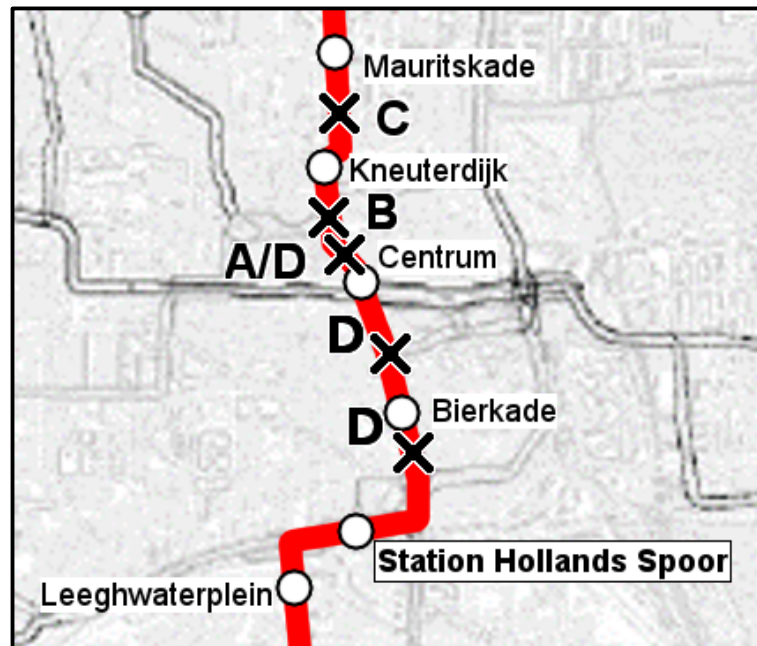


Figure 4.4: Different disruption locations considered.

The number inside brackets represents the internally used corresponding disruption management protocol at HTM. Two other locations have also been analysed, but their findings are not found to be worth noting, either because of a similar result as one of the other locations, or a clearly dominant alternative.

Disruption A and B are located very close to each other, with the difference that location A represents a disruption at a track leading to an important junction, whereas location B represents that major junction itself. Disruption location D represents a section of disrupted tracks through the centre of The Hague.

In choosing these locations, the same main criteria have been taken into account as discussed in §4.3, namely no suitable alternative for passenger route choice and multiple unobvious alternatives available.

4.4.2 Variations in passenger flows (morning peak vs. rest-of-day)

It is expected that differences in passenger flows might affect the outcome in assessing different alternatives available. If there is a high demand from the origin terminal to the destination terminal and no demand to or from stops in between, it is expected that detouring in general leads to relatively less total generalized passenger travel time as compared to short-turning, and vice-versa.

In order to test this hypothesis, the effect of variations in passenger flows will be analysed. To capture the effect of varying passenger flows at its fullest, the two dayparts which differed the most from each other will be taken into account. For the northern part of line 1 this turned out to be morning-peak demand levels on the one hand and rest-of-day demand levels on the other hand. Morning-peak is defined as passengers checking-in between 7 and 9 in the morning, while rest-of-day is defined as the period

between morning-peak and evening-peak (evening-peak starting at 4 in the afternoon). Figure 4.5 and Figure 4.6 present the origin-destination relations between the different stops for the northern part of line 1, for the morning-peak and the rest-of-day, respectively. Note that the relations are only represented in the direction of Zwarte Pad (Scheveningen).

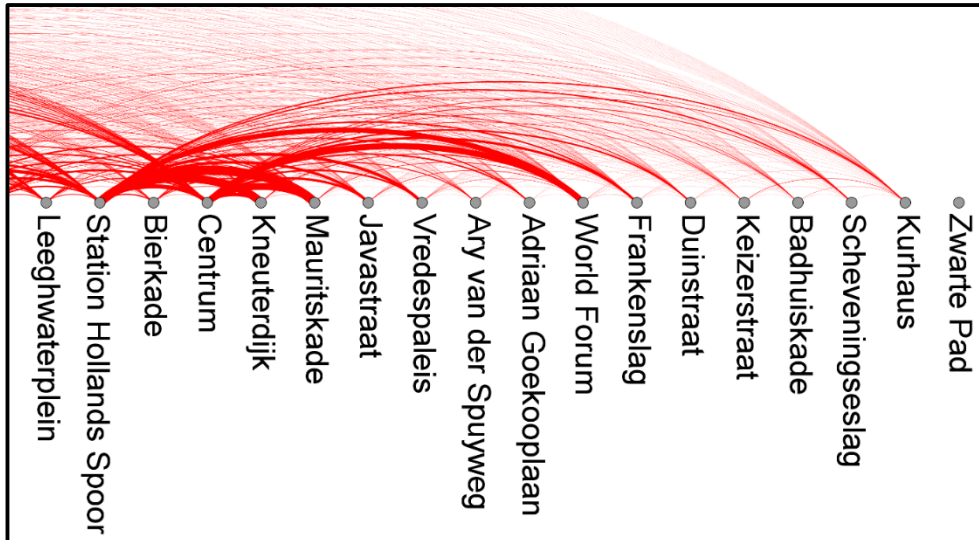


Figure 4.5: Origin-destination relations for the northern part of line 1 (morning-peak).

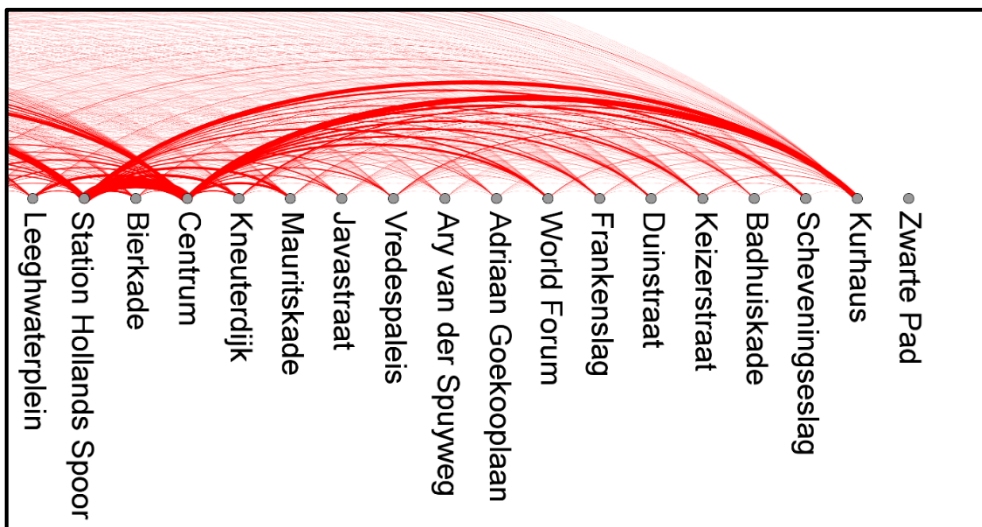


Figure 4.6: Origin-destination relations for the northern part of line 1 (rest-of-day).

It can be seen that the stops between stop Centrum and Kurhaus, such as Kneuterdijk, Mauritskade and World Forum, are of more importance during the morning-peak than for the rest-of-day, and stops Centrum and Kurhaus are of relative less in importance. Or, the other way around, stops Centrum and Kurhaus are of far more importance during the rest-of-day than during the morning-peak. Considering the locations of the stops this makes sense, with many offices located between stops Centrum and Kurhaus, and stops Centrum and Kurhaus being important stops for passengers travelling with a leisure motive.

4.4.3 Disruption management protocols

Finally, for cases where the currently used disruption management protocol is not part of the set of alternatives, the protocol will also be assessed.

4.4.4 Actual disruption July 15th 2016, Javastraat / Alexanderstraat

To see what the framework can mean for managing real disruptions, an actual disruption that took place will be analysed using the developed framework. For this analysis actual crew and vehicle schedules are used in order to assess the resource perspective of the different alternatives in a more thorough manner.

The disruption took place on Friday July 15th, 2016 at the junction of the Javastraat and Alexanderstraat. It was caused by an external accident with severe injury, causing the tramway to be blocked in the direction of Delft. Service in the direction of Scheveningen was not directly influenced and could be maintained. The disruption started at 21:12, and lasted for 47 minutes until 21:59. It caused the disrupted vehicle to be held at the junction for the entire time, and the 3 vehicles scheduled behind it to be affected. This disruption was chosen due to its location on the northern part of line 1, its relatively recent occurrence and its duration, which seems appropriate for using this framework.

4.5 Case study conclusions

Concluding, in order to demonstrate the developed framework and also to find general trends of importance in the management of unplanned disruptions, the framework will be applied to several fictive situations. The main criteria in determining the different locations are the non-existence of obvious alternative passenger route choices, and the existence of different non-obvious alternatives. Table 4.3 summarizes this chapter in a scenario-matrix for the fictive and non-fictive case studies.

Table 4.3: Scenario-matrix for (fictive and non-fictive) case-studies.

	Generated detouring alternatives	Generated short-turning alternatives	Disruption management protocol
Disruption location A - Morning-peak - Rest-of-day			
Disruption location B - Morning-peak - Rest-of-day			
Disruption location C - Morning-peak - Rest-of-day			
Disruption location D - Morning-peak - Rest-of-day			
Actual disruption July 15th, 2016			(+ actual implemented measure)

5

Model implementation

In this chapter the implementation of the previously defined methodology will be discussed. First, the model input will be discussed, consisting of network input, passenger demand data, and used variable values. Second, the model implementation will be discussed, consisting of the alternative generation model developed using MATLAB, and the alternative assessment model using Simio (discrete event-based simulation). Finally, model replications, verification and validation will be elaborated upon.

5.1 Model input

5.1.1 Network

For the network input, the network of the summer of 2016 is used. Due to the on-going construction works throughout the network, there was no clear suitable network to be used. By using this network, different alternatives were expected to be generated, without one being clearly dominant over others. This is perceived to be of major importance in demonstrating the developed framework. For the future network however, after the long-term construction works at “Toernooiveld” are finished, it is expected that this will provide a very suitable alternative in case of a disruption at the discussed locations.

The trip times between stops used in as the network input in this research are retrieved from the planning department at HTM, which are used in the planning process. In contrary to what is done in the planning process, the same trip times have been used for the two considered parts of day. At some locations trip times between stops differed between morning-peak and rest-of-day, but trip times were found to be longer at some locations and shorter at others, leading to no significant differences overall which could affect the generation of alternatives. Short-turning locations are defined in the model input.

A total of 535 nodes have been used, representing every stop in all directions in the network, excluding stops in Zoetermeer. Even though only one-way operations have been simulated, it was decided to use the total network instead of only in the direction of Scheveningen. This was done because certain tracks are used in different directions for different alternatives.

Walking times between stops have been retrieved using Google Maps (see also Appendix D (p. VI)).

5.1.2 Passenger demand data

For the used passenger demand data, average passenger flows of all business days in September 2016 are used. This is perceived to be a suitable representation of passenger demand flows over the network

for a regular business day. It was also considered using the passenger demand data of the overall summer of 2016, but due to the summer holiday this was expected to give an underestimation of passengers travelling to stops Kneuterdijk until Scheveningen, and an overestimation of passengers travelling to Scheveningen as compared to a regular day. Using passenger demand data prior to the summer seemed to be unsuitable since line 1 operated a different route due to construction works.

One important note to make is that in September 2016, construction works took place at line 9 between Madurodam and Scheveningen. Passengers travelling to Scheveningen using line 9 had to transfer to a bus at Madurodam. Line 1 could serve as an alternative between stops station Hollands Spoor / Bierkade and stops Kurhaus / Zwarte Pad, which could lead to an overestimation of passengers using line 1 between these stops. In order to assess this relation, the share of passengers travelling from station Hollands Spoor / Bierkade to Kurhaus / Zwarte Pad for both lines have been looked into, for the two weeks prior to the construction works and two weeks during the construction works (Table 5.1).

Table 5.1: Effect of construction works line 9, showing share of trips with OD relation station Hollands Spoor / Bierkade and Kurhaus / Zwarte Pad.

	Morning				Rest-of-day			
	Prior		Construction		Prior		Construction	
	Share	Total trips	Share	Total trips	Share	Total trips	Share	Total trips
Line 1	0.4%	13,806	0.3%	13,792	7.1%	50,333	3.2%	48,298
Line 9	0.8%	15,238	0.2%	7,058	3.7%	56,333	0.9%	23,412

It can be seen that both lines show a decrease in share of passengers travelling between the considered stops. This is (probably) due to the start of the construction works coinciding with the end of summer holiday, showing the seasonal effects. Furthermore, it can be seen that the decrease in share is greater for line 9, which could indicate some shift of passengers from line 9 to line 1. Still, it is decided to use the passenger demand data of September 2016, since the (possible) effect of line 9 on line 1 is limited and the effect applies only for a limited origin-destination relation. Furthermore, the results in Table 5.1 show that the seasonal effect is much greater, making the passenger demand data of the summer less suitable for representing an average day.

A random passenger arrival at the origin stops is assumed. With a frequency of 6 vehicles per hour, this seems to be an appropriate assumption (Van Oort, 2011). Due to this stochastic element, several replications of the simulation model will be needed in order to assure the results are statistically sound. This will be discussed in §5.3.

See also Appendix D (p. VI) for the data preparation of the passenger demand data and examples of input matrices.

5.1.3 Used thresholds in alternative generation

In the previously discussed methodology, two thresholds have been presented in the alternative generation process. These thresholds are used in order to exclude unreasonable alternatives beforehand.

The thresholds for the case studies were retrieved using reverse engineering by relying on expert opinion. The different disruption locations were submitted to experts within HTM and it was up to them to indicate the alternatives to be taken into consideration and which alternatives which would not be considered in any case. The threshold value for the increase of travel time for alternatives turned out to be around 35%, while the threshold value for number of passengers at skipped stops seemed to be 3.7 times as much passengers skipped for alternatives in relation to the alternative with the least skipped stops. In order to be on the safe side in the generation of alternatives and to reduce the chance of missing a possible alternative, threshold values of 40% for the travel time and 4.0 for the skipped passengers are used.

5.1.4 Capacity of the network

As has been discussed in the methodology, the capacity of the network is something to be taken into account when detouring vehicles using a different route. No literature has been found dealing with the capacity of tram-networks, where trip times have been compared to the applied frequency. Based on limited data available regarding operations in the HTM network, a flow-dependent travel time variable has been constructed.

The data available only allowed for comparing the influence of frequency on the travel time on lines traversing the same routes, and not if the frequency was increased due to another line being detoured. Four high frequently traversed tracks have been considered, where the relation between a higher number of vehicles traversing the track than planned and the travel time has been considered. This led to a data set of 305 data points where the actual frequency of that hour was higher than was planned. Logically, the greater the exceedance, the fewer data points were found. For instance, the amount of cases where the number of vehicles traversing was six or higher than as planned, amounted to 36.

Nonetheless, a trend was found of an increase of travel time in the cases where the number of vehicles traversed exceeded the planned frequency, approximately beginning at a frequency of 24 vehicles per hour. The constructed flow-dependent travel time variable therefore has no increase in travel time up to a frequency of 24 vehicles per hour, then gently exponentially increasing up to an increase of 20% for a frequency of 40 vehicles per hour (see Figure 5.1). This is not a defined maximum capacity, but no cases were found where the actual number of vehicles traversing that track was higher than 40, and it is not expected that the actual frequency will be higher than 40 in the context of this research.

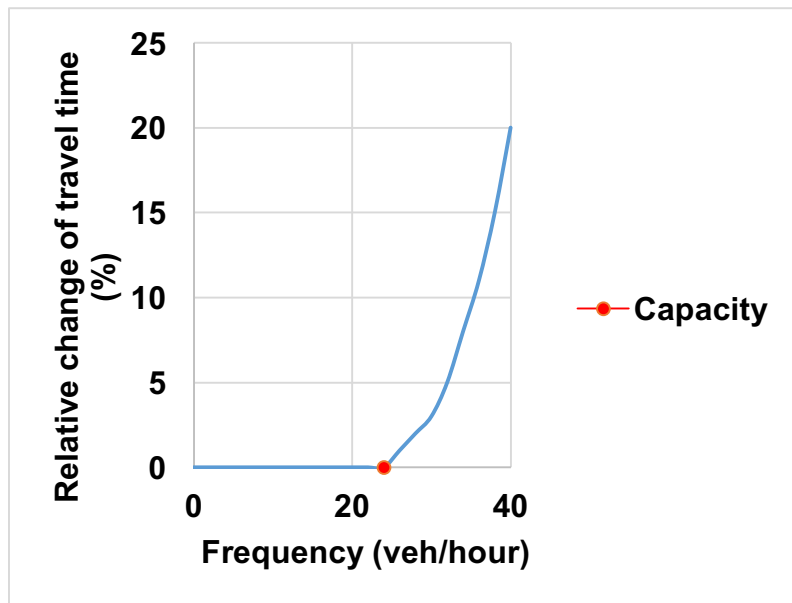


Figure 5.1: Used flow-dependent travel time variable.

5.1.5 Willingness-to-walk

The willingness-to-walk of passengers in case of unplanned disruptions is also a very much unexplored field. There is research available based on empirical data looking into the walking distances passengers undertake to a public transport stop in unplanned operations (Hoogendoorn-Lanser, 2005), but this is expected to differ from the case being considered here, with an unplanned disruption, for which its duration is not known for passengers beforehand and where no suitable alternative is available. Based on the empirical data available and expert judgement, the following step-function has been assumed, defining the probability of passengers willing to walk dependent on the travel distance (Figure 5.2).



Figure 5.2: Assumed willingness-to-walk of passengers.

As can be seen, for short distances it is assumed a large share of the passengers walk. This share decreases slowly with an increase of walking distance, until 15 minutes. Then the willingness-to-walk decreases steeply, and then again slowly until nobody is assumed to walk anymore for distances further away than 25 minutes.

Due to the uncertainty of the variable, and the expected impact it can have, this variable has been taken into account during the sensitivity analysis, which can be found in §6.2.1.

5.1.6 Weight factors for different trip elements

The used weight factors for the different trip elements are equal to generally accepted values found in literature, and are represented as factor of in-vehicle travel time:

Table 5.2: Used weight-factors for different trip elements,

Trip element	Value
In-vehicle (β^{ivt})	1
Waiting (β^{wait})	2 (Wardman, 2004)
Waiting, denied boarding ($\beta^{wait,denied}$)	3.5 · 2 (Börjesson & Eliasson, 2014)
Walking (β^{walk})	2 (Wardman, 2004)
Transfer ($\beta^{transfer}$)	5 (Balcombe et al., 2004)

5.1.7 Actual disruption July 15th 2016, Javastraat / Alexanderstraat

The actual network at that time is used as model input, which is the same network as was used previously for the fictive disruptions. For the passenger demand data, the average of the two previous Fridays is used. Unfortunately, the passenger demand data of the influenced vehicles turned out to be corrupted, making it not possible to determine the origin-destination relationship for these passengers.

Unlike for the fictive disruptions, where a random arrival of passengers was assumed, for this disruption the average of the passenger demand data of the week prior to and the week after the disruption has been used, on vehicle level. At the considered hours the frequency is lower compared to daytime frequency (4 instead of 6), causing passengers less likely to arrive at random (Van Oort, 2011).

Actual vehicle location data is used to determine the actual implemented measures.

5.2 Implementation of conceptual framework

The proposed framework consists of two models. The first model is used to generate alternatives, in order for the framework to be generally applicable, and is implemented using MATLAB. The second model is used to assess the different generated alternatives from a passenger perspective, which is being conducted using the discrete event-based simulation tool Simio.

5.2.1 Generation of alternatives (MATLAB)

For the generation of alternatives, MATLAB was used to define the different alternatives using the previously discussed *k-shortest path method* and the threshold values discussed in 5.1.3. In this research a pre-scripted script is used to find all *k-shortest path* without any loops (Shirazipour, 2011).

The network input is stored in an Excel sheet, and consists of an origin node, destination node, trip time between nodes and the available short-turning nodes in the network. Furthermore, the original route is also part of the model input, represented by the list of nodes the original route traverses.

Output of the model is a list of alternatives, with for each alternative a list of nodes representing the route of that specific alternative, the total trip time and the nodes that are skipped in comparison with the original route. Furthermore, a list of nodes representing the short-turning possibilities is also output of the model. The running time of the alternative generation model turned out to be approximately 25 minutes on a regular laptop. This is rather long and not suitable for real-time usage, but it is expected that this can be improved by using a more efficient modelling language and/or a more efficient network input. The used network input made sure no alternatives were excluded, but it is clear that a large part of the network is not part of any of the alternatives for these case studies. However, this long running time is not expected to be a problem for the framework to be used in real-time, since alternatives can be generated beforehand or using other methods, of which one of the most suitable would be expert judgement.

5.2.2 Assessment of alternatives (Simio, *discrete event-based simulation*)

For the assessment of the different alternatives, discrete event-based simulation is used. This approach has been chosen since it is a relatively simple method, only simulating the model at the occurrence of an event. This is perceived to be suited for mimicking the disrupted operation and passenger behaviour prior to, during and after the disruption. Events can be of all kind, and in context of this research events range from the arrival of passengers at a stop, the arrival of a vehicle at a stop or the start of the disruption. Simio has been chosen as the tool since its availability and as it is a powerful though easy tool to build such a model.

Each passenger is generated as a separate entity, based on random (from Poisson distribution) arrival for a given arrival rate of passengers per hour. Arrival rates are retrieved from historical data. Upon creation, passengers are assigned their destination, based on the historical passenger demand data, as well as the corresponding original boarding stop, original alighting stop, the disrupted boarding stop and the disrupted alighting stop. The disrupted stops are being defined using the previously discussed passenger path choice presented in §3.3.1.

Based on the current system state (disrupted or not), passengers are assigned their original boarding- and alighting stop or their disrupted boarding- and alighting stop. These are the same if the alternative assessed traverses these stops.

Depending on whether the original boarding- and alighting stops match the disrupted boarding- and alighting stops, the walking distance and whether the line is disrupted, passengers travel from their origin to their destination, incurring the different travel time elements along the way.

In the assessment of alternatives, a model-warm up period is used of one hour. This is a bit more than the time needed for one vehicle to travel from the origin terminal to the destination terminal. After the disruption an aftermath period of again one hour is used, in order to assess all effects of the disruption

also in the recovery period. Important to note is that statistics such as all different travel time elements are only counted from the start of the disruption, since the alternatives do not have an effect on this period. Statistics during the aftermath period are taken into account, since it is expected these might be influenced by different alternatives.

The running time of the assessment of alternatives turned out to be 12 seconds for four simulation replications, making it possible for use in real-time operations.

5.3 Replications, verification & validation

5.3.1 Replications

Due to stochastic elements in the model (random arrival of passengers, probability of passengers walking), it is necessary to conduct multiple replications for output analysis. This can be done using the following formula (Cats, 2011; Dowling, Skabardonis, & Alexiadis, 2004), based on a sample of m simulation runs:

$$N(m) = \left(\frac{S(m) \cdot t_{m-1, (1-\alpha)/2}}{\bar{X}(m) \cdot \varepsilon} \right)^2$$

Where:

$N(m)$ = number of replications required based on a sample of m simulation runs.

$S(m)$ = estimated standard deviation of the output measure based on a sample of m simulation runs.

$t_{m-1, (1-\alpha)}$ = corresponding critical value of the student's-t distribution

$\bar{X}(m)$ = estimated mean of the output measure based on a sample of m simulation runs.

ε = allowable percentage of error of the estimate $\bar{X}(m)$.

α = level of significance.

For $\alpha = 0.05$ and $\varepsilon = 0.05$, a sample of $m = 10$ replications, and the total generalized passenger travel time as output measure, this led to $N(10) = 6.3$ at a maximum, showing that the 10 replications conducted are sufficient for output analysis.

5.3.2 Verification and validation

Model verification is important to show that the model developed does what it was intended to perform (Law & Kelton, 2000), and thus to show that the simulation model does not contain bugs. Verification of the model has taken place constantly throughout the modelling process. The model has been built up in small steps, starting with a small network without a disruption and only one passenger, developing into a model with one passenger being affected by a disruption in various manners. All the different kind of origin-destination combinations for this one passenger have been tested and the model was constantly updated until it performed what it is supposed to do, as well as using extreme values (for instance in walking distances, willingness-to-walk) to test the defined logic. This has been done for both kinds of alternatives available, and later the different journey stages (such as waiting at the boarding stop, passengers on-board) which a passenger can be in at the start of a disruption have been tested.

For the reference scenario, in the case of no disruption, the average in-vehicle time of passengers in the model was compared to the average travel times in reality using smartcard data. The average in-vehicle travel time of passengers is the result of various processes, such as the generation of passengers, the assignment of destinations and trip time between the different stops. The difference between the output of the model and the smartcard data was found to be 5 seconds, on an average in-vehicle time of 12 minutes and 16 seconds. This is perceived to be insignificant, because the difference can arise due to other factors, such as a measuring the in-vehicle time in the model versus the difference between check-in and check-out times in reality. The average waiting time of passengers in the undisrupted situation turned out to be exactly 5 minutes, which was to be expected since random arrival is assumed with a frequency of 6 vehicles per hour. So by constructing the model in steps, constantly updating the model if the output seemed not to be representative using extreme values and comparing the average travel time of passengers in the model with reality, the model is verified.

Model validation is defined by Law and Kelton (2000) as: "Validation is concerned with determining whether the conceptual simulation model (as opposed to the computer program), is an accurate representation of the system under study". Model validation in this context is a lot harder than the model verification. Several aspects have been assumed in the conceptual model, for instance passengers walking to another stop if their stop is skipped. The assumptions have been made based on knowledge available and seem logical, but it in order to be validated an extensive passenger survey would be needed (leading only to stated preference of passengers during disruptions) or tracing passengers in case of an unplanned disruption. This is perceived to be not possible in terms of time and resources available for this research. What has been done is to check the plausibility of the conceptual model using expert judgement, in order to validate the model as much as possible.

It was hoped that by simulating an actual disruption, a part of the validation could be conducted. For instance, following the model logic the model showed that for a disruption the number of passengers boarding at the last stop served before the detour should increase since passengers from close-by skipped stops would walk to this stop and board the vehicle there. Unfortunately, the smartcard data turned out to be corrupted for vehicles not traversing their original route. Check-ins and check-outs are registered at stops which were not served by the vehicle, and also stops that were served before the detour, so before the detour, turned out not to be registered.

6

Results and analysis

In this chapter, the outcome of the previously discussed cases will be presented. First an overview of the general results for all four disruption locations will be given and discussed, followed by the results and analysis per disruption location. Due to the extensive amount of results per disruption location, not all results will be discussed and analysed at the same level of detail. The results and analysis of disruption location A will be discussed in full detail in §6.1.1, while for the three other disruption locations only the notable aspects will be discussed. Extensive results can be found in the appendices, which will be referred to when applicable.

Following the results and analysis per disruption location, the results of a sensitivity analysis will be presented in order to give an indication of the sensitivity of the results based on the used model input. Two aspects of the model input have been considered, namely the distribution of people walking to a stop served versus waiting until service is resumed, and the sensitivity towards a possible overestimation of the passenger demand between HS / Bierkade and Kurhaus due to construction works on line 9.

After the sensitivity analysis, the actual disruption which took place on July 15th 2016 will be examined using the developed framework, as well as actual vehicle and crew schedules. To conclude an overall analysis will be given to sum up the main findings.

6.1 Results

Table 6.1 presents an overview of the general results of the four different disruption locations as discussed in §4.4.1. Note that besides the detour alternatives and the short-turning alternatives, a do-nothing alternative has also been taken into consideration. In this scenario, no action will be undertaken and vehicles are just lined up after each other, waiting for the disruption to be solved. The amount of passengers transported was around 2200 for the morning-peak and around 1650 for rest-of-day passenger demand levels.

Table 6.1: Overview of general results for the four disruption scenarios.

	Generated alternatives (detour + ST)	Top alternative passenger perspective	Extra TGTT (morning-peak)	Extra TGTT (rest-of-day)	Corresponding with current protocol
Disruption A	9 (5 + 3)	Detour 6 / ST Centrum - Kneuterdijk	164 (+20%)	137 (+22%)	No
Disruption B	8 (5 + 2)	ST Centrum – Mauritskade / Detour 1	282 (+34%)	224 (+36%)	No / Yes
Disruption C	7 (4 + 2)	Detour 4	190 (+23%)	130 (+21%)	No
Disruption D	7 (5 + 1)	Detour 6	164 (+20%)	176 (+28%)	No

Overall it shows that 4 to 5 detouring alternatives have been generated for the different locations. Looking at the considered network this makes sense, since there are three branches leading to the destination terminal of line 1 in Scheveningen. For these three branches, the most western branch has the option to make a loop at station Hollands Spoor, which is an important stop for line 1. Depending on the location of the disruption, the middle branch also makes use of the western branch, hence a total of 4 or 5 generated detour alternatives per disruption location.

Furthermore, it can be seen that the effects of a disruption at location B are more severe than the effects of a disruption location A, C or D. Location B has less suitable alternatives available since it represents an important junction, basically combining the disruptions of A and C in terms of alternatives available.

It can also be seen that current protocols do not correspond with the alternatives having the lowest TGTT found in this research. Later on, it will be shown that current disruption management protocols are mainly driven from the resource perspective on the disrupted line.

Important notion to make is that the capacity of the network did not turn out to influence in generating the alternatives. It was found that the residual capacity of the network was often higher than the frequency of 6 vehicles per hour of line 1, and the effect of locations where the capacity was exceeded, the total extra travel time was very limited. This is probably due to the fact that capacity exceedance according to the assumed values only took place at limited sections, leading to a small increase in travel time for that section. However, the main cause is probably the fact that only one disrupted line is considered. In reality, if a track is disrupted, all planned lines have to be rerouted. If the disrupted lines use the same detours, the effect will be much greater due to the exponential increase in travel time. In order to take this into account, a network-wide assessment should be conducted, unlike to only one disrupted line, as considered in this research.

Finally, the results show that for disruption A, B & C the effects of a disruption are approximately similar during the morning-peak and the rest-of-day when applying the proposed measure, while for disruption D it shows that the effects are more severe during the rest-of-day. In §6.1.4 the results of disruption D

will be looked closer upon to get to the how and why of the increased passenger impact in the rest-of-day compared to the morning-peak for the proposed measure.

6.1.1 Disruption location A (Centrum – Gravenstraat / Kneuterdijk)

For this disruption location, five detour alternatives along with 3 short-turning alternatives have been generated. Figure 6.1 presents an overview of the generated alternatives in relation to the original route, while Table 6.2 gives an overview of their characteristics. Note that the same detour is denoted by the same number throughout all disruption locations.

The skipped stops represent number of stops that are skipped by that detour in relation to the original route. For the detouring alternatives, the extra trip time represents the delay upon arrival at the destination terminal each vehicle incurs by that alternative. For the short-turning alternatives the walking times between the last stop upstream and the first stop downstream are given. Finally, the number of directly affected passengers are given. Directly affected passengers are defined as passenger of which their origin and/or destination stop is skipped. The disruption management protocol is denoted by the asterisk (*).

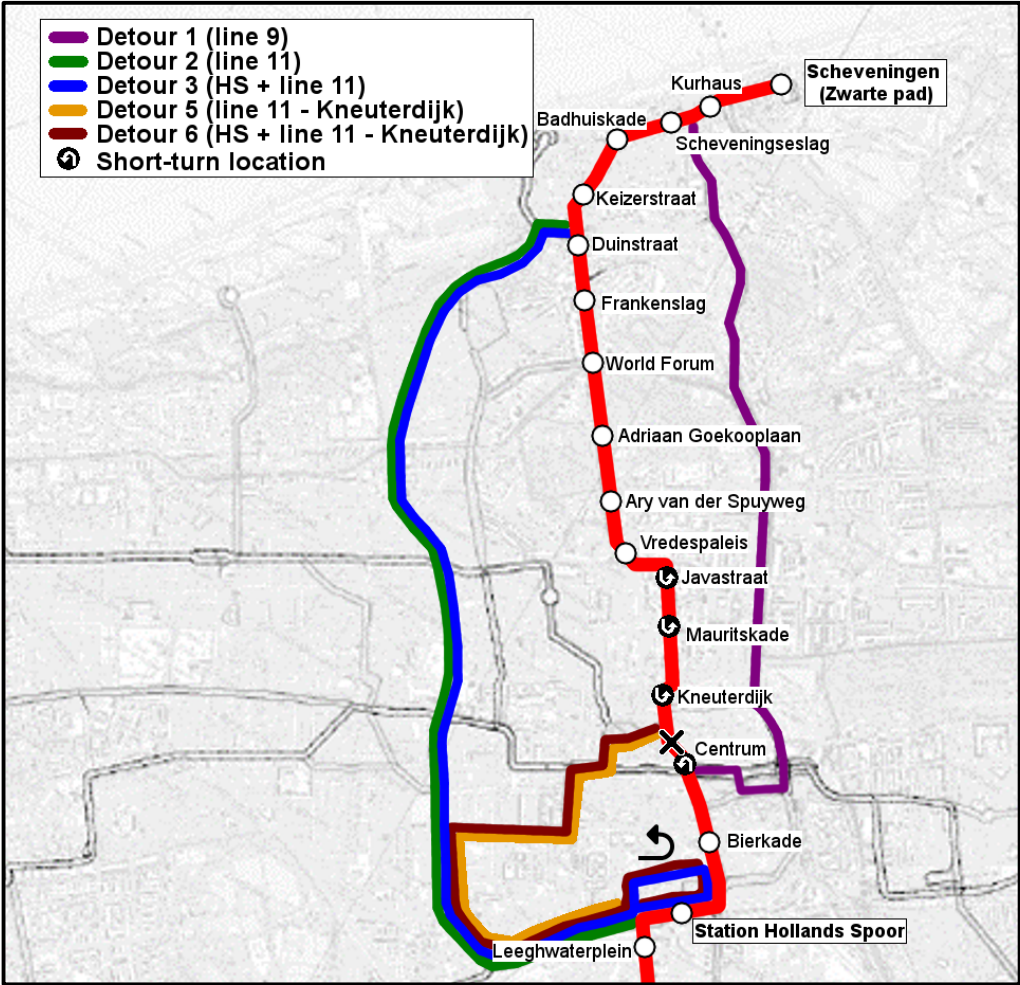


Figure 6.1: Generated alternatives for disruption location A.

Table 6.2: Disruption location A - Characteristics of the different generated alternatives.

	Skipped stops	Extra trip time [min]	Walking times ST	Passengers affected - morning	Passenger affected - rest-of-day
Detour 1 (*)	12	0	-	456	482
Detour 2	12	3.2	-	667	561
Detour 3	11	7.7	-	562	446
Detour 5	3	7.0	-	538	468
Detour 6	2	11.5	-	281	297
ST Centrum – Kneuterdijk	0	-	5	0	0
ST Centrum – Mauritskade	1	-	12	86	51
ST Centrum - Javastraat	2	-	17	205	91

It should be noted that for Detour 1 as well as the short-turning possibilities the stop Centrum of the original route is replaced by the stop Kalvermarkt-Stadhuis. These two stops are located at the same junction and therefore treated as one. Furthermore, it is important to note that the short-turning possibility at Mauritskade differs a bit in operational complexity than the other three locations; in order to short-turn at Mauritskade, a short stretch has to be driven backwards in order to turn around. This is mainly using exclusive right-of-way, and the part on the public road shared with other traffic is comparable to short-turning at a wye.

Figure 6.2 and Figure 6.3 show the assessment of the different alternatives from a passenger perspective on the x-axis and the resource perspective on the y-axis, for the morning-peak passenger demand levels and the rest-of-day passenger demand levels, respectively. For the short-turning alternatives, the resource perspective cannot be expressed in delayed arrival at the destination terminal; in case of short-turning, the resources stay on one side of the disruption and do not arrive at their destination terminal as long as the disruption lasts.

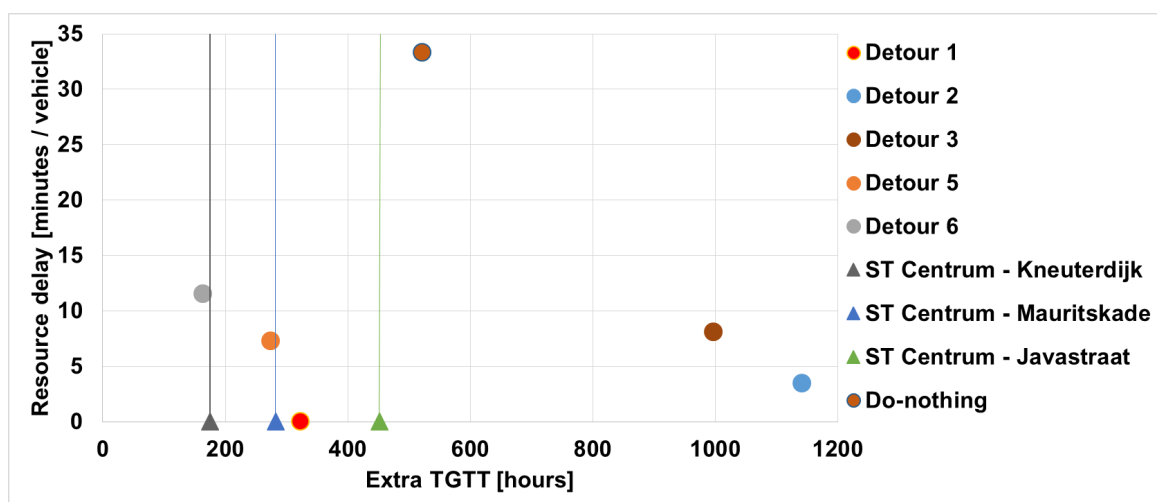


Figure 6.2: Disruption location A - Extra TGTT versus resource delay (morning-peak).

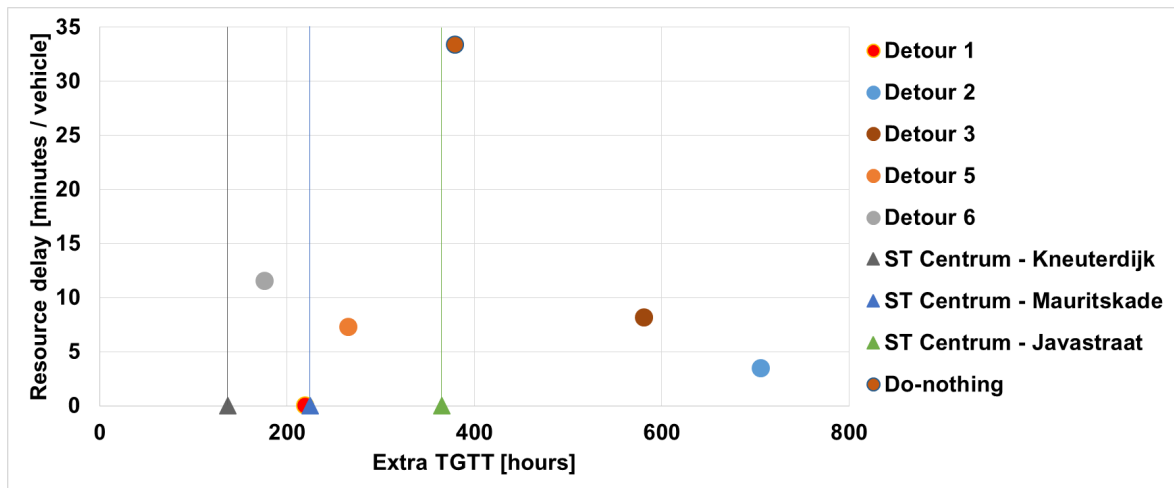


Figure 6.3: Disruption location A - Extra TGTT versus resource delay (rest-of-day).

When only considering the detours, it can be seen that for the morning-peak Detour 6, Detour 5 and Detour 1 form a so-called Pareto front. This implies that when considering a detour to implement in case of this disruption, from a passenger as well as a resource perspective it is best to only consider Detour 6, Detour 5 and Detour 1, and to discard Detour 2 and Detour 3, since regardless of considering the passenger or resource perspective, there is always a better alternative available. However, there might be other factors of influence which have not been taken into account in this approach which could justify these alternatives. For the rest-of-day peak only Detour 6 and Detour 1 form a Pareto front when considering detours.

The disruption management protocol available for traffic controllers to use suggests Detour 1 as the response to this disruption location. Depending on the availability of extra vehicles and crew, and the expected duration of the disruption, a shuttle-tram might be installed in addition to the detour between Scheveningen and stop Javastraat. This shuttle-tram has not been taken into account in assessing the alternatives since the limited disruption duration considered. For a disruption of an hour as considered here, it is not very likely that an extra shuttle-tram can be installed, also because of the dependence on spare vehicles and drivers. Detour 1 has no extra trip time as compared to the original route, which means no rescheduling of vehicles and personnel has to take place, making it the easiest alternative to implement. By applying Detour 1 during the morning peak, the amount of extra TGTT for passengers on this line is over 50% higher as compared to the two alternatives with the least amount of extra TGTT, Detour 6 and short-turning between Centrum and Kneuterdijk.

A remarkable aspect to note is that whereas in the morning-peak Detour 6 is the preferred alternative from a passenger perspective according to the developed framework, for the rest-of-day short-turning between stops Centrum on the one hand and Kneuterdijk on the other hand incurs less extra total generalized passenger travel time (see Figure 6.4).

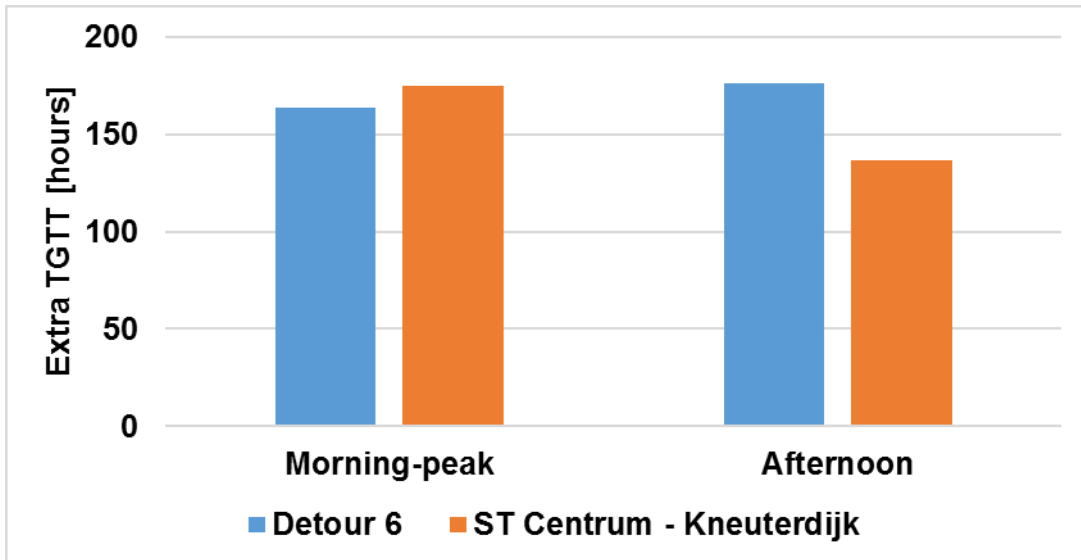


Figure 6.4: Disruption location A – Comparison between detouring and short-turning for morning-peak and rest-of-day passenger demand levels.

When comparing Detour 6 to short-turning between Centrum and Kneuterdijk, it can be seen that Detour 6 is favourable for passengers originating prior or from stop Station Hollands Spoor and travelling to Kneuterdijk and further, while short-turning is favourable for passengers travelling to Bierkade and Centrum (see Figure 6.1).

Figure 6.5 presents the origin-destination relations for the northern part of line 1 in the morning-peak, while Figure 6.6 gives the origin-destination relations for the rest-of-day. Note that, just as the rest of the results, the relations are given one-way; from Leeghwaterplein in the direction of Zwarte Pad in this case. The skipped stops by Detour 6 are highlighted.

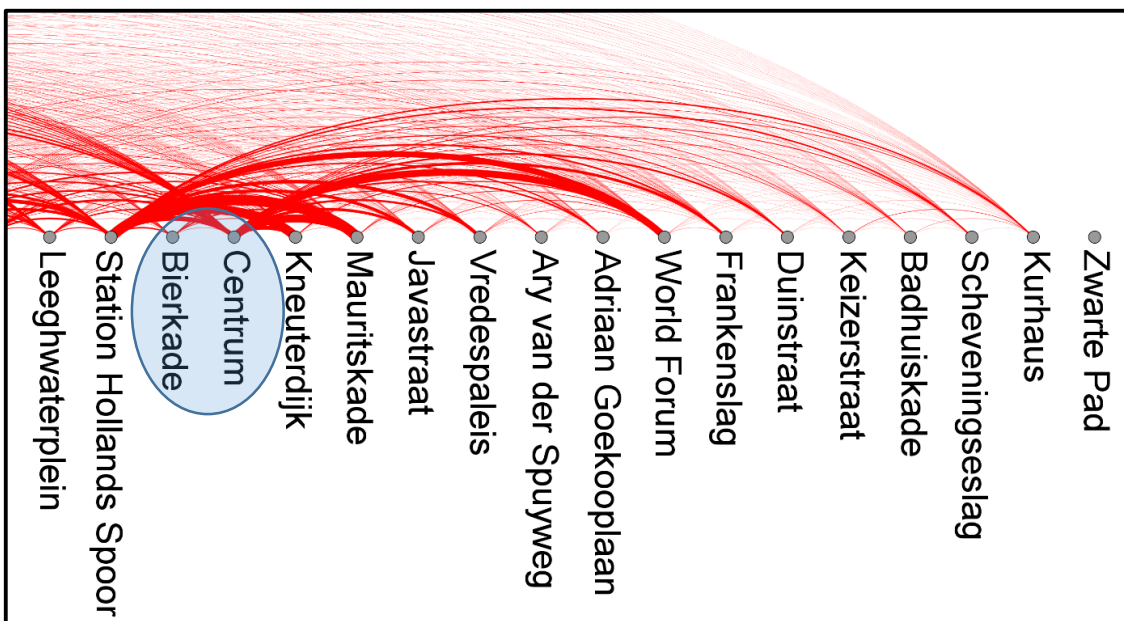


Figure 6.5: Origin-destination relations morning-peak, with the skipped stops of Detour 6 highlighted.

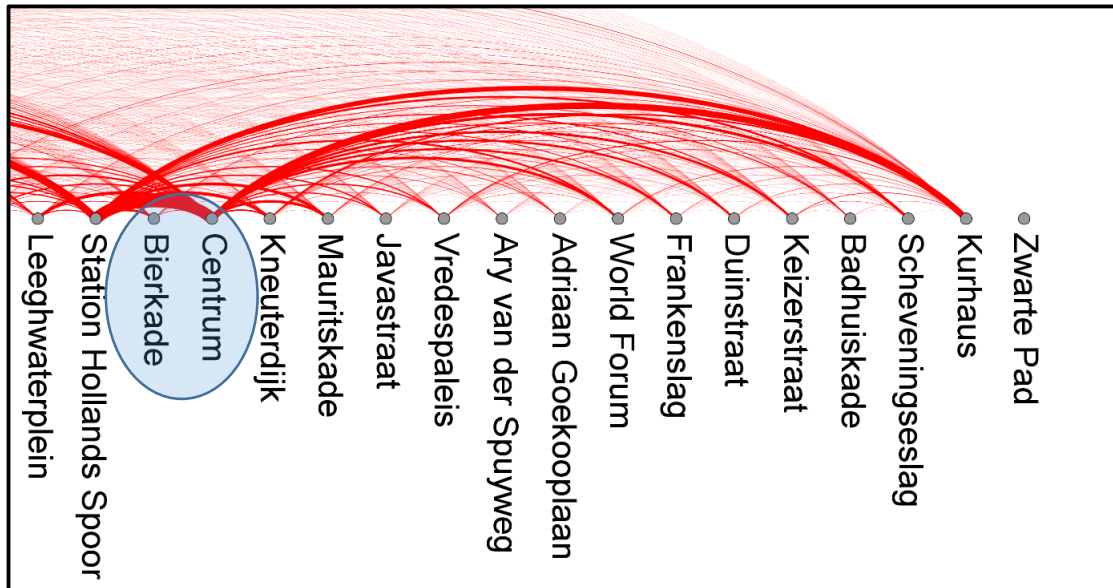


Figure 6.6: Origin-destination relations rest-of-day, with the skipped stops of Detour 6 highlighted.

It can be seen that during the morning-peak, Bierkade and Centrum are relatively less important stops than in the rest-of-day; during the morning-peak stops Kneuterdijk, Mauritskade and World Forum show a lot of attraction. For the rest-of-day passenger demand levels however, Bierkade and especially Centrum are relatively more important stops compared to the stops Kneuterdijk and beyond. Table 6.3 presents the number of passengers destined for stops Bierkade / Centrum versus passengers originating prior to or from stop Station Hollands Spoor and destined for stops Kneuterdijk and further, for morning-peak and rest-of-day respectively. These groups of passengers are of main importance, since passengers from Bierkade or Centrum to Kneuterdijk and further are affected in the same manner by both alternatives, as well as passengers originating from stops Kneuterdijk and further. Based on these numbers of passengers, it shows the ratio of passengers favoured by detouring versus passengers favoured by short-turning.

Table 6.3: Passengers favoured by detouring versus passenger favoured by short-turning, for morning-peak and rest-of-day (per hour), location A (Detour 6).

	Kneuterdijk and further (originating prior / from Station HS)	Bierkade / Centrum	Ratio passengers detouring : short-turning
Morning-peak	282	125	1 : 0.4
Rest-of-day	154	169	1 : 1.1

Table 6.3 shows that stops Bierkade / Centrum attract more passengers in the rest-of-day than they do in the morning-peak, absolutely but moreover relatively to stops Kneuterdijk and further. The share of passengers destined for Bierkade / Centrum is 44% of passengers destined for Kneuterdijk and further in the morning-peak, while this increases to 110% in the rest-of-day. So, due to the increased relative importance of the stops favoured by short-turning as compared to detouring in the rest-of-day, short-turning becomes a more favourable alternative in the rest-of-day than detouring, from a passenger perspective. The results show that in the morning-peak, the detour has a slightly lower TGTT, even though more than twice as many passengers are favoured by the detouring alternative. This is probably

due to the fact that passengers which are considered to be relatively favoured by detouring are also negatively affected by it.

Finally, for all alternatives the total generalized passenger travel time is given according to the different trip elements, in Figure 6.7 for the morning peak and in Figure 6.8 for the rest-of-day. A distinction has been made between regular waiting, waiting until the disruption is over because the origin and/or destination stop is skipped, walking time, in-vehicle time, transfer and denied boarding, and these various trip elements are weighted as has been previously discussed. For the do-nothing alternative, the skipped waiting does not represent waiting at skipped stop until the disruption is over, but represents the waiting of passengers on-board the vehicle until service is resumed. Alternatives which skip a lot of stops and have a lot of these stops outside of the considered walking distance, logically tend to have more skipped waiting time than the other alternatives. In some cases this also leads to denied boarding, which makes sense considering that if a lot of passengers opt to wait until the disruption is resolved, denied boarding may arise after the disruption.

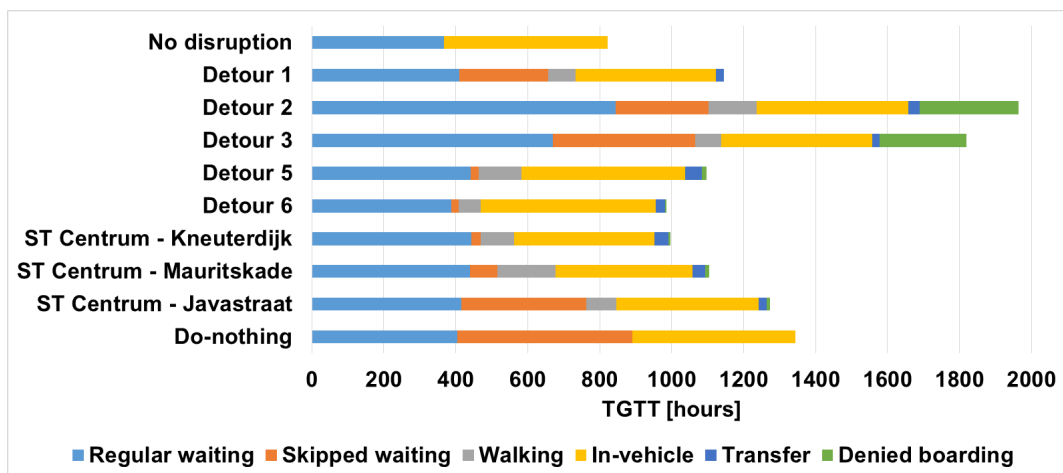


Figure 6.7: Disruption location A - TGTT per alternative, distinguished by trip element (morning-peak).

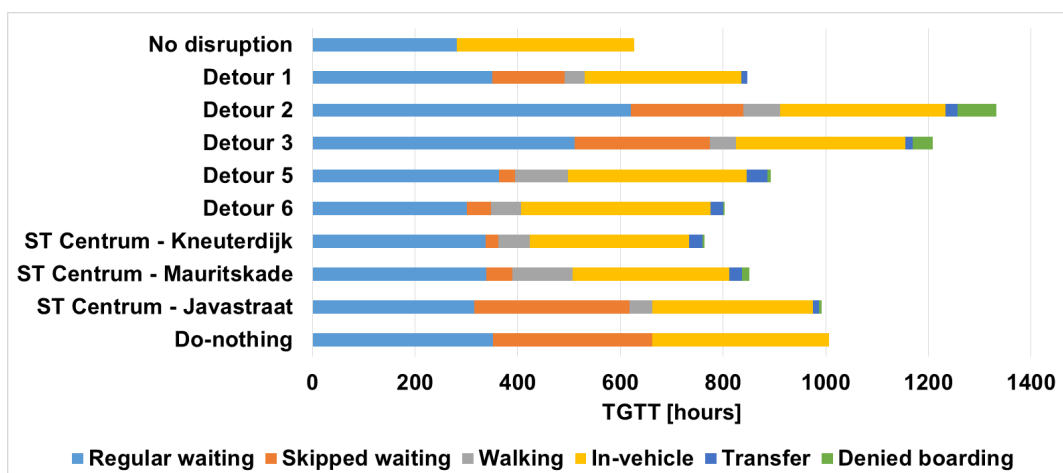


Figure 6.8: Disruption location A - TGTT per alternative, distinguished by trip element (rest-of-day).

Looking at the share of the different trip elements in case of no disruption, it can be seen that the total regular waiting time accounts for approximately 45% of the TGTT, while the total in-vehicle time

represents the remaining 55% of the TGTT. This distribution is very plausible, since the average in-vehicle time of passengers is a little over 12 minutes (as was discussed in §5.3.2). Assuming a random arrival of passengers, a vehicle headway of 10 minutes and a waiting weight factor of 2, the weighted average waiting time accounts to 10 minutes, hence being 45% of the TGTT.

Furthermore, it can be seen that the protocol, Detour 1, yields a considerably longer TGTT compared to Detour 6 or short-turning between Centrum and Kneuterdijk (49% for morning-peak passenger demand level, 39% for rest-of-day passenger demand level). It is important to note that these potential savings are only on the disrupted line in the direction of Scheveningen, and are neglecting the resource perspective and the possible knock-on effects. Therefore it cannot be stated that by implementing the alternatives with the lowest TGTT will yield the stated decrease of overall TGTT, but it does show that there are alternatives available yielding a lower TGTT on the disrupted line only.

One important note to make is that in-vehicle crowding has not been taken into account; passengers in general value a cramped vehicle differently than a nearly empty vehicle (Wardman & Whelan, 2011). From these results the utilization rates cannot be determined, but in the cases of denied boarding it is certain that the vehicle was very crowded; otherwise there would not have been denied boarding. Therefore, the total generalized passenger travel time of the alternatives showing denied boarding are most probably an underestimation. For this particular disruption location (and also for the rest) this does not pose a problem, since the alternatives showing denied boarding are the alternatives with the highest TGTT anyway.

On the other hand, the amount of skipped waiting time for some alternatives is expected to be somewhat overestimated. Especially for Detour 2 & 3, many passengers destined for stop Centrum will opt to wait according to the model, since the walking time is too long. However, in reality it is possible to reach stop Centrum from Leeghwaterplein with other lines. Therefore, the amount of skipped waiting time of these detours is probably overestimated. Taking into account this overestimation of amount of skipped waiting time and underestimation of the value of skipped waiting time, the outcome is not expected to change since even without the skipped waiting time these two alternatives have the highest TGTT.

6.1.2 Disruption location B (Centrum – Gravenstraat – Kneuterdijk junction)

For disruption location B, five different detouring alternatives have been generated as well as two short-turning alternatives. A disruption at this location shows to have the most severe effects from the five considered locations; in case of detouring, a lot of stops have to be skipped. Figure 6.9 and Table 6.4 show the different alternatives on the map and its characteristics, respectively.

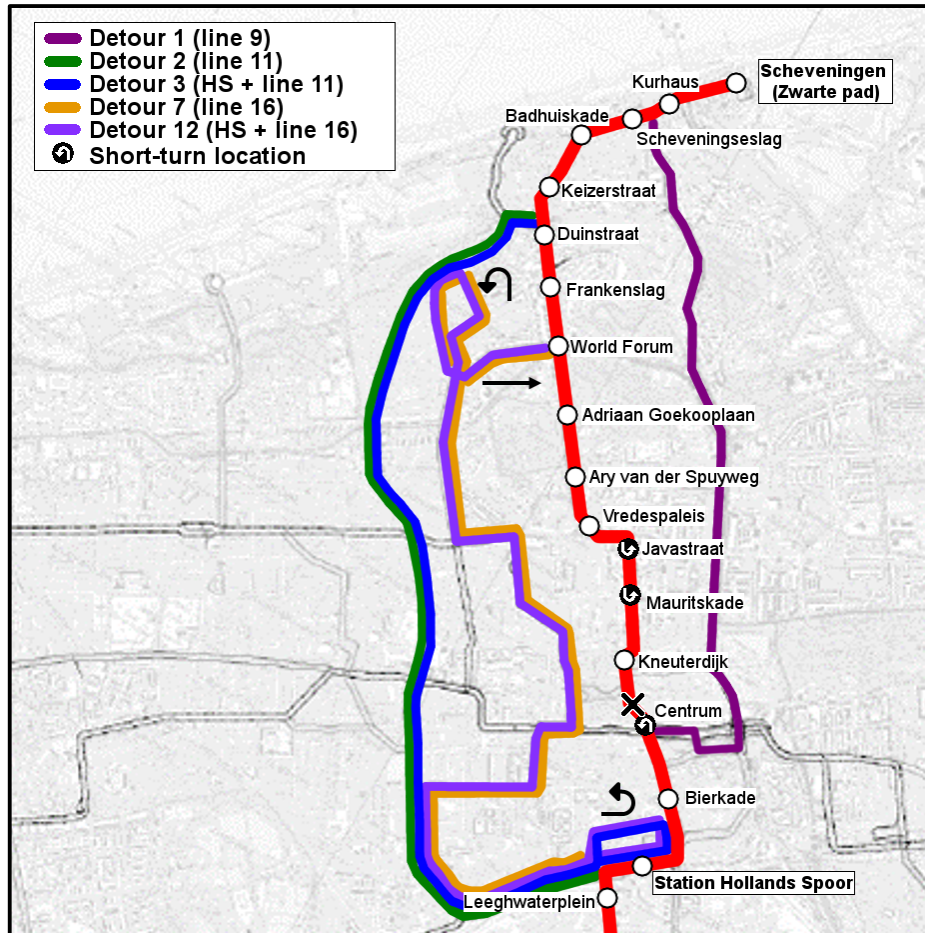


Figure 6.9: Generated alternatives for disruption location B.

Table 6.4: Disruption location B - Characteristics of the different generated alternatives.

	Skipped stops	Extra trip time [min]	Walking times ST	Passengers affected - morning	Passenger affected - rest-of-day
Detour 1 (*)	12	0	-	456	482
Detour 2	12	3.2	-	667	561
Detour 3	11	7.7	-	562	446
Detour 7	9	15.7	-	551	542
Detour 12	8	20.2	-	499	412
ST Centrum – Mauritskade	1	-	12	86	51
ST Centrum - Javastraat	2	-	17	205	91

Also for this disruption location the model shows a difference in the alternative having the lowest TGTT when comparing morning-peak with the rest-of-day passenger demand levels (see Figure 6.10 and Figure 6.11), but in contrary to the previous case here the short-turning alternative has a lower TGTT in the morning while the detouring alternative has a lower TGTT in the rest-of-day. Considering these two alternatives, detouring is preferred for passengers originating prior to or from stop Centrum and travelling to Kurhaus, whereas short-turning is preferred for passengers travelling from stop Mauritskade and further. Since Detour 1 skips almost all stops downstream of the disruption, short-turning is also favourable for passengers travelling to stops Javastraat and further.

Passengers destined for stop Kneuterdijk are affected in the same manner for both alternatives; they will have to walk from stop Centrum to Kneuterdijk. Looking back at the origin-destination relations of both dayparts (Figure 6.5 & Figure 6.6), it shows that the stops Mauritskade and further are more important in the morning-peak than the rest-of-day. Likewise, stop Kurhaus is more important in the rest-of-day, hence the difference in alternative with the lowest TGTT. See also Appendix F (p. X) for the number of passenger travelling from stops Mauritskade and further, travelling to stops Javastraat and further and the passengers originating prior to or from stop Centrum travelling to Kurhaus.

Unlike the previously discussed disruption, when only considering detouring this disruption location does not present alternatives forming a Pareto-front, but Detour 1 forming a Pareto-point on its own. This means that, when only considering detouring, Detour 1 is assessed the best from both the passenger perspective as well as the resource perspective.

Again, the skipped waiting time of detours 2 & 3 is expected to be somewhat overestimated. Looking at the assessment of the alternatives from the passengers' perspective this does not influence the outcome. One interesting aspect to notice is that for this disruption location and length most of the detours are worse from a passenger perspective than the do-nothing scenario, which is due to the many stops the detours skip.

See also Appendix F (p. X) for the TGTT for the different alternatives distinguished by trip element, as well as the number of passengers favoured by detouring compared to short-turning.

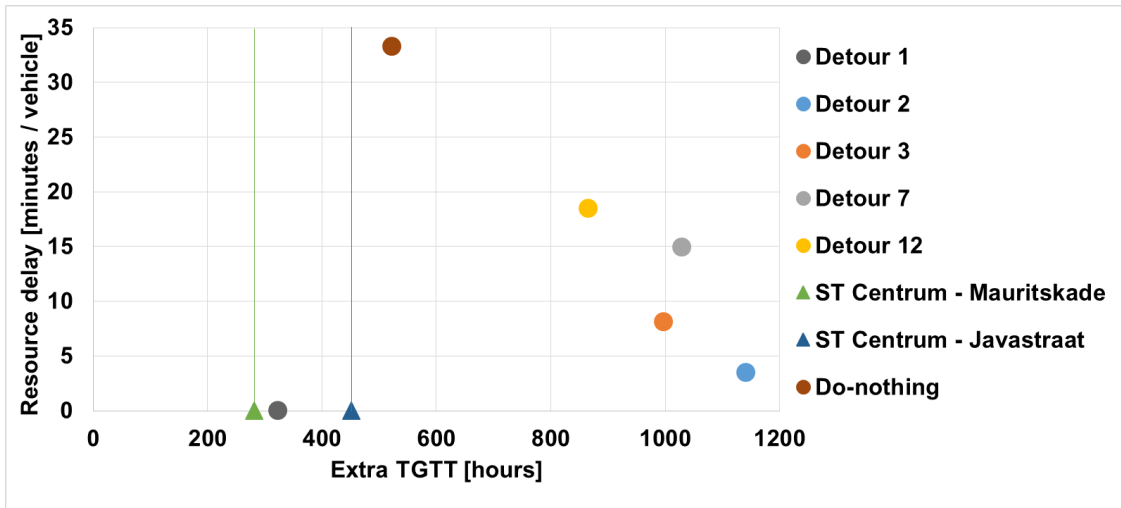


Figure 6.10: Disruption location B - Extra TGTT versus resource delay (morning-peak).

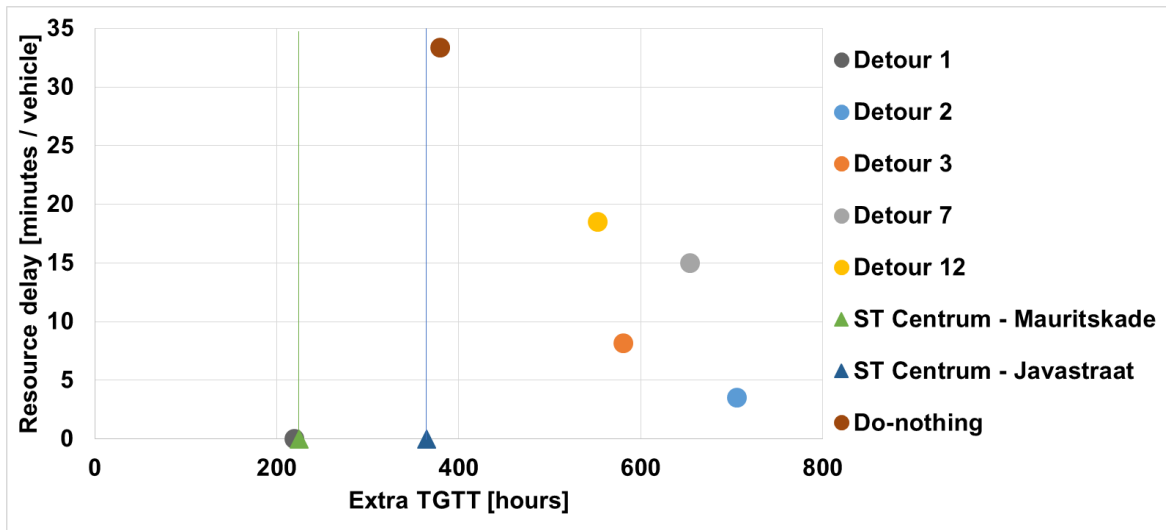


Figure 6.11: Disruption location B - Extra TGTT versus resource delay (rest-of-day).

6.1.3 Disruption location C (Kneuterdijk – Mauritskade)

The third disruption location that has been assessed is a disruption between the city centre of The Hague and Scheveningen. Compared to the previous discussed disruption is that a detour is available which only differs from the original route after the city centre, but is able to get back to the original route at World Forum. Taking this detour also incurs traversing the loop at Statenkwartier due to a missing arc. An additional assessment has been conducted in order to define the effects of adding the missing arc. Figure 6.12 presents the different alternatives illustrated on the map, while Table 6.5 presents the alternatives' characteristics.

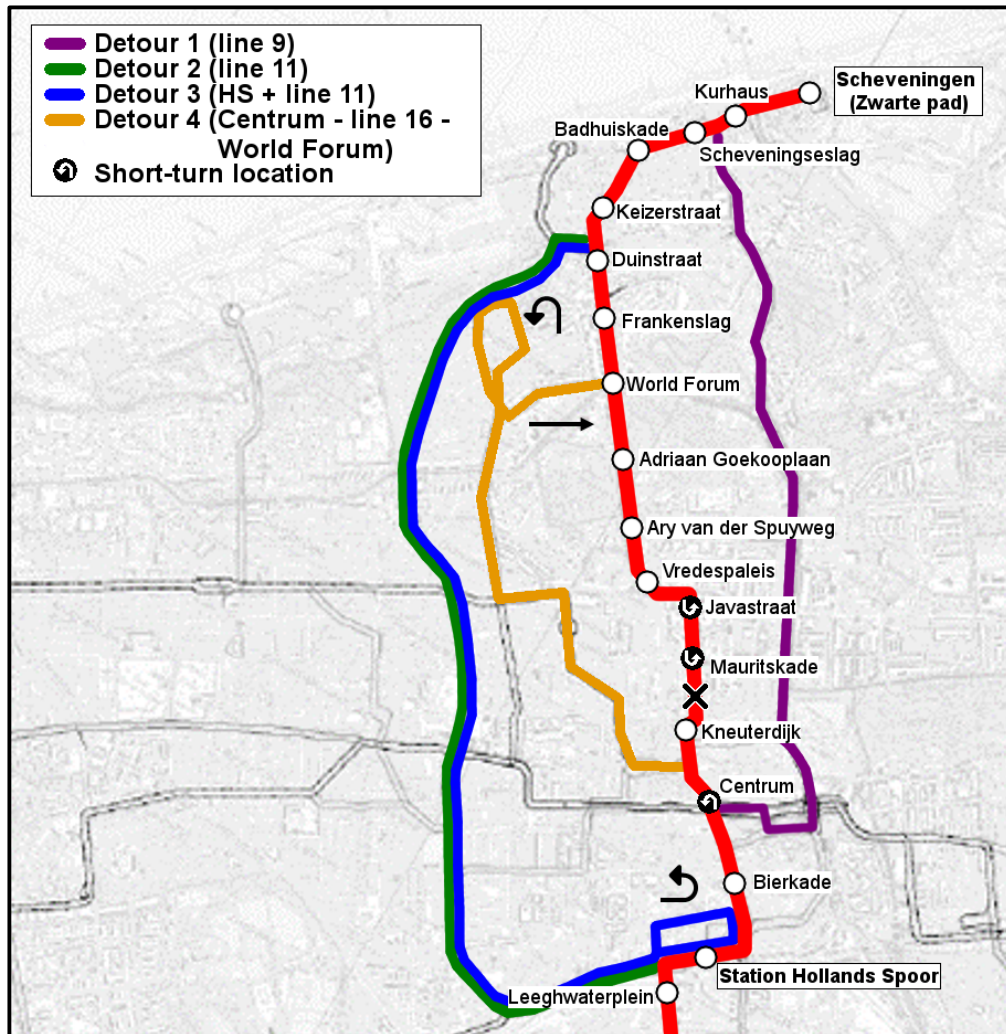


Figure 6.12: Generated alternatives for disruption location C.

Table 6.5: Disruption location C - Characteristics of the different generated alternatives.

	Skipped stops	Extra trip time [min]	Walking times ST	Passengers affected - morning	Passenger affected - rest-of-day
Detour 1 (*)	12	0	-	456	482
Detour 2	12	3.2	-	667	561
Detour 3	11	7.7	-	562	446
Detour 4	6	11.3	-	307	152
ST Centrum – Mauritskade	1	-	12	86	51
ST Centrum - Javastraat	2	-	17	205	91

For this disruption location, it can be seen that a Pareto-front between resource delay and extra TGTT exists between Detour 4 and Detour 1. In between in terms of TGTT is also the short-turning alternative, but as discussed no resource delay is assigned to this alternative. Detour 1 results in 1.5 times as much extra TGTT as compared to Detour 4 for passengers travelling on the disrupted line for this considered disruption. This does not mean that by applying Detour 1 the total of passengers incur 1.5 times as much extra TGTT as compared to Detour 4, since the resource delay incurred by applying Detour 4 possibly affect subsequent activities.

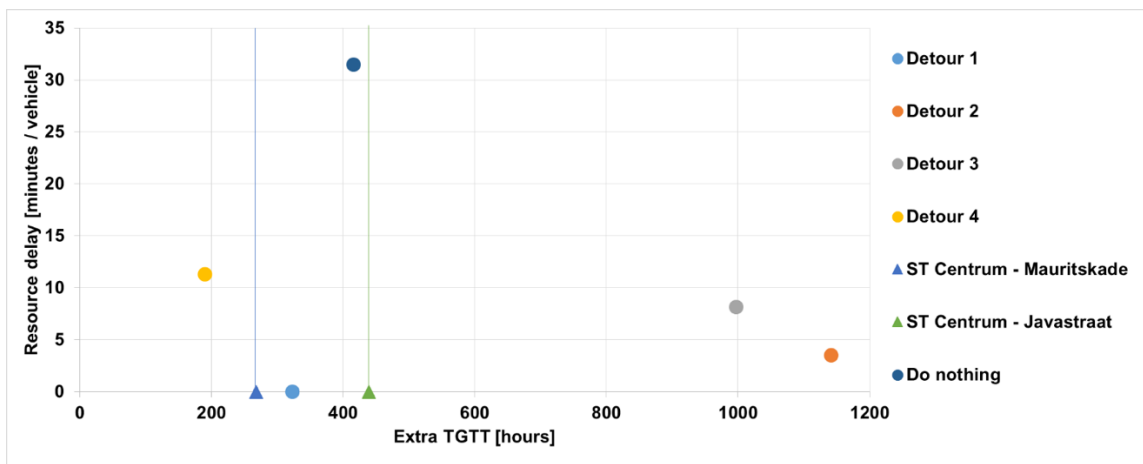


Figure 6.13: Disruption location C - Extra TGTT versus resource delay (morning-peak).

As discussed, Detour 4 traverses a loop at Statenviertel in order to get to World Forum due to a missing arc. For passengers, traversing the loop can be perceived as very illogical and unnecessary. By assessing Detour 4 in the fictive situation of not having to traverse the loop, some of the benefits of adding the arc can be estimated. It is estimated that adding the arc can reduce the detour by 5 minutes. Figure 6.14 presents the found extra TGTT for the alternatives versus the resource delay, including Detour 4 without loop.

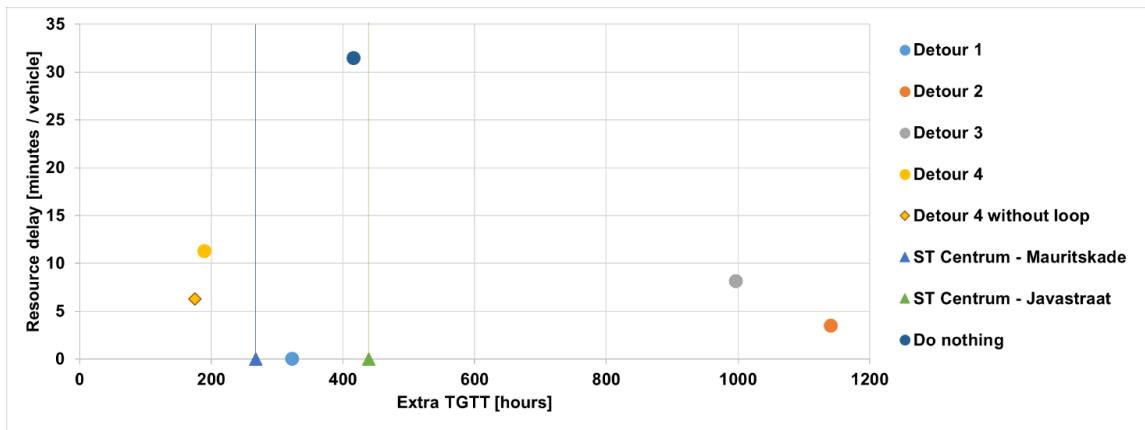


Figure 6.14: Disruption location C – Extra TGTT versus resource delay, with assessment of Detour 4 without loop (morning-peak).

It can be seen that the effect of adding the arc is limited for the TGTT (15 hours), but that the estimated 5 minutes of reduction in trip time has a significant effect on the resource delay. The current protocol is to apply Detour 1. If this is the current protocol because of its limited resource delay, then adding an arc might be of influence in the choice between Detour 1 and Detour 4. Then the effective benefits of adding the arc are not only the lower extra TGTT for Detour 4, but the difference in TGTT between Detour 4 without arc and Detour 1. However, there are a lot more aspects to be taken into consideration when considering adding the arc, such as costs (construction and maintenance) and frequency of usage.

In Appendix G (p. XII) the additional results can be found, such as the extra TGTT versus resource delay in the rest-of-day and the TGTT per alternative distinguished by trip element.

6.1.4 Disruption location D (HS – Centrum)

The final disruption is stretching through the centre of The Hague. Due to various consecutive sections being disrupted, it is expected that short-turning turns out to be a relatively bad alternative in terms of TGTT. Figure 6.15 illustrates the different generated alternatives on the map, while Table 6.6 presents the alternatives' characteristics.

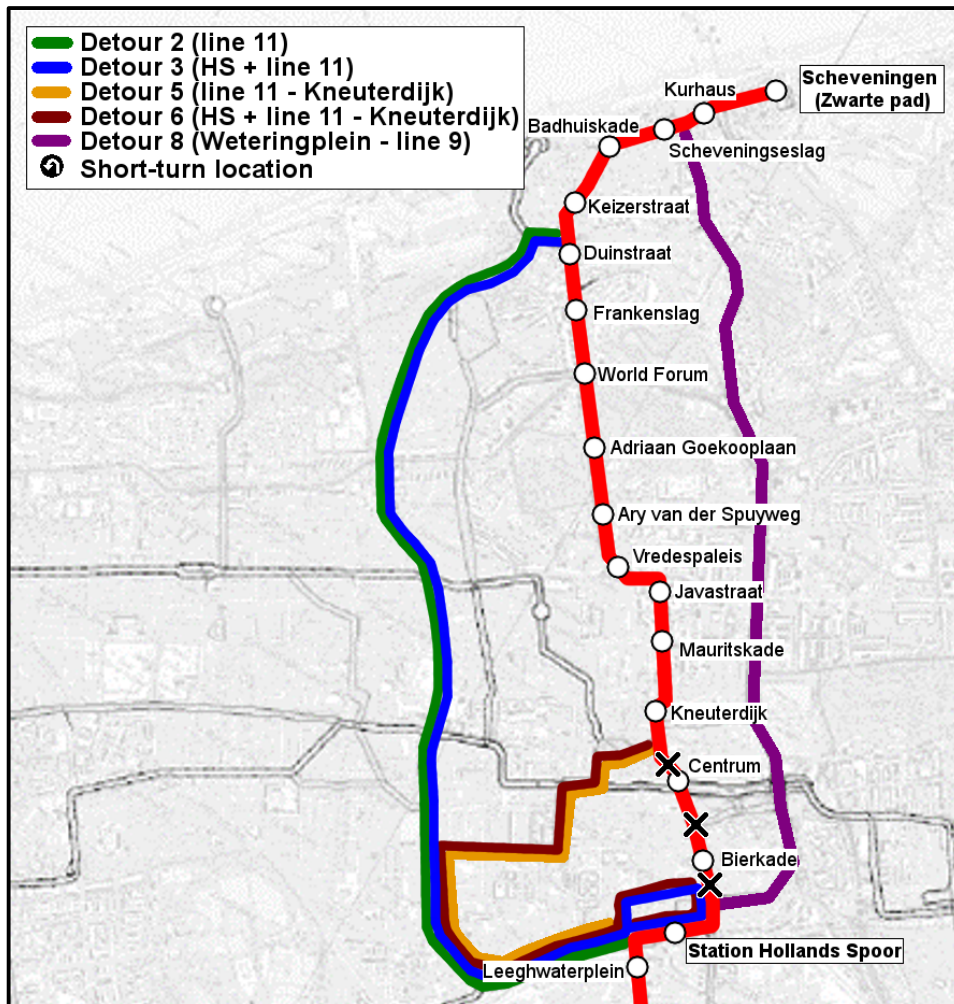


Figure 6.15: Generated alternatives for disruption location D.

Table 6.6: Disruption location D - Characteristics of the different generated alternatives.

	Skipped stops	Extra trip time [min]	Walking times ST	Passengers affected - morning	Passenger affected - rest-of-day
Detour 2	12	3.2	-	456	482
Detour 3	12	7.7	-	667	561
Detour 5	3	7.0	-	538	468
Detour 6	2	11.5	-	281	297
Detour 8 (*)	14	0	-	585	482
ST HS - Kneuterdijk	2	-	21	281	297

Figure 6.16 presents the outcome of the alternative assessment model for morning-peak passenger demand levels. It can be seen that short-turning performs weak, as was expected. Furthermore, it is interesting to note that Detour 8, being the alternative advised in the disruption management protocols, performs over 4 times as worse as the best alternative in terms of total generalized passenger travel time. A notion to be made is that the protocol prescribes in a shuttle tram being installed between Scheveningen and the centre of The Hague. However, as discussed earlier, a shuttle tram is not likely to be installed for a disruption with a duration as considered in this research. Also, traffic controllers are not obliged to follow the protocol, so if no shuttle tram is installed they might be more inclined choosing Detour 5 or 6.

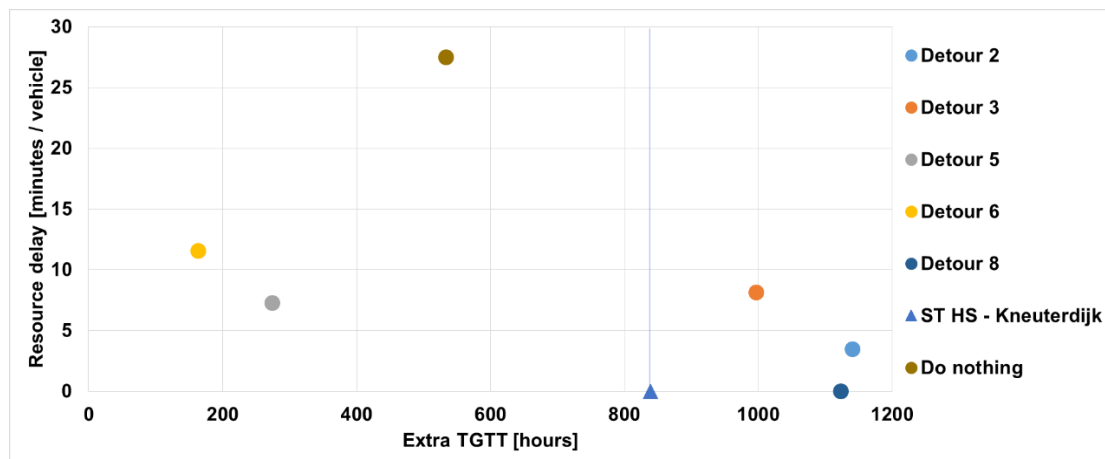


Figure 6.16: Disruption location D - Extra TGTT versus resource delay (morning-peak).

Appendix H (p. XIV) presents the remainder of the results of the assessment of alternatives for disruption location D.

6.2 Sensitivity analysis

Along with the variables used as input for the model comes along a certain uncertainty. Here, two uncertain aspects will be discussed of which are expected to have influence on the model outcomes. These two aspects are the assumed willingness-to-walk of passengers depending on the distance on the closest stop served and the possible overestimation of passengers travelling line 1 between stops HS / Bierkade to Kurhaus due to the construction works on line 9, as compared to a regular day.

6.2.1 Willingness-to-walk

As discussed earlier, the willingness-to-walk of passengers, especially in the case of unplanned disruptions, is still a much unexplored field. Therefore, it is important to test the effect of different levels of the willingness-to-walk of passengers.

In order to do so, first two cases have been selected for which it is most likely that the willingness-to-walk has a great effect on the outcome of the results. These are cases for which one of the better alternatives has a high skipped waiting, or where the best alternative has high walking times. The selected cases are disruption location B for morning-peak demand levels and disruption location A for rest-of-day demand levels.

For disruption location B, the best alternative from a passenger perspective in the morning-peak was found to be short-turning between stops Centrum and Mauritskade. This alternative has a walking time of 12 minutes, which the majority of passengers is willing to walk in the reference case.

For both cases a lower willingness-to-walk and a higher willingness-to-walk have been tested. Lower willingness-to-walk is defined as that passengers are 5 minutes less willing to walk than in the reference case, whereas for the high willingness-to-walk passengers are 5 minutes more willing to walk. Concretely this has as an effect that in the lower case, far fewer passengers are willing to walk the skipped part between stops Centrum and Mauritskade, whereas in the higher case far more passengers are willing to walk the skipped part between Centrum and Javastraat.

Figure 6.17 shows the outcome of using a lower willingness-to-walk and a higher willingness-to-walk than in the reference case for disruption location B. It can be seen that the willingness-to-walk of passengers influences the outcomes of the passenger perspective. Whereas in the reference case short-turning shows better results from a passenger perspective, with a lower willingness-to-walk it is Detour 1 that is preferred. When considering the higher willingness-to-walk, it shows that the three alternatives score approximately equal from a passenger perspective.

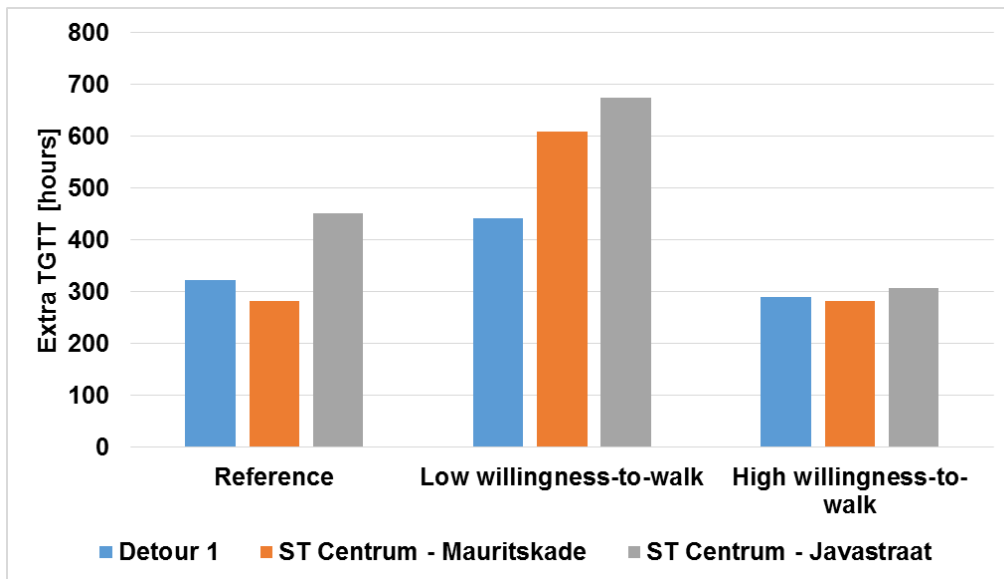


Figure 6.17: Sensitivity of alternatives of disruption location B for willingness-to-walk for the morning-peak.

For disruption location A, the results of the sensitivity analysis did not show a difference in outcome. It did show that the alternatives short-turning between Centrum and Mauritskade/Javstraat are more sensitive to the willingness-to-walk than Detour 6 and short-turning between Centrum and Kneuterdijk, but it did not change the outcome in terms of the alternative having the lowest TGTT. The results can be found in Appendix I (p. XVI).

Note that the willingness-to-walk of passengers is typically a variable that can highly fluctuate per day or even per time of day. It is safe to assume that passengers are more willing to walk on a sunny day in spring than on a rainy day in winter, as well as differences between day- and night-time. It is up to the traffic controller to take all these factors into account in the decision making process when managing disruptions.

6.2.2 Construction works line 9

As has been discussed earlier, the used passenger demand data might have been somehow overestimated as compared to a regular day between stops HS / Bierkade and Kurhaus, due to construction works which took place on line 9. To test the effect on the outcomes of this possible overestimation, the alternatives with the lowest TGTT have been assessed for a halved passenger demand between HS / Bierkade and Kurhaus, for disruption location A and B. These two locations have been chosen since these showed that the difference in TGTT between the detouring alternatives and the short-turning alternatives was relatively small. It was expected that the TGTT of short-turning alternatives would reduce more than the detouring alternatives, since the impact of short-turning is higher for passengers travelling from HS / Bierkade to Kurhaus compared to the detouring alternatives.

The effect on the outcomes of the possible overestimation of passengers travelling between HS / Bierkade and Kurhaus using line 1 due to the construction works on line 9 turned out to be minimal. The greatest effect was found for disruption location B for rest-of-day passenger demand levels (see Figure 6.18).

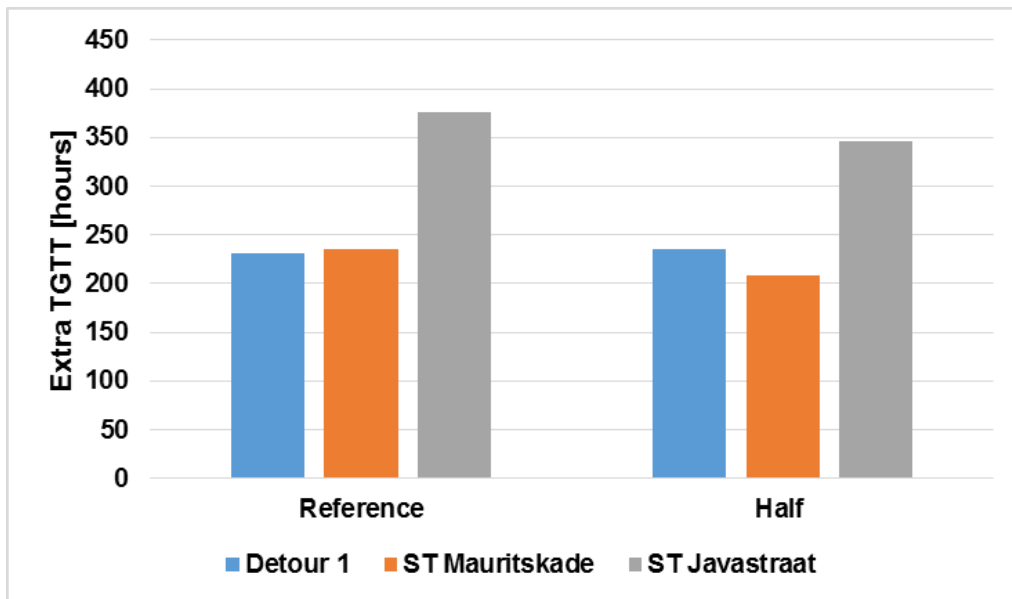


Figure 6.18: Effect of possible overestimation of passengers travelling between HS / Bierkade and Kurhaus (location B, rest-of-day).

As can be seen, in the reference case the extra TGTT of the alternatives Detour 1 and short-turning between Centrum and Mauritskade are approximately equal. If the used number of passengers between HS / Bierkade and Kurhaus was twice as high in the used input data as compared to a regular day, the difference between Detour 1 and short-turning between Centrum and Mauritskade would remain very small, with a small advantage for the short-turning alternative. This was the greatest effect on the outcomes found, making it safe to assume that the possible overestimation in the used passenger demand data does not significantly affect the outcomes.

The remainder of the results of the sensitivity analysis (location A morning-peak & rest-of-day, location B morning-peak), can be found in Appendix I (p. XVI).

6.3 Disruption Javastraat / Alexanderstraat, July 15th 2016

Up until now, only fictive disruptions have been analysed. This showed the passenger perspective as well as a part of the resource perspective of the different generated alternatives. In order to see what the framework can mean for managing real disruptions, an actual disruption that took place is analysed using the developed framework. For this analysis actual crew and vehicle schedules are used in order to assess the resource perspective in a more thorough manner.

6.3.1 Generated alternatives & implemented measure

For this disruption, three alternatives have been generated. These are all detouring alternatives; short-turning is not considered an option due to the excessive walking times between two closest short-turning locations, which are stops Mauritskade and stop World Forum (27 minutes). Figure 6.19 gives an overview of the generated alternatives, while Table 6.7 presents some of the alternatives' characteristics.

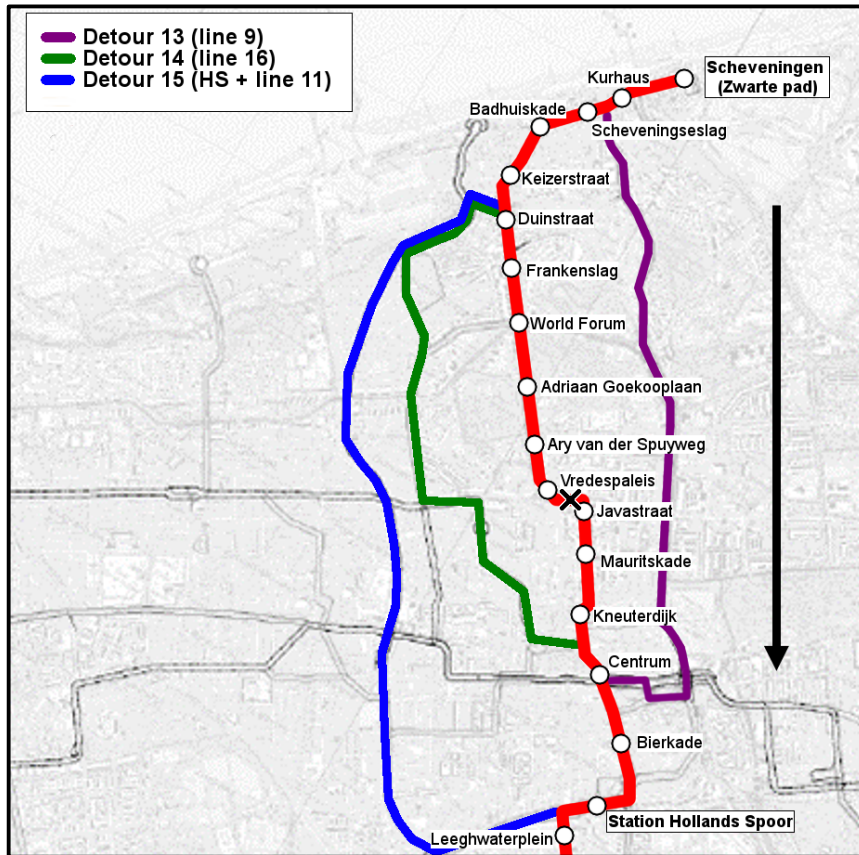


Figure 6.19: Generated alternatives for the actual disruption.

Table 6.7: Characteristics of generated alternatives.

	Skipped stops	Extra trip time [min]	Walking times ST	Passenger affected
Detour 13 (*)	12	0	-	163
Detour 14	9	5.8	-	123
Detour 15	12	2.7	-	292

The actual implemented measure as a response to the disruption was actually a combination of two alternatives generated, namely a combination of Detour 13 and Detour 14. Of the three vehicles being detoured, the first and the third vehicle traversed Detour 13, while the second vehicle traversed Detour 14. This is in contrary to the general policy to implement only one alternative per disrupted line. In communication towards the passengers HTM stated that line 1 was traversing via line 9 (Detour 13) between stops Kurhaus and Centrum. Therefore, in modelling the actual solution used, it is assumed that passengers had no information of the second vehicle using Detour 14; there was a mismatch between the information provided and the actual operations. This has as effect that the only passengers which are benefited by using a different detour for the second vehicle are passengers who opt to wait until the service is resumed at stops Scheveningseslag, Badhuiskade and Keizerstraat.

As for the resource perspective, the vehicle schedules showed that there is a 6 minute buffer time scheduled at the destination terminal in Delft. This buffer time is also validated by checking the actual vehicle location data of the second detoured vehicle in the actual implemented measure. Furthermore,

no crew changes were scheduled at the destination terminal in Delft. Therefore, the extra trip time of all generated alternatives can be compensated at the destination terminal in Delft, leading to no knock-on effects for the return trip.

6.3.2 Model outcome actual disruption

Figure 6.20 shows the total generalized passenger travel time for the generated alternatives, for the actual implemented solution as well as for the case without a disruption. Since passenger demand level is taken on vehicle level and thus no random arrival is assumed as previously, no waiting time occurs in the undisrupted case. The regular waiting time is in fact thus the delay passengers incur downstream of the disruption, or the waiting time that occurs when passengers walk from a skipped stop to a stop served.

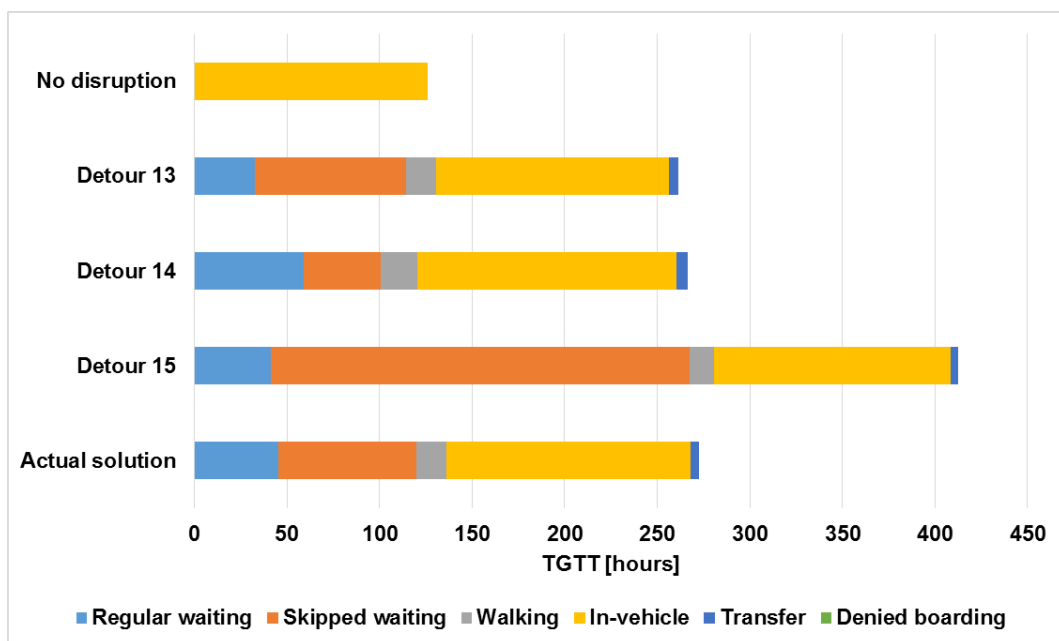


Figure 6.20: Outcome of result for the generated alternatives and the actual solution.

As can be seen, Detour 13, Detour 14 and the actual implemented solution have a very similar total generalized passenger travel time. Detour 13 has a relatively large share of skipped waiting time, which makes sense since it skips more stops than Detour 14. Detour 14 on the other hand has less skipped waiting time but more regular waiting time and more in-vehicle time. This also makes sense due to the lesser skipped stops and the longer detour, leading to more delay for passengers downstream of the disruption. The actual solution implemented actually has a higher TGTT than the other two alternatives. This is due to the fact that only a very limited amount of passengers benefits from the second vehicle being detoured using Detour 14 (only passengers who opt to wait until service is resumed at Scheveningseslag, Badhuiskade and Keizerstraat), while it increases the in-vehicle time for passengers from Kurhaus and causes delay for passengers downstream of the disruption. However, the difference between Detour 13 and the actual implemented solution is just over 10 hours. On a total of 505 passengers this is negligible and probably within the inaccuracy margins of the model and its input.

If there is a recommendation to be made out of these results, then it is important to note that Detour 14 has a smaller share of skipped waiting time. As discussed previously, the skipped waiting time is probably somewhat underestimated, since the same weighting factor is used for skipped waiting as for regular waiting. Therefore, Detour 14 would be recommended, although the scheduled buffer time will be used fully, making it more vulnerable to knock-on delays for its return trip and replacing the moment of rest of the driver.

6.4 Discussion

6.4.1 Detouring versus short-turning

First, looking at the differences between the two considered measures, detouring and short-turning, the results show that short-turning is the alternative having the lowest TGTT in 2 out of 8 cases (location A for rest-of-day, B for morning-peak), whereas detouring has the lowest TGTT for the remaining 6 cases. Table 6.8 presents the difference in extra TGTT between the detour alternative with the lowest TGTT and the short-turning alternative with the lowest TGTT, for all four disruption locations and the two considered dayparts.

Table 6.8: Difference in extra TGTT between detour alternative with lowest TGTT and short-turn alternative with lowest TGTT.

	Difference detouring and short-turning (morning-peak)	Difference detouring and short-turning (rest-of-day)
Location A	- 6%	+ 28%
Location B	+ 15%	- 2%
Location C	- 29%	- 40%
Location D	- 80%	- 64%

Disruption location A is the only location for which a relatively short walking distance (5 minutes) between the last stop upstream and the first stop downstream is applicable for the short-turning alternative. Disruption location B has a short-turning alternative with longer walking time (12 minutes), but due to the nature of the disruption location, all generated detouring alternatives skip a lot of stops, leading to short-turning being the alternative with the lowest TGTT for morning-peak demand levels. This indicates a trade-off between passengers affected and the walking distance of the short-turn alternative.

Considering only one location with corresponding alternatives, the results indicate that passenger demand levels affect the outcome in terms of lowest passenger impact on the disrupted line (see Table 6.8). For two disruption locations, defining the alternative with the lowest TGTT on the disrupted line yielded a different alternative for morning-peak passenger demand levels than rest-of-day passenger demand levels (location A & location B). This indicates that taking into account passenger demand levels in the management of disruptions can be of importance when the goal is to minimize passenger impact. Note that passenger demand levels can vary for different times of day, but can also vary because of seasonal effects. Especially for the considered line 1 seasonal effects on the passenger demand levels can be very significant.

For the considered disruption locations A and B in this research, the difference in ratios between passengers favoured by detouring and passengers favoured by short-turning, and its relation to the difference in extra TGTT incurred by detouring compared to short-turning and the walking time between short-turning stops is presented in Table 6.9. The ratios for both locations have been derived from the previously discussed results (Table 6.3, Table 7.8 and Table 7.9, respectively).

Table 6.9: Detouring versus short-turning, locations A & B.

	Walking distance ST (min)	Morning-peak		Rest-of-day	
		Ratio passengers detour : ST	Difference extra TGTT	Ratio passengers detour : ST	Difference extra TGTT
Location A (Detour 6, 11.5 min)	5	1 : 0.4	- 6%	1 : 1.1	+ 28%
Location A (Detour 1, 0 min)	5	1 : 24.1	+ 85%	1 : 4.0	+ 61%
Location B (Detour 1, 0 min)	12	1 : 16.6	+ 15%	1 : 3.2	- 2%

It can be seen that relatively more passengers need to be favoured by the short-turning alternative if the walking distance between the short-turning stops is higher. Furthermore, even if the detour is relatively long (11.5 minutes), detouring still yields a lower TGTT if the share of passengers favoured by detouring is high compared to the passengers favoured by short-turning. Concluding, three main variables have been identified of influence when considering detouring and short-turning:

- Share of passengers favoured by detouring versus passengers favoured by short-turning
- Walking time between short-turning stops
- Extra trip time due to detour

6.4.2 Skipped stops versus skipped passengers

Second, when only considering the detouring alternatives, looking at the alternative having the lowest amount of passengers affected corresponds with the detouring alternative having the lowest TGTT in 7 out of 8 cases, whereas looking at the detouring alternatives skipping the least number of stops corresponds with the lowest TGTT in 6 out of 8 cases. The number of passengers affected seems to be a better indicator than the number of skipped stops, which is expected since not every stop is as important as others.

The mismatches all occurred for the disruption location B, where Detour 12 is the alternative having the least skipped stops for both dayparts, and the least number of affected passengers in the rest-of-day. It has a very much longer trip time than the alternative with the lowest TGTT (Detour 1), while the stops last stop it serves upstream and the first stop it serves downstream, are also considered out of reasonable walking distance of some major stops. This indicates that it is important not only to look at

the number of passengers directly affected, but also to the major stops that are skipped and are not within walking distance, as well as the increased trip time of a detour.

6.4.3 Current disruption management protocols

Third, comparing the outcomes with the disruption management protocols, it indicates that current disruption management protocols are mainly driven from a resource perspective. Only for disruption location B in the rest-of-day the disruption management protocol entails the alternative leading to the lowest TGTT according to the model. For disruption location B for rest-of-day passenger demand levels this is probably due to the fact that the alternative proposed in the protocol is best (according to the model) from both considered perspectives. Table 6.10 presents the potential in TGTT savings, by comparing the alternative with the lowest extra TGTT with the extra TGTT incurred by the protocol.

Table 6.10: Potential savings in extra TGTT.

	Potential savings in extra TGTT (morning-peak)	Potential savings in extra TGTT (rest-of-day)
Location A	49%	39%
Location B	13%	0%
Location C	41%	41%
Location D	85%	73%

All disruption management protocols are part of the Pareto-front; this means that other alternatives are not better on both the passenger perspective and the resource perspective. Another important aspect to note again is that by not implementing the alternative with the lowest TGTT, this does not necessarily mean that it is not the best alternative for the total of passengers. It only says something regarding passengers on this disrupted line, in the considered direction. An alternative having the lowest TGTT but also having a high resource delay might be worse for the total of passengers if the resources are scheduled thereafter, the delay cannot be compensated by buffer time and the resources cannot be replaced by spare resources.

6.4.4 Current practice

Fourth, looking at the actual disruption it showed that the disruption management protocols are not implemented necessarily exactly as they are stated. The author experienced one other major disruption from within the traffic control centre and for this disruption it also showed that actual response differed a bit from the protocol. This is perceived to be due to the fact that traffic controllers take into account the actual situation, such as time of day and the corresponding passenger demand levels, but also because traffic controllers do not have a clear overview regarding the different alternatives and their corresponding consequences for the passenger- and resource perspective.

As for the considered actual disruption on July 15th 2016, it showed that three alternatives were proposed by the model, of which two were approximately similar from both perspectives. The actually implemented measure was a combination of these two alternatives. This is not to be recommended, since in communication with the passengers only one alternative is communicated. Therefore, the merits of combining two alternatives are relatively limited, while the disadvantage remain equal. For this actual

disruption the alternative with the higher resource delay would be recommended, since for the corresponding resource schedules the extra resource delay could be compensated.

6.4.5 Willingness-to-walk

Fifth, for (at least) one case (disruption location B for morning-peak demand levels), the outcomes showed to be sensitive to the used willingness-to-walk variable of passengers. Short-turning showed to be more sensitive than detouring, which makes sense since more passengers have to walk some part for the short-turning alternatives. It is not expected that the willingness-to-walk has an effect on the outcomes of the other cases. Further research is recommended regarding the willingness-to-walk of passengers during disruptions. Furthermore, the willingness-to-walk variable is not expected to be fixed; it is expected to depend on many factors, two major aspects being current weather and the current time of day. These are aspects to be taken into account by the traffic controller.

6.4.6 Threshold values alternative generation

Sixth, Detour 2 and Detour 3 are not part of the Pareto-front for any of the considered cases. This shows that there is always a better alternative available from both the passenger perspective as well as the resource perspective, according to this model. Looking at their characteristics and the used threshold values in generating the alternatives, it shows that especially Detour 2 leads to more directly affected passengers than all the other alternatives. This indicates that the used threshold value for passengers affected might be somewhat too high.

6.4.7 Effect of model limitations

Finally, another characteristic of both detours resulting in a relatively high extra TGTT is the fact that both detours have some major important stops out of walking distance, leading to relatively large share of skipped waiting and denied boarding. However, at least one major stop (Centrum) is reachable using other lines, making the outcomes of these detours somewhat overestimated in terms of TGTT. But, looking at the results of the other trip elements it is not expected to have an influence on the outcomes.

7

Conclusions and recommendations

In this final chapter, the main findings and conclusions of this research will be presented. Furthermore, the scientific contribution of this research will be considered, and the research questions as defined in chapter 1 will be answered. The implications of the research in practice will be discussed, followed by concrete recommendations towards HTM based on the findings of the research and the applicability of the framework at HTM. Finally, recommendations will be provided for improvement of the developed methodology.

7.1 Findings and conclusions

In this study a generic framework was developed for public transport operators to use in managing unplanned disruptions from a passenger perspective in rail-bound urban public transport. The main research question was formulated as follows:

How can disrupted operations in rail-bound urban public transport systems be managed, in order to minimize total generalized passenger travel time, taking into account operational consequences?

Although the study is conducted at the public transport operator of The Hague, HTM, the goal was to provide a framework that is generically applicable. In order to do so, a model was developed in order to generate different alternatives, followed by a model to assess these alternatives from a passenger as well as a resource perspective. Different hypothetical disruptions as well as one actual disruption have been handled using the developed framework, in order to test and demonstrate the framework, as well as to determine the different alternatives available for these specific disruptions and their assessment from a passenger perspective and a resource perspective. Finally, some general guidelines are retrieved, indicating important aspects to take into account when managing unplanned disruptions.

Concluding, the various case studies conducted demonstrate that the developed framework can provide public transport operators with different alternatives for managing disruptions, as well as an indication of their effects on the passenger perspective on the one hand and the resource perspective on the other. It showed that by taking the passenger perspective into account explicitly (something which is generally underexposed in the management of disruptions) using an estimation of the passenger demand levels, an estimation of the passengers' impact of the different alternatives available can be provided, in relation

to no disruption and also in relation to the other alternatives available. It also showed that the outcome of the alternative leading to the lowest total generalized passenger travel time on the disrupted line can be dependent on the passenger demand level.

Concrete, the case studies showed that short-turning is beneficial only if short-turning does remain serving relatively important stops which are not served by detouring. Dependent on the relative importance of stops being served by the short-turning alternative and being skipped by the detouring alternative, the walking distance between the two ends of the short-turning alternative can vary.

In general, when only considering detouring, the number of passengers affected directly is a better indicator than the number of stops skipped. Directly affected passengers are defined as passenger which have their origin and/or destination stop skipped. The number of passengers affected is however not always the applicable guideline. There is a trade-off to be made between number of passengers affected and the extra trip time of the detour. The results also showed that for some cases not only the number of directly affected passengers is of influence, but rather the number of affected passengers outside of walking distance to a stop that is served.

Currently used disruption management protocols show that current practice is mainly driven from a resource perspective. This is perceived to be due to the fact that by minimizing the resource delay the management of disruption is less complex. Less rescheduling of vehicles and personnel is needed and effects on other activities is minimized. Besides that, it is also perceived to be due to a lack of information available for the traffic controllers to use. Currently, no explicit and quantitative information is available regarding the different alternatives available for traffic controllers to use.

Comparing the protocols with the alternatives having the lowest TGTT, it shows that when only considering the passenger perspective of passengers on the disrupted line, a huge potential for TGTT savings exists (up to 85% in the considered disruption scenarios). This does not mean that implementing the alternative with the lowest TGTT yields the stated potential savings in TGTT overall, but it does show that different alternatives are available, yielding less TGTT for passengers on the disrupted line. It is up to the traffic controller to weigh up these potential TGTT savings for passengers on the disrupted line against the consequences from the resource perspective.

7.2 Research contribution

This framework aims to provide in a systematic approach in handling unplanned disruption in rail-bound urban public transport by taking the passenger perspective explicitly into account, while also taking note of the operational consequences of alternatives. Although certain aspects can be found in earlier research, this comprehensive approach was not found in the available literature.

By taking into account the passenger demand levels explicitly, the framework showed that alternatives are available in the management of disruption which yield a considerably lower TGTT for passengers on the disrupted line (in the considered direction) as compared to the disruption management protocols available, which seem to be mainly driven from a resource perspective. For one of the considered

disruption scenarios in this research, the potential savings in extra TGTT by implementing a different alternative than the protocol for passengers on the disrupted line was up to 85%. Besides a framework to generate and assess different alternatives available in the management of disruptions, some general guidelines have been defined regarding the two considered measures, detouring and short-turning.

Relating back to the research questions, the framework developed provides with a model to generate different detouring and short-turning alternatives, which is universally applicable. To do so, the k -shortest path algorithm is used to define different detouring possibilities, which are reduced to detouring alternatives using filters for the travel time and affected passengers, as well the principle of dominant alternatives and the capacity of the network.

In order to assess the different alternatives, an estimation of the passenger demand is made using historical smartcard data and assumption have been made regarding the behaviour of passengers during disruptions. The two main assumptions are:

- Passengers for which their original boarding stop and/or alighting stop is not skipped by the alternative, remain using that stop.
- Passengers for which their original boarding stop and/or alighting stop is skipped, will either walk directly to their destination, walk to another stop that is being served, or will wait until the disruption is over and service is resumed. The choice whether to walk or to wait is represented by a (given) probability distribution function depending on the walking distance.

All alternatives are then being assessed from the passenger perspective by their total generalized passenger travel time, which exists of the weighted total waiting time, weighted total in-vehicle time, weighted total walking time, and weighted total transfers. A distinction has been made between regular waiting time and waiting time after a denied boarding due to crowding, and has been taken into account according to available literature (Börjesson & Eliasson, 2014).

The resource perspective of the different alternatives is assessed by the delay of arrival at the destination terminal that is incurred by the different detours. Depending on the buffer time present in the schedules and the subsequent activities, the severity of this delay can be assessed. Since there is a wide variety in scheduled buffer times possible as well as a lot of different subsequent activities, the resource perspective has not been defined further. It is perceived to be very complex to assess the different alternatives from the resource perspective more thoroughly in a generic applicable manner, without leading to results very limitedly applicable.

The final research question relates to which factors should be taken into account in the management of disruptions. Two measures have been considered in this research, namely detouring and short-turning. Using the framework developed, an estimation of the incurred extra TGTT of all alternatives can be made. Based on the case studies conducted using the developed framework, three variables have been derived being of main importance in deciding upon either detouring on the one hand or short-turning on the other. The first two variables have explicitly been discussed during this research, the third one follows logically from the comparison between detouring and short-turning. The three variables are:

- Ratio of passengers favoured by detouring versus passengers favoured by short-turning
- Walking time between short-turning stops
- Extra trip time due to detour

Figure 7.1 presents the location of the different stops in relation the detouring alternative (arc) and the short-turning alternative (dashes).

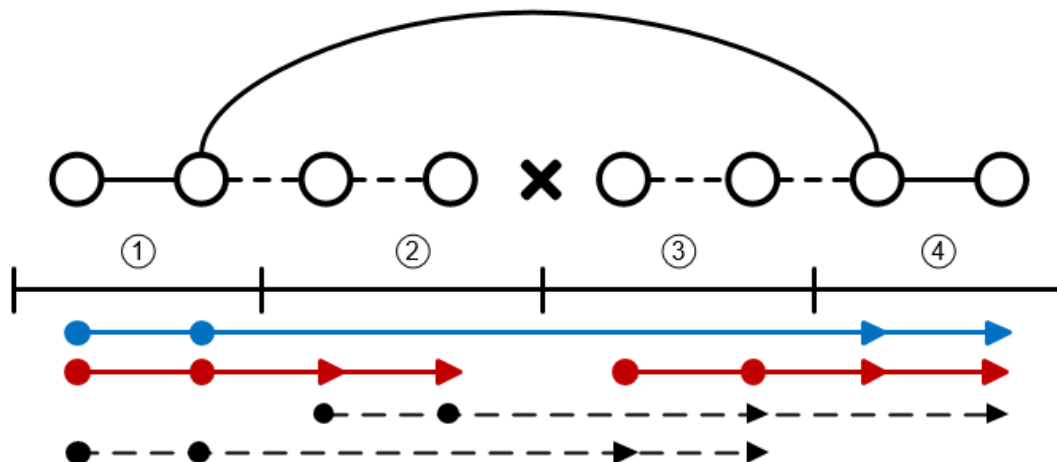


Figure 7.1: Different stops in relation to detouring and short-turning, and the favourable alternative depending on the OD-relation (blue = detour, red = short-turn, black = depending on distance).

Passengers generally favoured by a detouring alternative are passengers having their origin upstream of the disruption, before the detouring alternative differs from the original route, and have their destination downstream of the disruption, after the alternative has re-joined the original route. So, detouring is generally favourable for passengers travelling from stops in group 1 to stops in group 4 (blue OD-relation in Figure 7.1).

Short-turning is favourable for passenger destined for stops in group 2, as well as for passengers originating from stops in group 3 (red OD-relation in Figure 7.1). For passengers originating from stops in group 2, whether the detouring alternative or the short-turning alternative is favourable depends on the walking distance to the last stop served by the detour; the longer the walking distance to this stop, the more favourable short-turning becomes. The same applies for passengers destined for stops in group 3; the larger the distance to the first stop served downstream of the disruption by the detour alternative, the more favourable short-turning becomes (black OD-relation in Figure 7.1).

For passengers travelling outside of the disrupted area, so travelling between stops within group 1 or within group 4, there is no difference in passenger impact between the two alternatives, assuming an equal frequency. For passengers in group 4 however, the arrival time of vehicles at stops might differ compared to the planned arrival time, depending on the detour time. If passengers arrive at random, this has no effect. Furthermore, in case of detouring, passengers might have a longer waiting time (and a more crowded vehicle) for the first detoured vehicle if the detour time is longer than the original route.

Besides the number of passengers favoured by short-turning and the number of passenger favoured by detouring, the impact of short-turning and detouring also needs to be taken into account. If the walking

distance between the short-turning stops is short, the ratio of passengers favoured by short-turning and passengers favoured by detouring can be smaller.

Of course, these are not all the factors of influence. Others are for instance the walking distance to the stops served, the willingness-to-walk and the detour length. For some detours, short-turning always yields a lower TGTT than detouring. This occurs when the detour is longer than the weighted travel time needed to cross the disrupted area (thus the transfer penalty, weighted walking time, weighted waiting time).

Based on the main factors of influence in the decision between detouring and short-turning found in this research, a decision-tree has been constructed which gives a general indication of the favourable alternative (from the passenger perspective), based on the values of these variables. The decision-tree is illustrated in Figure 7.2.

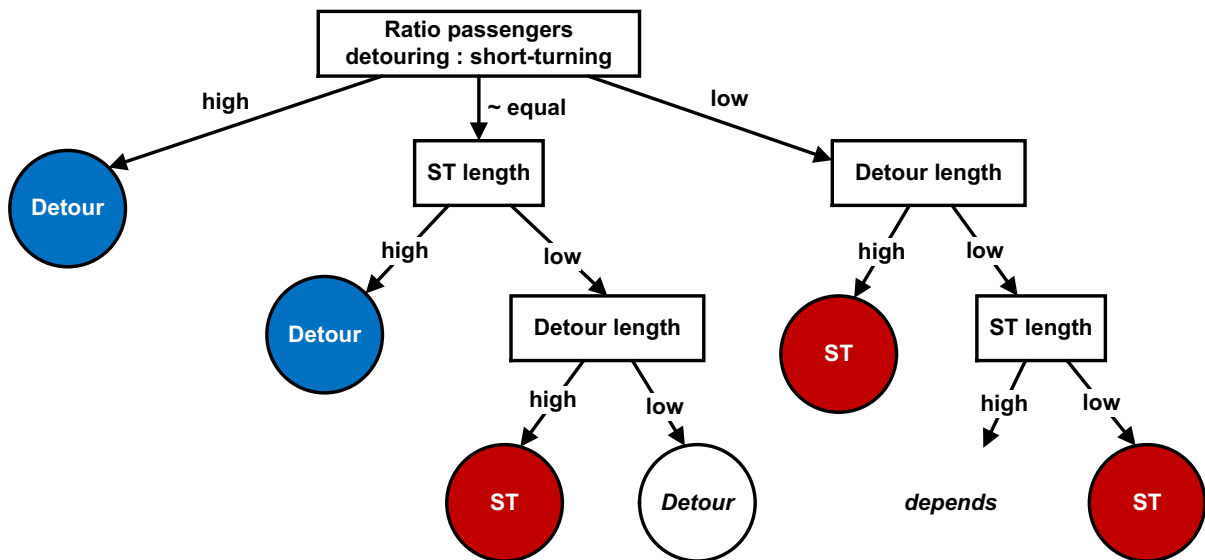


Figure 7.2: Decision-tree indicating favourable alternative (from a passenger perspective).

The ratio passengers detouring : short turning depicts the number of passengers favoured by detouring as compared to the number of passengers favoured by short-turning. No case has been found in this research with an approximately equal amount of passengers favoured by detouring as short-turning, and also having a low walking time between short-turning stops and a low detour time. However, it is expected that detouring would be the favourable alternative in this case, since in general a short-turn with a low walking distance has a higher impact on passengers than a short detour.

As for the case with many passengers favoured by short-turning, but a low detour length and a high walking time between short-turning stops, no general indication can be provided regarding the favourable alternative.

7.3 Practical implications

The goal of this research was to provide a framework which can be used by operators in managing unplanned disruption in rail-bound urban public transport. In this paragraph the practical implication of the framework is discussed. The framework is perceived to be suitable for the following aspects:

- As an additional support to traffic controllers by providing them with an assessment from different perspectives of different alternatives available, in order for them to make a well-informed decision.
- Only for disruptions for which passengers do not have an obvious alternative passenger route available.
- For disruptions with a limited duration, but long enough for an alternative to be implemented.
- Suitable to be used for strategic / tactical planning, but also in real-time.

The conducted case studies used in demonstrating the framework show that it is able to provide with the different alternatives available as well as an assessment of the different alternatives, from a passenger perspective as well as resource perspective. However, the assessment of alternatives is only given for the effects on the disrupted line. Especially the resource perspective of the alternatives is expected to have influence on the operation on other lines. The framework therefore cannot provide in 'the' optimal solution. It is still for the traffic controller to decide upon which alternative to implement, based on the current situation. Even when the framework provides an alternative which has the lowest TGTT and the lowest resource delay (forming a Pareto-point), there might still be plenty of other reasons (for instance capacity of the network) for a traffic controller to decide upon a different alternative. What this framework can provide in is presenting the different alternatives available to the traffic controller and their passenger impact for the disrupted line and resource delay, in order to assist the traffic controller in the decision-making process and supporting him / her in making a well-informed decision.

This framework makes use of historic passenger demand data of the disrupted line. Depending on the availability of alternative passenger routes, this passenger data varies in its accuracy. Using historic demand data is expected to represent actual passenger demand more in case of disruptions if there are no or limited suited alternative passenger routes available, and less if they are available. This limitation of being suited for a disrupted line with no real alternative available was taken into account when deciding upon the different case studies.

A similar aspect accounts for the duration of the disruption. Even if there are no clear alternative passenger routes available, if it is a long-lasting disruption it is expected passengers have prior knowledge and will make different trip- and/or route choices. Therefore the framework is considered to be suitable for relatively short disruption, but long enough for an alternative to be implemented (approximately 30 minutes to 2 hours).

In the case studies used to demonstrate the framework a usage of uni-directional vehicles was assumed. In determining the short-turning possibilities this led to a limited set of alternatives available as compared to using bi-directional vehicles. In the future (2022), it is expected that all vehicles of HTM will be bi-

directional. The short-turning possibilities will then increase, always being able to short-turn between (the last stop) upstream of the disruption to (the last stop) downstream of the disruption. This does give rise to other issues, such as driving on the wrong-side of track, safety issues when not boarding/alighting at a stop and challenges in for instance transfer synchronization. This framework in its current form is already suited for this increase in short-turn alternatives since the short-turn alternatives depend on model input.

This framework consists of two models, one for generating alternatives and one for assessing the alternatives from a passenger perspective. The running time of the alternative generation model was around 25 minutes on a regular laptop for the tram network of The Hague. Even though it is expected to be possible for the model to be set up in a more efficient manner, leading to lower running times, it is still not expected for the alternative generation model to be able to be used in real-time. This does not necessarily pose an issue however, since the set of alternatives is not likely to change over time for one and the same disruption location. Alternatives can therefore be generated in advance. Besides, alternatives can also be generated using very different methods. One of the most logical is to use the experience of a traffic controller in defining different alternatives. It is however advised also to use the developed model in order not to miss alternatives.

As for the assessment of alternatives, the running times for the considered disruptions turned out to be 12 seconds using a regular laptop for four replications. This makes it very suitable for implementation in real-time operations.

Besides usage in real-time operations, the framework can also be used on the strategic and tactical planning level. With the framework, the merits of for instance adding an extra short-turning location, switch or shortcut can be estimated, as is shown in 6.1.3. Furthermore, it can be used to assess the robustness of the scheduling process, for instance to see some effects of incorporating additional slack time in vehicle- and crew schedules.

The framework was developed focused on rail-bound urban public transport networks. It is perceived to be less suited for road-bound urban public transport networks, due to a massive increase of infrastructure availability and the corresponding increase of different alternatives. However, because of this increase of infrastructure availability compared to rail-bound networks, the issue of disruptions in road-bound urban public transport is perceived to be less severe.

Looking at heavy-rail public transport networks, the framework seems less suited for large scale networks such as national railways. Line spacing as well as stop spacing on a national scale is not comparable to line- and stop spacing on urban scale, and since this framework explicitly takes into account the possibility of passengers walking to stops served, the framework seems less suited for managing disruptions on large scale heavy-rail networks.

As for heavy-rail networks in an urban context, such as metro, the framework is perceived to be partially applicable. Passengers walking to different stops might still be an option, as well as the short-turning alternative. Detouring alternatives are less easy to implement, due to more stringent infrastructure and

safety constraints. On the other hand, single-track operations and relating trip cancellations are alternatives more often seen in disruption management of metro operations. This relates more to an extension of the alternative generation model than to the alternative assessment model.

7.4 Recommendations for HTM

7.4.1 Research findings

Comparing the currently used disruption management protocols with the outcomes of the case studies showed that current practice is mainly driven from a resource perspective. Using this framework, it is possible to provide traffic controllers with more information regarding the different alternatives available, in order for them to make a better-informed decision.

The results showed that different passenger demand levels are of influence on the passenger impact of the different alternatives on the disrupted line. These differences in passenger demand level are already taken into account implicitly by the traffic controllers, but it is advised also to consider it structurally in constructing the disruption management protocol. In case of an unplanned disruption, traffic controllers are already confronted with a high workload, and by structurally considering the different passenger demand levels they are not confronted with an even higher workload.

Furthermore, it is advised not to combine different alternatives in case of a disruption, when only one alternative can be communicated to the passengers. If only one alternative is communicated to the passengers, they do not take the other alternative into account while making their route-choice, resulting in the merits of combining the alternatives being very limited. This may seem obvious, but the analysis of the actual disruption showed that two alternatives were implemented while only one was communicated.

The data registration of data in case of unplanned disruptions is also something worth to look into for HTM. For the actual disruption, the data registered from both smartcard as well as automated vehicle location data turned out to be corrupted. This data might be useful in analysing disruptions and therefore it is recommended towards HTM to improve the data registration in case of unplanned disruptions.

Finally, the terms and conditions determined for the new concession are definitely something to take into account in the management of disruptions. In these terms and conditions, a cancelled trip is defined as a vehicle which does not arrive at its destination terminal. Having too many cancelled trips is being penalized, and in this context short-turning leads to being a far less attractive alternative than detouring. Assuming the client (MRDH) and HTM both have the passenger perspective at a high priority, these terms might be worth discussing.

7.4.2 Applicability framework at HTM

The applicability of the developed framework is perceived to be mainly of use in the passenger transportation management process of HTM, and secondary in the planning process of passenger transportation of HTM (see Figure 7.3).

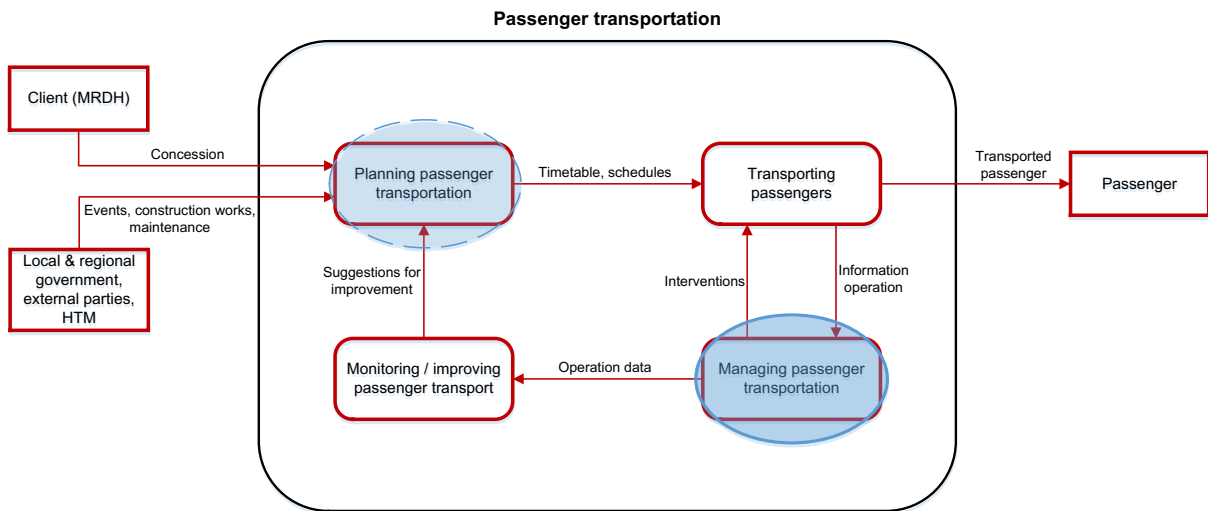


Figure 7.3: Applicability of framework in the passenger transportation process at HTM (Maas, 2016).

In the planning process, the benefits during unplanned disruptions of adding additional slack time in the vehicle- and crew schedules can be assessed. This can be of help in assessing and improving the robustness of the operations. So, instead of the improvements regarding additional slack time loops back to the planning process via the monitoring of passenger transportation, the benefits can be assessed proactively beforehand. Furthermore, the benefits during unplanned disruptions of adding additional infrastructure (extra arcs, short-turn possibilities) can be evaluated using this framework.

However, since both these benefits only apply for unplanned disruptions, the applicability of the framework is perceived to be limited for usage during the planning process, and more of use during the real-time management of passenger transportation, and specifically the management of operations (Figure 7.4).

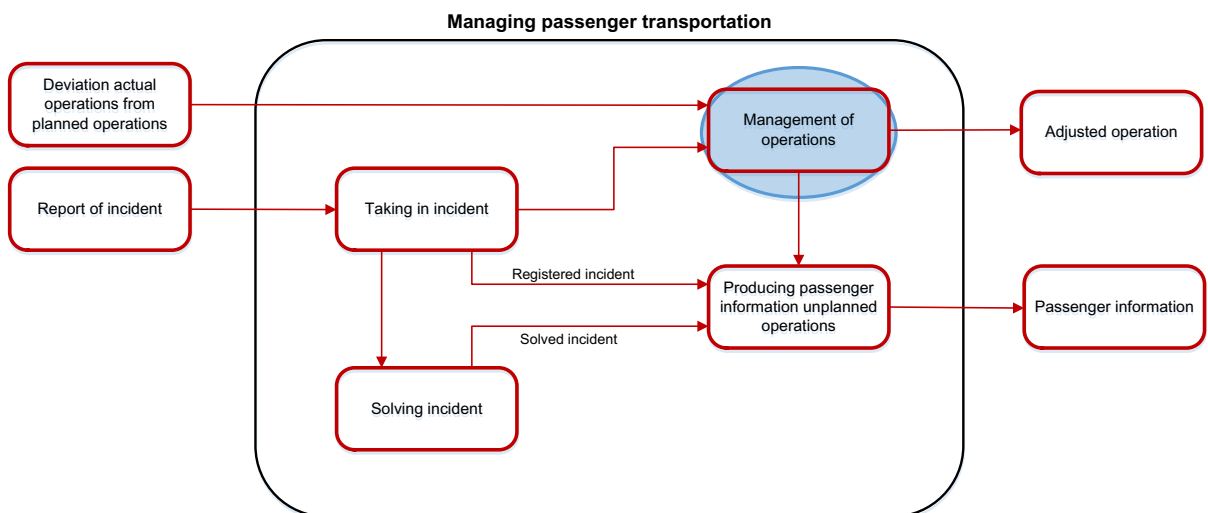


Figure 7.4: Applicability of framework within the process of managing passenger transportation (Maas, 2016).

The management of operations is conducted by the traffic controllers in the traffic control centre. Based on a deviation of actual operations as compared to the planned operation and/or a registered incident,

the traffic controllers decide upon an measure or intervention, using the protocols and resources available, after which the measure is implemented and communicated to the passengers (Figure 7.5).

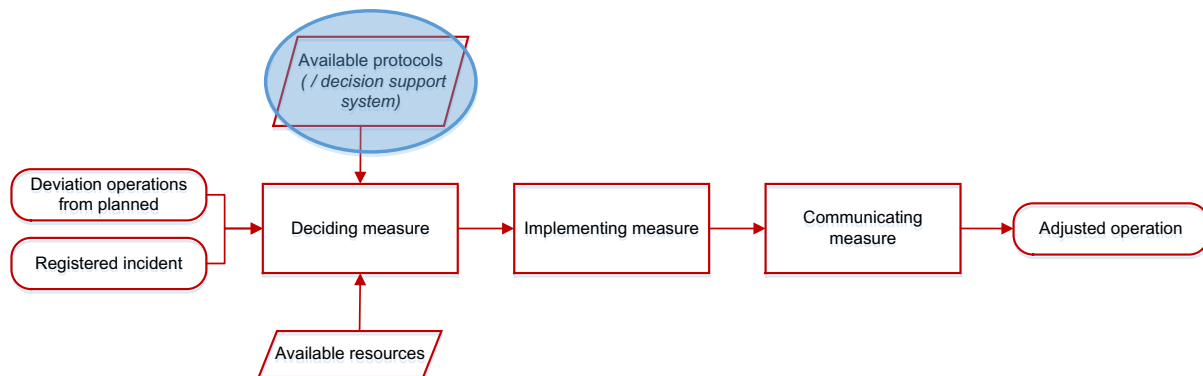


Figure 7.5: Applicability framework in management of operations process (Maas, 2016).

The main applicability of the developed framework is in constructing input for the traffic controllers in order to support them in deciding upon measures in the management of disruptions. In the current situation, this input consists of static pre-defined disruption management protocols, advising the traffic controllers which measure to implement in case of a disruption.

These protocols are currently constructed based on gut feeling and experience by one of the employees. With this framework, the different alternatives available for all protocols can be assessed in a systematic manner, to have more well-considered protocols. By varying the passenger demand levels, protocols for a specific location can also vary for different passenger demand levels, such as morning-peak and rest-of-day as considered in this research, or seasonal effects as a winter protocol and a summer protocol.

In support of implementing this framework in a tool by HTM, Appendix D(p.VI) presents the used input, in form of the input matrices needed for the network data as well as the data preparation conducted for the passenger demand data.

7.4.3 Decision support system

By using disruption management protocols, there will always be a delay between the construction of these protocols and the actual implementation. The current disruption management protocols are updated a few times per year, leading to delays up to a couple of months. For short-notice unavailability of infrastructure the protocols will not be altered, not to mention actual locations of vehicles. To remove the delay between the construction of the protocols and the actual implementation, the developed framework can be incorporated in a decision support system (DSS). Such a DSS is basically a simulation model as used in this research, which assesses different alternatives based on the real-time conditions.

If the vehicle- and crew schedules are incorporated in the DSS, then the resource perspective of the different alternatives can also be assessed in a more thorough manner than has been done in this research. For instance, based on the current locations of vehicles and personnel as well as their schedules, the future location of vehicle and personnel can be forecasted for different alternatives,

resulting in a list of the delays of each specific vehicle and driver. In this case, the resource perspective of the different alternatives gets more value for the traffic controllers. Based on the severity of the delay and for instance the ease of rescheduling different resources, a better consideration can be made between the passenger perspective and the resource perspective. Another aspect that could be implemented in the DSS is the effect of different alternatives on the KPI's, such as the number of cancelled trips, as set by the client (MRDH). It is still up to the traffic controller to decide upon the measure to incorporate, based on the assessment of the alternatives on the different aspects.

Note that the framework in its current form is not suitable for usage for all locations throughout the HTM rail network, and neither is it for relatively long lasting disruptions. This is due to the fact that historical passenger demand data is used, and this is assumed not to change. How to address this limitation in order to make it suitable for all locations in the network as well as longer lasting disruptions will be discussed in §7.5.

Figure 7.6 presents the additional inputs and outputs for the alternative assessment model for the discussed extensions.

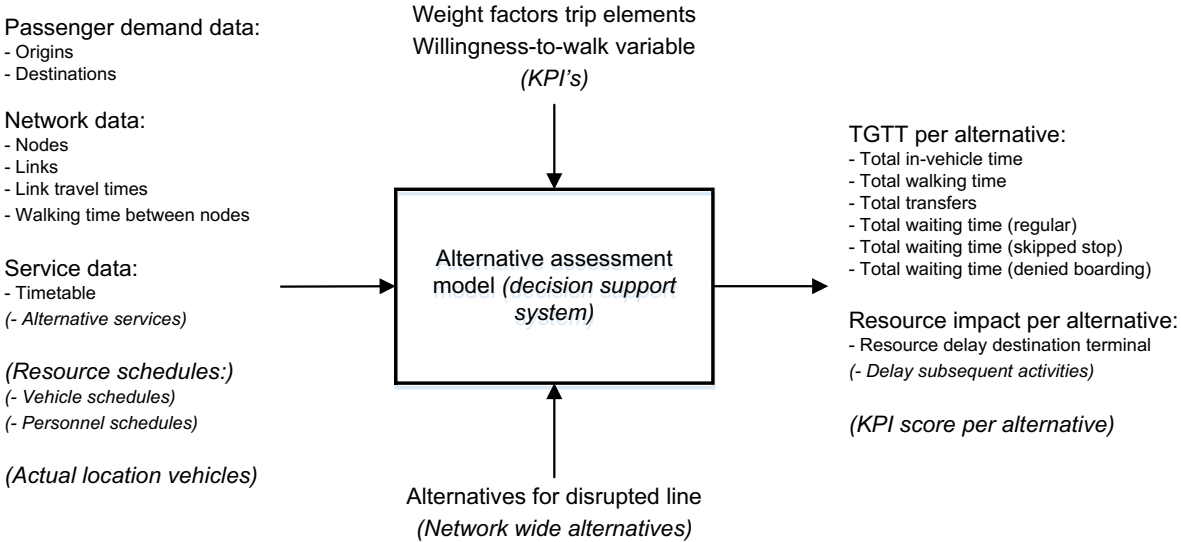


Figure 7.6: Additional inputs and outputs for the alternative assessment model and the discussed extensions.

7.5 Further research

Many of the limitations of the presented framework have already been discussed. In this paragraph they are collected and shortly discussed, along with recommendations for further research.

7.5.1 Network effects

The main limitation of this framework is that it does not take into account network effects. Other passenger route alternatives are neglected and historical passenger demand data of undisrupted operation is used. However, if actual passenger demand data for disrupted operations is available, this can be used without a problem since the passenger demand data is used as model input.

An estimation of the passenger demand data in case of a disruption with alternative passenger routes available can be made if the framework was to be extended with a passenger route choice model. This can for instance be done by a multinomial-logit model based on random utility maximization, where certain characteristics of the different alternative route choices available define the utility of that alternative. With this the share of passengers using the disrupted line, given an alternative, can be determined.

Another aspect of only considering the disrupted line is the capacity of the network. In the applied case studies, only one line was considered disrupted and the capacity of the network did not show to be an issue. However, if a track is disrupted it is likely that also other lines will be disrupted and need to be managed. Then the capacity of the network can turn out to be of issue, if the different disrupted lines all use the same detour for instance. It would then be of interest to look into a network-wide assessment of different alternatives available rather than assessing the disrupted lines individually. It would be possible doing so using the developed framework, when alternatives entail measures for all different disrupted lines. It is expected that cancellation of trips might be of more interest in that case.

This research only considered detouring to be possible between two stops on the disrupted line, without intermediate stops in between. However, in reality passengers alighting along the detour at stops of other lines is a possibility. This can be taken into account in the model by not only modelling the detour but also all stops that it passes along the way. For these stops, the walking distance to the skipped destination stop has to be determined to find the closest. So instead of choosing either the last stop upstream of the disruption or the first stop downstream of the disruption as the alighting stop for passenger with a skipped destination stop in case of a detour, all stops along the detour should be considered as well.

An even better generation and analysis of different alternatives could be made if not the origin stop and destination stop was taken into account, but the actual origins and destinations of passengers. This kind of data could for instance be derived from travel information planners, but is not expected to be available in this context in short-notice.

7.5.2 Travellers perceptions

The outcome of the model showed to be sensitive to the used willingness-to-walk of passengers. The willingness-to-walk of passengers in case of disruptions is still a much unexplored field in literature, partly because of its dependence on a variety of factors, such as different alternatives available but also more trivial aspects such as current weather. The willingness-to-walk variable is not expected to be fixed, and should therefore be taken into account by the traffic controller. Further research is needed on this aspect.

In-vehicle crowding has not been taken into account explicitly in this research. There is some research available regarding the perception of passengers for different crowding levels (Wardman & Whelan, 2011). The reason not to take it into account explicitly is because in this research only one line is considered. If it was to be taken into account explicitly, alternatives leading to more crowded vehicles in reality on other lines would then be underestimated compared to alternatives leading to more crowded vehicles on the disrupted line.

Furthermore, the effect of some passengers being more affected than others (or the equity of the alternative' effects) has not been considered explicitly. For instance, the waiting time for passengers who opt to wait according to the model until service is resumed because their skip is being stopped by an alternative, is equally weighted as the regular waiting time. This might not stroke completely with reality and is prone for further research. In general, the equity of an alternative could be assessed if not only the extra TGTT of an alternative would be presented, but also the distribution of passenger impact categorized by severity (e.g. to see if many passengers are impacted a little or few passengers are heavily impacted).

7.5.3 Expanding the framework

Two measures have been considered in this research. In reality, there are a lot of other possible measures to be implemented by the traffic controllers, such as for instance skipping stops, or combining different alternatives. The actual disruption showed that combining different alternatives is something that is conducted by traffic controllers. A very important aspect in disruption management in general but especially in combining different alternatives is the communication towards the passengers. It is expected that combining different alternatives can lead to a lower passenger impact, given that passengers have full information regarding the alternatives implemented so they can take it into account in their route choice. This is a very important aspect in the management of disruptions and suitable for further research.

The running time of the alternative generation model was quite high (around 20 minutes), making it unsuitable for usage in real time. As has been discussed previously, this does not have to pose major problems, since alternatives can be generated beforehand or differently, for instance by relying on expert opinion. However, there are other generation methods available in literature than the used k -shortest path algorithm, which might yield shorter running times and could possibly make it suitable for usage in real-time. Examples are for instance using ant-colony optimisation (Lucic & Teodorović, 2002), simulated annealing algorithms (Fan & Machemehl, 2006), genetic algorithms (Pattnaik, Mohan, & Tom, 1998) or branch and bound (Prato & Bekhor, 2006).

Finally, something that has been discussed before is the probable future implementation of bi-directional vehicles only. With these vehicles, short-turning is available at far more locations, in theory up until the disruption itself. It also gives a lot of challenges needing further research, such as handling with driving on the wrong side of track, safety issues which arise when not stopping at stops but also challenges in terms of transfer synchronization in order not to cause extra waiting time for the passengers. A feature that might be of support in this context, however probably less suitable for the disruption durations considered in this research, is the use of Californian switches. These are moveable switches which can be installed in order to act as a temporary switch. These might be of use in order to accommodate single-track operations, an aspect underexposed in tram operations but well known in heavy rail.

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Appendix A Public transport quality factors

Several aspects of public transportation have been defined for its evaluation by Peek & Van Hagen (2002). The basic requirements of public transport are its safety and reliability. Without a minimum amount of these two factors, passengers will not opt for public transport to use. Another important factor is the speed. If the total travel time of the journey will be excessively long, for instance compared to the same journey by car, only few passengers are expected to opt for public transport. The same counts for the convenience of the public transport journey. These three factors are so called dissatisfiers; they should be sufficient without a doubt. Passengers will be dissatisfied if these are not sufficient and most likely avoid public transport (Van Oort, 2011).

The satisfiers can provide additional quality aspects, which can satisfy the passengers but are not as decisive for passengers as the dissatisfiers are. An important satisfier is the experience of the entire journey as perceived by the passenger, including for instance the waiting times and the transferring of passengers (Van Hagen, Galetzka, & Pruyn, 2007).

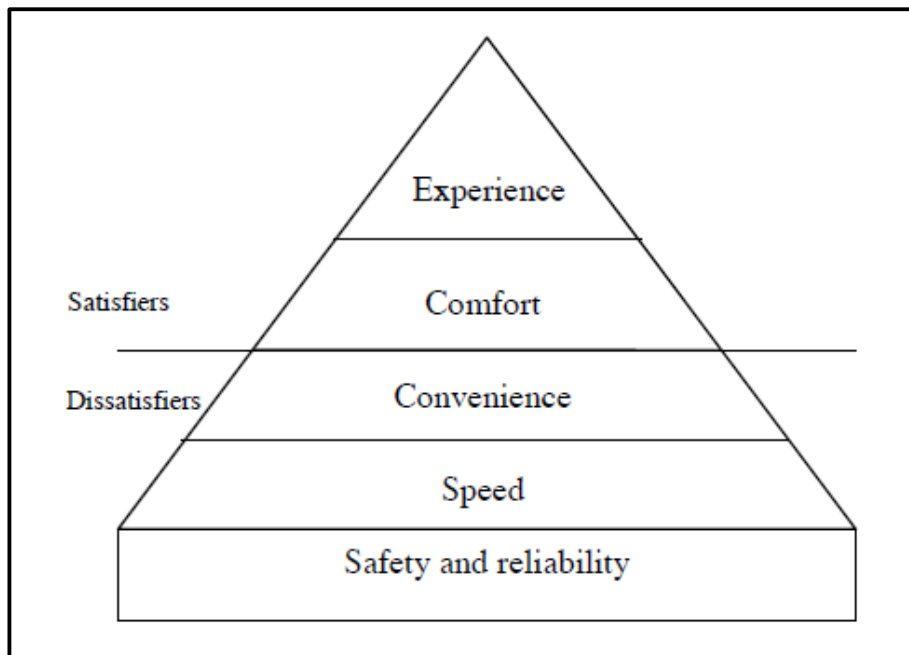


Figure 7.7: Pyramid of Maslow for public transport quality factors (Peek & Van Hagen, 2002).

Appendix B Equations used in determining passenger travel time

If both origin and destination are located upstream or downstream, the passenger travel time is determined the same as in undisrupted operation:

$$t_{i,j,p}^t = t_{i,p}^{wait} + t_{i,j,p}^v \text{ for } i, j \in S_{l,p,q} \text{ or } i, j \in S_{l,p,r}, p \in P_l \quad (\text{B.1})$$

If the origin is located upstream of the disruption, and the destination is a skipped stop, passengers alight the vehicle at the last stop upstream of the disruption, stop $S_{l,p,|q|}$, or the first stop downstream of the disruption, stop S_{l,p,r_1} , and walk to destination stop j from there. The travel time from origin to destination walking from the last stop served upstream of the disruption is then:

$$t_{i,j,p}^t = t_{i,p}^{wait} + t_{i,|q|,p}^v + t_{|q|,j,p}^{walk} \text{ for } i \in S_{l,p,q}, j \in S_{l,p,v}, p \in P_l \quad (\text{B.2})$$

The travel time from origin to destination walking from the first stop served downstream of the disruption is then:

$$t_{i,j,p}^t = t_{i,p}^{wait} + t_{i,r_1,p}^v + t_{r_1,j,p}^{walk} \text{ for } i \in S_{l,p,q}, j \in S_{l,p,v}, p \in P_l \quad (\text{B.3})$$

For an origin located upstream of the disruption and the destination located downstream of the disruption, the travel time composition depends on the alternative. In the case of a detour, the travel time can be calculated as follows:

$$t_{i,j,p}^t = t_{i,p}^{wait} + t_{i,j,p}^v \text{ for } i \in S_{l,p,q}, j \in S_{l,p,r}, p \in P_l \quad (\text{B.4})$$

In the case of short-turning, the travel time can be calculated as follows:

$$t_{i,j,p}^t = t_{i,p}^{wait} + t_{i,|q|,p}^v + t_{|q|,r_1,p}^{walk} + t_{r_1,p}^{wait} + t_{r_1,j,p}^v \text{ for } i \in S_{l,p,q}, j \in S_{l,p,r}, p \in P_l \quad (\text{B.5})$$

For situations where both the origin as well as the destination are being skipped, two possibilities arise. First, the possibility for passengers to directly walk from the origin to the destination:

$$t_{i,j,p}^t = t_{i,j,p}^{walk} \text{ for } i, j \in S_{l,p,v}, p \in P_l \quad (\text{B.6})$$

Secondly, passengers walking from origin to the closest stop being served, which is the last stop downstream being served stop $S_{l,p,|q|}$, boarding there and alighting to the closest stop to their destination, being the first stop being served downstream, stop S_{l,p,r_1} . Which one of the two choices depends on the one with the lowest perceived costs, which has been discussed in the previous section.

$$t_{i,j,p}^t = t_{i,|q|,p}^{walk} + t_{|q|,p}^{wait} + t_{|q|,r_1,p}^v + t_{r_1,j,p}^{walk} \text{ for } i, j \in S_{l,p,v}, p \in P_l \quad (\text{B.7})$$

Lastly, there is the situation where the origin stop is skipped and the destination stop is located upstream of the disruption. The passenger travel time can be determined as follows:

$$t_{i,j,p}^t = t_{i,r_1,p}^{walk} + t_{r_1,p}^{wait} + t_{r_1,j,p}^v \text{ for } i \in S_{l,p,v}, j \in S_{l,p,r}, p \in P_l \quad (\text{B.8})$$

Appendix C Passenger transportation process at HTM

Figure 7.8 illustrates the main process of passenger transportation at HTM. Based on the concession with the client (MRDH), and for instance local and regional governments, and external parties, the passenger transportation is planned, resulting in a timetable for passengers to use, as well as vehicle- and crew schedules. During the actual transportation of passengers, information regarding the actual operation is being used to manage the passenger transportation. This management takes place in the (central) traffic control centre. Based on this information, traffic controllers can intervene in the passenger transportation process, making adjustments compared to the planned operation.

Data regarding the operation and the management of passenger transportation process is also being monitored. Suggestions for structural improvements in the planning process are then taken into account in the planning process. An example of this is for instance if the travel time between two stops are structurally planned too short. Then the suggestion for improvement would be to increase the travel time between these two stops in order to be able to better match the actual operations to the planned operations.

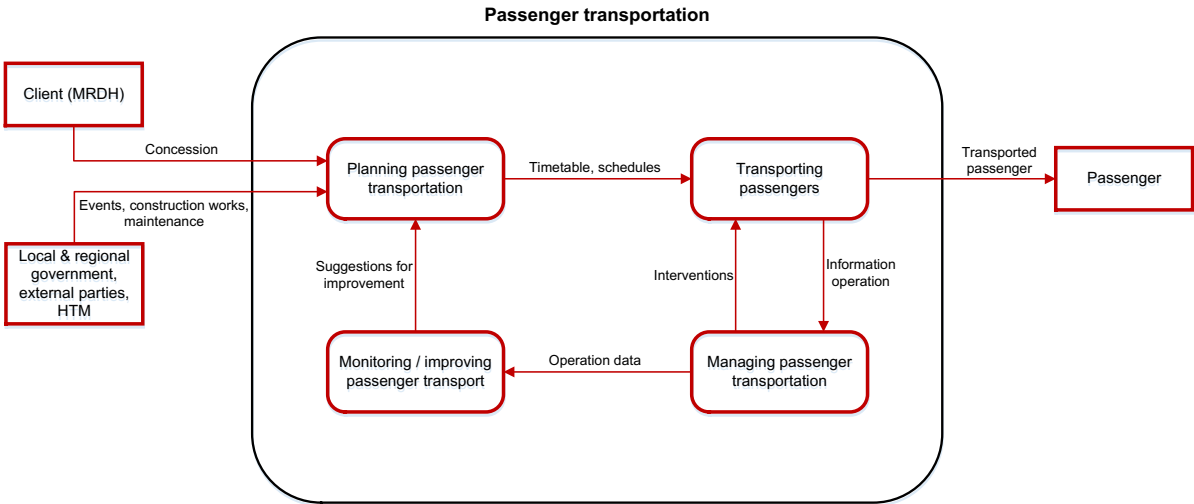


Figure 7.8: Passenger transportation process (Maas, 2016).

Figure 7.9 illustrates the sub-process of the management of passenger transportation. There are two main triggers for managing the current operations, which are a deviation from actual operations to the planned operations or a reported incident. A report of incident can come from all kinds of parties, such as emergency services or local government. Based on the deviation of actual operations compared to the planned operations and/or the reported incident, the operations is being managed. Based on the measures taken, passenger travel information is being adjusted.

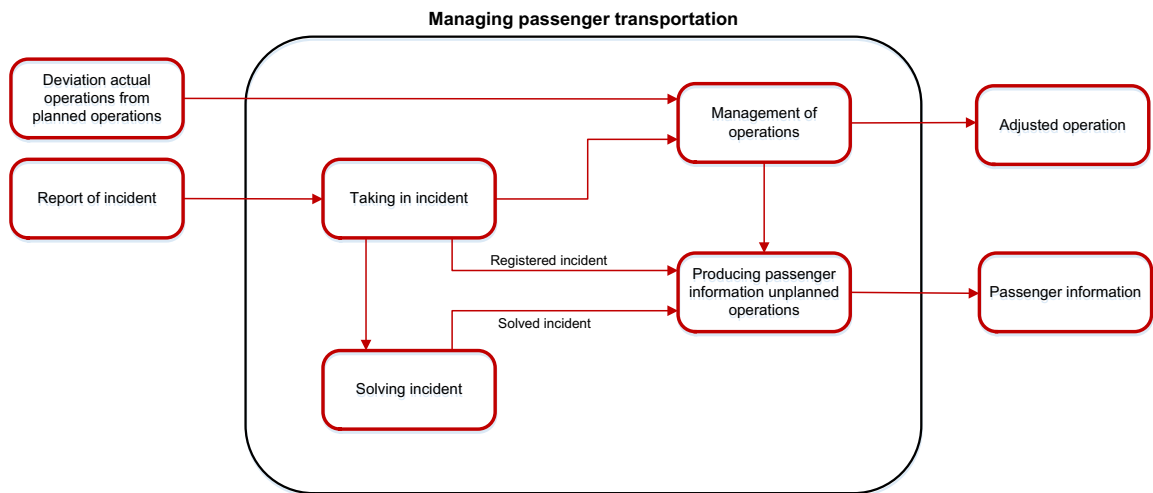


Figure 7.9: Managing passenger transportation sub-process (Maas, 2016).

Appendix D Input and data preparation

Network data

The network data used is the same as is being used by the planning department of HTM for the construction of the timetables. The network data consist of a set of nodes where the nodes represent stops. Links are represented by a source node and a target node and are assigned a cost in the form of travel time. Each stop in each direction is represented by a node, and short-turn possibilities are therefore represented by a link between a stop on the one direction of the line and a stop on the other direction of the line. Three matrices form the input for the network data, which are:

- Matrix defining nodes in the network.
- Matrix defining links in the network, indicating the travel time of a link and its residual capacity.
- Walking time matrix, indicating the walking time between all stops.

Table 7.1 presents an example of a matrix defining different stops as nodes. Note that stops in this context represent a stop in a specific direction.

Table 7.1: Matrix defining nodes in the network.

Stop	Node
Stop 1	1
Stop 2	2
Stop 3	3
Stop 4	4

An example of the input matrix for defining the links is as follows (Table 7.2), representing the link travel time between nodes as well as the residual capacity (in veh/hour) of that link. As can be seen, in this example it is possible to go from node 1 directly to node 3, but not vice versa.

Table 7.2: Fictive travel time matrix between nodes 1 to 4.

Source node	Target node	Travel time	Residual capacity
1	2	1	13
1	3	4	8
2	3	4	2
3	4	2	0
2	1	1	7
3	2	2	8
4	3	2	0

A route over the network is then just represented as a list of links, defined by their source and target node (Table 7.3). The route in this example thus skips node 2.

Table 7.3: Example of route representation.

Source node	Target node
1	3
3	4

The walking time between stops have been determined using Google Maps. The coordinates from the different stops have been retrieved from the planning department. Using the Google Maps Distance Matrix API implemented in a pre-scripted Excel VBA (Analystcave, 2014) the walking distances between all stops on line 1 have been retrieved. An example of the input matrix for the walking times between stops is as follows (Table 7.4):

Table 7.4: Fictive walking time matrix between nodes 1 to 4.

	Node 1	Node 2	Node 3	Node 4
Node 1	0	3	15	21
Node 2	3	0	12	18
Node 3	15	12	0	6
Node 4	21	18	6	0

Note that passengers are assumed to walk to upstream stops as well, hence the complete matrix.

Passenger demand data

The passenger demand data used in this research is derived from historical smartcard data. Some transformation steps have been conducted in order to make the smartcard data usable as input in the simulation model. The passenger demand data consists of two aspects:

- Arrival rate per origin
- Destination probability for each origin

First, an origin-destination (OD) matrix of the considered line for the applicable time period is constructed. In this research this was the average of all working days in September, for the time periods morning-peak (07:00 up to 09:00) and rest-of-day (09:00 up to 16:00). The time periods relate to the check-in time. Then, the OD-matrix of the considered line for the applicable time period is converted to an OD-matrix per hour. An example of an OD-matrix to be used in one direction is as follows (Table 7.5):

Table 7.5: Fictive OD-matrix between nodes 1 to 4.

	Node 1	Node 2	Node 3	Node 4
Node 1	0	74	85	23
Node 2	0	0	12	99
Node 3	0	0	0	54
Node 4	0	0	0	0

In the simulation model, entities (passengers) are generated for each origin stop. Entities are generated using an arrival rate, which depicts the number of arrivals per hour. A non-stationary exponential distribution is used to calculate the rates (SIMIO, 2015). The rate units for the Poisson arrival process is arrivals per hour, which are extracted from the OD-matrix per hour for each origin. An example of an input matrix for the arrival rate per origin is as follows (Table 7.6):

Table 7.6: Fictive arrival rate matrix for nodes 1 to 4.

Origin	Arrival rate (per hour)
Node 1	182
Node 2	111
Node 3	54
Node 4	0

In order to assign the destinations to the generated entities for each origin, the probability for each destination depending on the origin needs to be determined. This is done using the OD-matrix, where the share of each destination for each origin is determined. These shares per destination for an origin are then used as probability of assigning that destination to an entity for that origin. An example of an input matrix for the destination probability for each origin is as follows (Table 7.7):

Table 7.7: Fictive destination probability matrix for nodes 1 to 4.

	Node 1	Node 2	Node 3	Node 4
Node 1	0	40.66%	46.70%	12.64%
Node 2	0	0	10.81%	89.19%
Node 3	0	0	0	100%
Node 4	0	0	0	0

Note that the each stop in each direction is a separate node, and that the OD-matrix used is the OD-matrix in one direction. Therefore, nodes are only assigned as a destination if they are located downstream of the origin node.

Appendix E Disruption location A, Centre of The Hague (99)

Table 7.8 presents the number of passengers favoured by detouring (Kurhaus) and the number of passengers favoured by short-turning (Mauritskade – Scheveningseslag), for location B, Detour 1. In brackets are the number of passengers travelling to stops Javastraat and further, which are also considered to be favoured by short-turning due to the long walking distances to stops that are served by the detour.

Table 7.8: Passengers favoured by detouring versus passengers favoured by short-turning, for morning-peak demand and rest-of-day, per hour (location B, Detour 6).

	Kurhaus	Mauritskade - Scheveningseslag	Ratio passengers detour : short turning
Morning-peak	16	33 (353)	1 : 24.1
Rest-of-day	66	67 (200)	1 : 4.0

Appendix F Disruption location B, Centre of The Hague (207)

Figure 7.10 and Figure 7.11 present the total generalized passenger travel time, distinguished by trip element for the morning-peak and the afternoon, respectively. It can be seen that for the morning-peak demand levels, a lot of denied boarding arise. This is probably due to the fact that a lot of major stops are being skipped these detours, which are also out of walking distance. For rest-of-day passenger demand levels the problem of denied boarding is less severe, since the passenger demand is lower compared to the morning-peak and capacity stays the same.

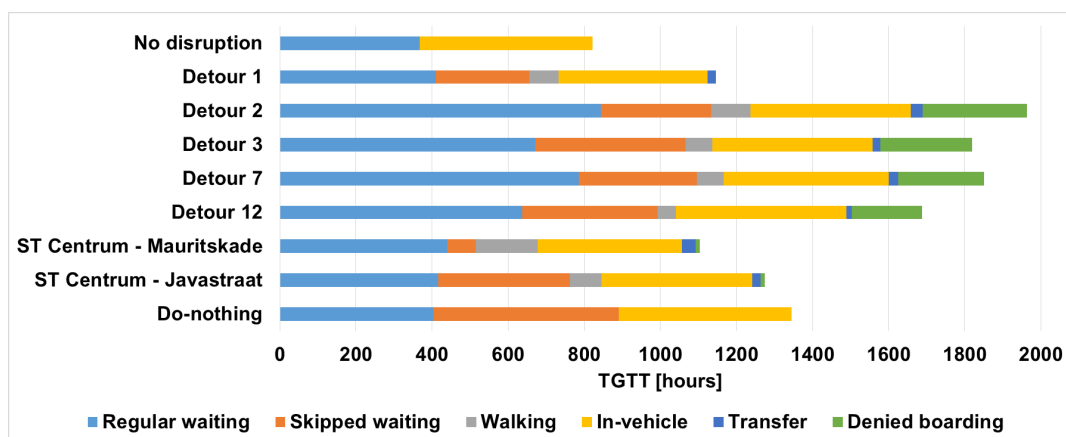


Figure 7.10: Disruption location B - TGTT per alternative, distinguished by trip element (morning-peak).

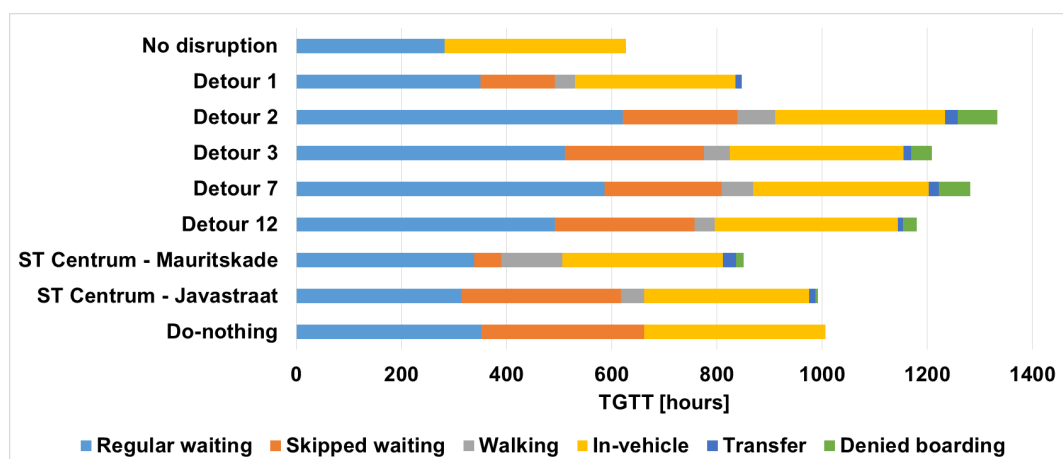


Figure 7.11: Disruption location B - TGTT per alternative, distinguished by trip element (rest-of-day).

Table 7.9 present the amount of passengers travelling from stops Mauritskade and further, which are favoured by short-turning. In brackets are the number of passengers travelling to stops Javastraat and further, which are also considered to be favoured by short-turning due to the long walking distances to stops that are served by the detour. Furthermore, it shows the number of passengers originating prior to or from stop Centrum travelling to stop Kurhaus. They are favoured by the detouring alternative. In

this table Detour 1 is the considered detour alternative, since Detour 1 yields the lowest TGTT of the detour alternatives.

Table 7.9: Passengers favoured by detouring versus passengers favoured by short-turning, for morning-peak demand and rest-of-day, per hour (location B, Detour 1).

	Kurhaus	Mauritskade - Scheveningseslag	Ratio passengers detouring : short- turning
Morning-peak	16	25 (240)	1 : 16.6
Rest-of-day	66	46 (167)	1 : 3.2

Appendix G Disruption location C, Kneuterdijk – Mauritskade (8)

Figure 7.12 presents the extra TGTT on the one hand and the resource delay on the other, for the alternatives for disruption location C for rest-of-day passenger demand levels. It can be seen that Detour 4 yields the lowest extra TGTT, while Detour 1 and short-turning between Centrum and Mauritskade are approximately equal from the passenger perspective.

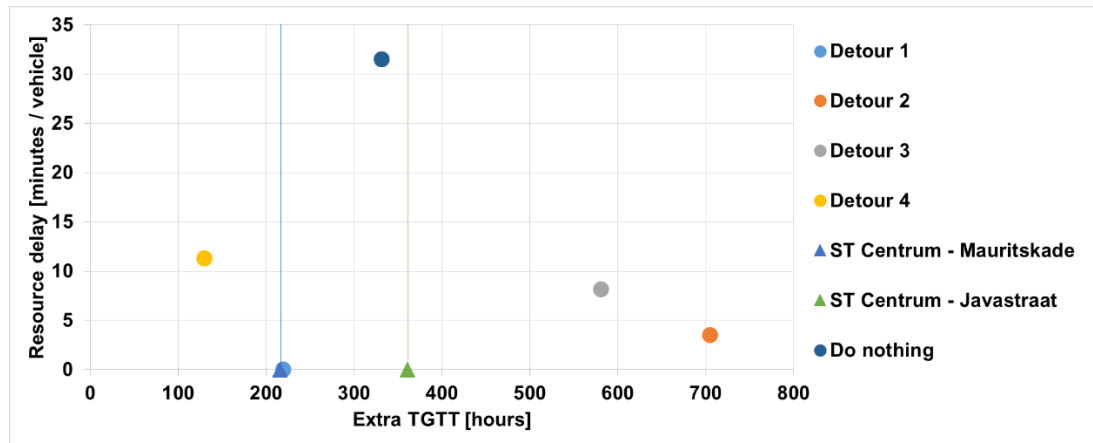


Figure 7.12: Disruption location C - Extra TGTT versus resource delay (rest-of-day).

Figure 7.13 and Figure 7.14 present the TGTT per alternative for disruption location C, distinguished by trip element, for morning-peak passenger demand levels and rest-of-day passenger demand levels, respectively.

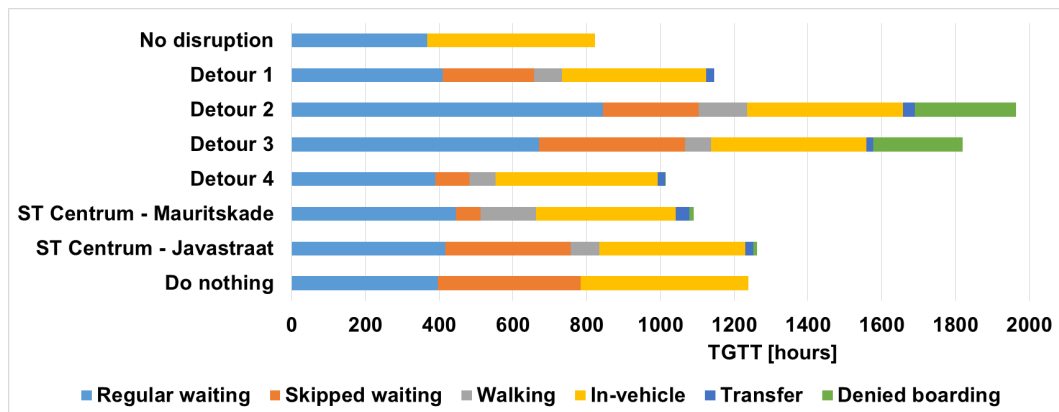


Figure 7.13: Disruption location C - TGTT per alternative, distinguished by trip element (morning-peak).

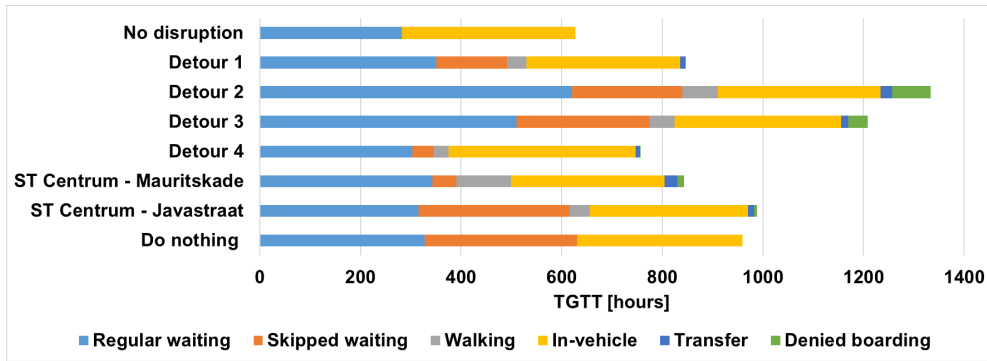


Figure 7.14: Disruption location C - TGTT per alternative, distinguished by trip element (rest-of-day).

Appendix H Disruption location D, HS – Centre (97, 98, 99)

Figure 7.15 presents the extra TGTT on the one hand and the resource delay on the other hand, for disruption location D for rest-of-day passenger demand levels, while Figure 7.16 and Figure 7.17 present the TGTT for the different alternatives distinguished by trip element, for the morning-peak passenger demand levels and the rest-of-day passenger demand levels, respectively.

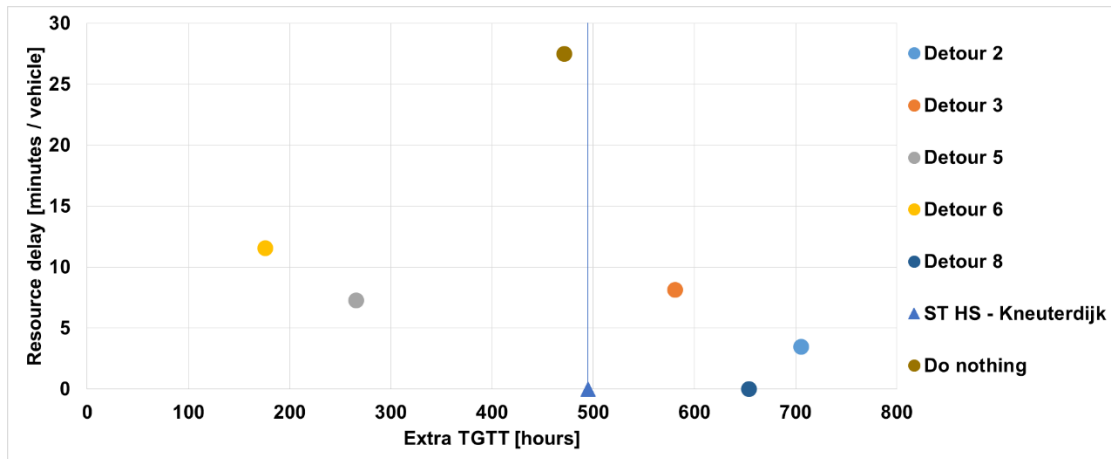


Figure 7.15: Disruption location D - Extra TGTT versus resource delay (rest-of-day).

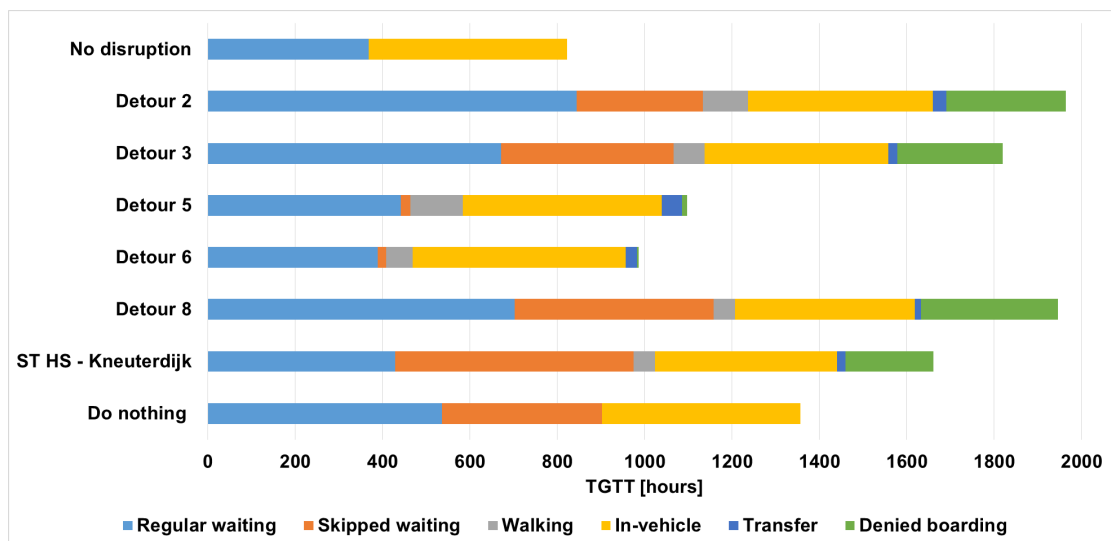


Figure 7.16: Disruption location D - TGTT per alternative, distinguished per trip element (morning-peak).

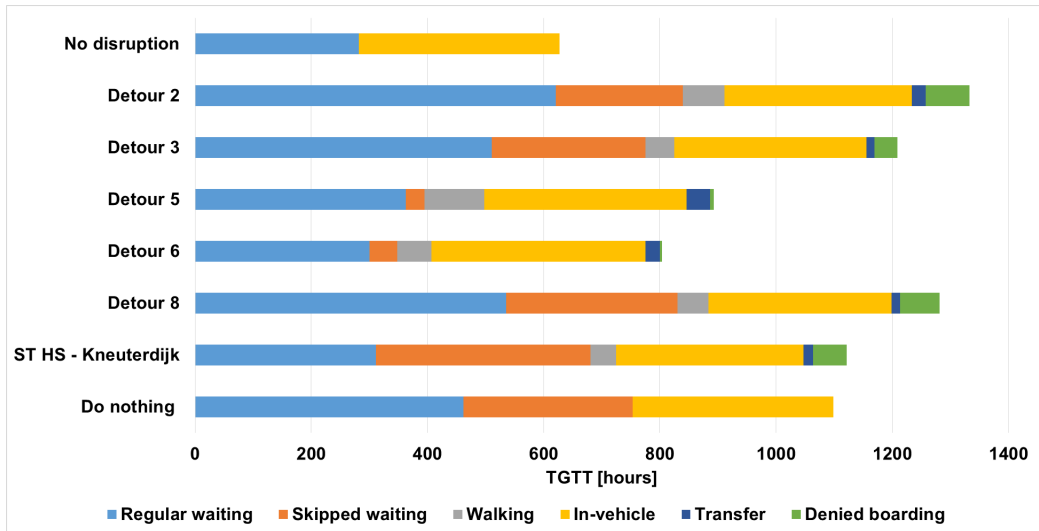


Figure 7.17: Disruption location D - TGTT per alternative, distinguished per trip element (rest-of-day).

Appendix I Sensitivity analysis

Figure 7.18 presents the results of the sensitivity analysis for disruption location A, looking into the sensitivity of the willingness-to-walk of passengers. It shows that the willingness-to-walk does affect the extra TGTT of the alternatives, and it shows that the short-turn possibilities between Centrum and Mauritskade / Javastraat are more sensitive than the other alternatives, but that the outcome does not change. Short-turning between Centrum and Kneuterdijk remains the alternative with the lowest TGTT, followed by Detour 6.

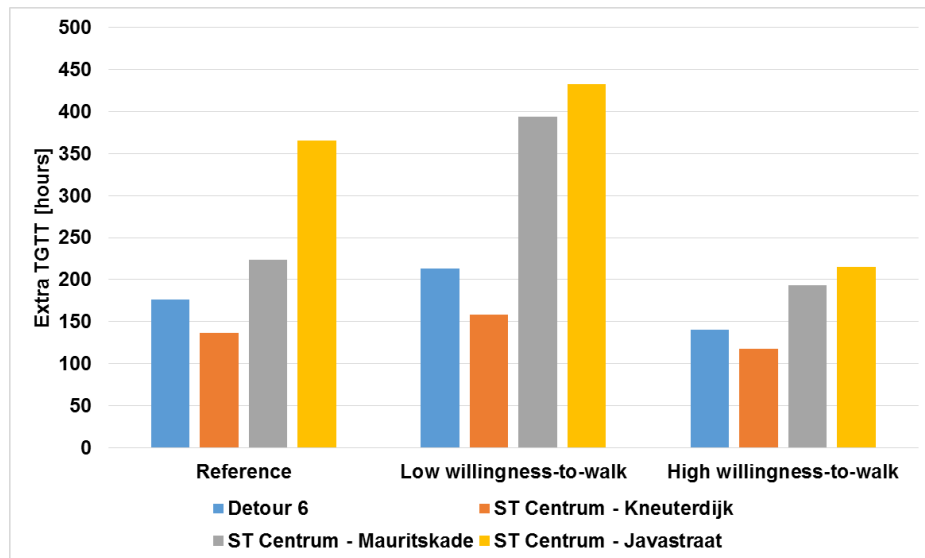


Figure 7.18: Sensitivity of alternatives for disruption location A for willingness-to-walk, rest-of-day demand levels.

In the remaining figures (Figure 7.19, Figure 7.20, Figure 7.21), the effect of a possible overestimation of passengers travelling between HS / Bierkade and Kurhaus is indicated. This is done by halving the number passengers travelling between these stops (e.g. assuming half of the passengers using line 1 has switched from line 9 due to the construction works). The effects are given for location A morning-peak demand levels, Location B morning-peak demand levels and location B rest-of-day demand levels. It can be seen that the effect of the possible overestimation for these cases is very limited and does not affect the outcome.

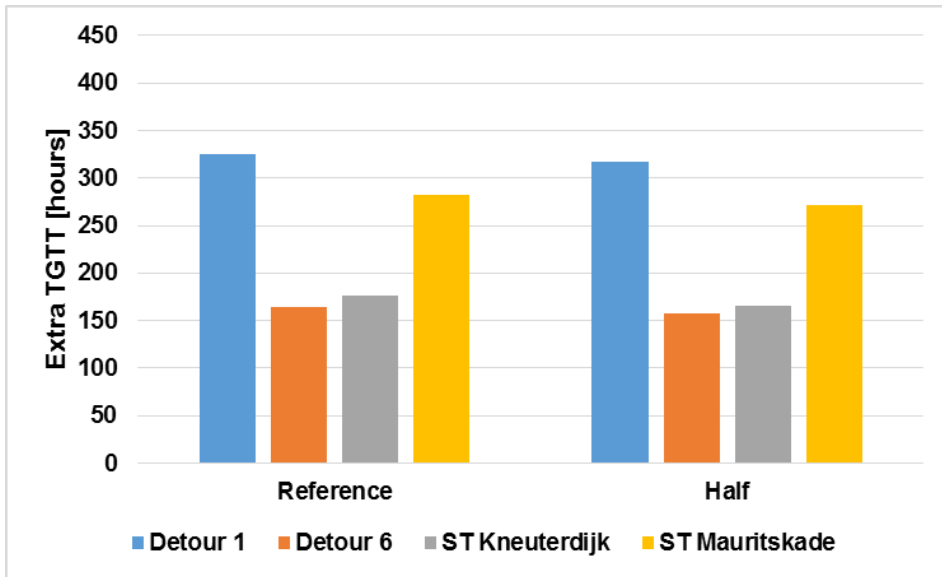


Figure 7.19: Effect of possible overestimation of passengers travelling between HS / Bierkade and Kurhaus (location A, morning-peak).

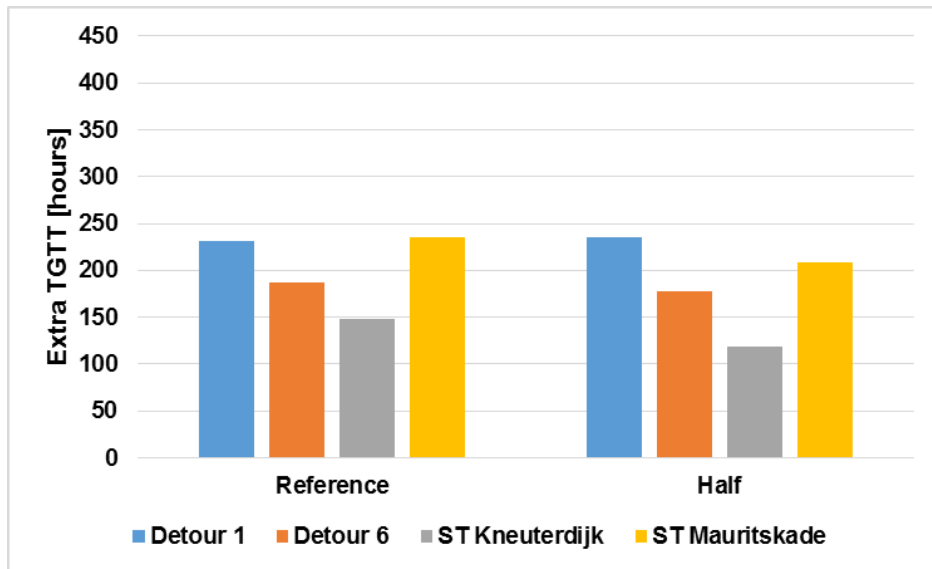


Figure 7.20: Effect of possible overestimation of passengers travelling between HS / Bierkade and Kurhaus (location A, rest-of-day).

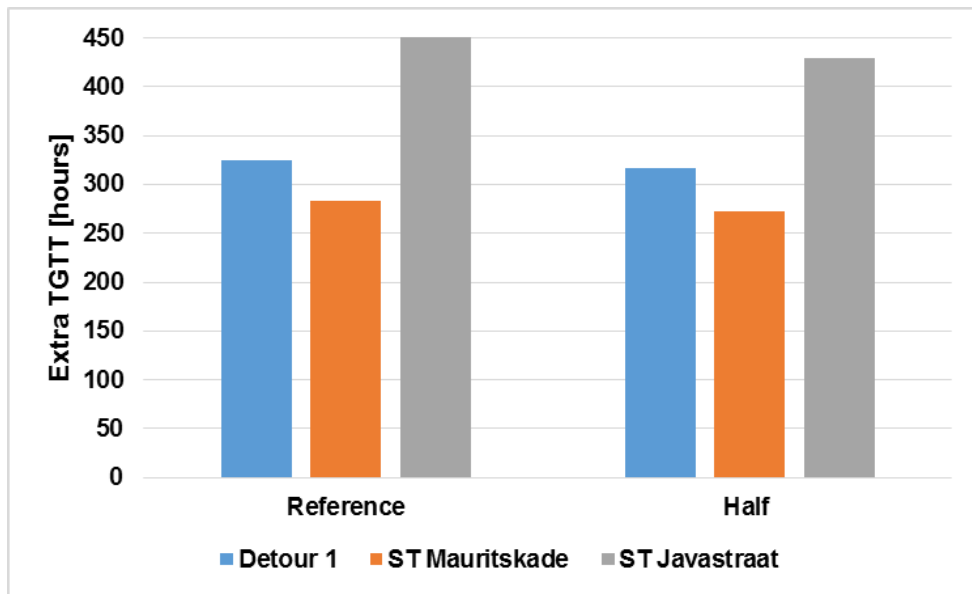


Figure 7.21: Effect of possible overestimation of passengers travelling between HS / Bierkade and Kurhaus (location B, morning-peak).