Managing disruptions in public transport from the passenger perspective:

A study to assess and improve operational strategies for the benefit of passengers in rail-bound urban transport systems

Master thesis, by A. L. Durand

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Master thesis, by A. L. (Anne) Durand

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Cover picture provided by the RET.
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Preface

This report presents the result of my graduation research, the final product in my Master in Transport, Infrastructure and Logistics at Delft University of Technology. The topic of this study is the management of disruptions in rail-bound urban public transport from the perspective of passengers. This research was conducted at the RET, the main public transport operator in Rotterdam, and contains recommendations for the RET but the general framework developed in this study is meant to be applicable to many other public transport operators and its application allowed to gain multiple insights for rail-bound urban public transport in general.

I would like to thank the RET for giving me the opportunity to conduct this project and for the warm welcome I received at the CVL (traffic control centre) office. I am also deeply thankful to my thesis committee. Stephan, thank you for believing in me all along and for your great interest in the project. Niels, thank you for trusting me from the moment I started to look for a master thesis. Your support and your feedback were invaluable during this project. Jan Anne, thank you for your enthusiasm and your inspiring feedback. Serge, your thorough comments were always precious. I thank the four of you for your patience and your understanding.

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To finish, I would like to thank all of my family for their support, in particular my brother and my sister but most especially my parents. I tend to get emotional when I think about how blessed I am to receive so much unconditional support from you, so I will cut short here: *merci pour tout*.

Anne Durand
Germany/The Netherlands
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Executive Summary

Disruptions in public transport can have consequent impacts on passengers, especially if not properly addressed. They may result in negative publicity for public transport operators, translating into revenue loss. In urban public transport systems, in particular, where a lot of passengers use the system on a daily basis, an efficient disruption management system is crucial.
Yet so far, research on passengers in non-recurrent – i.e. disrupted – conditions is scarce and public transport operators are being mostly focused on the supply side when analysing, and thus tackling disruptions: the timetable, the crew schedule, etc. Although such a focus is understandable, it is not necessarily always beneficial for passengers. Fortunately, with the increase in passenger data due to the implementation of smart cards, it is getting easier to study the passenger perspective. To determine what is best for passengers, it would be useful to have two occurrences of the same disruption, in the same circumstances, but addressed with different control strategies, to be able to compare how each of them impacted passengers. However, it is unlikely to be possible to find such occurrences in practice. This makes the identification of passenger-oriented strategies difficult.

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

How can service control strategies used in non-recurrent conditions in a public transport system be improved and developed when the passenger perspective is taken into account?

The focus of this research is on the incident phase, i.e. the phase from the start of the incident until the cause of the disruption is resolved. The service recovery phase, from the end of the incident phase until the operations plan is restored up to some targets, is not within the scope.
In this study, an assessment framework is developed. It aims at allowing for multiple service control strategies – including the one used by traffic controllers, but not only – to be assessed and then compared from a passenger perspective for one given disruption, in order to derive how each strategy affects passengers.
The framework application reveals that on a yearly basis, **savings in terms of societal costs could amount to approximately 900 K€**, if every disruption similar to the in-depth case study – occurring slightly more than once a week – is handled like in the best case scenario developed through the assessment framework. To give an order of magnitude, saving 1€ of societal costs means reducing the waiting time of one passenger by five minutes.

The development of the assessment framework is split into two main phases:
1. Theoretical development of the assessment framework,
2. Application of the assessment framework.

1. Theoretical development of the assessment framework
First, a literature review is used to define key elements of the framework such as data needs and structure, and to get a good understanding of the meaning of “taking the passenger perspective in non-recurrent conditions”: it starts with using impacts that directly relate to passenger needs, and to measure these impacts with recurrent (undisrupted) conditions as a reference. These impacts are defined:

- At a local scale, for a few stops:
  - Bunching, which translates into an additional effective in-vehicle time at stops.
  - Crowding and comfort aspects, assessed in two complementary ways:

- Via additional perceived in-vehicle time between stations; the more crowded a vehicle, the longer in-vehicle time is perceived to be,
- Via denied boarding, which causes an extension of waiting time.
  - Unplanned transfers, which translates into a penalty and additional waiting time.
  - Additional waiting time at the first stop.
- At a global scale, on a network level:
  - Additional travel time.

Then, these impacts are embedded into a three-step methodology aiming at using them to assess disruptions. Firstly, vehicle data are used to compute supply-side impacts. Secondly, these impacts are translated into the previously defined passenger impacts, via the use of passenger data. Thirdly, passenger impacts are aggregated into an additional generalised costs (AGC) value that allows for various scenarios to be easily compared, including at the OD-pair (Origin Destination) level. The methodology is used separately for the local and the global scales.
Yet so far, only the disruption to be investigated has vehicle data (AVL data). This is why a method is selected to generate vehicle data for alternative strategies, so that different strategies can be compared for the same disruption. Discrete-event simulation is chosen. Once the list of measures to include in the assessment is established, alternative strategies are generated in the simulation model based on a "what-if" approach, a heuristic optimisation procedure. For each modification, the variable inputs of the model are thus incrementally modified, based on the results from the local-scale assessment of previous strategies. The local-scale assessment is the one that allows to craft new strategies because of its focus on the microscopic level (track, road, etc.). The generation of alternative stops when enough combinations of measures have been tested.
A schematic overview of the assessment framework is displayed in Figure 1.

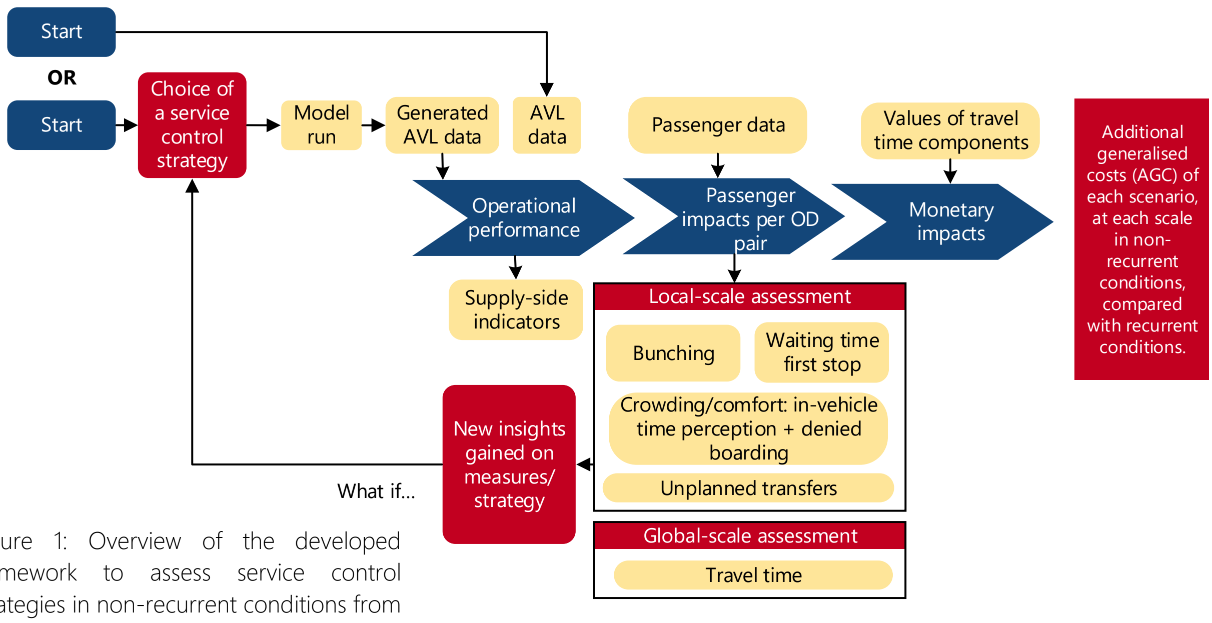


Figure 1: Overview of the developed framework to assess service control strategies in non-recurrent conditions from a passenger perspective.

2. Application of the assessment framework

The application of the framework is meant to both test it and to measure the nature of the improvements it achieves. The framework is applied on an in-depth case study, a partial blockage during the morning peak in the metro of Rotterdam, operated by the RET. This partial blockage created a bottleneck, where both directions had to share one track. Three main measures to test in the assessment are selected: single-track operations, short-turning and holding. Since the first measure currently lacks research, this study can fill two needs with one deed.

The application of the assessment framework allows to transform intuitions from observations into facts backed by a scientific approach: although predefined strategies at the RET are a good basis, there is still room for improvement to take the passenger perspective into account at the traffic control centre. For this specific case study, additional generalised costs – mostly waiting time costs – can be reduced by around 35% by implementing the three following changes in the strategy:

- By modifying the sequence of trains in the bottleneck for single-track operations. During the transition phase (from steady operations in recurrent conditions to steady operations in non-recurrent conditions), trains need to be sent in the bottleneck in a way that anticipates gaps in headway created by the unplanned event. Implementing this change alone reduced AGC by around 12%.
- By implementing holding for regularity purposes. Coupled with the sequence modification, an 18% reduction in AGC was achieved.
- By not short-turning (or by redirecting) one train, so that it can fill the gaps in headway created by the unplanned event.

The local-scale assessment gives more accurate insights than the global-scale one, for which changes across scenarios are too subtle. Still, the global-scale assessment reveals two main facts:

- First, another service control measure, diversion, could be used in the strategies.
- Second, the potential of the multimodal network may not be fully utilised since a transit assignment model shows that the tramway might not be as popular an alternative as expected. This is why the traffic control centre needs to play an active role in re-directing passengers, especially ahead of the disrupted corridor.

In addition, a sensitivity analysis on the crush capacity value shows that capacity is a major variable. Increased crush capacities lead to fewer, yet non-null denied boarding occurrences. This analysis allows to derive a bandwidth for the results, displayed in Table 1. This is important since the outcome of the assessment is also meant to be of a quantitative nature, such as societal costs per disruption.

Table 1: Bandwidth for additional generalised costs (AGC) for a few scenarios.

Scenario	**(A)**	**(B)**	**(C)**	**(D)**
Short description of the scenario	*Dispatchers' strategy: short-turning + single-track operations*	*(A) + Different sequence in the bottleneck.*	*(B) + Holding for regularity purposes.*	*(C) + A redirected train.*
Bandwidth for AGC / Societal costs per disruption	43 – 57 K€	37 – 50 K€	35 – 47 K€	28 – 35 K€

After validation of the results through interviews, it is concluded that the assessment framework is successfully developed.

Further impacts and practical recommendations to the RET

The framework has only considered the passenger perspective and does not include any impacts related to vehicle and crew schedules or to the level of adaptation that each measure may require from dispatchers. However, the conducted case study shows that passenger-oriented strategies for the incident phase are based on a regularity paradigm while current rescheduling practices are still mostly carried out with a punctuality paradigm. A shift in paradigm would impact vehicle and crew schedules and thus dispatchers' work habits. This makes the passenger perspective thorny to take into account at the traffic control centre: any change comes at a cost. Multiple actions can therefore be recommended to the RET to allow for the focus to shift towards regularity. They can be divided into two main categories:

1. The adaptation of the work environment of dispatchers.
2. An emphasis on the importance of regularity in the organisation, from the traffic control centre to managers who set disruption-related targets.

Ideally, it would be interesting to balance demand- and supply-oriented impacts, both short- and long-term ones. Based on the results of the assessment, it is recommended for the RET to perform a cost-benefit analysis to be able to estimate to what extent being passenger-oriented is worthwhile.

Main conclusion: answer to the main research question

Service control strategies for non-recurrent conditions can be developed and improved for the benefit of passengers via the use of an assessment framework, where multiple passenger impacts due to disruptions can be assessed. By using the framework, the decision-maker can then compare the performance of various service control strategies in response to one specific disruption. This makes this assessment framework unique.

Practical implications for rail-bound urban public transport systems in general

Even though it is difficult to standardise a response to be passenger-oriented in all situations, the application of the framework allows to conclude that service control strategies used in non-recurrent conditions can be improved for the benefit of passengers in two main ways:

- Via **refined pre-planned service control strategies**, developed taking into account the full network. Predefined strategies for partial blockages in rail-bound systems need to have **a variant for peak hours**. This variant could include an estimate of the amount of trains to short-turn for each blockage for instance.
- Via **real-time decisions** that would anticipate better the occurrence of **headway gaps** caused by the unplanned event; an adaptation of the work environment of dispatchers may be needed.

In addition, the application of the framework provides new insights on single-track operations and short-turning.

- When applying single-track operations, there is a trade-off between regularity and bottleneck capacity. The longer the single-track length, the more difficult it is to find a balance. This is why in (sections of) network lacking crossovers, operators are advised to look at long-term solutions to be able to dispatch extra capacity within a reasonable amount of time.
- A systematic short-turning pattern should only be implemented where a third track is available.

Recommendations for further research

In order to be more comprehensive, the next step to improve the assessment framework could be to integrate some non-passenger-related impacts. That way, it could suggest more explicitly trade-offs between passengers and the operations plan for instance. With such an improvement, the framework could then also take into account the recovery phase. Another recommendation for improvement concerns the model used for the generation of vehicle data: it would be recommended to upgrade it in a way that passengers can also be modelled. That way, it would be possible to estimate impacts with a better accuracy, notably extreme-value-based impacts, which usually better reflect passenger inconvenience. Furthermore, it is recommended to gain more knowledge on the behaviour of urban public transport passengers in non-recurrent conditions, especially on their reaction to crowded vehicles and preferences regarding re-routing choice.

Table of Contents

Preface I

Executive Summary III

Table of Contents VIII

List of Figures XI

List of Tables XIV

List of Abbreviations XVII

Chapter 1 Introduction 1

1.1. Problem definition 1
1.2. Research objectives and research questions 4
1.3. Relevance and contribution of the study 5
1.4. Scope 6
1.5. Thesis structure 8

Chapter 2 Passenger perspective and disruption management practices in public transport systems 11

2.1. The passenger perspective in public transport systems 11
2.2. Disruption management process 13
2.3. Inventory of service control interventions 16
2.4. Literature review conclusions 24

Chapter 3 Development of the assessment framework 27

3.1. Approach for the development of the assessment framework 27
3.2. Theoretical core of the assessment framework 30
3.3. Local-scale assessment framework development 37
3.4. Global-scale assessment framework development 48

3.5. Conclusion of the assessment framework development 51

Chapter 4 Introduction to the case study 55

4.1. The metro system in Rotterdam 55
4.2. Disruptions in the metro network of Rotterdam 57
4.3. Presentation of the selected disrupted situation 60
4.4. Conclusion of the presentation of the case study 64

Chapter 5 Application of the assessment framework 65

5.1. Generation of alternative strategies and local-scale assessment results 65
5.2. Global-scale assessment results 75
5.3. Validation of the assessment framework 80
5.4. Complementary analyses 80
5.5. Conclusion on the application of the assessment framework 84

Chapter 6 Discussions beyond the assessment framework 87

6.1. Generalisation of the results of the studied disruption 87
6.2. Impacts of service control measures on passengers 91
6.3. Further impacts 93
6.4. Conclusion of the discussion on the assessment framework 97

Chapter 7 Conclusions and recommendations 99

7.1. Main conclusion 99
7.2. Practical implications 101
7.3. Recommendations for the RET 102
7.4. Further research 104

Bibliography 109

Appendix A Generalised costs function constants 114

Appendix B Passenger-oriented disruption metrics 116

Appendix C Questionnaire 118

Appendix D Capacity calculation for single-track operations 121

Appendix E **Selection of the disrupted situation to be investigated** **124**

Appendix F **Inventory of service control measures used in the metro of the RET** **126**

Appendix G **Practical details on the local- and global-scale assessments setups** .. **127**

Appendix H **Specification of the model in ARENA** **133**

Appendix I **Details on the generated scenarios** **139**

Appendix J **Results of the assessment** **143**

Appendix K **List of interviewees for the validation of the results** **148**

Appendix L **Frequent service network of the RET** **149**

Appendix M **Track layout structure on the trunk section of the D and E lines** **151**

Appendix N **Results of the sensitivity analysis on the crush capacity values** **152**

Appendix O **Waiting time distributions and waiting time reliability buffer time estimation** **157**

Appendix P **Generalisation of the results to other disruptions on the trunk section of the D and E lines** **159**

Appendix Q **Clauses belonging to the "Fines, bonuses and maluses" part of the rail concession contract of the RET** **162**

List of Figures

Main Text

Figure 1-1: Phases of a disruption (adapted from Chu & Oetting (2013)). 7
Figure 1-2: Structure of the report. 9
Figure 2-1: The hierarchy of public transport passengers' needs (adapted from Van Hagen et al. (2000)). 11
Figure 2-2: Average additional minutes of travel time per passenger on each day (Carrel, 2009). EB stands for eastbound, WB westbound. 13
Figure 2-3: High-level view of the disruption management process ((Kohl et al., 2007) and adapted). 14
Figure 2-4: Mixes of pre-planning and real-time decision-making levels (Moore, 2003). 15
Figure 2-5: Holding of a vehicle (adapted from Van Oort (2011)). 16
Figure 2-6: Expressing in direction A - B (from Van Oort (2011)). 17
Figure 2-7: Deadheading in direction A – B, two ways. 18
Figure 2-8: Short-turning at point C (from Van Oort (2011)). 19
Figure 2-9: Diversion of a vehicle from its initially planned destination (one direction depicted only). 19
Figure 2-10: Detour of a vehicle from its initially planned trip (one direction depicted only). 20
Figure 2-11: Bus shuttle service implementation due to a complete blockage in a rail-bound network. 20
Figure 2-12: Single-track operations when B is unavailable (adapted from Song (1998)). 21
Figure 2-13: Cost of a trip for a passenger in various conditions. The reader must imagine that inconvenience can be translated as a cost. 24
Figure 3-1: Demand – supply interaction, adapted from Van Oort et al. (2015). 28
Figure 3-2: Phases of development of the assessment framework. 29
Figure 3-3: Scheduled passenger time and average additional travel time per passenger (Van Oort et al., 2015). 31
Figure 3-4: Waiting time distribution; recurrent performance (adapted from Uniman (2009)). 31
Figure 3-5: Waiting time distribution; non-recurrent performance. 32
Figure 3-6: Three-step approach used for each assessment scale, adapted from Van Oort et al. (2015). 33
Figure 3-7: Structure of an investigated disruption, for a given situation (day, time, location). 37
Figure 3-8: Theoretical overview of the assessment framework. 37
Figure 3-9: Terminology for partial blockage cases; example of a setup with a disruption in station D, westbound track. 38
Figure 3-10: Example of a spatial scope S. 38
Figure 3-11: Dwell time extension explanations. 40
Figure 3-12: Explanation of headways for the denied boarding calculations. 44
Figure 3-13: Flowchart of the module to calculate denied boarding occurrences. 45
Figure 3-14: Conceptual flowchart of the DES model to simulate operations. 47
Figure 3-15: "What-if" approach to generate alternative scenarios. 47
Figure 3-16: Detailed overview of the developed framework to assess service control strategies in non-recurrent conditions from a passenger perspective. 53
Figure 4-1: Map of the metro network of Rotterdam (RET, 2016b) with abbreviations. 55
Figure 4-2: Share of check-ins per mode operated by the RET in 2015 (RET, 2016c). 56

Figure 4-3: Average amount of check-ins in the metro of Rotterdam over a working day (data from January 2015 – May 2016).....56
Figure 4-4: Share of trip purposes between 07:00 AM and 12:00 PM, working days, in the metro of Rotterdam (RET, 2016a).....56
Figure 4-5: Corner of metro dispatchers at the traffic control centre of the RET......57
Figure 4-6: Amount of registered disruptions in the metro and corresponding starting time (data from January 2013 – July 2016).....57
Figure 4-7: Amount and average duration of each type of disruption (data from January 2013 – July 2016).....58
Figure 4-8: Service control strategy for a partial blockage in the northbound track between Leuvehaven and Beurs......59
Figure 4-9: Layout of the tracks in the disrupted area (RET, 2015). 61
Figure 4-10: Time-space diagram between Slg and Rcs on May 18th, from 07:40 AM until 08:50 AM. 62
Figure 4-11: Set of selected stations......63
Figure 4-12: Schematic overview of the model in ARENA......64
Figure 5-1: Local-scale assessment of the Base Scenario, one hour of the morning peak (strategy applied by dispatchers on May 18th 2016); passenger impacts translated into monetary costs and divided per direction......65
Figure 5-2: Two categories of strategies investigated.....66
Figure 5-3: Flowchart for the procedure to derive an ideal service control strategy. It needs to be read starting at Scenario 2, then 3, 4, etc......66
Figure 5-4: Inconvenience experienced for all passengers, translated in AGC, for Scenarios 1 to 7b, for a disruption in Mhv on May 18th 2016, 1 hour in the morning peak. Scenario 3 is within brackets because it is not a realistic option. Scenario 7a was only roughly estimated, hence it does not show here. The black dashed line is based on the total NB AGC for Scenario 1......67
Figure 5-5: Sequences of trains in the bottleneck (Mhv2) during the strategy application phase, with indication of the E line......68
Figure 5-6: Progression from Scenario 1 to Scenario 6b.....70
Figure 5-7: Pie charts of the additional generalised costs for Scenario 1, 6a and 6b. 70
Figure 5-8: Additional waiting time at each stop in the trunk section for Sc. 1, 6a, 6b and 7b, used for impacts (b), (d) and (e).....71
Figure 5-9: Additional waiting time in southbound stops in function of the amount of vehicles for Scenarios 1, 2, 4a, 4c and 6b. 72
Figure 5-10: Stops where denied boarding occurs.....73
Figure 5-11: Denied boarding occurrences in function of the average boarding demand at stops over one hour of the AM peak. Average boarding demands in Slg NB and Rcs SB are computed by taking into account occupancy rates of vehicles coming from respectively the D and the E line branches...73
Figure 5-12: Difference in passengers in the **metro** between the reference day and May 18th, for one hour of the morning peak......76
Figure 5-13: (Left) Difference in passengers in the **tram** between the reference day and Scenario 1.77
Figure 5-14: (Right) Difference in passengers in the **bus** between the reference day and Sc. 1. 77
Figure 5-15: (Left) I/C ratio for the **metro,** reference day.....78
Figure 5-16: (Right) I/C ratio for the **metro,** Scenario 1......78
Figure 5-17: (Left) I/C ratio for the **tram,** reference day. 78
Figure 5-18: (Right) I/C ratio for the **tram**, Scenario 1......78
Figure 5-19: (Left) I/C ratio for the **bus**, reference day. 78

Figure 5-20: (Right) I/C ratio for the **bus**, Scenario 1 ... 78
Figure 5-21: Waiting time distributions in Beurs, during one hour of the morning peak under different scenarios and visualisation of the percentiles used to compute the reliability buffer time metric. ... 83
Figure 6-1: Analogy with road traffic. ... 87
Figure 6-2: Main investigated strategies in this study, with short-turning and single-track operations. ... 91
Figure 7-1: Single-track operations during steady operations in non-recurrent conditions in a rail-bound urban public transport system; regularity/bottleneck capacity use trade-off. ... 102

Appendix Figures

Appendix Figure 1: Track layout betwen Zuidplein and Rijnhaven. ... 121
Appendix Figure 2: Average amount of check-ins per working day during the morning peak in the public transport network of Rotterdam. ... 125
Appendix Figure 3: Chosen time windows (left: northbound, right: southbound) ... 128
Appendix Figure 4: Aggregated stations. ... 130
Appendix Figure 5: Building blocks of the model in ARENA. ... 134
Appendix Figure 6: Comparison of additional bunching times, additional waiting times and denied boarding occurrences as derived from AVL data of May 18th and simulated AVL data, for model validation purposes ... 137
Appendix Figure 7: Comparison of additional perceived in-vehicle time between stops, as derived from AVL data of May 18th and simulated AVL data, for model validation purposes. ... 138
Appendix Figure 8: Short-turning of trains in Mhv, track 2. ... 141
Appendix Figure 9: Short-turning of trains in Bre. ... 141
Appendix Figure 10: Time-space diagram of Scenario 7b. ... 142
Appendix Figure 11: Average additional perceived in-vehicle time between stops compared to the reference day, for Scenarios 1, 6a and 6b. ... 143
Appendix Figure 12: Affected passengers and additional travel time per passenger in the Base Scenario compared to the reference day ... 147
Appendix Figure 13: Frequent service network of the RET (RET, 2016b) ... 149
Appendix Figure 14: Tram network of the RET (RET, 2016b). ... 150
Appendix Figure 15: Track layout between Slinge and Rotterdam Centraal (RET, 2015). ... 151
Appendix Figure 16: Inconvenience experienced for all passengers, crush capacity assuming 3 standing people per square metre. The equivalent for 2 standing people per square metre can be found in Figure 5-4. Chart legend in Appendix Figure 17. ... 154
Appendix Figure 17: Inconvenience experienced for all passengers, crush capacity assuming 3.5 standing people per square metre. ... 154
Appendix Figure 18: (Left) I/C ratio for the metro, Scenario 1, $cc2$ ... 156
Appendix Figure 19: (Right) I/C ratio for the metro, Scenario 1, $cc3$. ... 156
Appendix Figure 20: (Left) I/C ratio for the metro, Scenario 6b *bis*, $cc2$. ... 156
Appendix Figure 21: (Right) I/C ratio for the metro, Scenario 6b bis, $cc3$ ... 156
Appendix Figure 22: Waiting time distributions in Beurs SB during one hour of the morning peak for different scenarios; data fitted to kernel distributions. ... 158
Appendix Figure 23: Link loads from OV-Lite between Slg and Rcs during one hour of the morning peak (left), one hour of the in-between peak time (middle) and one hour of the evening peak (right), with OD matrix for spring season ... 159

List of Tables

Main Text

Table 1-1: The STO model for the public transport production process (Van Oort, 2011). 6
Table 2-1: Conditions for levels of pre-planning (adapted from Moore (2003)). 15
Table 2-2: Inventory of service control measures and their prerequisites (inspired and adapted from Van Oort (2011)). 22
Table 2-3: Implementation phase for each service control measure. 23
Table 2-4: Inventory of service control measures and their impact on passengers as found in the literature. 23
Table 3-1: Description of the two levels of assessment. 30
Table 3-2: Output of the model in ARENA. 47
Table 4-1: Working day frequencies in the metro of Rotterdam in 2016. 56
Table 4-2: Main characteristics of the selected disrupted situation. 61
Table 4-3: Comparison of the reference day, the actual strategy used by dispatchers and the predefined strategy, basis of 50 min. 62
Table 5-1: Additional generalised costs in euros in Scenario **1** per OD pair and per passenger. 74
Table 5-2: Additional generalised costs in euros in Scenario **1** per OD pair. 74
Table 5-3: Additional generalised costs in euros in Scenario **6b** per OD pair and per passenger. 75
Table 5-4: Additional generalised costs in euros in Scenario **6b** per OD pair. 75
Table 5-5: Average and perceived frequencies (NB frequency; SB frequency) for the assessed scenarios. 76
Table 5-6: Analysis of the route choice of the OD pair Spijkenisse Centrum – Melanchtonweg. 77
Table 5-7: Comparison of impact (f), additional generalised costs and estimates of lateness for Scenarios 1, 6a, 6b and 6b bis. 79
Table 5-8: Bandwidth for additional generalised costs for Scenarios 1, 4c, 6a and 6b. 81
Table 5-9: RBT in Scenarios 1, 4c, 6a and 6b for Beurs SB, 1 hour of the morning peak, and corresponding long-term societal impacts. Denied boarding occurrences are calculated with the local-scale assessment framework, with 3 people per $m2$. 83
Table 6-1: Estimated amount of D line trains to short-turn for various partial blockages between Slg and Rcs during one hour of single-track operations of the morning or evening peak (lengths from internal documents of the RET). Tr. 1: NB operations, 2: SB. 88
Table 6-2: Amount of gaps in headways during the transition phase between Rcs and Slg during the transition phase caused by various partial blockages on the trunk section. 90
Table 6-3: Inventory of service control measures for which new insights on their impact on passengers were gained during this study (holding and short-turning based on the work of Schmöcker et al. (2005) and Wilson et al. (1992)). 93

Appendix Tables

Appendix Table 1: Summary of studies that investigated the weight of the waiting time component 114
Appendix Table 2: Overview of travel time component weights (Bovy & Hoogendoorn-Lanser, 2005; Van der Waard, 1988; Wardman, 1998, 2004). 115
Appendix Table 3: Values of monetary constants used for in the AGC function, corrected for the 2016 inflation. Value of Time from Kouwenhoven et al. (2014). 115
Appendix Table 4: In-vehicle time multipliers (2nd, 3rd, 4th and 5th columns based on Wardman & Whelan (2011)). 115

Appendix Table 5: Comparison of the incident-related metrics used at the RET in April 2016 for the metro vs. the metrics required in the study of Barron et al. (2013) 117
Appendix Table 6: Occupation time components..... 122
Appendix Table 7: Overview of the general structure of current predefined service control strategies at the RET..... 126
Appendix Table 8: Selected time windows for the case study. 129
Appendix Table 9: s2s matrix for 1 hour in the morning peak on the trunk section of the D and E lines. S: outer edge near Slinge, N: outer edge near Rotterdam Centraal. 131
Appendix Table 10: Inventory of the incident-phase service control measures used at the RET and in this study..... 131
Appendix Table 11: Occupation of the stops at the beginning of the simulation, i.e. at 07:53 AM. . 133
Appendix Table 12: Dwell time at stops, as implemented in the model. 135
Appendix Table 13: Travel times between stops, as implemented in the model (Both, 2015). 135
Appendix Table 14: Holding times & corresponding stops and trains. 137
Appendix Table 15: Comparison of the local-scale assessment final results – additional generalised costs (AGC) – between the reality and the implementation in the model..... 138
Appendix Table 16: Candidate vehicles for short-turning. 139
Appendix Table 17: Holding times for trains in Scenario 6a. Holding times in Scenario 6b are based on the same reasoning and are therefore relatively similar. 140
Appendix Table 18: Occupation times for short-turned trains in Mhv2 (Scenario 7a) (Both, 2015; Van Ravels, 2016)..... 141
Appendix Table 19: Occupation times for short-turned trains in Bre (Scenario 7b) (Both, 2015; Van Ravels, 2016)..... 141
Appendix Table 20: Additional generalised costs in euros in Scenario **1** per OD pair..... 143
Appendix Table 21: Additional generalised costs in euros in Scenario **1** per OD pair..... 144
Appendix Table 22: Additional generalised costs in euros in Scenario **4c** per OD pair and per passenger. 144
Appendix Table 23: Additional generalised costs in euros in Scenario **4c** per OD pair 144
Appendix Table 24: Additional generalised costs in euros in Scenario **6a** per OD pair. 144
Appendix Table 25: Additional generalised costs in euros in Scenario **6a** per OD pair. 145
Appendix Table 26: Additional generalised costs in euros in Scenario **6b** per OD pair and per passenger. 145
Appendix Table 27: Additional generalised costs in euros in Scenario **6b** per OD pair..... 145
Appendix Table 28: Comparison between the results of the global-scale assessment with average and perceived frequencies. 146
Appendix Table 29: Crush capacities of scenarios with 2 or 3 people standing per square metre of available floor..... 152
Appendix Table 30: Comparison of results for denied boarding occurrences (DB occ.), balance index and total additional generalised costs with different crush capacities; Scenarios 1-2-3. 153
Appendix Table 31: Comparison of results for DB occurrences, BI and total AGC with different crush capacities; Scenarios 4a-4b. 153
Appendix Table 32: Comparison of results for DB occurrences, BI and total AGC with different crush capacities; Scenarios 4c-5a. 153
Appendix Table 33: Comparison of results for DB occurrences, BI and total AGC with different crush capacities; Scenarios 5b-6a. 153
Appendix Table 34: Comparison of results for DB occurrences, BI and total AGC with different crush capacities; Scenarios 6b-7b. 154

Appendix Table 35: Crush capacities of lines in OV-Lite with 2 or 3 people standing per square metre of available floor. 155
Appendix Table 36: Detail of the denied boarding occurrences in Scenario 1 in Bre SB from 07:46 to 08:46 AM, with a crush capacity assuming 3 people per square metre. 157
Appendix Table 37: Estimated waiting times for each group of passengers boarding each train. 157
Appendix Table 38: Average occupation, boarding and alighting rates in the **AM peak**, possibility for denied boarding to occur and maximum headway for different crush capacities. 160
Appendix Table 39: Average occupation, boarding and alighting rates in the **PM peak**, possibility for denied boarding to occur and maximum headway for different crush capacities. 161

List of Abbreviations

General abbreviations

ABS	Agent-Based Simulation
AGC	Additional Generalised Costs
AVL	Automatic Vehicle Location
APC	Automatic Passenger Count
ATT	Additional Travel Time
AWT	Additional Waiting Time
BI	Balance Index
DB	Denied Boarding
DES	Discrete-Event Simulation
EB	Eastbound
FIFO	First In, First Out
GC	Generalised Costs
IVT	In-Vehicle Time
LF	Load Factor
MRDH	Authority of the Metropolitan Region Rotterdam – The Hague (in Dutch: Metropoolregio Rotterdam – Den Haag)
NB	Northbound
NS	Dutch Railways (in Dutch: Nederlandse Spoorwegen)
OD	Origin – Destination
OV	Public Transport (in Dutch: Openbaar Vervoer)
PRDM	Percentage Regularity Deviation Mean
PTO	Public Transport Operator
RET	Rotterdam Electric Tram (in Dutch: Rotterdamse Elektrische Tram)
S2s	Station-to-station
SB	Southbound
StD	Standard Deviation
STO	Strategic, Tactical, Operational
TT	Travel Time
UIC	Union Internationale des Chemins de fer (International Union of Railways)
VoT	Value of Time
VoWT	Value of Waiting Time
WB	Westbound
WT	Waiting Time

Abbreviations of names of metro stations

Metro stations are mentioned with their full name as much as possible in this report but for conciseness purposes, they may be abbreviated with three to four letters. The abbreviations that will be used are mentioned in the table below.

Abbreviation	Full name
Aks	De Akkers
Ald	Alexander
Bre	Beurs
Lhv	Leuvehaven
Mhv	Maashaven
Mltw	Melanchtonweg
Rcs	Rotterdam Centraal Station
Rhv	Rijnhaven
Slg	Slinge
Spc	Spijkenisse Centrum
Shs	Stadhuis
Whp	Wilhelminaplein
Zpl	Zuidplein


5621

Chapter 1 Introduction

From a vehicle failure to the degradation of infrastructure or even a targeted attack, unplanned disruptions in public transport can have a considerable impact on passengers. Nielsen (2011) uses the phrase "time-critical environment" to describe the minutes that follow the beginning of a disruption. Disproportionate consequences can follow if a disruption is not properly addressed, especially during peak hours, where both vehicles and infrastructure are close to full capacity. It might result in negative publicity for both the public transport operator and the infrastructure manager, translating into revenue loss. Therefore, in urban public transport systems, where a lot of travellers use the system on a daily basis, an efficient disruption management system is crucial.

This chapter aims at presenting the context of the research and its organisation. First, the problem definition is established and the terminology used in this report is introduced. Following this, the research objective and research questions are laid out. Next, the relevance and the contribution of this study are explained. Then, the scope is presented. The chapter ends with an outline of the research.

1.1. Problem definition

1.1.1. Recurrent versus non-recurrent conditions

In public transport operations, an operations plan is a full planning that describes how resources – crew, rolling stock – are organised for daily operations, and how operational procedures should ideally take place. Both disturbances and disruptions are deviations from the operations plan, yet they are fundamentally different: disturbances refer to **recurrent conditions** and to minor quasi-continuous events while disruptions refer to **non-recurrent conditions** and major events. In particular, a disruption has "*a beginning and an end in time and a location at which its effects are felt*" (Carrel, 2009). Because of the scale of a disruption, it is likely to significantly affect passengers. However, research on disruptions in public transport has not been traditionally focused on the passenger perspective.

1.1.2. The passenger perspective in public transport disruption management

In high-frequency public transport systems, research on non-recurrent conditions was initially focused on resources rescheduling, with the development of multiple models and algorithms, as highlighted by Van der Hurk (2015). For instance in rail transport, the problem of disruption management is usually divided into three categories: timetable adjustment, crews rescheduling and rolling stock rescheduling (Jespersen-Groth et al., 2009). Only in the past three to four years has the focus in research started to shift towards passengers (Van der Hurk, 2015). Thus exploring the impacts of taking the perspective of passengers into account for disruption management might deliver new insights for research.
In a study analysing the interaction between travel demand and capacity constraints, D'Acierno et al. (2012) demonstrated that neglecting passengers in the rescheduling process can produce strategies that may considerably reduce the utility perceived by customers. In a competitive environment, where people have more platforms than ever to express their (dis)satisfaction, public transport operators (PTOs) seek to perform better to satisfy their customers. Consequently, operators are undeniably interested in seeing how the passenger perspective could be better integrated during non-recurrent conditions.

1.1.3. Research problem

So far, research on passengers in public transport has mostly focused on recurrent conditions with a focus on the improvement of reliability via routine service control strategies. Indeed, most travellers tend to give travel time reliability a high importance (Van Oort, 2011). For instance, Van Oort et al. (2015) developed a framework to estimate the average impacts of unreliability per passenger in recurrent conditions. The implementation of such an impact in a transport model showed an improved predication quality of the model, which demonstrates the importance of taking a component much valued by passengers into account.
The lack of reliability in non-recurrent conditions has been shown to affect passengers even more than in recurrent conditions (Uniman et al., 2009), yet research is scarcer when it comes to analysing passenger impacts during disruptions. Two studies are worth mentioning though: one conducted by Carrel (2009) and another one by Barron et al. (2013).

First, Carrel (2009) investigated rescheduling practices carried out by dispatchers (also called traffic/service controllers) of the Central Line in the London Underground metro system. He found that the lack of official policies to respond to certain types of disruption had led dispatchers to develop their own strategies, characterised by a strong preference for manageable and robust solutions. In addition, he pinpointed that these strategies focus purely on the management of resources and are not necessarily the most beneficial for passengers. Therefore, Carrel (2009) concluded that policies should be defined prior to disruptions, to allow for the passenger perspective to be better taken into account. These policies are usually referred to as **pre-planned** or **predefined service control strategies**.
Carrel (2009) used the following methodology to compare rescheduling practices: he compared similar disruptions and their associated response strategies on different days on the Central Line. At the end of his research, he acknowledges that an immediate extension of his work would be to build a predictive model that would allow to assess the performance of different strategies for the same disruption. Yet a few years later, little work has been done to extend Carrel's research. Recently, Babany (2015) noted that "*it is difficult to identify alternative strategies for similar incidents that could be effectively compared and assessed*" (p. 19).

Second, Barron et al. (2013) demonstrated that few PTOs could actually qualify as being passenger-oriented. Barron and his colleagues looked at the link between metrics used to analyse disruptions and actual reliability. Twenty-two metro companies provided them with incident data. Their finding confirms their hypothesis: using supply-oriented metrics (such as frequency of incidents) to analyse disruptions can mislead PTOs regarding the way to mitigate the impact of future disruptions on passengers. Only one metro system was found to measure the most passenger-oriented metrics: the amount of passengers affected by a disruption and their extra travel time. The team of researchers estimated it was no coincidence that it was also the most reliable metro system of the group.
Anderson et al. (2013) argued that the lack of passenger-oriented incident metrics is mostly due to the difficulty to collect relevant data. Although limitations still exist, technology has evolved in the past few years and smart card data for instance have tangible applications at the operational level (Pelletier et al. (2011). Van Oort & Cats (2015) show that such data could effectively contribute to support both operational and design decisions for PTOs. Therefore, in a passenger-focused context, it can be argued that ignoring such sources may lead to missed opportunities.

As already mentioned in sub-section 1.1.1, multiple optimisation algorithms have been developed in the literature in the past few years to investigate passenger-oriented rescheduling processes for disruption management. The passenger perspective was taken into account by including variables such as passenger travel time and waiting time in objective functions, as summarised by Carrel (2009). However, he notes that despite the relevance of these studies, their real-life applicability is limited. Indeed, service controllers face a wide range of other variables that can be complicated to encapsulate together in an algorithm: uncertainties, terminal capacity, safety, crew management, etc. Recently, some studies have investigated the development of algorithms with combined approaches: passengers/timetable (Cadarso et al., 2013) and passengers/rolling stock (Veelenturf, 2014). Even though such algorithms are deemed essential as decision support systems (Kroon & Huisman, 2011), Carrel (2009) underlines that most studies producing algorithms do not necessarily fully acknowledge the complexity of dispatchers' environment.

To sum up, the following gaps are identified:

- So far, most of the research on passengers in public transport has focused on recurrent conditions.
- In public transport systems around the world, service control strategies for non-recurrent conditions are not necessarily as passenger-oriented as they could be.
- This can be accounted for by multiple factors, notably the fact that technical data has been available since longer than passenger data. In this context, the multiplication of available passenger data can make it easier to take the perspective of passengers into account: not using such data can be viewed as an untapped potential.
- In the past few years, multiple researchers took the perspective of passengers into account through the development of advanced rescheduling algorithms. However, they do not necessarily fully acknowledge the complexity of dispatchers' environment. The growing focus on passengers must not overshadow the other constraints that dispatchers face.
- The impossibility to test, in practice, two different strategies for a single disruption makes the identification of passenger-oriented strategies difficult. Comparing and assessing alternative strategies for non-recurrent conditions is thus a real challenge, as highlighted by Carrel (2009).

1.1.4. Case study

A case study is used to illustrate the approach taken throughout this research. This case study is conducted within the RET, the main public transport operator of Rotterdam. The RET operates metros, tramways, buses and ferries. To allow for more expertise within the limited timeframe available to conduct the research, the focus is placed on one of the modes of transport that the RET operates: the **metro**. This choice is made given the extensive use of the metro network: during a regular working day, around 54% of all check-ins are done in the metro system. In addition, little passenger-oriented research was conducted on metro systems (Babany, 2015). Public transport users in Rotterdam have been making use of a contactless smart card since 2005, and valid for all public transport operators in the Netherlands since 2012 (Van Oort et al., 2014). Both origins and destinations of passengers within each mode are registered.

In accordance with the context described in the previous sub-sections, the RET would like to know how to integrate more the passenger perspective into their rescheduling processes during disruptions. The RET has already predefined service control strategies for disruptions in the metro, each strategies being made up of multiple **service control measures** (or actions/interventions). Yet the traffic control centre and managers working on disruption management acknowledge that the passenger perspective has never been formally taken into account in the design of the predefined strategies; the full analysis is presented in Chapter 4. Besides, there is also a **real-time decision component** in which the passenger perspective may be even more difficult to take into account, as underlined by Carrel (2009).

1.2. Research objectives and research questions

1.2.1. Research objectives

This study aims at closing the gaps mentioned in sub-section 1.1.3. It elaborates mostly on the studies conducted by Van Oort et al. (2015) and Carrel (2009). This study aims at extending their approach to evaluate the impacts of alternative service control strategies on passengers in non-recurrent conditions, and thus assessing to what extent the passenger perspective can be integrated to rescheduling practices, while bearing in mind the other variables that dispatchers have to consider.
The metro system of Rotterdam is used as a case study.

The main **theoretical objective** of this study is to develop a methodology to assess service control strategies from a passenger perspective, *by* using a combination of vehicle and passenger data and *by* using a simulation model to test various strategies for a single disruption.
The main **practical objective** of this study is to help the RET to see in what way passengers could be more taken into account in their rescheduling practices, *by* testing alternative strategies and assessing them from a passenger perspective, without forgetting the multiple variables that dispatchers have to consider.

1.2.2. Research question

In order to achieve the aforementioned objectives, the following research question is formulated:

Research question
How can service control strategies used in non-recurrent conditions in a public transport system be developed and improved when the passenger perspective is taken into account?

The nature of the sought improvement remains, at this stage, open. The perspective of passengers that is chosen in this study will determine on which criteria service control strategies for disruptions are improved. To be able to answer this research question, eight sub-questions are formulated, already giving a first glance at the outline of the research. They are equally divided into two categories: theoretical/methodological sub-questions and practical sub-questions, related to the case study.

A Questions: Theoretical/methodological sub-questions

First and foremost, understanding what the "passenger perspective" means is crucial, hence the following sub-question:

> **A1.** What is "the passenger perspective" within the framework of a public transport system and how is it currently assessed in literature??

Next sub-question deals with service control measures that can be used as strategy components to address disruptions:

> **A2.** In theory, what are the measures that can be used by dispatchers to address a disruption?

The two following sub-questions target the methodological core of the research itself:

A3. What are the impacts that would assess best the inconvenience experienced by passengers?

A4. With what methodology should these impacts be assessed?

B Questions: Practical sub-questions related to the case study

Before applying the developed methodology to a case, getting a good understanding of the system is crucial. It allows to see the bigger picture before diving into details:

B1. How are operations and disruption management currently organised for the metro of Rotterdam?

Next sub-question aims at making an analysis of the current situation at the RET, applying the developed methodology:

B2. For the selected case, how does the current predefined service control strategy perform?

Although the answer to B2 is case-specific, a generalisation will be made.
Then, alternative strategies are developed and assessed:

B3. Which alternative strategies could be developed and how do they perform when assessed by the developed framework?

The last sub-question aims at shedding light on the other variables that dispatchers need to consider when performing rescheduling:

B4. What are the challenges for the implementation of passenger-oriented service control measures in non-recurrent conditions?

1.3. Relevance and contribution of the study

The **scientific relevance** of this research can be explained by exploring the current scientific literature in terms of disruption management. Most of it is meant either for airlines or for railway operators and their infrastructure managers. This is reflected by practices of these companies, which are already quite advanced. For instance, the contingency plans of the main Dutch train operator NS vary depending on the time of day (Ghaemi & Goverde, 2015) unlike predefined strategies at the RET. In comparison, urban public transport systems and especially metro systems have attracted less attention, possibly due to:

- First, the apparent lower complexity of the operations. This may be due to the fact that both infrastructure and operations are often managed by the same company.
- Second, the variability in characteristics of metros over the world, which makes it difficult to generalise an analysis or a solution. For instance, just for the network topology, Derrible and Kennedy (2010) used three indicators to make a classification of metro systems: state, form and structure, each being again divided into three categories. But many other differentiating characteristics exist: the type of operations, how infrastructure is shared (or not), etc.

Although metro systems can benefit from the outcomes of railway transportation studies, they also have some differentiating characteristics, such as a relative small spacing between stops and a high frequency (one train every three minutes in a network section in Rotterdam). To the author's knowledge, the only studies available in scientific literature for disruption management in the network of Rotterdam are that of Both (2015) and Yap (2014). This study will therefore provide new insights, both for the metro of Rotterdam and for metro systems in general, on the theme of passenger-oriented rescheduling strategies in non-recurrent conditions.

From the scientific relevance come the **scientific contributions**. The first one results directly from the main theoretical objective: it is a methodology meant to assess rescheduling measures from a passenger perspective. A second deliverable is a model that allows for alternative strategies to be modelled. A third deliverable is a literature review of service control measures, with a special focus on the impacts of each of these measures on passengers.

The **societal relevance** of this study lays in the fact that it can benefit both passengers and public transport operators, here the RET. The findings of this research can benefit passengers in the sense that the study enhances their key role as "sole judges of service quality" (Berry et al., 1990). It can also assist the RET as it gives the operator another perspective for disruption management that fits well within their business plan "De Perfecte Reis" (The Perfect Trip) and their motto "Aardig onderweg" ("On the way in pleasant conditions").

From the societal relevance come the **practical contributions**. The first one is an analysis of how passenger-oriented current rescheduling practices for non-recurrent conditions are. The second one is a set of recommendations to the RET on how to take more into account the passenger perspective in their strategies to address disruptions.

1.4. Scope

1.4.1. Levels of decision

The focus of this project lies at the operational level, i.e. decisions with a relatively short-term horizon. However, these decisions are part of a bigger system and this thesis seeks to acknowledge the **bigger picture** in disruption management (see sub-questions B1 and B4, and their answers later on in the report). The organisational framework formalised by Van de Velde (1999) allows for a better understanding of decisions and their related timeframes within the public transport production process. The work of public transport companies can be divided into three levels. Table 1-1 provides a short description of each level as well as decisions that have to be taken at each stage. The approach used by Van Oort (2011) is chosen to describe each level.

Table 1-1: The STO model for the public transport production process (Van Oort, 2011).

Type of process	**Type of level**	**Typical timeframe**	**Input**	**Output**	**Actors**
Planning	**S**trategic	Long term (>2 years)	Political ideas, trends, existing infrastructure.	Service and infrastructure network, capacities.	Authority, operator.
	Tactical	Medium term (1-2 years)	Network, crew and fleet constraints.	Crew, fleet and public schedules.	Operator, unions.
Operational	**O**perational	Short term (days, real-time)	Network, schedules, available crews and fleet.	Actual public transport services.	Passengers, drivers, dispatchers.

1.4.2. Phases of a disruption

A disruption is made up of two main phases, as displayed in Figure 1-1. First comes the congestion management or **incident phase**, which is when dispatchers allocate capacity in such a way that the peak demand due to the disruption can be smoothed. It is the phase from the start of the incident until the cause of the disruption is resolved. Moore (2003) demonstrated with a real-life case that the incident phase is where passengers are impacted the most. During the incident phase, a strategy is implemented. It may be withdrawn when the cause of the disruption ends or later. Second comes the (service) **recovery phase**, when traffic controllers work to bring the system back to a target state, usually the service plan. Dispatchers may make use of different service control actions for each phase.

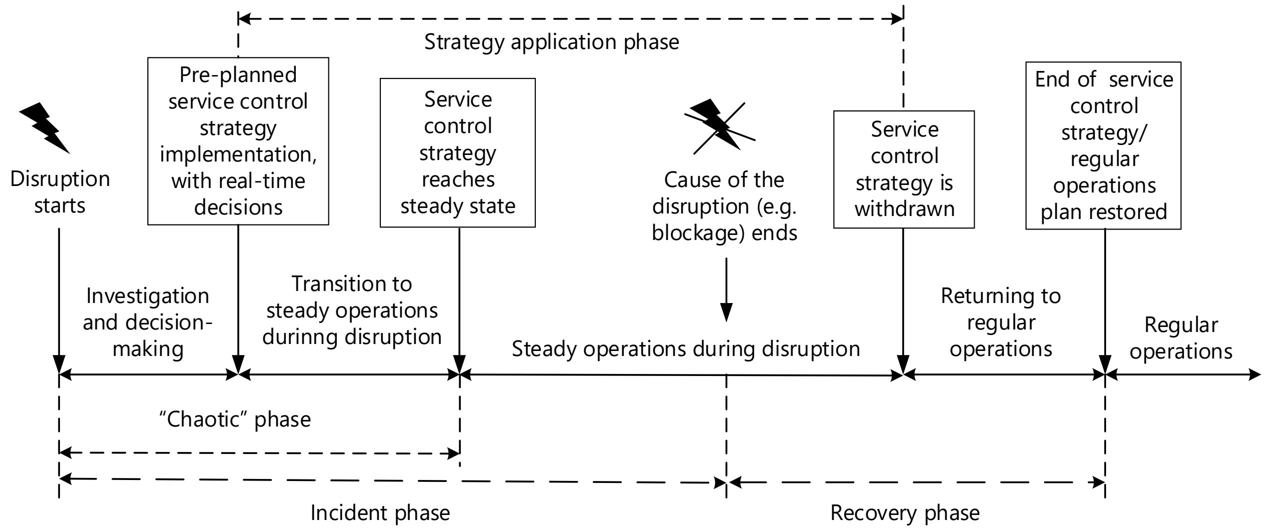


Figure 1-1: Phases of a disruption (adapted from Chu & Oetting (2013)).

The focus of this research is placed on the incident phase and the strategy applied during this phase.

1.4.3. Case study

With the 2016 metro network of Rotterdam, there are 204 predefined service control strategies for potential disruptions, each one corresponding to one or several track portion(s), covering the whole network but often non-overlapping. One specific disruption that happened in the metro network of the RET, on which dispatchers used one of these predefined strategies, will be selected and used to test the developed assessment framework. There are full blockages and **partial blockages**, however it is deemed more interesting to focus on the latter since there is arguably more room for improvement when at least one of the tracks is available.
The alternative strategies that will be developed are therefore most relevant to other rail-bound urban public transport systems. However, the assessment framework developed in this research to quantify passenger impacts could be used in other public transport systems.

1.5. Thesis structure

The outline of the study is described in this section and can be visualised in Figure 1-2, where each sub-question is associated with a chapter.

This thesis starts with a literature review in Chapter 2 on three of the main topics of this thesis:
- The meaning of the passenger perspective in public transport systems and the existence of methods to assess situations from this perspective,
- The disruption management process in public transport systems,
- Service control measures, their applications, restrictions and impacts on passengers.

In each of these topics, an overview of the state-of-the art research is provided, with examples coming from urban public transport systems but also heavy railways. By the end of Chapter 2, the reader should have an increased understanding of the context of the research and the knowledge gaps that it aims at filling.

In Chapter 3, the assessment framework is developed. This chapter starts in a broad way and progressively zooms in on the theoretical development of the assessment framework. First, the method used to develop the framework is explained, presenting the guiding thread of the study. Second, the theoretical core of the framework is laid out. Then, a zoom into both scales of assessment is done. By the end of Chapter 3, the reader should have a clear overview of the theoretical foundations of the assessment framework.

Chapter 4 serves to introduce the case study, in order to get a better understanding of the bigger picture of the system where the assessment framework will be applied. The case study for the framework application is also selected and presented.

In Chapter 5, the assessment framework is applied to the selected disruption, to test its applicability and the relevance of its outcomes. A validation step comes as a conclusion of the development of the assessment framework. In addition, some complementary analyses are conducted, such as a sensitivity analysis.

In Chapter 6, a generalisation of the results obtained through the application of the assessment framework is provided. Then, this generalisation is applied to the investigated service control measures, echoing to the literature review. This is meant to bring insights to other public transport operators on a number of measures. In a third part, the other impacts that were not explored in the framework but that remain important to acknowledge are discussed, in relation with the diagnosis of operations and disruption management system at the RET done in Chapter 4.

Chapter 7 presents the main conclusion, the practical implications for public transport operators, recommendations for the RET and suggested recommendations for the improvement of the assessment framework and for further research.

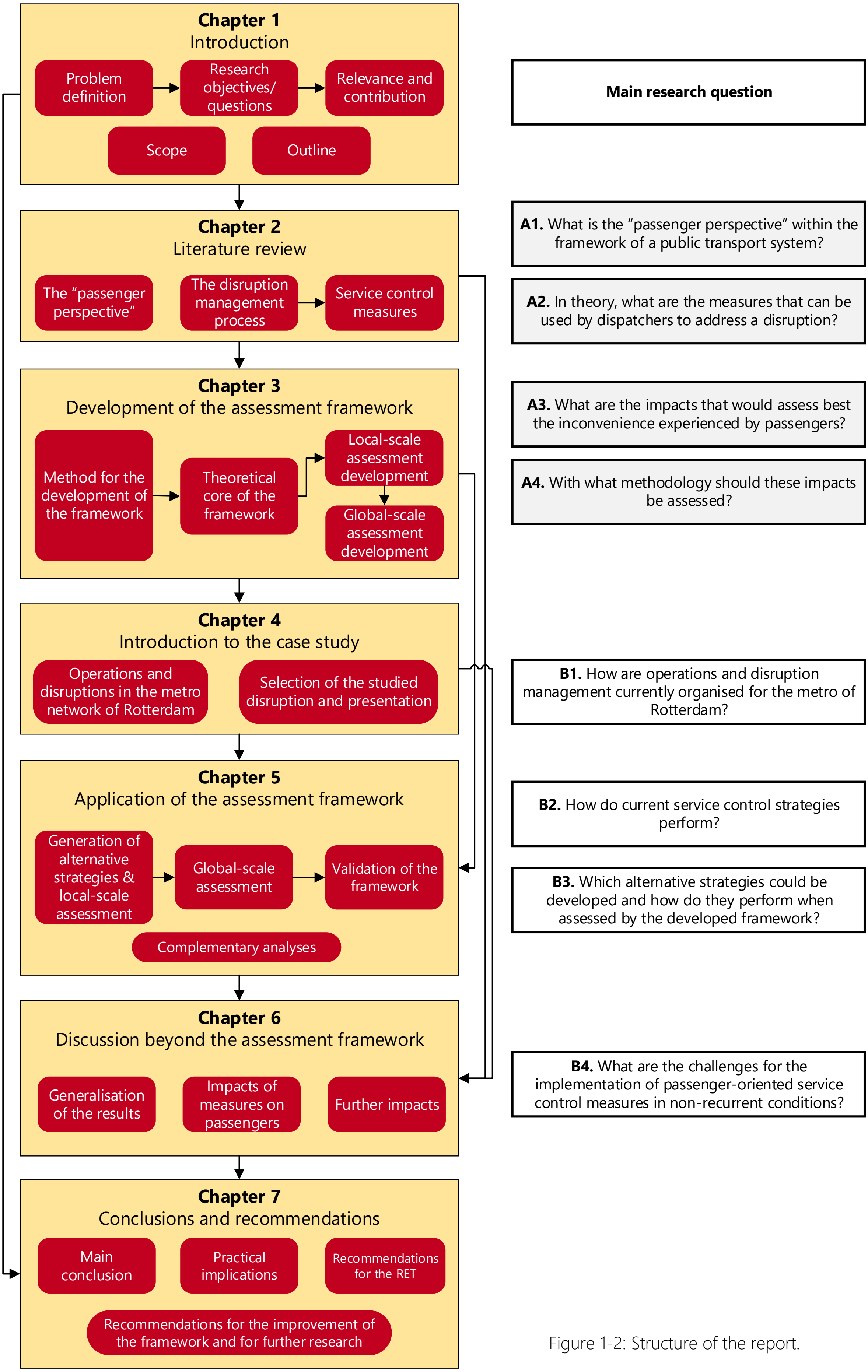


Figure 1-2: Structure of the report.

Chapter 2 Passenger perspective and disruption management practices in public transport systems

This chapter presents the literature relevant to the contextualisation and the understanding of this research. It aims at answering the two following sub-questions:

A1. What is "the passenger perspective" within the framework of a public transport system and how is it currently assessed in literature?

A2. In theory, what are the measures that can be used by dispatchers to address a disruption?

The chapter starts with a discussion around the phrase "the passenger perspective", frequently mentioned in this study, in section 2.1. Evaluation methods of the passenger perspective are also discussed. This section therefore aims at answering sub-question A1. Section 2.2 serves as an introduction to the environment in which traffic controllers work and in which service control strategies are being used. Then, section 2.3 makes an inventory of service control measures and describes how each of them impacts passengers according to previous studies, thereby answering sub-question A2. The chapter ends with a summary of the main findings of this literature review.
Literature from various public transport modes is used in this chapter, with a special focus on rail-bound modes.

2.1. The passenger perspective in public transport systems

The understanding of what "the passenger perspective" means requires to take into consideration multiple aspects, starting with the identification of needs of passengers. This is explained in sub-section 2.1.1. Next sub-section then elaborates on the evaluation of the passenger inconvenience as currently done in research, both in recurrent and in non-recurrent conditions. The section ends with a short conclusion.

2.1.1. Meaning of "the passenger perspective"

Public transport passengers are consumers. Like all consumers, they have needs that they expect the producer or service provider to be aware of (Grönroos, 1979). In analogy to the hierarchy of Maslow (Maslow, 1954), Van Hagen et al. (2000) have ranked the importance of the needs of passengers as a pyramid, as shown in Figure 2-1. It reflects the perception of the quality offered by the operator.

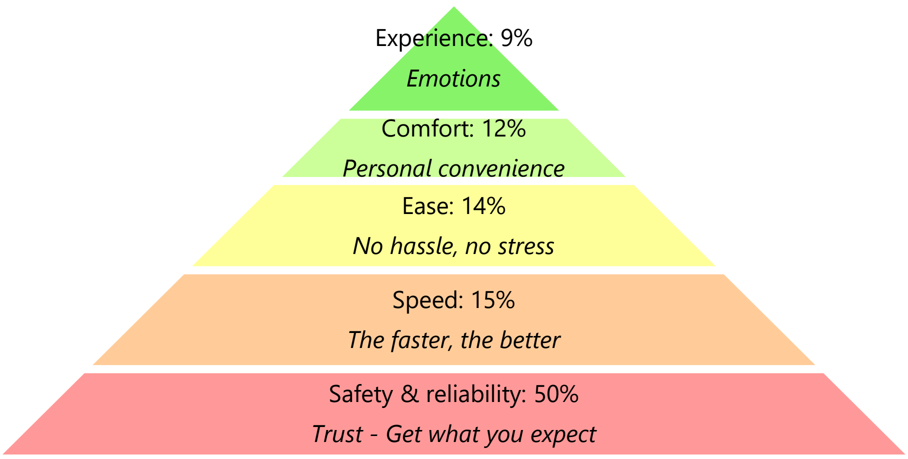


Figure 2-1: The hierarchy of public transport passengers' needs (adapted from Van Hagen et al. (2000)).

At the base of the pyramid lies safety and reliability. It means that passengers want a safe and secure journey that matches the quality aspects they expect, such as travel time. These are considered as the basics, but passengers become increasingly satisfied as they perceive the journey to be fast and stress-free, e.g. with logical and unambiguous travel information. Experience (daylight, pleasant smells for example) and comfort (sheltered waiting areas for instance) make the difference between an indifferent/mildly satisfied customer and a satisfied one.

2.1.2. Evaluation of the passenger inconvenience in public transport systems

Recurrent conditions

According to Goodman & Murata (2001), the evaluation of the inconvenience of passengers must be related to their expectations: of speed, of reliability, of comfort, etc. Expectations are not necessarily based on a schedule. Due to stochasticity in recurrent conditions, a waiting time scheduled to be 5 minutes may be closer to 6 minutes. Regular users may barely register the extra minute of waiting time, because they have changed their expectations.

Travel time (measure of speed) and measures of reliability are mostly used in the literature as proxies to describe the passenger inconvenience. Van Oort et al. (2015) listed the three main categories of impacts that public transport passengers may experience, in an aggregate way, in recurrent conditions. They all relate to the needs shown in Figure 2-1:

1. Impact on the duration of travel time components, such as waiting time (WT) and in-vehicle time (IVT). This category of impacts relates to speed and reliability, and ease to a larger extent (stress of being late for instance).
2. Impact on passenger perception of the used public transport mode, depending on the variability of travel time components. This category relates to reliability and ease.
3. Impact of crowding that affects the level of comfort of passengers. This translates into two sorts of inconveniences: an extension of travel time components (first category of impacts) and degraded comfort (e.g. no seat). Regarding the hierarchy of needs, this category relates to comfort mostly, but also, to a certain extent, to speed, ease and reliability.

Van Oort et al. (2015) used impacts from the first and the second categories to assess service reliability in recurrent conditions. In the past few years, research on the development of passenger-oriented reliability measures has flourished (see Wood (2015) and Uniman (2009)). Yet none of these developments allow for **a systematic evaluation of the benefit of operational measures on passengers**. Fairly recently, Fadaei & Cats (2016) have precisely intended to bridge this gap. They observed that in the past fifteen years, empirical studies of bus design and operational measures considered only vehicle-related performance while little attention was given to impacts on passengers. Consequently, they proposed an assessment framework using both vehicle and passenger data (resp. AVL – Automatic Vehicle Location – and APC – Automatic Passenger Count – data) to evaluate both operator and passenger benefits of various measures, comparing indicators before their implementation and after. Indicators used for passenger impacts were: walking time, WT and perceived and effective IVT. Perceived IVT relates to crowding: the more crowded a vehicle, the longer IVT is perceived to be. This framework was tested in a high-frequency urban transport system in recurrent conditions. It does not seamlessly translate to non-recurrent conditions since it does not allow to compare and assess different strategies for the same disruption, yet it provides a good basis.

Non-recurrent conditions

In disrupted conditions, recurrent conditions are often assumed to match passenger expectations and are thus taken as the reference point. Most studies assessing passenger inconvenience in non-recurrent conditions use a mix of AVL and APC data to determine the value of one or two passenger indicators related to travel time and reliability in disrupted conditions, and compare these to the values in recurrent conditions – see Uniman (2009) for instance. To the author's knowledge, the only study that looked into evaluating the impacts on **passengers** of **different measures** used as a response to a certain type of historical **disruption** is that of Carrel (2009). The passenger impacts he considered are IVT and WT, as well as amounts of transfers. He found that in spite of a structural inconvenience during disruptions that passengers will experience and over which PTOs have little power, there are **passenger-friendly ways to address a disruption**. He demonstrated based on historical data that for similar disruptions on the Central Line of the London Underground, two approaches would lead to a completely different impact on passengers. Figure 2-2 illustrates this approach.

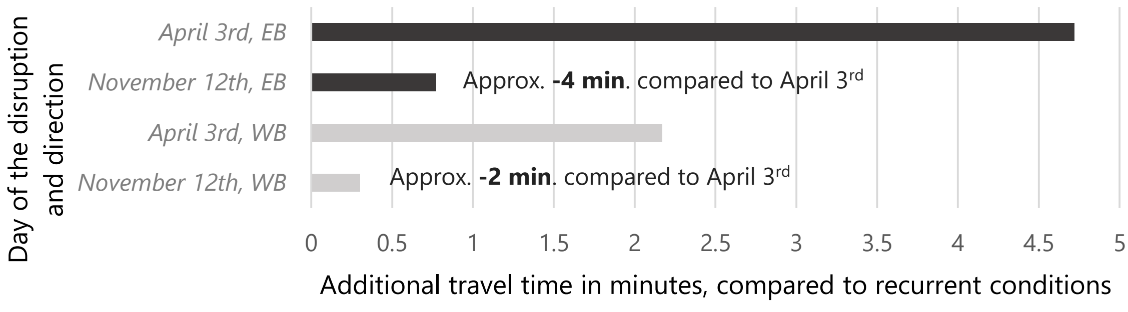


Figure 2-2: Average additional minutes of travel time per passenger on each day (Carrel, 2009). EB stands for eastbound, WB westbound.

On April 3rd, trains were short-turned and diverted in compact groups while on November 12th, short-turned and diverted trains were much more spread. This led to a difference in travel time as shown in Figure 2-2. Given the hierarchy in Figure 2-1, if passengers were also properly informed on November 12th, it is likely that they were not overly dissatisfied with the service despite the disruption. This demonstrates that PTOs do have the power to make a difference in the way they address the disruption and can limit the negative impacts on passengers.

The approach of Carrel (2009) is based on historical data but he suggests to extend it to predictive operations, i.e. **to predict, given a certain, fixed disruption, which strategy could be more beneficial to passengers**.

2.1.3. Conclusion of the passenger perspective in public transport systems

Taking the passenger perspective means using impacts that directly relate to passenger needs to measure how inconvenienced they are, and using these insights to take action. In non-recurrent conditions, passenger inconvenience is often measured in reference to recurrent conditions. Three main categories of impacts exist. In the past few years, a few studies have already developed some more or less elaborated assessments to evaluate passenger inconvenience but none so far has focused on the effects of various measures in response to a given disruption.

2.2. Disruption management process

This section explains first the different types of considered disruptions, in sub-section 2.2.1. Then the disruption management process in a public transport company is presented in sub-section 2.2.2. A special focus on the literature dealing with predefined strategies as a response to disruptions is done in sub-section 2.2.3 and the section ends with a short conclusion.

2.2.1. Types of disruptions

Causes of a disruption can be exogenous or endogenous to the system. The former are beyond the direct control of the PTO while the latter can be influenced by the PTO, though employee discipline or maintenance policies for instance. In spite of the large range of possible disruptions, they can be classified in a finite number of categories. Carrel (2009) provides an example for rail-bound systems:

1. Non-moving line blockage, which is when a vehicle is not able to move beyond a certain station or point of the line. This causes a partial blockage. In high-frequency systems, it is generally not possible for a train to overtake another one without causing delays.
2. Slow-moving line blockage, coming from a defect vehicle which is only able to proceed at a limited speed, causing delays as well.
3. Single train delay, caused for instance by a train departing late from the depot.
4. Train blocked in terminal, for which the effects on other trains depend on the terminal configuration. If the terminal has more than one reversing track, this will result in reduced terminal capacity but not a complete blockage.
5. Reduced infrastructure capacity, which, unlike the other categories, does not necessarily involve a train. Capacity may be reduced on one track or both (complete blockage), due to a power failure for instance.

From this classification, three main types of effects on the service emerge: a gap in service, general lateness, an incorrect sequence of trains or a combination of these (Carrel, 2009). Which measure is used as a response to a disruption depends on these effects and the cause. Section 2.3 discusses service control measures and will link these types of disruptions to service control measures.
This study focuses on partial blockages, encompassing the first and the last categories of disruptions.

2.2.2. Description of the disruption management process

Kohl et al. (2007) state that disruption management is "*an ongoing process rather than a single problem that can be formulated explicitly*." Figure 2-3 presents a high-level view of the disruption management process. When an unplanned event occurs, dispatchers either notice it on their monitoring screens or get notified by a driver for instance. Then, they need to make a decision whether or not to act immediately. This is a critical moment. Studies have shown that the more dispatchers wait to take action, the more negative the impact on passengers is (Moore, 2003; Shen, 2000). The reason why dispatchers may choose not to act is because the issue could potentially be solved within a few minutes. **Uncertainty** is therefore inherent to the work environment of dispatchers in general, where proactivity and reactivity are entangled.

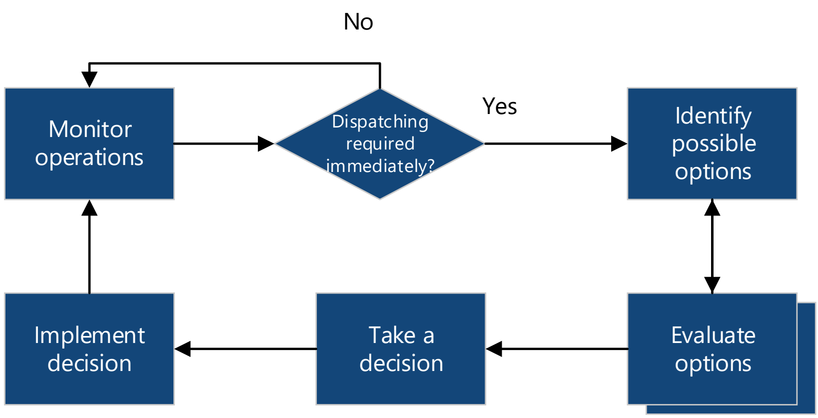


Figure 2-3: High-level view of the disruption management process ((Kohl et al., 2007) and adapted).

In order to make the phases "Identify possible options" and "Evaluate options" as efficient as possible, many PTOs now used pre-planned or predefined service control strategies.

2.2.3. Integration of pre-planned service control strategies within the disruption management process

There are different levels of pre-planning. According to Moore (2003), each level of pre-planning corresponds to certain conditions, as shown in Table 2-1. In particular, she argues that non-recurrent rail blockages – the focus of the case study in this research – require partial pre-planning. It means that elements supporting the decision-making process of dispatchers should be provided, albeit not with too many details (full pre-plan) but with more specifications than guidelines. The latter only present the appropriate underlying approach to a disruption. The levels of pre-planning and real-time decision-making are shown in Figure 2-4. The elements of the pre-planning could highlight capacity issues, suggest single-tracking solutions and make a difference between times of day (Moore, 2003).

Table 2-1: Conditions for levels of pre-planning (adapted from Moore (2003)).

Conditions	Estimated Passenger Impact	**Disruption Type**		
		Rail Blockage, Complete or Partial	Bus Route Blockage	Slow Moving Blockage, Delay
Recurrent	Severe	F	P	P
Recurrent	Moderate	F	P	G
Non-recurrent	Severe	P	P	G
Non-recurrent	Moderate	P	G	R-T
F = Full pre-planning	**P** = Partial pre-planning		**G** = Guidelines	**R-T** = Real-time

It should be noted that **pre-planning does not take away dispatchers' work**: their intervention, tailor-made for each situation, adds a considerable amount of value. They are the ones who identify and evaluate options, and take a decision as depicted in Figure 2-3. Thus, pre-planned strategies represent a complementary support to real-time traffic management, as shown in Figure 2-4.

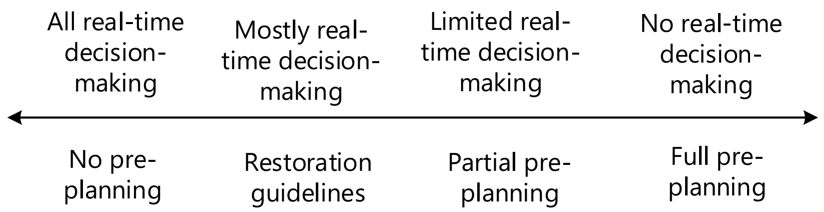


Figure 2-4: Mixes of pre-planning and real-time decision-making levels (Moore, 2003).

Moore (2003) argues that pre-planning has two main advantages:

- It allows for a faster response to a disruption, since time is the primary concern for dispatchers. The faster the response, the fewer impacted passengers.
- The pre-planning process itself requires to sit down and think about all the important issues and potential consequences beforehand, something that may be difficult for dispatchers when a disruption springs out. Managers, analysts and planners may be involved in order to bring various perspectives.

In addition, Chu & Oetting (2013) argue that the standardisation and the anticipation provided by predefined strategies allow for a better communication to passengers because disruptions are addressed in a standard way. However, pre-planning remains a relatively new practice (Carrel et al., 2013).

2.2.4. Conclusion on the disruption management process

Disruptions manifest themselves on a public transport service in a finite number of ways. Using a pre-planned strategy for the disruptions that may severely impact passengers is likely to bring multiple benefits to the disruption management process *and* to passengers: they benefit from quick and well though-out solutions and are better informed through standardised processes.
In the context of non-recurrent railway blockages, a strategy consisting of a mix of partial pre-planning and real-time decision-making is considered to be a good option. The relatively recent interest in pre-planning both in research and in practice reinforces the relevance of this study.

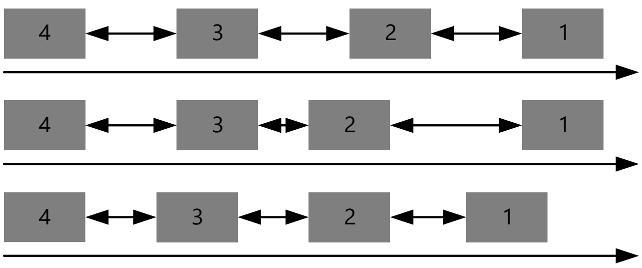
2.3. Inventory of service control interventions

Any strategy is made up of service control measures. Therefore, the most common ones ought to be presented. In addition to listing and explaining each measure, the aim of this section is threefold:
1. To explain for which type of disruption each measure is most relevant and why it works.
2. To present the general conditions for success of each of these measures as found in literature. The type of action that can be taken at the operational level is dependent on conditions that are defined during the planning process. In his PhD dissertation, Van Oort (2011) shows that both the network and the timetable affect the possibility to use certain operational measures.
3. To define broadly how each measure impacts passengers as found in literature.

2.3.1. Speed control measures

Speed control measures are frequently used for routine service control but can also complement other measures for disruption management, particularly during the service recovery phase.

Holding
Holding consists of delaying the departure of vehicles at holding points in order to reduce headway variance. This is commonly used to improve regularity and thus prevent extreme waiting times and loads of passengers. This measure can be used for all types of disruptions, from delays to blockages. During blockages, vehicles can be held upstream to avoid the formation of a queue and downstream to prevent the gap created by the unplanned event from widening. Holding is illustrated in Figure 2-5.



(a) Vehicles drive with equal headways
(b) Vehicle 2 gets delayed. Front headway increases, behind it decreases.
(c) By holding vehicles 1 and 3, regularity is partially restored

Figure 2-5: Holding of a vehicle (adapted from Van Oort (2011)).

In recurrent conditions or at the end of the recovery phase, holding is largely influenced by the amount of slack time in the timetable – applied with a tight schedule, it may negate any benefit of applying

this measure. Besides, redundant infrastructure capacity at the holding point is necessary to avoid blockings (Van Oort, 2011; Wilson et al., 1992).
This measure attracted a substantial amount of interest in research. A relevant study to mention here is that of O'Dell (1997), who found that the best compromise between ease of implementation for dispatchers and effectiveness was to hold a small amount of vehicles that are not full downstream of the blockage. The reader can also refer to the work of Sanchez-Martínez (2015) for an extensive state-of-the-art on the holding measure. Regarding passengers, a trade-off must be made between on-board passengers who suffer from an additional in-vehicle time and passengers who will benefit from a decrease in headway variability (Schmöcker et al., 2005).

Freezing
Freezing is when vehicles are stopped either immediately or at the next station. This is used in case of high uncertainty or/and safety threats, caused by major incidents like a bomb threat or a failure of the traffic control centre. Freezing is perceived negatively by passengers, especially when they are in a vehicle between stops (Paquel, 2011).

Slowing down and speeding up
In urban public transport, slowing down and speeding up are mostly used in routine service control, i.e. not during disruptions, either to increase punctuality or to even out headways. The tight schedule in high-frequency public transport systems does not allow for these measures to be very much used. However, speed optimisation is a recurrent topic in heavy railways, both for conflict resolution and for delay recovery; see D'Ariano et al. (2007) and Vromans (2005) respectively.
Slowing down vehicles requires redundant infrastructure capacity where the speed is being reduced, especially for rail-bound modes, but also for buses, at terminals for instance (Van Oort, 2011). Speeding up vehicles can only be done if the situation is safe enough.
Speeding up is particularly appreciated by passengers while slowing down is less popular, although it may be perceived more positively than a complete standstill (Paquel, 2011).

2.3.2. Station-skipping control measures

Station-skipping control measures are considered to be more drastic than other measures and can have a rather detrimental impact on travellers' experience if information is not communicated clearly enough or if it is provided too late.

Expressing
Expressing means that a vehicle with passengers skips one or multiple stations that it was supposed to serve, thereby allowing for a gap reduction in service and/or to split bunched vehicles. Expressing thus aims at balancing headways and improving service past the end of the express segment. It is considered best to express a vehicle with a long preceding headway, a short following headway and a high passenger load past the expressed segment (Macchi, 1989). Figure 2-6 presents an illustration of this measure.

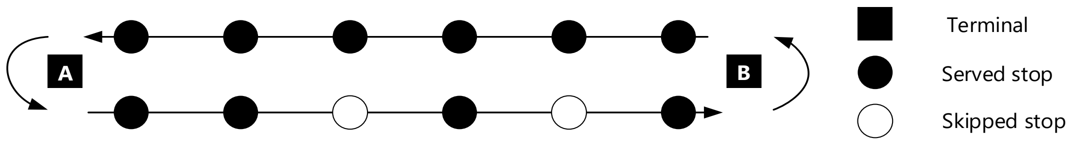


Figure 2-6: Expressing in direction A - B (from Van Oort (2011)).

Shen (2000) highlights that expressing should not be used as the primary strategy in case of a disruption, especially when capacity is already reduced, for it provides little additional benefits over the holding and short-turning combination. An aggressive expressing policy can waste vehicle capacity and is likely to annoy passengers since no one likes to be skipped several times in a row. Therefore, he concludes that expressing should be applied to one or maximum two vehicles during the service recovery phase only in order to avoid overcrowding, with a careful selection of the expressed segment; passenger demand patterns are essential to take into account (Eberlein, 1995). This is also true for deadheading (see below).
In order to quantify the effect of expressing on passengers, Wilson et al. (1992) suggest to distinguish between four categories of passengers that are affected by this measure:

- Expressed passengers, who benefit from a reduced in-vehicle time,
- Passengers waiting downstream, who benefit from a decreased waiting time if headway variance is reduced,
- Skipped segment boarders ("skipped passengers"), who see the vehicle passing by but cannot board it,
- Skipped segment alighters ("dropped passengers"), who have to alight at the station where expressing is initiated or earlier because they are bound for stations within the express segment.

Deadheading
Deadheading means that an empty vehicle skips one or multiple stations which it was supposed to serve. This measure is used to return a late vehicle back to schedule and is therefore more appropriate during the service recovery phase. It may be used occasionally in the incident phase when extra service is needed in the opposite direction, to fill a gap due to a blockage for instance. However, just like expressing, it would not be at the core of a strategy during the incident phase. The two most frequent examples of deadheading situations are illustrated in Figure 2-7 and presented below.

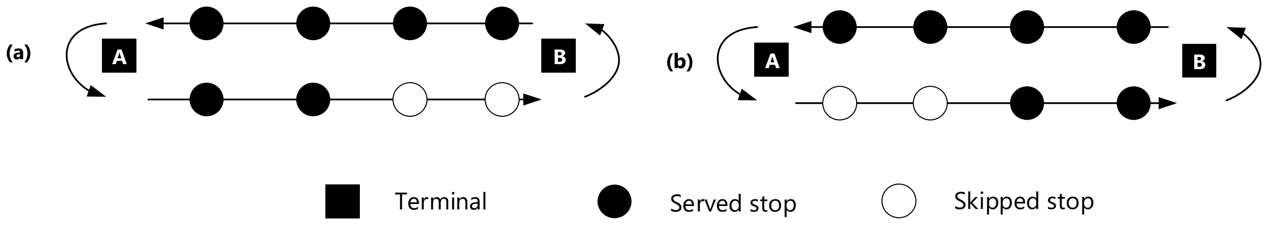


Figure 2-7: Deadheading in direction A – B, two ways.

- In situation (a), passengers are forced to alight at a station. The vehicle then skips following stops until the terminal station where it can depart with more schedule adherence than in a do-nothing situation.
- In situation (b), passengers are prevented from boarding at one terminal. The vehicle then skips a certain amount of stations. Traffic controllers usually find this situation convenient because forbidding boarding at a terminal station is easier than forcing passengers to alight at a station on the line (Wilson et al., 1992). Besides, this situation requires less dwell time at the beginning of the deadheading segment than situation (a).

It can also be expected that, even in situation (a), deadheading results in slightly less confusion for passengers than expressing. Indeed, with deadheading, passengers know that their alighting station will be skipped for sure while it may be unclear with the expressing measure. In general, passengers who belonged to the "expressed passengers" category for expressing become either "dumped passengers" (situation (a)) or "skipped passengers" (situation (b)).

Short-turning

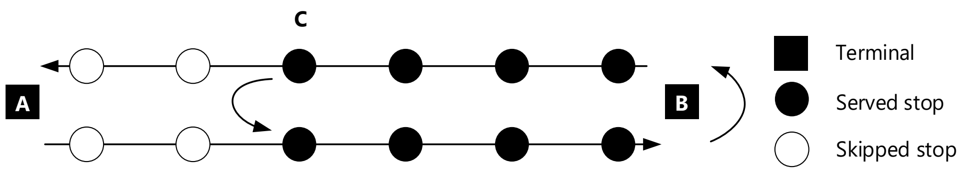
Short-turning is when a vehicle turns to run in the opposite direction before it has reached its terminal, as depicted in Figure 2-8. It is common during the incident phase, when a vehicle short-turns because of a blockage taking place downstream. In addition, this measure can fill a gap in the opposite direction to reduce headway variance or reduce the lateness of a service by shortening its cycle time. The disadvantage of this measure is that it reduces the service at the end of the line and forces passengers to alight and board another vehicle. This measure requires the presence of short-turning facilities that can accommodate the short-turned vehicle(s). This measure is therefore usually easier to apply in road-bound systems than in rail-bound systems.

A substantial amount of research has been produced on short-turning, but mostly within the framework of routine service control as opposed to disruptions (Ghaemi & Goverde, 2015).

Again, Wilson et al. (1992) suggest to distinguish between four categories of passengers that are affected by this measure:

- Reverse direction passengers, who may benefit from an additional service,
- Short-turn point boarders, who are denied boarding and must wait longer,
- Skipped segment boarders, who will never see the vehicle coming and thus experience a longer waiting time,
- Skipped segment alighters, forced to alight earlier than planned.

Figure 2-8: Short-turning at point C (from Van Oort (2011)).



Diversion

In networks with branches, vehicles with a destination on one of the branches may be diverted in order to serve another branch. Figure 2-9 illustrates this intervention. This measure can be taken either because the original destination cannot be reached (e.g. due to a blockage), or to fill a gap in service in a certain branch, or to reduce the cycle time of a trip if the branch of diversion is shorter than the original branch, to catch up with a delay. This measure can therefore be used during the incident phase and during the service recovery phase. It requires to have a junction between a trunk portion and at least two branches in the network. The effect on passengers travelling to the original branch is similar as if the vehicle were short-turned.

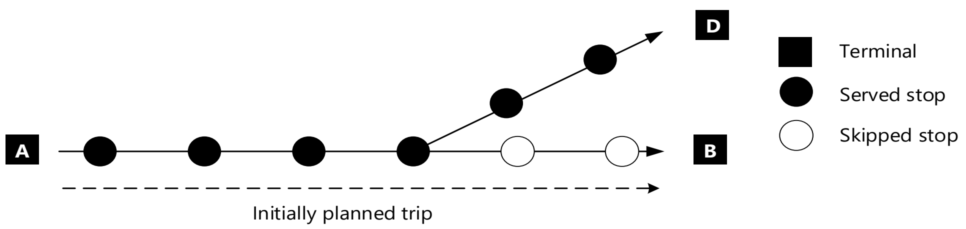


Figure 2-9: Diversion of a vehicle from its initially planned destination (one direction depicted only).

Detour

A detour means using another route than the one that was scheduled for a certain distance and may entail skipping some scheduled stops along the way, as depicted in Figure 2-10. It is mostly used when a blockage occurs along the line. This measure requires to have redundant infrastructure, which is why it is more relevant in bus and tram networks than in metro networks, where the structure presented in Figure 2-10 can rarely be found. The reader can refer to Yap (2014) and Roelofsen (2016) for an analysis of a detour of tram lines that takes into account the effects on passengers.

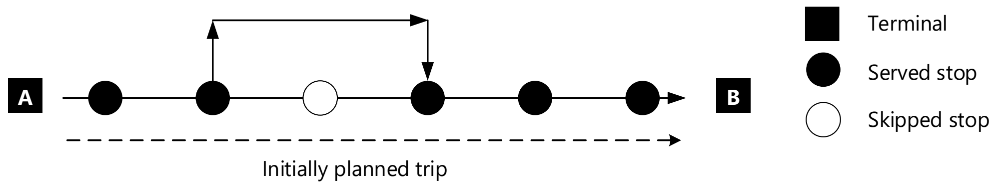


Figure 2-10: Detour of a vehicle from its initially planned trip (one direction depicted only).

Cancelling
Cancelling trips may occur when there is a shortage in resources but it can also be a measure used for disruption management: dispatchers may remove a vehicle for one or multiple trips to reduce congestion during the incident phase, due to a slow-moving line blockage for instance, or to put late vehicles back on schedule during the service recovery phase. The impact on passengers depends on the scheduled frequency on the line where the trip is removed. In a low-frequency line, passengers may need to wait for an inconveniently longer time than passengers in a high-frequency line.

2.3.3. Other measures

Since the measures described below fit in neither of the two categories previously mentioned – speed control measures and station-skipping control measures – they are called "other" measures.

Gap vehicle addition
Adding an unscheduled trip can be an option to provide extra capacity and/or to fill a gap caused by a disruption. A spare vehicle or a vehicle from another line may be used. However, using this control measure is not always possible due to multiple reasons:

- It requires planning. Spare crew and spare vehicles need to be available within a reasonable amount of time.
- PTOs that operate within the framework of a concession may not be allowed by their authority to add unscheduled vehicles to their daily operations due to contract clauses.

This measure is more typically implemented during the service recovery phase because adding a vehicle during the incident phase where dispatchers strive to avoid congestion is uncommon (Carrel, 2009). The impact on passengers of this measure is discussed with next measure.

Non-rail-bound shuttle service implementation
In disrupted rail networks, when tracks on both sides of a segment are unavailable (complete blockage), or simply when demand is exceeding supply by far, implementing a shuttle service with buses may be the only solution, to fill the gap as illustrated in Figure 2-11. However, cities where the public transport offer is dense, such as the inner city of Paris, do not offer this kind of service in general (Paquel, 2011). A condition for success of this measure is to be able to dispatch shuttles within a reasonable amount of time.

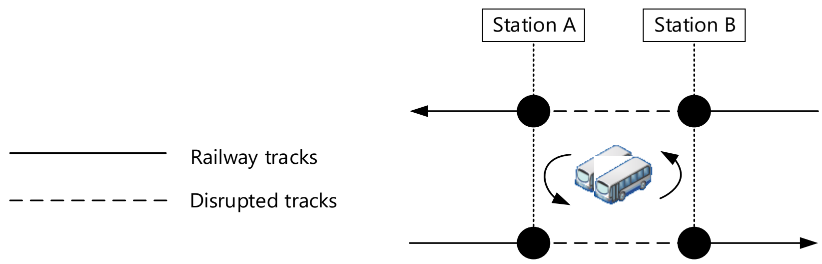


Figure 2-11: Bus shuttle service implementation due to a complete blockage in a rail-bound network.

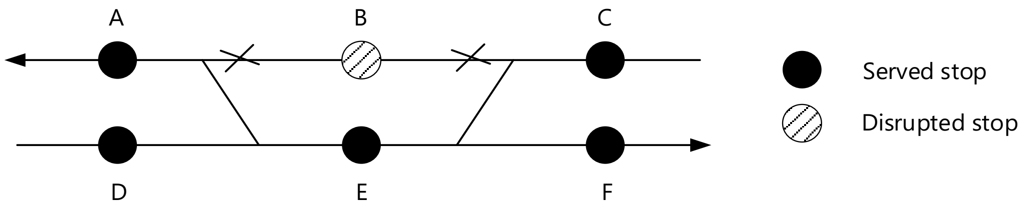
Such a measure is mostly used during the incident phase but it may be extended to the beginning of the service recovery phase to alleviate the transition.

Both the shuttle service implementation and the gap vehicle addition are measures that come as a replacement of a previously planned service. They are rather difficult to quantify from the passenger perspective for the following reasons:

- They come from the cancellation or the overcrowding of a service, where passengers experience an inconvenience I. These measures are most likely preferable to a do-nothing scenario. Yet they are not expected to fully compensate for the inconvenience I, since both of these measures entail at least one transfer more than during normal conditions, and additional waiting time.
- They are heavily context-dependent; research on these topics does not necessarily differentiate between different groups of passengers as was done for short-turning, expressing, etc. Studies rather concentrate on optimal organisational and network designs to minimise passenger inconvenience (usually waiting time and/or in-vehicle time). For respective examples, the reader can refer to Fang & Zeng (2015) and Jin et al. (2014). This will be further detailed in Chapter 5, page 82.

Single-track operations

This measure is used in rail-bound systems. For instance, a metro system usually consists of two parallel tracks in two different directions with some crossover tracks connecting them. Single-track operations may be used as a control measure when one track is unavailable and on the condition that crossover tracks are available and accessible on both sides of the disruption. This measure is therefore typical during the incident phase, when there is a partial blockage. This measure can be implemented in various ways, by playing on the sequence of trains sent in one direction in a row, as depicted in Figure 2-12. This type of measure can only be implemented when the situation is deemed to be safe enough. Consequently, metro systems with a safety system which is not adapted to this type of operations (for instance if changing track direction is difficult) are less likely to use this measure.



Basic structure:

D – E – F - … - C – E – A – … - D – E – F - … - C – E – A - …

Figure 2-12: Single-track operations when B is unavailable (adapted from Song (1998)).

In general, when the term *single-track operations* is mentioned in literature, it refers to the scheduling problem on lines with single-track portions. The only studies of the author's knowledge dealing with single-track operations within the framework of rescheduling because of a partial blockage are that of Xu et al. (2015), Song (1998) (both for metro systems) and Louwerse & Huisman (2014) (in heavy railways).

Xu et al. (2015) and Louwerse & Huisman (2014) used optimisation models in which they did not take any passenger-related performance indicator into account.

Song (1998) determined for each station in each direction of the Red Line of Boston's metro the best strategy in case of a 20-minute partial blockage, based on the maximum throughput capacity. He did consider single-track operations as depicted in Figure 2-12, as well as short-turning loops on both sides of the disruption and shuttle operations. However, aside from choosing the strategy with the maximum throughput capacity, Song (1998) did not consider further impacts on passengers.

2.3.4. Conclusion of the inventory of service control interventions

This section has presented the measures that dispatchers may apply during the disruption management process and their impact on passengers. Their prerequisites were also presented, as shown in Table 2-2. Empty cells mean that no specific condition is required. Brackets mean that the item is not necessarily a mandatory prerequisite.

In the context of a high-frequency rail-bound transport system such as a **metro system**, freezing, slowing down, speeding up and detours are not much used. Hence they will no longer be mentioned in this report, where the case study is a metro system. Table 2-3 summarises the most common implementation phases of each measure, as deduced from the literature review. Table 2-4 makes an inventory of how each measure roughly affects passengers according to literature. The description of the type of impact is only given with a (+) or a (-) sign, meaning that groups of passengers are on average respectively positively or negatively impacted by the decision. When no relevant study with the passenger perspective was found, Table 2-4 explicitly mentions it. This overview reveals that in most cases, a service control measure is always a trade-off between different groups of passengers. Analysing impacts on different groups of passengers therefore provides meaningful insights. Early studies focusing on passenger impacts already adopted this approach, like Deckoff (1990).

When reading Table 2-2, Table 2-3 and Table 2-4 together, one can see that all measures used during the incident phase and that have an impact on passengers also have a prerequisite at the strategic level, except cancelling, which can be quite drastic from a passenger perspective. Therefore **the incident phase of a disruption can be particularly complex for dispatchers**, with multiple fixed constraints and trade-offs to make between groups of passengers. Besides, this inventory has shown that single-track operations, although relevant for the incident phase in case of a partial rail blockage, was never studied from the passenger perspective. Replacement measures, also relevant for rail blockages, can be more difficult to assess than measures that remove a service.

Table 2-2: Inventory of service control measures and their prerequisites (inspired and adapted from Van Oort (2011)).

Type of measure	**Service control measure**	**Prerequisites**	
		Strategic level	*Tactical level*
Speed control	Holding	Redundant infrastructure capacity	Slack time
	Freezing		
	Slowing down	Redundant infrastructure capacity	
	Speeding up		Slack time
Station-skipping	Expressing		
	Deadheading		
	Short-turning	Short-turn facilities	
	Diversion	Junction	
	Detour	Redundant infrastructure capacity	
	Cancelling		
Other	Gap vehicle addition	Redundant fleet and crew	
	Non-rail-bound shuttle service implementation	(Redundant fleet and crew)	
	Single-track operations	Crossover tracks (Adapted safety system)	

Table 2-3: Implementation phase for each service control measure.

Type of measure	Service control measure	Type of phase	
		Incident phase	*Recovery phase*
Speed control	Holding	X	X
Station-skipping	Expressing		X
	Deadheading		X
	Short-turning	X	X
	Diversion	X	X
	Cancelling	X	X
Other	Gap vehicle addition		X
	Non-rail-bound shuttle service implementation	X	
	Single-track operations	X	

Table 2-4: Inventory of service control measures and their impact on passengers as found in the literature.

Type of measure	Measure	Groups of impacted passengers	Type of impact	Source
Speed control	Holding	Downstream passengers on platforms	(+)	(Schmöcker et al., 2005)
		On-board passengers	(-)	
Station-skipping	Expressing	Expressed passengers	(+)	(Wilson et al., 1992)
		Passengers on platforms downstream the skipped segment	(+)	
		Skipped segment boarders	(-)	
		Skipped segment alighters	(-)	
	Deadheading	Reverse direction passengers	(+)	(Wilson et al., 1992)
		Skipped segment boarders	(-)	
		Skipped segment alighters	(-)	
	Short-turning	Reverse direction passengers	(+)	(Wilson et al., 1992)
		Short-turn point boarders	(-)	
		Skipped segment boarders	(-)	
		Skipped segment alighters	(-)	
	Diversion	Diverted branch boarders	(+)	(Carrel, 2009)
		Original branch boarders	(-)	
		Original branch alighters	(-)	
	Cancelling	All passengers	(-)	(Carrel, 2009)
Other	Gap vehicle addition	Replacement measure (see page 20)		
	Non-rail-bound shuttle service	Replacement measure (see page 20)		
	Single-track operations	No literature		

2.4. Literature review conclusions

This chapter presented three aspects relevant to this thesis, the meaning of "the passenger perspective", the disruption management process and service control measures. This section links the main findings of this literature review with the two sub-questions presented at the beginning of the chapter.

> **A1.** What is "the passenger perspective" within the framework of public transport systems and how is it currently assessed in literature?

Taking the passenger perspective means using impacts that directly relate to passenger needs to measure how inconvenienced users are, and using these insights to take action for the benefit of passengers. Three main categories of impacts exist: relating to travel time extension, travel time variability and comfort/crowding.

Figure 2-13 shows the cost components of travelling for a passenger in various conditions. To read it, the reader must imagine that inconvenience can be translated as a cost. In recurrent conditions, there is often a relatively small inconvenience experienced by passengers due to deviations from the operations plan. The inconvenience experienced by passengers because of a disruption can therefore be measured by comparing the cost of a certain impact to its cost in recurrent conditions. Arguably, in non-recurrent conditions, there is a fixed or structural inconvenience (effective and/or perceived, e.g. annoyance or stress due to a standstill) and a variable one. The variable one can be influenced by the strategy applied by dispatchers (the focus of this thesis), but also by how informed passengers are, how pleasant waiting is, etc.

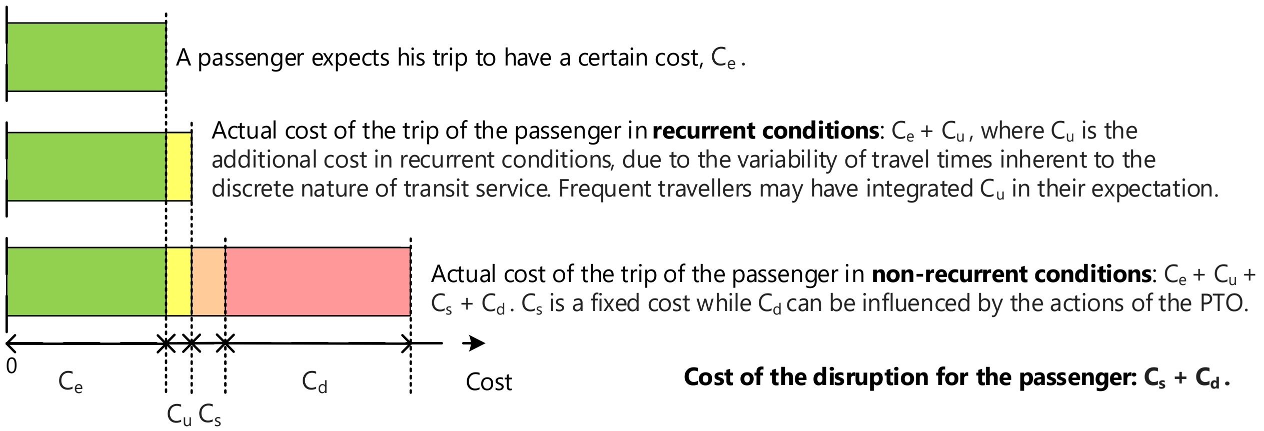


Figure 2-13: Cost of a trip for a passenger in various conditions. The reader must imagine that inconvenience can be translated as a cost.

One may thus wonder: *which strategies to use to make the variable cost component C_d as small as possible for a given, fixed disruption?* Even though current literature does not provide the assessment framework to answer this question, there are two main evaluation frameworks from which one could get inspiration. First, Fadaei & Cats (2016), who developed a systematic way to evaluate the impacts of design and operational measures on passengers and the operator in recurrent conditions. Second, Carrel (2009), who compared the impact on passengers of the responses to two somewhat similar disruptions. Both studies used a combination of vehicle and passenger data.

Carrel (2009) mentioned that his work could be extended to be able to predict, given a certain disruption, which strategy could be more beneficial to passengers. This is precisely a goal of this thesis.

A2. In theory, what are the measures that can be used by dispatchers to address a disruption?

An answer to this question can be found in sub-section 2.3.4. Nevertheless, it is worth underlining a few points here.
Current literature is scarce on the appropriate strategies to adopt for high-frequency rail-bound urban public transport systems, particularly during the incident phase. The topic of single-track operations particularly lacks insights from the academic world.
In addition, the literature review has shown that making a distinction between different groups of passengers when assessing inconvenience can provide meaningful insights into the trade-offs that need to be made between different (groups of) OD-pairs.

The consequence for this research is that the case study is particularly appropriate since it is a high-frequency rail urban public transport system where single-track operations are being used. Besides, the RET uses predefined strategies, which, in the context of a rail blockage, are shown to be important. Yet this is a relatively new practice, even more with the special focus on passengers, hence the relevance of this thesis.

Next chapter elaborates on the concepts presented in the answer to sub-question A1, with the development of a framework to evaluate the inconvenience experienced by passengers during disruptions.

Chapter 3 Development of the assessment framework

In this chapter, the assessment framework is developed. Its aim is to allow for a comparison of different service control strategies, based on the impacts they have on passengers. The two following sub-questions will be answered:

> **A3.** What are the impacts that would assess best the inconvenience experienced by passengers?
>
> **A4.** With what methodology should these impacts be assessed?

To begin with, section 3.1 explains the method used to develop the framework. Based on the elements presented in this method, the theoretical core of the framework is set up in section 3.2. The two following sections zoom into more details, from assumptions to calculations. The chapter ends with a conclusion and a flowchart that summarises the assessment framework.

3.1. Approach for the development of the assessment framework

This section explains the method used to develop this assessment framework, divided into four phases. Details are provided for the phases related to the theoretical development of the framework.

3.1.1. First phase: literature review

The literature review in Chapter 1 (research problem) and Chapter 2 forms the first step in the development of the assessment framework.
The starting point of the assessment framework comes from the main theoretical objective, defined based on the idea that this research extends the studies conducted by Van Oort et al. (2015) and Carrel (2009). From this objective, the aim of the framework can be defined: *to allow for multiple service control strategies – including the one used by traffic controllers, but not only – to be assessed and then compared from a passenger perspective for one given disruption, in order to derive how each strategy affects passengers*.
The literature review in Chapter 2 allows to get inspiration from other studies. It is thus used to define data needs, passenger impacts and requirements on the outcomes of the framework. The remainder of this sub-section presents these aspects.

Data needs
In all of the studies where the passenger perspective is assessed, a combination of **vehicle and passenger data** is used. The approach used both by Van Oort et al. (2015) is particularly interesting; Fadaei & Cats (2016) made use of a similar approach. Van Oort et al. (2015) postulate that insights coming from supply-side (AVL) data can be translated into passenger impacts by using-demand side (APC) data. This is due to the passenger trip chain and the vehicle processes being intertwined in a specific way, as shown in Figure 3-1. A vehicle is scheduled to leave a stop at a certain departure time with a time interval from its predecessor called headway. A passenger who arrived after the departure of the predecessor has to wait, leading to waiting time. Besides, the variation in headways causes a variation in WT. This passenger can board if and only if there is enough room in the vehicle. If not, he/she has to wait an extra headway. Once the passenger has boarded and the vehicle leaves, he/she experiences an effective in-vehicle time similar to the travel time of the vehicle. This travel time can also contain dwell times at stops where the passenger does not want to alight. However, due to crowding, he/she might perceive a different in-vehicle travel time. If the passenger makes a transfer,

a new WT arises, affected by how synchronised both services are. In non-recurrent conditions, this transfer may be a forced one, in case of the implementation of a measure such as short-turning for instance. The research on the total trip chain during disruptions is not within the scope of this thesis. Note that in Figure 3-1, only relationships from the supply side to the demand side are depicted, but reverse relationships also exist. For instance, dwell times can be affected by passengers' behaviour.

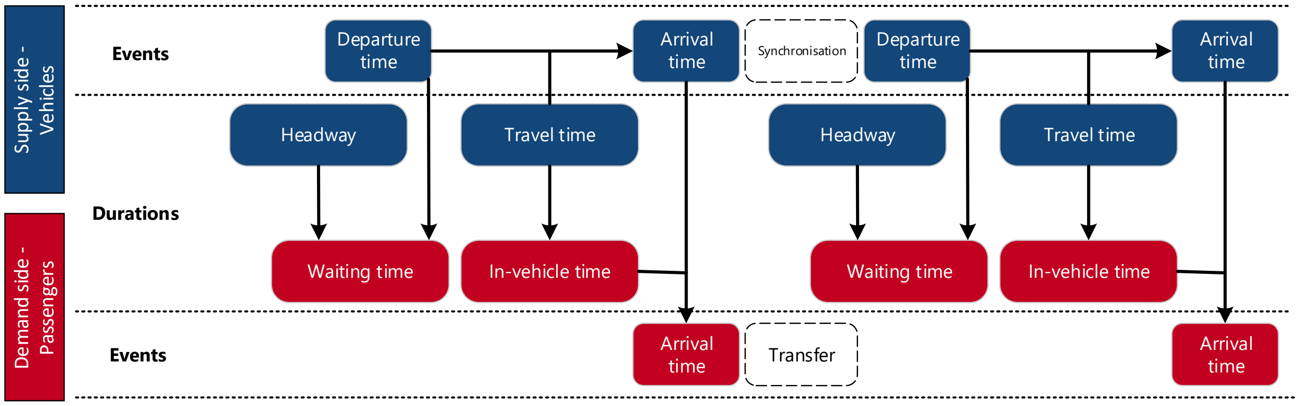


Figure 3-1: Demand – supply interaction, adapted from Van Oort et al. (2015).

Passenger impacts

It is suggested that passenger impacts be defined based on the three main categories defined by Van Oort et al. (2015):

1. Duration of travel time components,
2. Variability of travel time components,
3. Crowding, affecting that affects the level of comfort of passengers.

The specific choice of the impacts used in the assessment comes in section 3.2; calculation details come in sections 3.3 and 3.4.

Outcomes of the assessment

To allow for comparisons, both Van Oort et al. (2015) and Fadaei & Cats (2016) aggregated impacts into a single **monetary value**. The other advantage of this is that it allows to quantify societal costs. The approach consisting of computing vehicle performance indicators based on AVL data, to translate them into passenger impacts and to aggregate these impacts into a single monetary value is called by Van Oort et al. (2015) the **three-step approach**; more details follow in section 3.2.

In addition, the outcomes of the assessment framework are suggested to be at an **OD-pair level** since the literature review demonstrated that differentiating between groups of passengers allows to derive interesting insights on trade-offs between groups of passengers.

3.1.2. Second phase: choice of the method to generate different strategies for one disruption

In a second phase, analytical thinking is used to choose the method to be able to compare multiple strategies for one disruption.

Ideally, in order to compare the impacts on passengers of various service control strategies, one would have the AVL data of multiple alternative situations with an *identical* disruption (type of disruption, time of day, type of day, season, blockage duration, etc.) but with every time a different strategy. This is unlikely to ever happen; this is one of the challenges highlighted by Carrel (2009) and Babany (2015). Consequently, there is a need to **simulate AVL data** for hypothetical scenarios. A simulation model will therefore need to be developed. For the simulation to yield realistic vehicle data, it should fulfil a number of a number of conditions:

- The initial situation, at the very start of the disruption, must be taken into account.
- Safety constraints need to be implemented – these are particularly relevant in a rail-bound system. It means that the infrastructure and the safety procedures will need to be properly represented.
- Vehicles will need to be modelled but not passengers.
- It must be relatively easy to use and to find documentation on it, given the time restrictions of this study. Given the approach described in the previous sub-section, only vehicles need to be simulated (only relationships from the supply side to the demand side are considered) therefore passengers will not need to be simulated.

Plenty of tools exist. Free and open source ones are interesting for their transparency and flexibility but due to the time constraint, a proprietary tool is preferred. Two main categories of simulation tools exist: discrete event simulation (DES) or agent-based simulation (ABS) (or a combination). Since DES allows to easily model systems with queues and predictable interactions and has benefitted from more research than ABS, a DES tool is chosen. ARENA, developed by Rockwell Automation in 2000, was selected because it can allow for all of the aforementioned conditions to be fulfilled. **No analytical optimisation** will be used, also due to time constraints, but DES allows for the model to be controlled relatively easily. Therefore the result of **incremental changes** can be better analysed and thus an incremental approach will be used. This is further developed in sub-section 3.3.4.
The model should also be verified and validated before use.

3.1.3. Third and fourth phases: Test of the developed framework and validation

Once the theoretical foundations of the framework are laid out, it needs to be applied. Therefore the third step is a test of this framework, detailed in Chapter 5. Ideally, it would be tested on multiple cases. However, due to time constraints, one in-depth case study is preferred. It should not be too specific in order to allow for a generalisation of the results.
The last step is the validation of the results of the framework by experts, through interviews.

3.1.4. Summary

The development of the assessment framework happens in four phases. Since the first two phases are related to the theoretical development of the framework, they are already briefly presented in this section and will be detailed in the remainder of this chapter. The last two phases will be in Chapter 5. These phases are depicted in Figure 3-2.

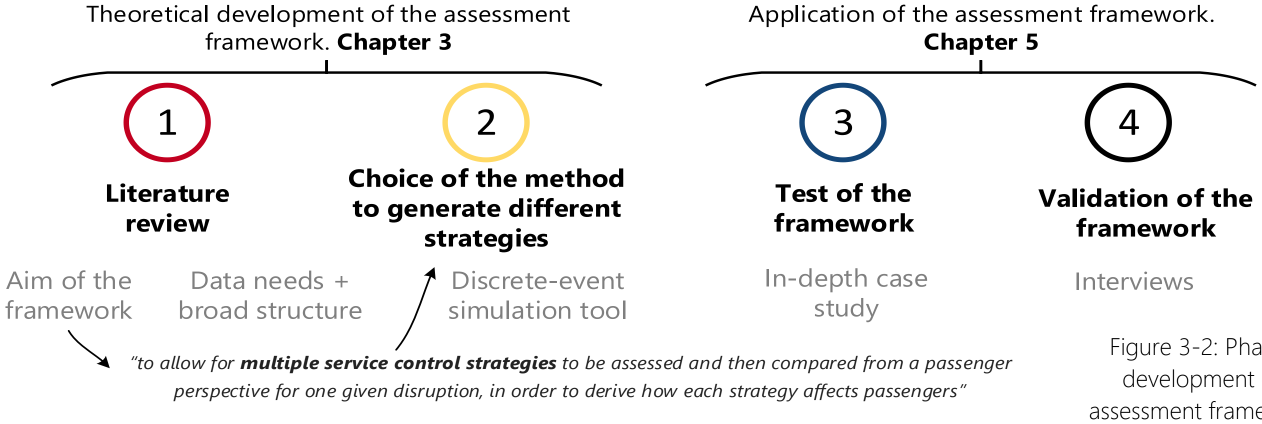


Figure 3-2: Phases of development of the assessment framework.

3.2. Theoretical core of the assessment framework

This section details the core of the assessment framework, with the elements evoked in previous section. Firstly, the different scales of assessment are presented. Then, the impacts are defined. Thirdly, the three-step approach is presented into more details. Fourthly, a section presents a transit assignment model used throughout the framework and lastly, some terminology is presented. The section ends with a conclusion.

3.2.1. Scales of assessment

Unlike previous studies, it is argued here that it may be relevant to distinguish between different scales of assessment. The trip chain shown in Figure 3-1 was rather focused on meso- to microscopic features. However, a disruption happens in a **network**, hence the need to also look at the macroscopic level. Different impacts will be assessed for each scale. Given the time constraints of this study, a microscopic assessment is only feasible at a local scale, i.e. for a few stops. At this scale, vehicle movements are taken into account. At the global scale, the whole network is considered. The time boundaries of this scale are bound to be larger than the local scale, i.e. to spill over the service recovery phase. Such boundaries will be defined by the tooling used for the global-scale assessment.
The characteristics of each scale as well as the pros and the cons are summarised in Table 3-1.

Table 3-1: Description of the two levels of assessment.

	Local scale	**Global scale**
Space boundaries	A few stops.	The whole network (bus / tram / metro).
Time boundaries	Time window(s) that comprise the strategy application phase.	Same or longer.
Pros	Detailed enough to take into account vehicle movements. The assessment can be limited to the incident phase, the scope of this study.	Comprehensive assessment that allows for an evaluation of changes for each OD pair.
Cons	Too detailed and time-consuming to be applied at a network level. The impact of a disruption on passengers may be underestimated.	Too rough to assess certain strategies. Assessment that contains the recovery phase, which is not the main focus of this study.

3.2.2. Assessed impacts

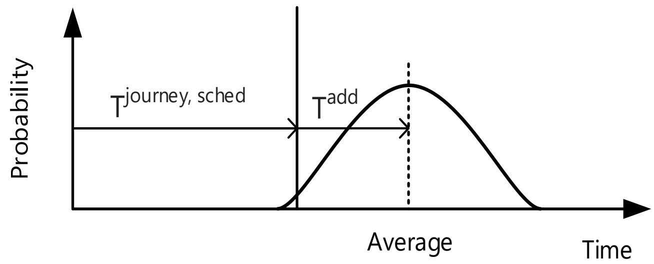
Due to the simulation, **passenger impacts** ought not to be too specific, otherwise they may become irrelevant. This is why impacts will be defined using average values (average waiting time, average number of transfers, etc.) instead of extreme values (e.g. 90^{th} percentile): the former are likely to be more accurate than the latter with simulated data.

Duration of travel time components, crowding and comfort
From the categories of impacts defined by Van Oort et al. (2015) and recalled in sub-section 3.1.1, the first and last categories arguably directly apply for **non-recurrent** conditions.

- **Duration of travel time components**. In the case of a disruption, there will most likely be an increase in the duration of travel time components. Concretely, passengers will experience an increase in travel time of T^{add} on average; see Figure 3-3. If T^{add} exceeds their planned buffer time, they are late at their destination.

- **Crowding and comfort**: With a decrease in service regularity and capacity, an increase in crowding are a decrease in comfort are expected. The increase in crowding can be such that demand may exceed capacity, leading to passengers being denied boarding one or multiple times. The decrease in comfort can be expressed by passengers not being able to seat and thus perceiving time longer than usual.

Figure 3-3: Scheduled passenger time and average additional travel time per passenger (Van Oort et al., 2015).



Variability of travel time components

The second category of impacts is thornier. To explain, one can take the example of waiting time variability. In recurrent conditions, for a given stop during a given period of the day, a WT distribution can be plotted, with WTs sampled over one or multiple passengers during many days: see Figure 3-4.

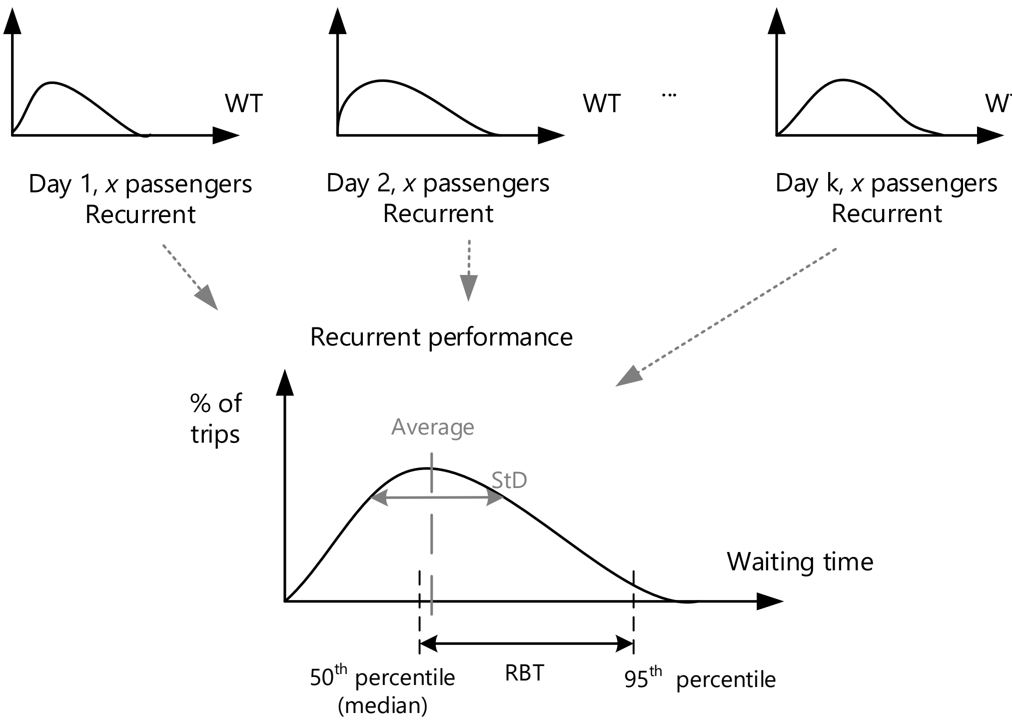


Figure 3-4: Waiting time distribution; recurrent performance (adapted from Uniman (2009)).

From such a distribution, two types of variability indicators can be computed, as identified by Lomax et al. (2003). These types of indicators represent different approaches toward measuring reliability.

- Measures of statistical range or variability, which relate to the "mean-variance" approach. It assumes that travellers place a disutility on travel time variability and the associated uncertainty (Uniman, 2009). The most commonly used measure for travel time variability is standard deviation (StD) (Kouwenhoven et al., 2014). It represents how spread out from the average values are: see Figure 3-4. In their research, Van Oort et al. (2015) used the WT StD as an indicator of variability.

- Measures of additional budgeted time, related to the slack or buffer time that passengers add through a shift in their departure time. These are measures of differences in percentiles' values, found to capture best travel time variability than the StD (Lam & Small, 2001). The most used indicator is the Reliability Buffer Time (RBT), first introduced by Furth & Muller (2006). Uniman (2009) defines the RBT as the difference between the 95th percentile travel time and the 50th percentile travel time. For example, a RBT of 5 minutes means that if a commuter plans 5 minutes of buffer time for her/his journey, she/he will be on time at their destination 95% of the time, thus late at work once per month on average. The waiting time RBT as illustrated in Figure 3-4 can be interpreted similarly provided that other travel time components remain unchanged.

In **non-recurrent** conditions, the only waiting time distribution that can be plotted is that of **one** day, with WTs sampled over the passengers who waited at a given stop during the period of the disruption: see Figure 3-5. Because the distribution expresses a variation across **passengers** on one day and not across **different days**, measures of statistical range make little sense.

In addition, in case of denied boarding, it is necessary to know how many times each sampled passenger was denied boarding to be able to compute any of the variability indicators mentioned above. With the framework developed in this chapter, it is not straightforward; see page 44 for more details. Therefore, because of the time constraint of this research, it was decided to include neither of these approaches in the assessment framework. Note that variability is not excluded from the assessment framework though, since it can be taken into account in the WT calculation.

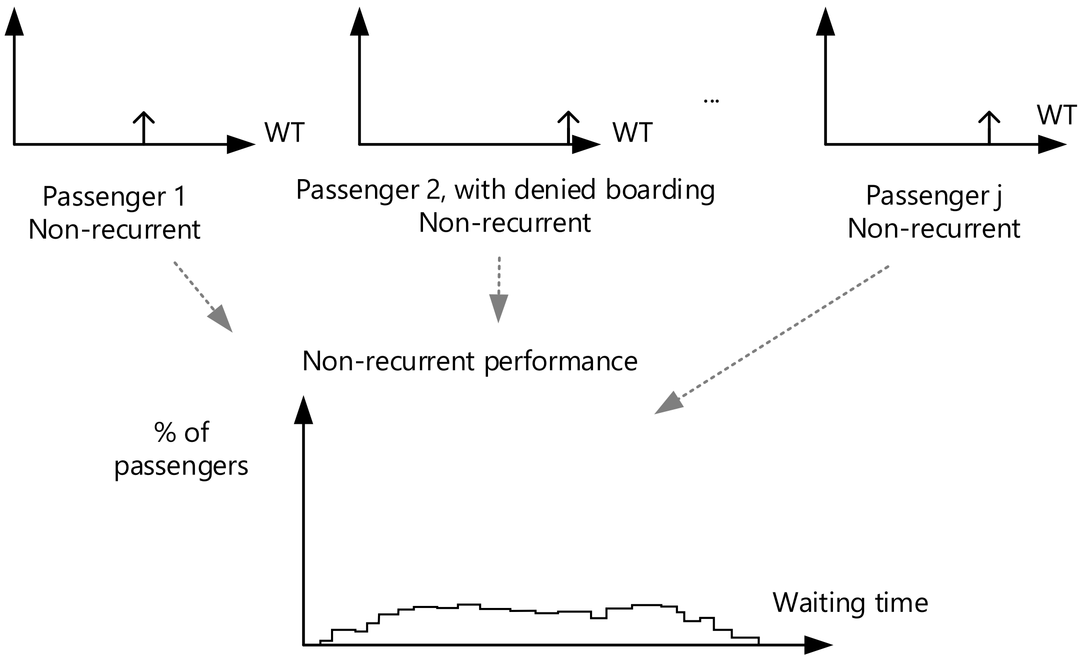


Figure 3-5: Waiting time distribution; non-recurrent performance.

However, the RBT remains a relevant metric for an **a posteriori analysis**. As highlighted by Furth & Muller (2006), passengers' perceptions tend to be based on extreme values, which the RBT is able to capture. A high waiting time RBT in non-recurrent conditions might lead passengers to readjust their usual waiting time RBT, extending the impacts of the disruption up to multiple days or even weeks after the disruption.

Impacts assessed at the local scale
Given the previous considerations, the following passenger impacts can be assessed at the local scale:

- Impacts on the **duration of travel time components:**
  (a) Average additional in-vehicle time,
  (b) Average additional waiting time at the first boarding and at planned transfers.
- Impacts on **comfort** due to **crowding**:
  (c) Average additional perceived in-vehicle time, based on crowding levels,
  (d) Average additional denied boarding occurrences (may be abbreviated as DB), with their associated waiting times.
- **Measure-specific** impact:
  (e) Average amount of unplanned transfers (due to short-turning for instance), with their associated waiting times.

Note that impacts (d) and (e) are amounts of passengers who will also experience impact (b).

Impacts assessed at the global scale
It is not worth quantifying impacts that can already be quantified – and with more accuracy – at the local scale. Due to the level of accuracy that can be obtained at a macroscopic scale, it is suggested to focus solely on travel time duration. Therefore, the last assessed impact is:
(f) Average additional travel time.

3.2.3. Three-step approach

As evoked in the first section of this chapter, it is suggested that this assessment framework be built on a **three-step approach** as depicted in Figure 3-6.

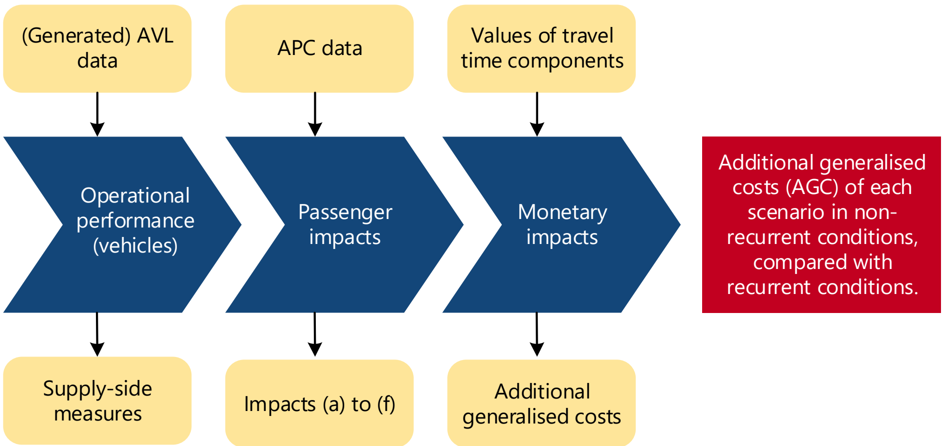


Figure 3-6: Three-step approach used for each assessment scale, adapted from Van Oort et al. (2015).

Step 1 consists of the analysis of vehicles' performance, using (simulated) AVL data. At this point, supply-side impacts are obtained.
Step 2 consists of the calculation of passenger impacts. Since supply-side impacts are at the stop level (at a stop or between stops) while passenger impacts are at the journey level, one needs to bridge the gap between both levels. For instance, one minute of additional in-vehicle time between two stops impacts all passengers travelling through this link, which could mean a great number of OD pairs. The translation from supply-side impacts to passenger impacts can be done with a transit model, or manually. By weighing times by demand, the framework allows to shed light on the OD pairs with high passenger volumes.

In **Step 3**, passenger impacts are translated into monetary costs, all aggregated into a single value with the use of weights: the additional generalised costs (AGC) for each scenario in non-recurrent conditions, compared to recurrent conditions. Indeed, literature shows that different travel time components do not weigh equally for passengers. **The AGC per passenger represent the cost of the disruption for one passenger**, as shown in Figure 2-13 in the literature review conclusion.

A main assumption in this framework is that passengers do not cancel their trip because of the disruption. Therefore all passengers have a certain additional generalised costs. It may be argued that the degree of validity of this assumption depends on the ratio commuters/leisure passengers. Indeed, commuters are not likely to give up on their journey while leisure passengers are more likely to. Typically, it can be expected that this assumption be most valid during the morning peak. Still, it may lead to an overestimation of passenger impacts.

Local scale

The impacts assessed at the local scale boil down to three main components: in-vehicle time, waiting time and transfers. The simplest form of the AGC function for one passenger is presented in Formula 3.1. Other travel components such as access and egress times are out of the scope of the local-scale assessment. Monetary constants that will be used in this research can be found in Appendix A . The premium placed on waiting time encompasses both the stress related to the uncertainty and the exposure to the waiting environment.

$$AGC = VoT \times \Delta t_{in} + VoWT \times \Delta t_w + P \times \Delta N \quad (3.1)$$

With:

AGC	$additional\ generalised\ costs\ function\ for\ a\ passenger$
VoT	$value\ of\ time$
$VoWT$	$value\ of\ waiting\ time$
Δt_{in}	$additional\ in-vehicle\ time\ compared\ with\ the\ reference\ day$
Δt_w	$additional\ waiting\ time\ compared\ with\ the\ reference\ day$
ΔN	$additional\ number\ of\ transfers\ compared\ with\ the\ reference\ day$
P	$penalty\ for\ transferring$

In this study, Formula 3.1 can be re-written as Formula 3.2.

$$AGC = (Impact\ (a) + Impact\ (b) + Impact\ (c) + Impact\ (d) + Impact(e)) \times monetary\ values \quad (3.2)$$

Global scale

Impact (f), average additional travel time, can also be translated into a cost. Next sub-section shows how a transit assignment model allows to do this seamlessly.

3.2.4. Transit assignment model

Although this sub-section is more specific to the case study of this thesis, it also gives an idea on how a transit assignment model can be used to assess passenger impacts in general.

A transit model of OmniTRANS called OV-Lite is used, where urban public transport modes are represented. The idea is to use the model in a similar way than Van Oort, Brands & De Romph (2015), but for non-recurrent conditions and with a null elasticity, since it is assumed that passengers do not cancel their trip. Both the inputs and the outputs of this model are used.

What is OV-Lite?

OV-Lite is a deterministic iterative model that performs transit assignments based on the OtTransit algorithm (more details below). OV-Lite is a tool usually used at the strategic level, as it allows to model how demand varies depending on the network availability, how passengers are distributed over the network, etc.

OV-Lite is developed in OmniTRANS, a transportation modelling software in which the four-step model is implemented: trip generation, trip distribution, modal split and assignment. The particularity of OV-Lite is that the trip generation and the trip distribution steps are skipped, hence the name "Lite". Instead of using zonal data to determine the amount of trips between each zone, i.e. to determine the OD (Origin-Destination) matrix, the latter is directly an input of the model. Each zone is represented by a centroid. The OD matrix in OV-Lite stems directly from smart card data. The model distinguishes between several periods of the day.

Network representation

The network in OV-Lite consists of unidirectional links connected by nodes. Transit lines follow a predefined order of links and nodes. Each link has a certain travel time between nodes. Stops are nodes of the network where passengers may board, alight or transfer. This is due to the input being smart card data: only the journey in the public transport network is known. Each line is characterised by several parameters: the stops it serves, seating and crush capacity (seating plus standing capacity) and frequency. Indeed, OV-Lite uses a frequency-based service network representation. It means that frequency is the only information that OV-Lite has about the timetable. With this representation, waiting time at stops is assumed to be half a headway, meaning that a random pattern of arrivals of passengers at stops is assumed. This is a reasonable assumption as long as the frequency is superior or equal to 5 vehicles per hour (Nuzzolo, 2003).

Why using OV-Lite? Local- and global-scale assessments

The frequency-based service representation is not adapted to model vehicle movements. However, the inputs of OV-Lite can be used for the *local-scale assessment* to save time: loads per OD-pair, coming as a result of the assignment, but also boarding, alighting and occupation rates (see page 44). All of these could be deduced directly from APC data, without the intermediary of a model, but it would be time-consuming to compute all of them and it is preferable to be consistent.

At the *global scale*, OV-Lite fits within the description of the global-scale assessment in Table 3-1. Disruptions result in changes in frequencies and infrastructure availability. Once these changes are known, they can be implemented in the model. Assuming no change in demand, one can find the effects of a disruption on every single OD pair, and therefore travel time. OV-Lite as owned by the RET in 2016 does not contain a capacity-constrained assignment, which will have repercussions on the interpretation of results. Changes in frequencies need to be known beforehand for each assessed scenario, hence the local-scale assessment needs to be performed first.

Trip assignment algorithm

OmniTRANS uses the Zenith algorithm to assign public transport trips over the network. The procedure is briefly described here, based on OmniTRANS (2014) and Veitch & Cook (2011).

- First, candidates for access (first boarding) and egress (last alighting) stops are determined by looking for stops inside a search radius around the centroids of the model.
- Then, the algorithm looks for feasible paths between all pairs of access-egress stop candidates with a backward search. All transit lines are processed from each destination node in a reverse direction to calculate the generalised costs (GC) from stops on these lines to this destination node.

When a stop that has already been processed is found, a logit *transit line* choice model is applied to determine the shares of each processed path. The higher the transit line logit scale parameter, the more passengers favour the cheapest transit line in terms of GC.

- Once all candidate access stops are reached by the backward search algorithm, splitting proportions for all first-stop access candidates are determined using a logit *access stop* choice model. The degree to which passengers prefer stops with low GC is controlled by an access stop logit scale parameter. Then, the GC for each origin centroid are calculated as a weighed sum of the GC over all access candidate stops.

Thus, logit scale parameters reflect the knowledge that passengers have about their available options in the network. The generalised costs for each OD pair are then computed according to Formula 3.3.

$$GC = VoT \times T = VoT \times t_{in} + VoWT \times t_w + P \times N + VoWk \times (t_a + t_e + t_t) \qquad 3.3$$

With: $VoWk$ $Value\ of\ Walking$ t_e $Egress\ time$
t_a $Access\ time$ t_t $Transfer\ time$

Formula 3.3 presents the GC function for the global-scale assessment. The AGC of a scenario can then easily be found. Unlike the local-scale assessment, the global-scale assessment allows to take into account access, transfer and egress walking times; a passenger originating from a given stop will not necessarily make his/her first boarding at this stop.

Parameter values

Values of time and waiting time will not be modified to match the ones of the local-scale assessment: it is chosen to keep the parameters with which the model was calibrated instead, including logit scale parameters. The transit line and the access stop logit scale parameters are respectively equal to 0.2 and 0.4. Parameters equal to 1 would mean a perfect knowledge and thus an all-or-nothing assignment using the shortest path while parameters equal to 0 mean a distribution of passengers according to frequencies of different lines. Since no literature was found indicating how they might change between recurrent and non-recurrent conditions, these parameters are kept unchanged. Hence care will need to be taken when interpreting outputs. Thus, OV-Lite is used as a tool to model a possibility rather than reality.

Skim matrices

In addition to assigning passenger loads on the network, OtTransit provides skim matrices as outputs. As explained above, OtTransit generates many possible paths for each OD pair and calculates the share of total demand to assign to each. Skim matrices are matrices of the same size than OD matrices, containing weighted averages of all the possible paths between each OD pair. Multiple skim matrices can be generated: with GC, with travel times, with waiting times, with the amount of transfers, with transfer penalties and with fares (assumed to be equal to zero in this study). OV-Lite is therefore well-suited for the three-step approach presented in Figure 3-6, since the average additional travel time for each OD pair can be translated into monetary values simply by using a different skim matrix.

3.2.5. Terminology

Before moving on to explaining how each impact is computed, it is necessary to introduce the terminology that will be used. The structure of an investigated disruption is shown in Figure 3-7.

The reference day is not a *scenario* per se, and the Base Scenario, which represents a real-life situation, is not to be confused with the *designed scenarios*. Properly speaking, a scenario is a “story” illustrating visions or aspects or a possible future. However, terms in the mathematical formulas in the remainder of this chapter need to allow to refer to reference day, the base scenario and crafted scenarios at the same time. For instance, waiting times need to be computed regardless of the situation. Instead of writing $t_{wait}^{reference}$ and $t_{wait}^{base\ scenario}$ and $t_{wait}^{m}\ \forall\ m$ in a formula, it is simpler to write $t_{wait}^{n}\ \forall\ n$: for mathematical convenience, the reference day and the Base Scenario may therefore be referred to as respectively "Scenario" 0 and "Scenario" 1.

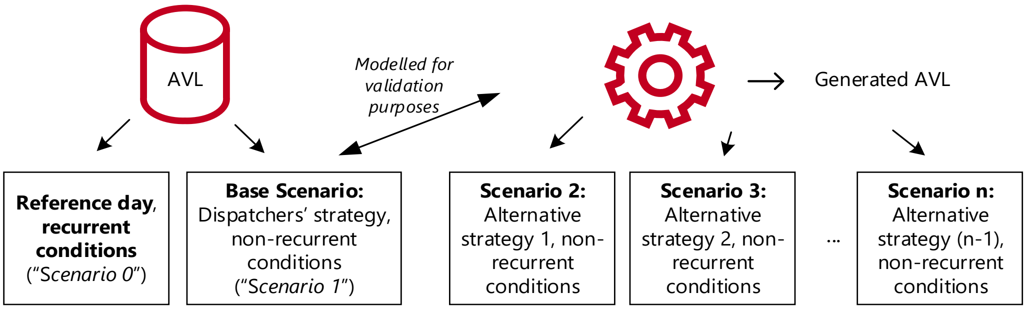


Figure 3-7: Structure of an investigated disruption, for a given situation (day, time, location).

3.2.6. Conclusion of the theoretical overview of the assessment framework

Figure 3-8 summarises the findings of this section: the six passenger impacts that will be quantified in the assessment framework, the two scales plus the approach for the assessment at each of the scales.

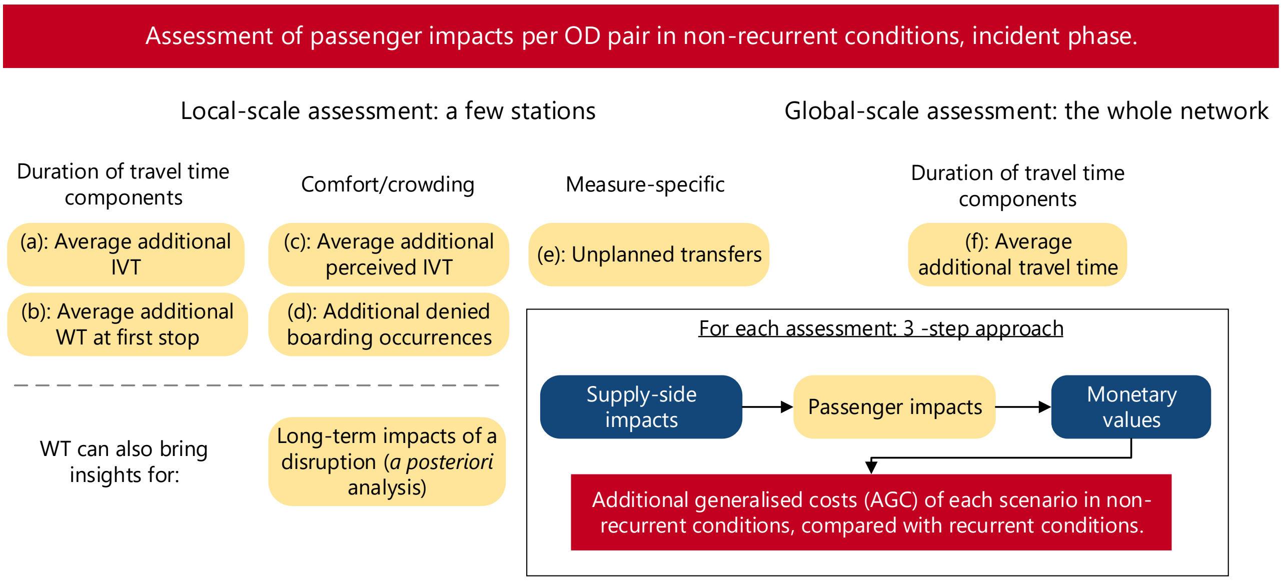


Figure 3-8: Theoretical overview of the assessment framework.

Sections 3.3 and 3.4 elaborate respectively on the calculation details for the local-scale assessment and for the global-scale assessment.

3.3. Local-scale assessment framework development

First, the main assumptions are presented. The spatial and the time scopes are also defined. Next, Formula 3.1 is detailed and the calculation methods and related assumptions for each impact are presented. This section also explains how AVL data, and thus how alternative scenarios, are generated.

3.3.1. Main assumptions and scopes for the local-scale assessment

The main assumptions are as following:

- Passengers do not change route. Although this assumption is coherent for the few first minutes, it may lead to an overestimation of costs for longer incident phases, where some passengers, especially those who do have a choice in route and enough knowledge of the network, are expected to change route.
- Passenger impacts are not time-specific, only averages are considered over a certain period of time.
- There is a uniform distribution of travellers across the studied period. Passengers arrive randomly at stops. This is a common assumption, realistic in the case of a high-frequency public transport system. It means fixed boarding, alighting and occupation rates. This may lead to an over- or underestimation of passengers, even during peak hours: a study in the Netherlands showed that 60% of all morning peak travellers start their trip between 07:30 and 08:30 (Yap, 2016).
- Travel times between stations remain unchanged. This assumption is valid when the PTO where the case study is conducted applies the passenger-friendly policy where vehicles are only supposed to stop at stations and not in-between, which is the case at the RET.

For the **spatial scope**, a selection of stops is made for each investigated case; see Figure 3-9 for an illustration and the adopted terminology. The selection must make sense, i.e. it should be preferably between junctions or terminals; Figure 3-9 is meant for explanatory purposes. Indeed, as part of the local-scale assessment, it is assumed that outside of the selected stops, passengers do not experience any extra inconvenience. Note that the word *stop* is used to refer to a station in *one* direction.

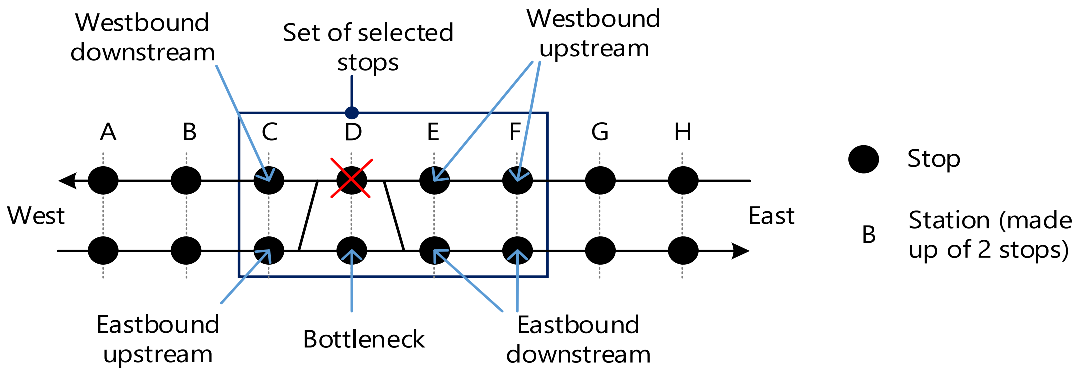
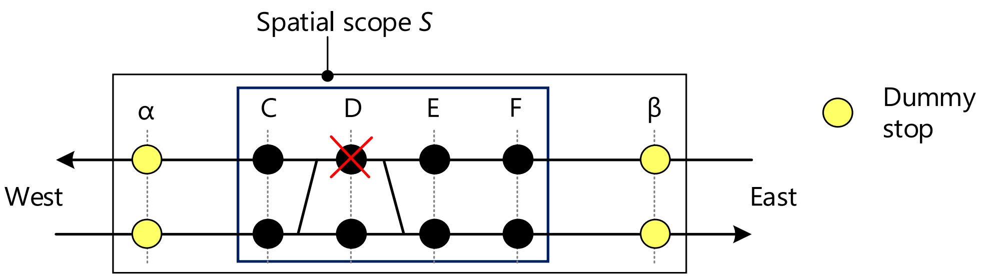


Figure 3-9: Terminology for partial blockage cases; example of a setup with a disruption in station D, westbound track.

Stations C, D, E and F in Figure 3-9 are not enough to study passenger impacts though. Indeed, with the selected set, a passenger travelling between stations B and H in Figure 3-9 would not be part of the assessment, which is an issue. The selected stops are part of a network. Therefore, it is suggested to create *dummy* stops, as shown in Figure 3-10: stations α and β.

Figure 3-10: Example of a spatial scope S.



α and β are fake stations. Travel time components to and from them will not be computed. They are here to represent the fact that passengers may flow inward or outward of the set of selected stops, and that they must be part of the assessment. The set of selected stops plus the dummy stops form the spatial scope, noted S.
It is assumed that there is only **one line** going through the stations. If there are multiple lines, then they are seen as one. Therefore it is assumed that in an ideal and undisrupted situation, headways are even. It may not be the case in reality, with multiple lines; as a consequence, the irregularity of headways will be overestimated for the reference day. However, it should not be too significant and since what matter here are *differences* between scenarios, it is deemed without major consequences.

The **time scope** presents an equal challenge to be determined. Two types of approaches are possible: a fixed time window approach or a rolling time window approach. The latter is deemed to be in fact more relevant to use here, just like Carrel (2009) did: this approach allows to follow a set of vehicles through stations and prevents a time window to start with a gap.

3.3.2. Step 3: Specification of the generalised costs function

This sub-section already presents step 3 of the three-step approach, because it gives the reader an idea of what needs to be obtained from steps 1 and 2. Sub-section 3.3.3 will elaborate on steps 1 - 2. The AGC function given in Formulas 3.1 and 3.2 are generic and meant for one passenger only, thus they require further elaboration. This is done with Formula 3.4, showing the additional generalised costs for a given scenario $n > 0$, for all passengers.

$$AGC^{n} = \sum_{(y,z)\in S} AGC^{n,(y,z)} = \sum_{(y,z)} \left(p^{(y,z)} \times \left(\left(\Delta t_{in,e}^{n,(y,z)} + \Delta t_{in,p}^{n,(y,z)} \right) \times VoT + \Delta t_{wait}^{n,y} \times VoWT + db_{pass}^{n,y} + \sum_{\forall s \in r_{(y,z)}} \lambda^{n,s} \times \left(\Delta t_{wait}^{n,s} \times VoWT + P \right) \right) \right) \quad 3.4$$

With:

n	$scenario, n > 0$	
s, y, z	$stops\ belonging\ to\ the\ defined\ scope$	
(y, z)	$OD\ pair\ with\ stop\ y\ as\ an\ origin\ and\ stop\ z\ as\ a\ destination$	
S	$spatial\ scope$	
$r_{(y,z)}$	$route\ between\ y\ and\ z; contains\ stops\ when\ y\ and\ z\ are\ not\ successive\ stops\ and\ y \neq z.$	
AGC^{n}	$additional\ generalised\ costs\ of\ scenario\ n$	
$AGC^{n,(y,z)}$	$additional\ generalised\ costs\ of\ scenario\ n\ for\ all\ passengers\ travelling\ on\ the\ origin - destination\ pair\ (y, z)$	
$p^{(y,z)}$	$amount\ of passengers\ travelling\ from\ y\ to\ z$	
$\Delta t_{in,e}^{n,(y,z)}$	$average\ additional\ effective\ IVT\ per\ passenger\ in\ scenario\ n\ along\ the\ route\ from\ y\ to\ z$	For impact (a).
$\Delta t_{in,p}^{n,(y,z)}$	$average\ additional\ perceived\ IVT\ per\ passenger\ in\ scenario\ n\ along\ the\ route\ from\ y\ to\ z$	For impact (c).
$\Delta t_{wait}^{n,y}$	$average\ additional\ WT\ per\ passenger\ in\ scenario\ n\ at\ stop\ y$	For impacts (b) (d) and (e).

$\lambda^{n,s}$	*probability of having to make an unplanned transfer at stop s in scenario n because of a service control measure*	For impact (e).
$db_{pass}^{n,y}$	*average denied boarding costs for one passenger at stop y in scenario n*	For impact (d).

Further details are provided for each impact:

- Impact (a): Additional in-vehicle time during disruptions can be caused by bunching, crowding at stops, or both. When the policy of the PTO is to avoid stopping between stations, all of the extra in-vehicle time happens at stops.
- Impact (b): Passengers boarding at a stop within the set of selected stops may experience additional waiting time at their planned boarding station(s).
  This also goes for those who have to transfer due to the application of a measure (such as short-turning) and those who are denied boarding. There are therefore *three components for additional waiting time*. Yet $\Delta t_{wait}^{n,y}$ only appears twice: this is because $db_{pass}^{n,y}$ already encapsulates a waiting time component (see page 44). Note that a passenger dropped at a station because of the application of a measure may be also denied boarding when wanting to board.
- Impact (c), the average additional perceived in-vehicle time, can be grouped with the in-vehicle time component, since they are both multiplied by the Value of Time.
- Impact (d), denied boarding occurrences, translates into an amount of passengers who must wait for at least one additional headway, which means an extra waiting time component (impact (b)).
- Impact (e) also translates into an amount of passengers (who get a penalty for unplanned transfer) and a waiting time component. An unplanned transfer can happen multiple times, hence the sum over stops in Formula 3.4.

3.3.3. Steps 1 and 2: From AVL data to passenger impacts, calculation details

This sub-section addresses the calculation of impacts (a) to (e): first, the calculation of items marked with "for impact …" after Formula 3.4 is explained and second, the calculation of $p^{(y,z)}$ is detailed.

For impact (a)

AVL data provides dwell times. This framework proposes to use dwell time distributions in recurrent conditions and dwell times in non-recurrent conditions to compute additional IVT during disruptions at stops. For the metro network of Rotterdam, the distributions of Both (2015) are used; there is one distribution per hour and per stop.

In recurrent conditions, dwell time extensions due to crowding may occur. Dwell time extensions due to bunching might also happen, but probably less significantly than in a disrupted situation; see A and B in Figure 3-11.

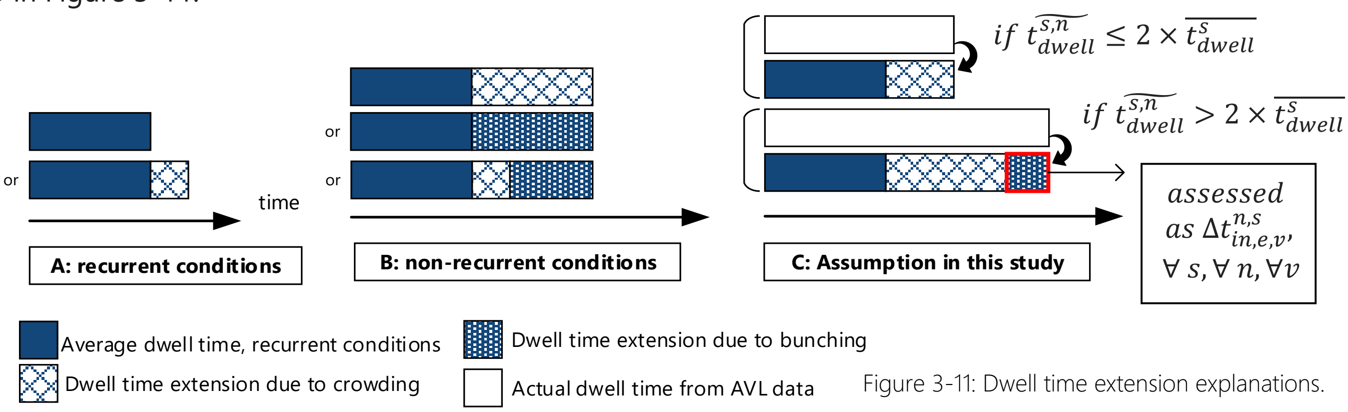


Figure 3-11: Dwell time extension explanations.

In case of a partial blockage, bunching is expected to occur upstream of the bottleneck and before a terminal stop. Often, bunching can be visualised with a time-space diagram, which is relatively easy to draw from AVL data. Crowding cannot be visualised as such. Many studies have investigated the link between dwell time extension and crowding in rail-bound systems. Multiple formulas exist to predict dwell time from variables such as alighting and boarding passengers, number of doors, degree of crowdedness, time of day, etc.; see Li et al. (2016) for a recent overview of dwell time estimation models. However, Li and his colleagues acknowledge that most formulas are difficult to generalise to other systems than those in which they were established. Besides, bunching is never considered.

For this research, it is deemed too time-consuming to apply such formulas or to develop a simulation to quantify this impact. In particular, it would become complex and heavy in assumptions when AVL data need to be generated. Consequently, a more practical approach is developed to estimate the dwell time extension caused by crowding, so that bunching effects can be assessed. Therefore, it is assumed that there is bunching at a stop s if and only if the actual dwell time at stop s in non-recurrent conditions $\widetilde{t_{dwell}^{s,n}}$ is superior to twice the average dwell time at this stop $\overline{t_{dwell}^{s}}$ in recurrent conditions[1]; see C in Figure 3-11. This approach presents the advantage to be easy to implement for cases with and without AVL data. However, the generalisation is quite simplistic and may overestimate the dwell time extension due to bunching.

$\Delta t_{in,e,v}^{n,s}$ represents the additional effective in-vehicle time at stop s in scenario n for vehicle v. If $\widetilde{t_{dwell}^{s,0}} = 0\ \forall s$ (i.e. no bunching for the reference day), the average additional effective IVT at stop s can be computed by summing the additional time for all vehicles and dividing this sum by the amount of vehicles that drove through the stop during the specified time window, as shown in Formula 3.5.

If $\widetilde{t_{dwell}^{s,0}} \neq 0$, $\Delta t_{in,e,v}^{n,s}$ needs to be computed by making a difference between bunching times in recurrent and non-recurrent conditions.

$$\Delta t_{in,e}^{n,s} = \sum_{v} \frac{\Delta t_{in,e,v}^{n,s}}{V^{n,s}}\ \forall\, n, \forall\, (y,z) \in S \qquad 3.5$$

With: $V^{n,s}$ $\quad$ $number\ of\ vehicles\ departing\ at\ stop\ s\ in\ scenario\ n$

The component $\Delta t_{in,e}^{n,(y,z)}$ from Formula 3.4 can then be computed as shown in Formula 3.6.

$$\Delta t_{in,e}^{n,(y,z)} = \sum_{\forall s \in r_{(y,z)}} \Delta t_{in,e}^{n,s}\ \forall\, n, \forall\, (y,z) \in S \qquad 3.6$$

For impact (b)

In this section, the calculation of $\Delta t_{wait}^{n,s}$ is detailed, which is also used for impacts (d) and (e). An assumption for the calculation of $\Delta t_{wait}^{n,s}$ is that the examined period is homogeneous in terms of scheduled departure times, scheduled trip times and headways (for instance peak hour on a working day for a specific season).

As shown in Figure 3-1, waiting time can be computed using actual headways. Using half a headway as an indicator of expected WT means overlooking irregularity aspects, which is not desirable for a

[1] This choice was made *a posteriori*: it stems from the time-space diagram drawn for the investigated case (see Figure 4-10 page 62). The assumption is that trains 63 and 64 NB do not experience bunching in Zuidplein given that when they arrive in Zpl, next station is already free or seconds away from being free. However, both of these dwell times are larger than $\overline{t_{dwell}^{Zpl\ NB}}$. It is assumed that the dwell time extension is due to crowding, and it is in fact approximately twice the average dwell time.

passenger-oriented research. Indeed, with the assumption of a uniform distribution of passengers, passengers are more likely to arrive during a long headway than during a short headway. Consequently, expected WT is skewed towards longer headways. Therefore, the formula for expected waiting time can be written as shown in Formula 3.7, already widely used in transportation research.

$$E\left(\widetilde{t_{wait}^{n,s}}\right) = \frac{E(\widetilde{h^{n,s}})}{2} \times \left(1 + CoV^2(\widetilde{h^{n,s}})\right) \ \forall\, n, \forall\, s \qquad 3.7$$

With:
- $E\left(\widetilde{t_{wait}^{n,s}}\right)$ *expected waiting time at stop s in scenario n*
- $\widetilde{t_{wait}^{n,s}}$ *actual passenger waiting time at stop s in scenario n*
- $\widetilde{h^{n,s}}$ *actual headway at stop s in scenario n*
- $CoV(\widetilde{h^{n,s}})$ *coefficient of variation of actual headways at stop s in scenario n*

If the service is regular, the coefficient of variation is equal to zero.
As underlined by Van Oort (2011), the coefficient of variation may be replaced by the PRDM (Percentage Regularity Deviation Mean, introduced by Hakkesteegt & Muller (1981)), shown in Formula 3.8.

$$PRDM^{s,n} = \frac{\sum_v \left| \frac{h_v^n - \widetilde{h_v^{n,s}}}{h_v^n} \right|}{V^{n,s}} \ \forall\, n, \forall\, s \qquad 3.8$$

With:
- v *vehicle*
- $PRDM^{s,n}$ *relative regularity at stop s in scenario n*
- h_v^n *scheduled headway for vehicle v in scenario n*
- $\widetilde{h_v^{n,s}}$ *actual headway for vehicle v at stop s in scenario n*

In the case of non-recurrent conditions, the reference timetable to compute the PRDM is the timetable of recurrent conditions. This means that cancelled trips need to be taken into account for the PRDM calculation, with an actual headway $\widetilde{h_v^{n,s}}$ equal to zero. As a result, the ratio $\left|\frac{h_v^n - \widetilde{h_v^{n,s}}}{h_v^n}\right|$ in Formula 3.8 is equal to 1 for each vehicle v cancelled. The use of the PRDM results in the average additional WT per passenger $E\left(\widetilde{t_{add\ wait}^{n,s}}\right)$ given by Formula 3.9. The PRDM is preferred here because it is straightforward to compute, given the single line, even-headway assumption.

$$E\left(\widetilde{t_{add\ wait}^{n,s}}\right) = \frac{E(\widetilde{h^{n,s}})}{2} \times (PRDM^{n,s})^2 \ \forall\, n, \forall\, s \qquad 3.9$$

As discussed before Formula 3.4, $PRDM^{0,s}$ will be slightly overestimated.
$\Delta t_{wait}^{n,s}$ is given by Formula 3.10 and is expected to be positive.

$$\Delta t_{wait}^{n,s} = E\left(\widetilde{t_{add\ wait}^{s,n}}\right) - E\left(\widetilde{t_{add\ wait}^{s,0}}\right), \forall\, s, \forall\, n > 0 \qquad 3.10$$

For impact (c)
The average perceived IVT can be assessed by multiplying IVT by factors that depend on the level of crowding. To find these factors, the meta-study by Wardman & Whelan (2011) can be used, where they determined different multipliers for seating and standing passengers by gathering the findings of 17 British studies on the valuation of rail crowding over 20 years. These multipliers and the ones chosen for the case study can be found in Appendix A .

Formulas 3.11 and 3.12 are then derived from a linear interpolation of the multipliers. The constants are thus specific to the case study, but the methodology could be applied to other cases. Note that the load factor LF is defined as the ratio in a vehicle of seating passengers per total amount of passengers. Formula 3.11 expresses $t^{n,l}_{in\,seat,p}$, the perceived IVT for a seating passenger on a certain link l for a certain scenario n, while Formula 3.12 is for standing passengers.

$$t^{n,l}_{in\,seat,p} = VoT \times t^{l}_{in} \times \begin{cases} 0.91 & 0.00 \leq LF < 0.50 \\ 0.30 \times LF + 0.76 & 0.50 \leq LF < 0.75 \\ 0.41 \times LF + 0.67 & 0.75 \leq LF < 1.00 \\ 0.45 \times LF + 0.63 & 1.00 \leq LF < 1.25 \\ 0.47 \times LF + 0.62 & 1.25 \leq LF < 1.50 \\ 0.54 \times LF + 0.50 & 1.50 \leq LF < 1.75 \\ 0.61 \times LF + 0.38 & 1.50 \leq LF < 2.00 \\ 1.6 & 2.00 \leq LF \end{cases} \quad 3.11$$

$$t^{n,l}_{in\ stand,p} = VoT \times t^{l}_{in} \times \begin{cases} 0.71 \times LF + 0.97 & 1.00 \leq LF < 1.25 \\ 0.83 \times LF + 0.82 & 1.25 \leq LF < 1.50 \\ 0.87 \times LF + 0.76 & 1.50 \leq LF < 1.75 \\ 1.00 \times LF + 0.54 & 1.75 \leq LF < 2.00 \\ 2.54 & 2.00 \leq LF \end{cases} \quad 3.12$$

It is assumed that for LF values below 0.50 or above 2.00, the functions take a constant value, equal to the value of the considered function for respectively LF=0.50 and LF=2.00. No lower or upper boundaries different than 0.50 or 2.00 is specified because it may lead to arbitrarily low or high time perception values with a linear interpolation.
Formula 3.11 is not necessarily realistic when the vehicle has a low load factor: instead of perceiving a shorter IVT, a longer one may be perceived since an almost empty vehicle can be seen as unsafe. Therefore, instead of a linear piecewise function, $t^{n,l}_{v,in\,seat,p}$ could be expected to be more of a parabolic function but no literature documents this quantitatively yet.
It is assumed that IVT do not vary across situations except when the track layout changes (e.g. driving on a straight line versus driving through a crossover).
The average perceived IVT $t^{n,l}_{in\,,p}$ for each passenger on one link can be found with Formula 3.13.

$$t^{n,l}_{in,p} = \sum_{v} \frac{\left(t^{n,l}_{v,in\,seat,p} \times p^{n,l}_{v,seat} + t^{n,l}_{v,in\,seat,p} \times p^{n,l}_{v,seat}\right)}{V^{l,n}} \ \forall\, l, \forall\, n \quad 3.13$$

With:
$p^{n,l}_{v,seat}$ — $amount\ of\ passengers\ seating\ in\ vehicle\ v\ on\ link\ l\ in\ scenario\ n$
$p^{n,l}_{v,stand}$ — $amount\ of\ passengers\ standing\ in\ vehicle\ v\ on\ link\ l\ in\ scenario\ n$
$V^{l,n}$ — $number\ of\ vehicles\ driving\ on\ line\ l\ in\ scenario\ n$

$p^{n,l}_{v,seat}$ and $p^{n,l}_{v,stand}$ are deduced from the denied boarding calculation explained in next paragraph. $\Delta t^{n,l}_{in\,add,p}$, the average additional perceived IVT on link l is computed by applying Formula 3.14.

$$\Delta t^{n,l}_{in\,add,p} = t^{n,l}_{in,p} - t^{0,l}_{in,p} \ \forall\, n > 0, \forall\, l \quad 3.14$$

Finally, $\Delta t^{n,(y,z)}_{in,p}$ is computed as shown by Formula 3.15.

$$\Delta t_{in,p}^{n,(y,z)} = \sum_{\forall l \in r_{(y,z)}} \Delta t_{in,p}^{n,l} \ \forall \, n > 0, \forall \, (y,z) \in S \qquad 3.15$$

As highlighted by Cats et al. (2016), using average load factors to take into account crowding effects neglects variations in passenger loads across vehicles and is likely to underestimate crowding effects. In this study, denied boarding is also considered and needs to be assessed in such a way that vehicle sequence matters.

For impact (d)

To assess denied boarding (DB) in such a way that vehicle sequence matters, the trip of each vehicle needs to be traced through the stops within the selected set, with time windows as boundaries. Some input and output data from OV-Lite are used, including:

- Boarding and alighting rates per station are used to compute boarding demand and alighting passengers for each vehicle in each station, by multiplying rates by a headway,
- Occupation rates of the outer links (right before or after the stations at the boundaries). These are useful at the beginning of the calculations, since a vehicle entering the studied system may already have a certain occupation,
- Seating and crush capacities. A sensitivity analysis will be conducted on the crush capacity value, since it is not a value that is well-known in general in public transport studies. Indeed, the crush capacity depends on many parameters: obviously, the vehicle and its layout, but also stops on the line (airport versus CBD), culture (interpersonal distance), age of passengers, etc.

The following additional assumptions are made, as illustrated in Figure 3-12:

- Headways at all stops upstream the bottleneck are identical to dispatching headways. Thus there are two types of headways only: dispatching headways and bottleneck headways. Alighting and boarding upstream of the bottleneck in both directions are computed with the dispatching headway, i.e. the headway at the terminal station.
- Headways at downstream stops are similar to bottleneck headways. Thus alighting and boarding at and downstream of the bottleneck are computed with the bottleneck headway.

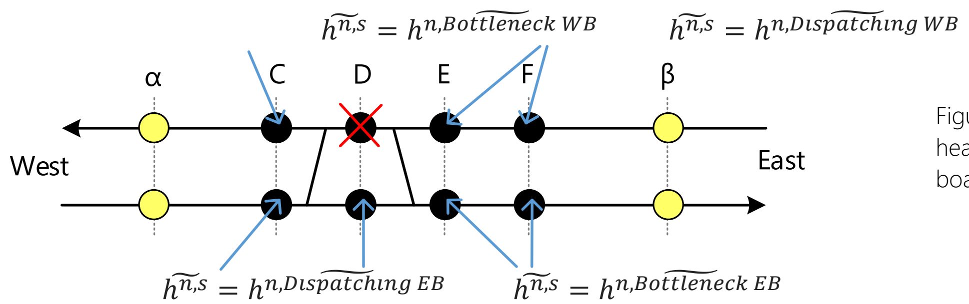


Figure 3-12: Explanation of headways for the denied boarding calculations.

The consequence is that dwell times are the same for all vehicles at each station.
These assumptions make the calculation procedures somewhat heterogeneous across impacts (for impacts (a) and (b), headways are considered *for each station* and not *per block of stations* as shown in Figure 3-12). These assumptions are meant to make the DB calculations easier to carry out within the time frame of the project, but DB may be underestimated if irregularity is underestimated.

Other assumptions are:

- A vehicle is labelled as full as soon as the crush capacity is reached.

- Each vehicle has a similar seating capacity and crush capacity, determined as weighted averages depending on the amount of wagons that each vehicle has.
- Passengers are not modelled as separate entities, therefore there is no queuing discipline. Thus it is assumed that passengers who are denied boarding multiple times experience the same inconvenience every time they have to wait. In reality, it can be expected that after being denied boarding more than once, passengers' marginal inconvenience increases.

Figure 3-13 describes how DB occurrences for every scenario n, every stop s and every vehicle v, noted as $db_v^{n,s}$, are computed. It also shows how and $p_{v,seat}^{n,l}$ and $p_{v,stand}^{n,l}$, used for impact (c), are calculated.

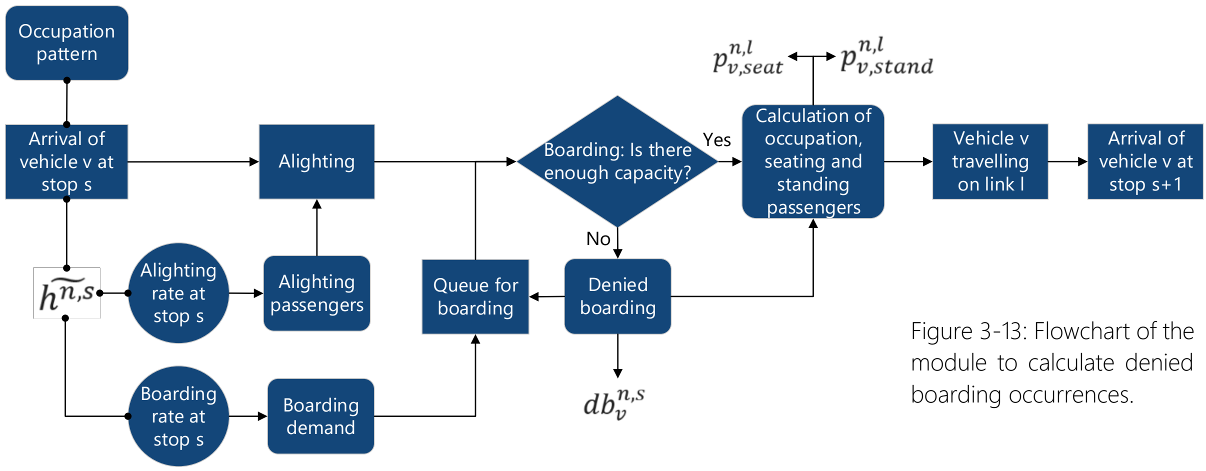


Figure 3-13: Flowchart of the module to calculate denied boarding occurrences.

If there is no denied boarding in recurrent conditions (which is expected – but this needs to be checked), then DB occurrences per stop $db^{n,s}$ found by applying Formula 3.16 are directly the difference between the reference day and a scenario. The total amount of denied boarding occurrences for a given scenario db^n follows immediately, given in Formula 3.17.

$$db^{n,s} = \sum_{v} db_v^{n,s} \;\; \forall s, \forall n > 0 \qquad 3.16$$

$$db^{n} = \sum_{s} db^{n,s} \;\; \forall n > 0 \qquad 3.17$$

Formula 3.18 is then used to allow for a translation at the OD level (see Formula 3.4) of denied boarding AGC. It is assumed that DB is equally distributed over passengers waiting at a given stop s. This means both an under- and an over-estimation of AGC for some passengers but being able to exactly compute DB AGC for each passengers requires a more sophisticated approach; see the long-term impact calculations in Chapter 5 and recommendations in Chapter 7.

$$db_{pass}^{n,s} = \frac{denied\ boarding\ AGC\ for\ stop\ s}{amount\ of\ boarding\ passengers\ at\ stop\ s} = \frac{db^{n,s} \times \Delta t_{wait}^{n,s} \times VoWT}{\sum_{\forall z \in r_{(s,z)}} p^{(s,z)}} \qquad 3.18$$

For impact (e)

The number of passengers who have an unplanned transfer in scenario $n > 0$ can be found by multiplying $p^{(y,z)}$ by a probability $\lambda^{n,s}$, where s is a stop where a measure is applied, on the route from

y to z. This type of impact could be produced by a station-skipping measure (see page 17) noted m. There are two different cases.

- *Directly impacted passengers*: they are dropped at a stop because of the application of a measure and must thus wait for at least one additional headway. In that case, $\lambda^{n,s}$ can be expressed as shown by Formula 3.19, where an equal distribution of passengers among vehicles is assumed.

$$\lambda^{n,s} = \frac{V_m^{n,s}}{V^{n,s}} \; \forall s, \forall n > 0 \qquad 3.19$$

With: $V_m^{n,s}$ $number\ of\ vehicles\ at\ stop\ s\ in\ scenario\ n > 0\ where\ measure\ m\ is\ applied$

- *Indirectly impacted passengers*: they need to transfer at some point during their trip because they could not board the vehicle they wanted to. This is the case if, for instance, two lines share a section at some point (trunk section) and then separate into branches. If the service of one of the lines is reduced to its branch part, passengers going from the trunk to this branch will be impacted. The thorny part is to determine the **additional** probability to transfer. Recall the "one line" assumption made at the beginning of the section: in recurrent conditions, if branch-bound passengers boarding from a trunk line section do indeed board the first vehicle that arrives on the trunk, independent of whether or not it goes to the right branch, they must transfer at some point to be able to reach their destination. In reality though, it can be expected that, in recurrent conditions, some people wait for the right vehicle to avoid transfers. Assuming no transfer in recurrent conditions, the additional probability to transfer $\lambda^{n,s}$ can be found by simply computing the ratio shown by Formula 3.19, with $V_m^{n,s}$ replaced by $V_m^{n,s\,up}$ the amount of vehicles for which measure m is applied at a stop *upstream* of stop s in scenario $n > 0$. This approach is chosen because it is straightforward, yet it goes against the "one line" assumption: here, branch-bound passengers in recurrent conditions are expected to wait for the right vehicle to board, while for the waiting time calculations, they were assumed to board the first incoming vehicle. Assuming that there is **already** a transfer probability in recurrent conditions makes the calculation of $\lambda^{n,s}$ significantly more complex. The simplification made here produces a slight incoherence in the assessment framework, due to the limited validity of the "one line" assumption in recurrent conditions.

Passenger demand component

Only $p^{(y,z)}$ for all $(y,z) \in S$ remains to be determined before being able to compute Formula 3.4. It is not possible to generate these values directly from the transit assignment in OV-Lite. Instead, a station-to-station (s2s) matrix for the whole network can be generated. This matrix contains the number of trips identified as going between a set of specified stops, where "going between" encompasses trips that make a transfer between modes. Therefore a method is developed to be able to obtain the desired matrix, explained in Appendix G .

The impacts presented in this sub-section will be computed for all scenarios, with and without AVL data. The generation of alternative strategies and thus scenarios, already presented in section 3.1, is explained in more details in next sub-section.

3.3.4. Generation of alternative scenarios with a model and analysis of results

In almost all of the calculations detailed in previous sub-section, headways are required. Therefore, in order to perform the same assessment but for scenarios with alternative strategies, arrival and departure times of each vehicle at all stops within the scope are required. As already explained in section 3.1, a discrete event simulation tool, ARENA, will be used.

The conceptual flowchart in Figure 3-14 shows how operations are simulated in the software. The inputs of the model are the initial situation (location of the vehicles in the network) and a control strategy. The latter has several components: dispatching times from terminals, holding times at stops, amount of dispatched vehicles and routing of vehicles. Vehicles are generated according to the chosen strategy. Each vehicle can only proceed to next stop if it is not already occupied by another vehicle. Otherwise, it has to queue. Queues have a FIFO (First In, First Out) discipline. Times are recorded at the arrival and the departure of each vehicle at each stop so that **a file comparable to an AVL file can be generated**. The outputs of the model are given under the format shown in Table 3-2.
Appendix H details the setup of the model for the case study, plus the verification, calibration and validation of the model.

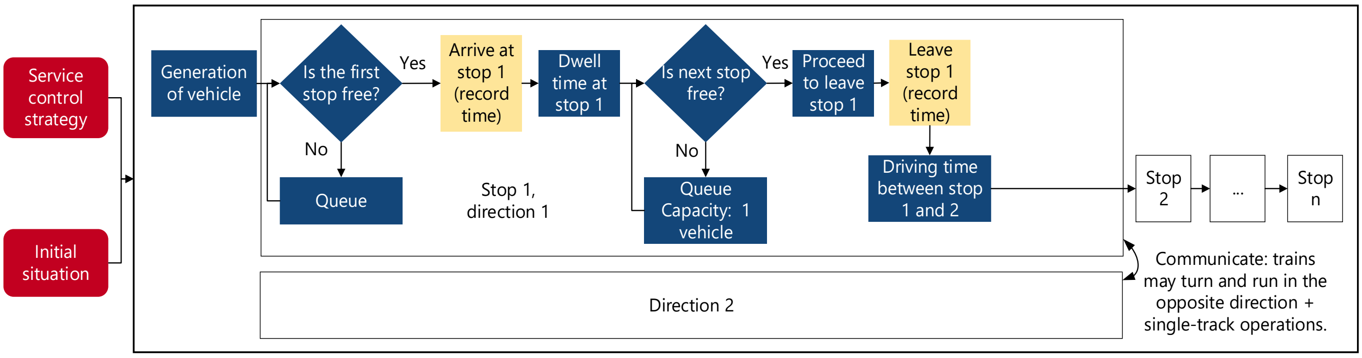


Figure 3-14: Conceptual flowchart of the DES model to simulate operations.

Table 3-2: Output of the model in ARENA.

Vehicle number	Stop	Event (departure or arrival)	Direction	Time (minutes)	If event = departure, bunching time

To generate alternative scenarios, the idea is to start from the service control measures that the dispatchers used in the investigated case and to see **what** would happen **if** they had been applied in a different way. Once enough insight is gained on these measures, other measures can be tested. Incremental changes should be made to allow for a good understanding of the phenomena involved. Therefore, if the strategy is made up of two measures, one can be fixed while the other varies, and vice-versa. In the end, it is expected that sufficient knowledge on the situation be gained to derive an ideal strategy. The generation stops when enough combinations of measures have been tested. The generation of alternative scenarios can be summed up by the flowchart in Figure 3-15. Naturally, for each service control strategy, multiple model runs may be necessary to obtain satisfying results.
In more scientific terms, this "what-if" approach is a **heuristic optimisation procedure**, i.e. a practical approximation method to develop an ideal solution. This solution is not guaranteed to be optimal though. *The* or *an* optimal solution could be found via an analytic optimisation method, often the chosen approach in research on service control measures. In this study, this is not necessarily desirable, since it aims at gaining insights into the different variables that influence a service control strategy.

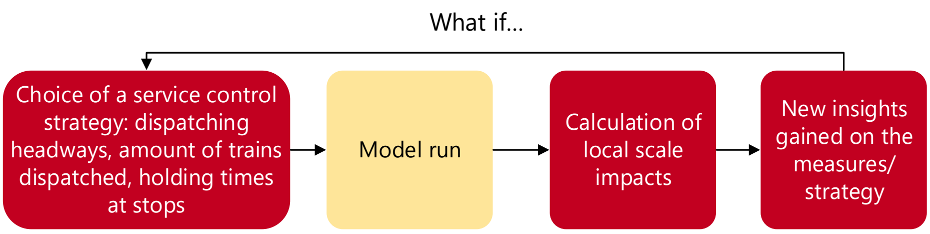


Figure 3-15: "What-if" approach to generate alternative scenarios.

Once all alternative scenarios are generated, three levels of analysis of the results can be used.

- First, the additional generalised costs values are used to compare each scenario. They can also be separated per direction; for instance, $AGC_{inbound}$ and $AGC_{outbound}$, to see which direction was most severely impacted. Obviously, the comparison must take into account the difference of passengers between both directions. A balanced distribution of the inconvenience experienced by passengers is desirable because people tend to remember their worst experience and base future trips on it (Furth & Muller, 2006). Therefore, a large inconvenience ought to be avoided. In this study, a metric called the Balance Index (BI) is introduced, as shown in Formula 3.20.

$$BI = \frac{AGC\ for\ all\ passengers\ from\ direction\ 1}{AGC\ for\ all\ passengers\ from\ direction\ 2} \qquad 3.20$$

  If there is the same amount of passengers in both directions, a BI of 1 is desirable: the scenario is *balanced*. If, for instance, there are 20% more passengers in direction 1 compared to direction 2, a BI of 1.1 would be more preferable to 0.9. Comparing average AGC was deemed less relevant since, if the distribution of AGC is widely spread, the average value is not very meaningful.
- Second, an analysis per impact can be conducted.
- Third, a comparison of performances at the OD pair level across scenarios can be done.

3.3.5. Conclusion of the local-scale assessment framework development

In the local-scale assessment, five passenger impacts are assessed. A three-step approach is used. First, from (generated) AVL data, sets of headways for each stop can be derived and supply-oriented indicators can be computed, such as average headways or the PRDM. Second, these indicators are translated into five passenger impacts, using passenger data from OV-Lite. Third, these impacts are aggregated into an additional generalised costs (AGC) function, which allows for an easy comparison between various scenarios.

In order to generate AVL data for alternative scenarios, a discrete-event simulation model is used. Alternative scenarios are developed based on a “what-if” approach, where the inputs of the model are incrementally modified. After each model run, the developed alternative is assessed and the process stops when enough combinations of measures have been created. The performances of scenarios can then be assessed by comparing the overall AGC, by impacts and by OD pair.

Next, the global-scale assessment, which provides a complementary approach to the local-scale assessment, is developed.

3.4. Global-scale assessment framework development

The global-scale assessment is complementary in the sense that alternative strategies are generated and first evaluated with the local-scale assessment, in an already detailed manner. The global-scale assessment exists to see effects on a network scale.

This section follows a similar structure than the previous one: first, the main assumptions are presented, and then the three-step approach is described in detail. This time though, the presentation is more linear (steps 1 – 2 – 3 instead of 3 – 1 – 2), since it is already clear, from sub-section 3.2.4, under which form the outputs of steps 2 and 3 will be (skim matrices).

3.4.1. Main assumptions and scopes for the global-scale assessment

The global-scale assessment is based on outputs from the local-scale assessment and the use of OV-Lite. The idea behind the global-scale assessment is to implement changes in the studied portion of the local-scale assessment to see how it affects the rest of the networks and all travellers in general.

The remark and the assumption from the local-scale assessment that still hold are respectively:
- The assessed impact – average additional travel time – is still aggregated per OD pair,
- There is a uniform distribution of travellers across the studied period and passengers also arrive randomly at stops.

Compared to the local-scale assessment:
- The "one line" assumption (see sub-section 3.3.1, page 38) is relaxed. Therefore, outputs of the local-scale assessment cannot be used *per se* and will need to be processed, under some new assumptions described in sub-section 3.4.2.
- Passengers may re-route in the network, as discussed in the presentation of OV-Lite page 35.

The relaxation of these two assumptions can be seen as an improvement compared to the local-scale assessment. However, in the global-scale assessment, passengers can never be denied boarding because the there is no capacity-constrained assignment in the model. The consequence of this is that the waiting time skim matrix is likely to be underestimated, and thus so will the travel time and generalised costs skim matrix.

The **spatial scope** is all transit lines implemented in the transit assignment model.

The **time scope** is less straightforward. Since the transit assignment model is frequency-based (see sub-section 3.2.4), the main parameter that will be adjusted to model various scenarios is line frequency. Therefore, it is assumed that these modifications **alone** can model a scenario. One of the outputs of the local-scale assessment being a set of headways for each stop within a certain spatial scope, a line frequency can be determined by averaging stop frequencies.

3.4.2. Step 1: Determination of the average and perceived frequencies

The impact assessed at the global-scale assessment is the average additional travel time for each OD pair of the network. To model each scenario, line frequencies are adjusted. In the local-scale assessment, the frequency f^n for the single line in a scenario n (including the reference day) is an average of the frequencies for each stop, $f^{n,s}$, as shown in Formula 3.21.

$$f^n = \frac{\sum_s f^{n,s}}{s_{single\ line}} \ \forall s, \forall n \qquad 3.21$$

With:
- f^n — $frequency\ of\ the\ single\ line\ in\ scenario\ n;\ average\ freq.\ over\ the\ stops$
- $f^{n,s}$ — $frequency\ of\ the\ single\ line\ at\ stop\ s\ in\ scenario\ n$
- $s_{single\ line}$ — $number\ of\ stops\ on\ the\ single\ line$

To relax the "one line" assumption and find $f^{n,l}$, the average frequency of line l in scenario n, f^n is multiplied by the share of vehicles of each line for scenario n, $\gamma^{n,l}$, as shown in Formula 3.22.

$$f^{n,l} = f^n \times \gamma^{n,l}\ \forall l, \forall n \qquad 3.22$$

With: l $line$
$f^{n,l}$ $frequency\ of\ line\ l\ in\ scenario\ n$
$\gamma^{n,l}$ $share\ of\ vehicles\ from\ line\ l\ driving\ through\ the\ stops\ of\ the\ scope\ S, one\ direction$

The advantage of using frequencies determined over rolling time windows is that globally, each time window contains the same vehicles, making $\gamma^{n,l}$ easy to determine. The exception though is in the direction where the blockage occurs: there will inevitably be more vehicles upstream of the blockage than downstream. If there are more upstream than downstream stops, then the amount of vehicles at stops upstream of the blockage will be chosen to determine $\gamma^{n,l}$, or vice-versa.

Two variants exist to compute $f^{n,s}$, used in Formula 3.19: using the **average** frequencies $f_{avg}^{n,s}$ or the **perceived** frequencies $f_{per}^{n,s}$ at stops. Recall that when describing how impact (b) is computed, page 41, it was mentioned that using half a headway as an indicator of expected waiting time means overlooking irregularity aspects, which is not desirable for a passenger-oriented research. Consequently, the PRDM was included in the calculation of the waiting time, yielding a *perceived* waiting time. A similar issue arises with frequency: using solely $f_{avg}^{n,s}$ also means overlooking irregularity aspects, hence perceived frequencies at stops $f_{per}^{n,s}$.
According to Van Oort & Van Nes (2009), the perceived headway can be defined as the headway that would result in the waiting time perceived by passengers at a given stop. This entails that the perceived headway is twice the average waiting time given the expected service regularity, as shown in Formula 3.23. Therefore, the perceived frequency can be defined as shown in Formula 3.24.

$$h_{per}^{n,s} = 2 \times E\left(\widetilde{t_{wait}^{n,s}}\right) \forall n, \forall s \qquad 3.23$$
$$f_{per}^{n,s} = \frac{60}{h_{per}^{n,s}} = \frac{60}{E(\widetilde{h^{n,s}}) \times (1 + {PRDM^{n,s}}^2)}\ \forall n, \forall s \qquad 3.24$$

With: $h_{per}^{n,s}$ $perceived\ headway\ for\ the\ single\ line\ (in\ one\ direction)\ in\ scenario\ n\ for\ stop\ s$
$f_{per}^{n,s}$ $perceived\ frequency\ for\ the\ single\ line\ (in\ one\ direction)\ in\ scenario\ n\ for\ stop\ s$

$f^{n,s}$ could therefore be replaced by $f_{per}^{n,s}$ in Formula 3.21. In the end, two frequencies per line and per direction can be obtained. They have pros and cons:

- The average frequencies are computed without taking irregularity into account, therefore they are expected to be overestimated compared to what passengers perceive. However, they do yield the right amount vehicles that effectively run.
- The perceived frequencies reflect better the reality of passengers since irregularity is taken into account but are likely to severely underestimate the amount of vehciles that run. With this approach, the travel time skim matrix is actually a skim matrix of *perceived* travel times.

Both frequencies will be implemented in the model and results will be compared. Since computations for steps 2 and 3 remain similar in any case, no distinction is made in the remainder of this section.

3.4.3. Step 2: Determination of the passenger impact (f)

Let $\Delta t^{n,(y,z)}$ be the additional travel time (abbreviated ATT) for a passenger going from origin y to destination z, $y \neq z$, in scenario $n > 0$. y and z can be any stop within the spatial scope of the global-scale assessment. $\Delta t^{n,(y,z)}$ is in fact impact (f). With the transit assignment model, it is possible to determine $t^{n,(y,z)}$, the travel time between all pairs (y, z) for all scenarios and for the reference day. Note that perceived frequencies for the reference day will also be computed, based on AVL data. Travel times are stored in the travel time skim matrix. $\Delta t^{n,(y,z)}$ can then be found with the relation shown in Formula 3.25, where it is expected that $t^{n,(y,z)}$ be larger or equal to $t^{0,(y,z)}$ (reference day).

$$\Delta t^{n,(y,z)} = t^{n,(y,z)} - t^{0,(y,z)} \; \forall \, n > 0 \qquad 3.25$$

3.4.4. Step 3: Translation into generalised costs

The translation into generalised costs is straightforward with the transit assignment model, since it provides a GC skim matrix.

Like the local-scale assessment, to understand the effect of the disruption and the associated strategy on passengers, it is suggested to divide the analysis of the results of the global-scale assessment for each selected scenario into three components:

- First, impact (f) and the additional generalised costs values will be used to compare each scenario,
- Second, the re-routing of passengers over the network will be analysed,
- Third, two estimates of lateness could be provided:
  - The amount of people who would miss their train connection at a given train station,
  - The amount of people who would be late at work/school.

  Additional assumptions for the calculation of these estimates will be provided in Chapter 5.

3.4.5. Conclusion of the global-scale assessment

In the global-scale assessment, one passenger impact is assessed for all passengers in the network represented in the transit assignment model: average additional travel time. This impact can in fact be assessed in two ways: by determining an effective value and a perceived value, using respectively effective and perceived frequencies. Once again, the three-step approach is used, which is rather straightforward thanks to the use of a transit assignment model.
More than the results, their interpretation will matter. Indeed, OmniTRANS was not specifically designed for this type of analysis (changes at the operational level). Still, it probably has the potential to show how network users would be impacted by a disruption, and how they would re-route.

3.5. Conclusion of the assessment framework development

This chapter has first presented the method used to create the assessment framework. In the rest of this chapter, the two first phases were then developed into more details: the insights gained from the literature study, coupled with the choice of a method to develop alternative strategies, allowed to progressively set up the theoretical framework of the assessment framework.
This chapter also allowed to answer two research sub-questions.

> **A3.** What are the impacts that would assess best the inconvenience experienced by passengers?

During non-recurrent conditions, passengers are likely to experience additional travel time. This impact will be assessed in this study at a network scale. In addition, more specific impacts will be assessed at a local scale:

- Bunching, which translates in an additional effective in-vehicle time at stops.

- Crowding and comfort aspects, assessed in two complementary ways:
  - Via additional perceived in-vehicle time between stations; the more crowded a vehicle, the larger the in-vehicle time perception,
  - Via denied boarding, which causes an extension of waiting time.
- Unplanned transfers, which translates into a penalty and additional waiting time.
- Additional waiting time at the first stop.

Each of these impacts relates to at least one of the passenger needs as defined by Van Hagen et al. (2000) (see beginning of Chapter 2).
In this research, waiting time is computed by associating irregularity aspects to the usual waiting time calculation. This provide a better estimate of waiting time and allows for reliability to be taken into account.
As a complement, it is suggested to roughly estimate long-term effects of a disruption; however, this is not integrated within the assessment framework itself.

A4. With what methodology should these impacts be assessed?

As hinted in the answer to previous sub-question, two different levels can be used to conduct the assessment:
1. A global scale, which takes the whole public transport network of the city where the case study is conducted into account. At this scale, the most aggregate impacts of all is assessed: additional travel time.
2. A local scale, which only takes a few stops into account. At this scale, more specific impacts can be assessed.

With the use of inputs and outputs from a transit assignment model, it is possible to perform most of the assessment at the OD level.
At both scales, the impacts are assessed with a three-step approach:
1. The first step consists of the analysis of vehicles' performance, using AVL data. At this point, supply-side impacts are obtained.
2. Then, passenger impacts are computed with passenger data from OV-Lite. By weighing times by demand, light is shed on the OD pairs with high passenger volumes.
3. Lastly, passenger impacts are translated into monetary values. Each scenario is then associated with an additional generalised costs value and can easily be compared to any other scenario.

The methodology – in particular the way impacts are computed – is developed by making sure that both scenarios with and without available AVL data can be assessed in a similar way. When no AVL data is available, it is generated with a discrete-event simulation model. This model is also at the core of the procedure to generate alternative strategies, integrated in the local-scale assessment: alternative scenarios are developed based on a "what-if" approach, where the inputs of the model are incrementally modified. Modifications correspond to different combinations or implementations of service control measures. This approach thus differs from that of Carrel (2009), who used solely historical data to compare strategies.

The answer to these sub-questions is summarised in the overview displayed in Figure 3-16.

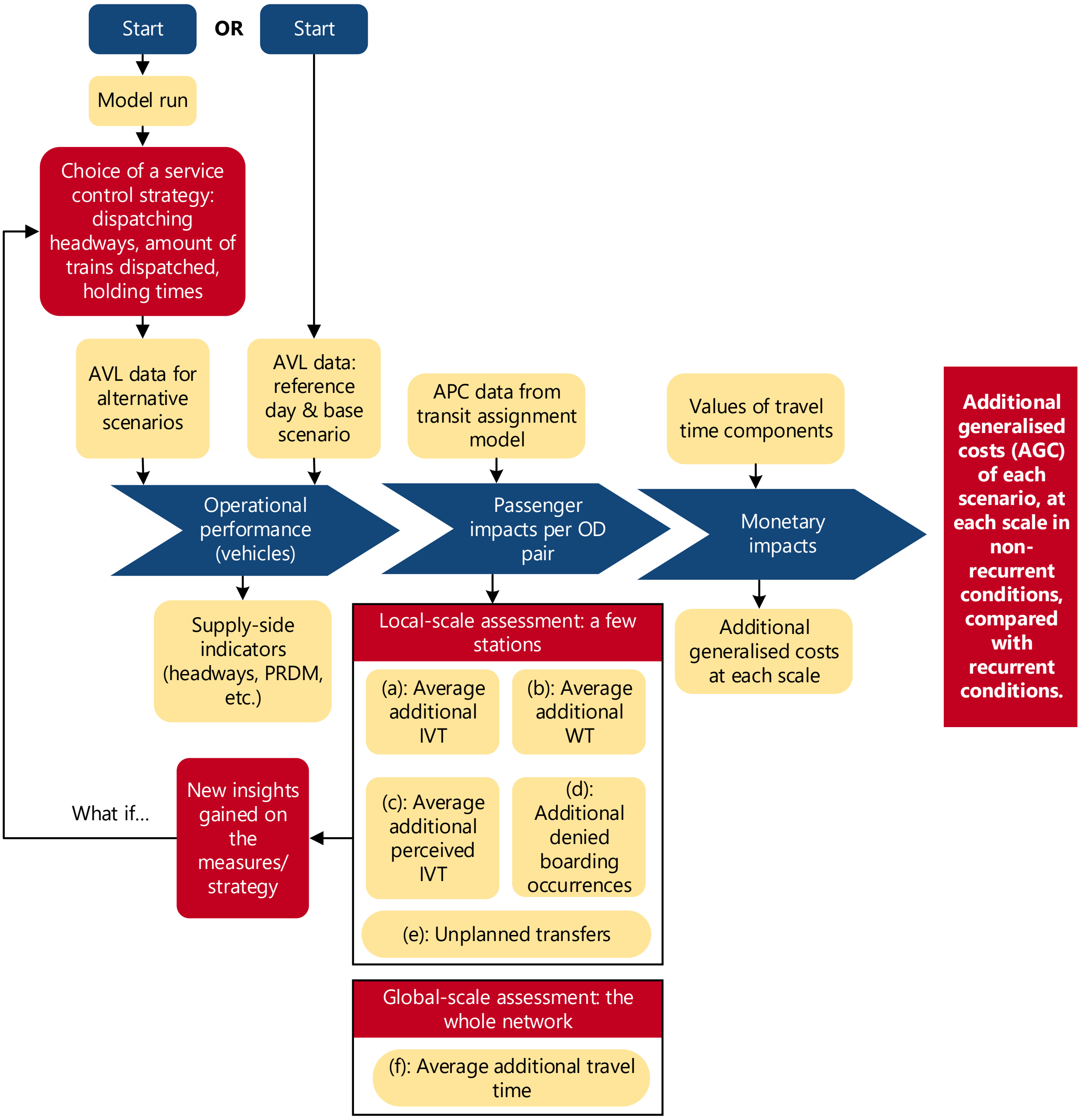


Figure 3-16: Detailed overview of the developed framework to assess service control strategies in non-recurrent conditions from a passenger perspective.

Before the application of this framework in Chapter 5, which is part of the assessment framework development as a test, an introduction to the case study itself will first be done in Chapter 4.


M

Chapter 4 Introduction to the case study

This chapter introduces the case study, to get a better understanding of the **system** in which it takes place. Carrel (2009) argues that it is through a good understanding the bigger picture that he managed to formulate insightful conclusions out of his analysis.

The aim of this chapter is to answer the following sub-question:

> **B1.** How are operations and disruption management currently organised for the metro of Rotterdam?

Basic information on the metro system is provided in section 4.1. Section 4.2 explains the disruption management system at the RET, with a special focus on the operational level. While the first section is purely factual, the second one presents a more critical view, particularly on how passenger-oriented actions are. Section 4.3 presents the selected case study and prepares the application of the assessment framework. The chapter ends with a conclusion.

4.1. The metro system in Rotterdam

4.1.1. Network

The metro network of the RET counts as of beginning of 2017 five lines and 53 stations. It is depicted in Figure 4-1. Each line shares at some point infrastructure with another line. For instance, in Blaak, the infrastructure consists of two tracks, one for each direction, which three lines share.

Abbreviation	Full name
Aks	De Akkers
Ald	Alexander
Bre	Beurs
Lhv	Leuvehaven
Mhv	Maashaven
Mltw	Melanchtonweg
Rcs	Rotterdam Centraal Station
Rhv	Rijnhaven
Slg	Slinge
Spc	Spijkenisse Centrum
Shs	Stadhuis
Whp	Wilhelminaplein
Zpl	Zuidplein

Figure 4-1: Map of the metro network of Rotterdam (RET, 2016b) with abbreviations.

4.1.2. Frequency of service

Headways vary throughout the day and differ on the network, as shown in Table 4-1. Only the frequency of line D doubles during both morning and evening peaks.

Table 4-1: Working day frequencies in the metro of Rotterdam in 2016.

	Early morning (5-7 AM)	**Morning peak (7-9 AM)**	**Midday (9 AM – 3 PM)**	**Evening peak (3-6 PM)**	**Early evening (6-7 PM)**	**Late evening (7 PM – 1 AM)**
Line A	4	6	6	6	6	4
Line B	4	6	6	6	6	4
Line C	4	6	6	6	6	4
Line D	4	12	6	12	6	4
Line E	4	6 (8 soon)	6	6	6	4

4.1.3. Passenger utilisation of the metro of Rotterdam

Public transport users in the Netherlands use the OV-Chipcard, a contactless smartcard they tap on terminals to pay their fare. In the metro of Rotterdam, passengers need to check-in at their departure metro station and check-out at their final destination metro station. In 2015, 54% of all check-ins were done in the metro; see Figure 4-2.

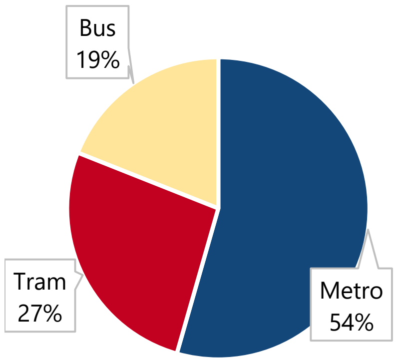


Figure 4-2: Share of check-ins per mode operated by the RET in 2015 (RET, 2016c).

De Vries (2010) stated that in the public transport system of Rotterdam, the morning peak is in general more concentrated than the evening peak. Figure 4-3 illustrates this statement for the metro system. 8 AM is the busiest hour in terms of check-ins during a working day, even though 4 and 5 PM are close behind.

Figure 4-4 shows the share of trip purposes for the metro in the morning, during working days, aggregated over two categories. The trip purpose "Other" was added to the leisure trip purpose, in line with the suggestion of Bel (2013). The largest passenger group is that of commuters.

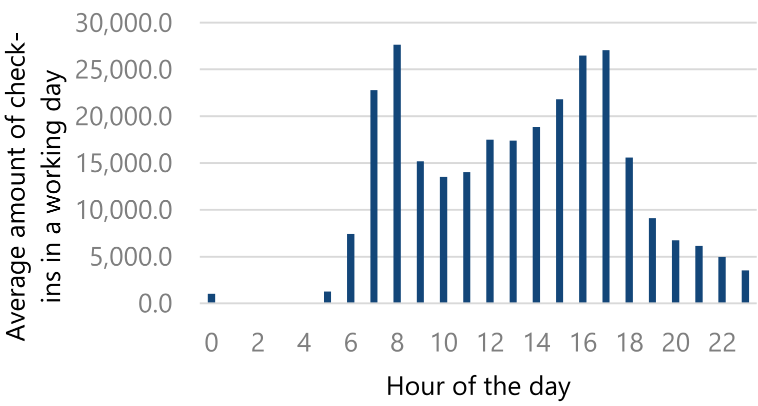


Figure 4-3: Average amount of check-ins in the metro of Rotterdam over a working day (data from January 2015 – May 2016).

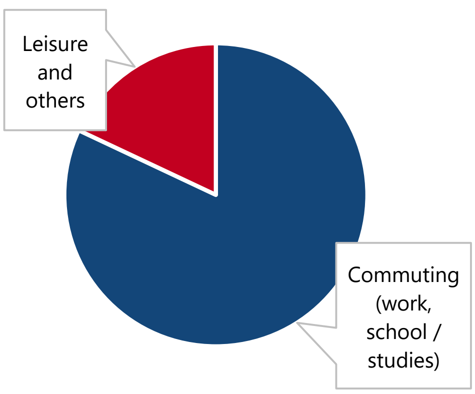


Figure 4-4: Share of trip purposes between 07:00 AM and 12:00 PM, working days, in the metro of Rotterdam (RET, 2016a).

4.1.4. The traffic control centre

The traffic control centre is in charge of ensuring the proper execution of daily operations. At the RET, it gathers in the same room:

- Dispatchers, divided into two groups: bus/tram on one side and metro on the other side. Figure 4-5 shows the workplace of metro dispatchers. They are monitoring traffic with desktop screens and screens on the wall. Dispatchers are the ones who register disruptions in the system.
- One or two passengers' informer(s). They are in charge of communications with passengers through in-station announcements and digital updates.
- Security agents. They watch live CCTV footages from stations, monitoring security over the network, check-ins at gates and crowding on platforms.

Figure 4-5: Corner of metro dispatchers at the traffic control centre of the RET.

4.2. Disruptions in the metro network of Rotterdam

Disruptions can be addressed in more or less passenger-oriented ways. In this section, the nature of disruptions in the metro of Rotterdam is first presented. Next, metrics used to analyse disruptions are discussed. Lastly, disruption management at the operational level is presented and commented.

4.2.1. Occurrence and causes of disruptions

The early morning is the most concentrated time period in terms of disruptions, as displayed in Figure 4-6.

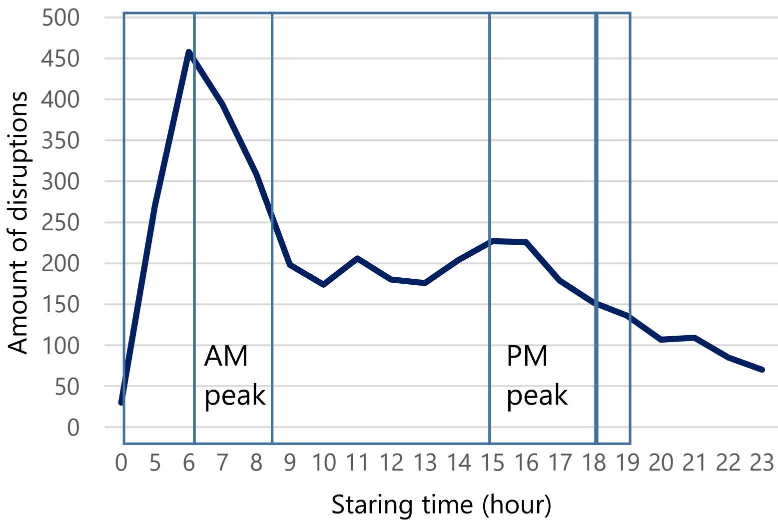


Figure 4-6: Amount of registered disruptions in the metro and corresponding starting time (data from January 2013 – July 2016).

This can be explained by the fact a vehicle with an equipment problem undetected during maintenance is likely to break down within the first hours of use. Morning peak travellers are then likely to be affected if the aftermath is consequent enough. Figure 4-7 displays the amount and average duration of disruptions by ground causes. Note that a disruption is defined at the RET as an unplanned event after which more than 10 minutes are required to return to the regular operations plan. Therefore the duration displayed in Figure 4-7 is the time from the beginning of the disruption until the time the timetable is fully restored. Using the disruption classification mentioned in sub-section 2.2.1 page 14, it is worth noting a few elements:

- Equipment failure is the most common type of incident, likely to cause non-moving or slow-moving line blockages if the failure occurs when the vehicle is in service. One single failure can affect an entire line and thus have a global effect, especially if the failure occurs on a portion with shared infrastructure. Failures may also occur in terminals, when the vehicle is about to leave. If the terminal has multiple tracks, the effects of the disruption might remain contained. Note that these incidents would be classified as endogenous; the best thing for passengers would be not to experience any of these disruptions in the first place.
- A high number of disruptions are poorly classified: the ground cause "Other incidents" contains quite a lot of disruptions. A look at the sub-causes reveals that most disruptions could be better registered, i.e. with more revealing ground causes.

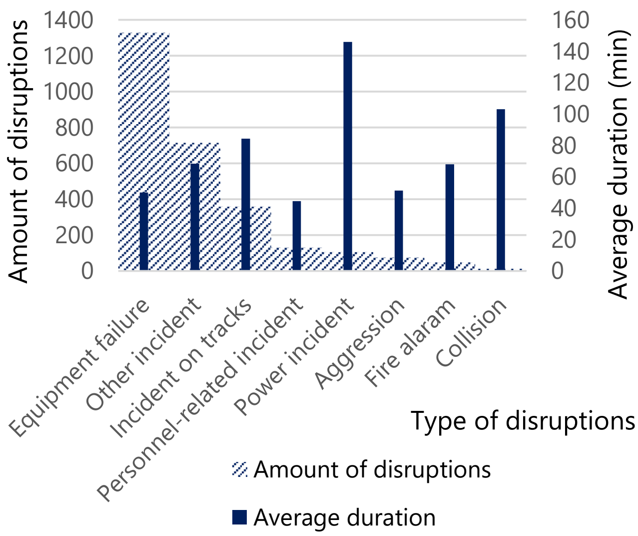


Figure 4-7: Amount and average duration of each type of disruption (data from January 2013 – July 2016).

- "Incident on tracks" could mean line blockages and/or reduced infrastructure capacity. These types of disruptions can be lengthy, especially if they require external intervention.
- When drivers start shifts in terminals, personnel-related incidents are likely to remain relatively contained, because they mean either a single train delay or a train blocked in terminal. When shifts starts at stations along a line, a late driver can have a considerable impact by causing a non-moving line blockage. Aggressions and fire alarms also cause non-moving line blockages and impact an entire line. In case of a fire, the whole system may be frozen.
- Power incidents and collisions are likely to cause complete blockages and thus arguably severely impact passengers. Power incidents are a major issue because they are particularly long to resolve and occurred on average once a month.

Therefore, all disruptions are different and their effect is heavily context-dependent. Several of them may cause partial blockages affecting entire lines. To address disruptions, actions are taken at multiple levels, starting at the strategic level, by analysing disruptions. This is discussed in next sub-section.

4.2.2. Metrics used at the RET to analyse disruptions

Arguably, registering the total duration of the disruption only does not provide a clear insight on the extent to which passengers were inconvenienced: returning to the regular operations plan after a 10- or a 20-minute blockage might take a similar amount of time yet passengers were impacted differently. Since April 2016, the RET has been registering the duration of the incident phase though. Aside from duration, other metrics exist to analyse disruptions.

As explained page 2, according to Barron et al. (2013), examining which incident-related metrics are used by at PTO can tell a lot about the goals of the management and to what extent passengers are taken into account. A data analyst at the RET was asked to indicate whether or not the RET would be able provide the indicators that Barron and his team (2013) requested to the 22 metro systems for their study. Results are reported in Appendix B . Two remarks can be made.

First, only two metro systems were able to provide the **number of passengers affected** and **total passenger delay**. These metro systems also proved to be the most reliable ones. The analysis conducted by Barron et al. (2013) led them to argue that managing a transit system on the basis of the number of passengers affected and total passenger delays, and not on the basis of incident frequency, leads PTOs to direct resources and investments in a way that benefits passengers. That, in turns, makes their systems more reliable. However, the extra travel time estimation of the RET is too approximate to qualify as a valid metric.

Second, at the RET, the emphasis is put on **duration** and **frequency** of occurrence. Although this allows to compute exposure, defined by Cats et al. (2016) as the share of time a certain network element is subject to disruptions when there is traffic, it does not cover the full picture. The extent to which passengers are inconvenienced is indeed not fully expressed by duration and frequency (Barron et al., 2013; Carrel, 2009).

Therefore, the RET probably lacks some relevant metrics to analyse incidents in a passenger-focused way. This underlines the relevance of the assessment framework for the RET.

4.2.3. Operational disruption management in practice at the RET

When a section of the metro network is unavailable, dispatchers at the RET are taught to respond by using the corresponding predefined strategies. These strategies, meant for the incident phase, state which actions are to be taken when a portion of the infrastructure is blocked and which stakeholders should be informed (this part is not discussed in this research though). The goal behind the use of such predefined service control strategies is to have a more uniform way of working within the traffic control centre. In turn, passengers are expected to benefit from the use of these predefined strategies with quicker and clearer information. An example of predefined strategy is presented in Figure 4-8.

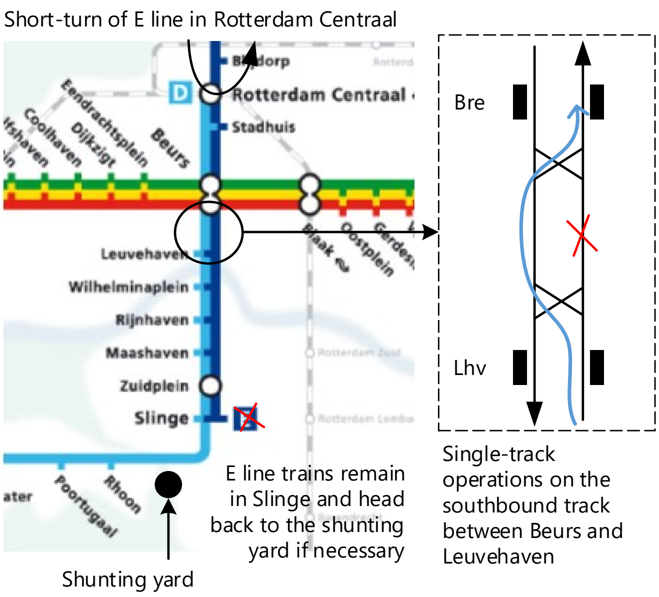


Figure 4-8: Service control strategy for a partial blockage in the northbound track between Leuvehaven and Beurs.

The remainder of this sub-section discusses these strategies. It is based on participatory observations at the traffic control centre and a questionnaire. The questionnaire can be found in Appendix C . A few disruption cases were selected and respondents were asked to explain what they would do and why if the disruption was to happen during the morning peak. The questionnaire was used to allow for dispatchers to answer questions at their own pace and without any language barrier since they could reply in Dutch. Two metro planners also answered the same questionnaire.

Predefined strategies were designed by small teams of experienced dispatchers who gathered around a table, with the map of the infrastructure, and decided on measures to suggest for each blocked section. Since the dispatchers who designed the strategies used to be drivers – like most dispatchers

– they did not feel the need to explicitly mention design objectives because they were already well-aware of possibilities and constraints. Answers to the questionnaire prove so: most dispatchers mention **staff availability** as the major constraint linked to the implementation of service control strategies, while none of the planners mentions it. Nevertheless, such an awareness is probably a double-edge sword: dispatchers' experience as drivers may have biased the way they designed and now use strategies, unconsciously forgetting to consider some passenger-related aspects. Discussions also reveal that dispatchers are influenced by the implicit assumption that "the sooner the timetable is restored, the better for passengers". As highlighted in previous studies, this is not necessarily true (see Kroon & Huisman (2011), for instance). In high-frequency public transport systems, an improvement in regularity matters more than an improvement in punctuality (Schmöcker et al., 2005).

In practice, these strategies present shortcomings.

- First, they were not designed for any specific time of day. Interestingly enough, when asked about a partial blockage between Slinge and Rotterdam Centraal, dispatchers never mentioned that the relatively high frequency of the D line during the morning peak could pose a problem to the single-track operations. Planners, however, did. A simple capacity calculation using the method of Chu & Oetting (2013) shows that a frequency of 24 vehicles per hour – 12 in each direction – is not feasible for the case they were questioned about; see Appendix D .
- The author has seen, in multiple AVL files, four or even five trains sent in a row in a single-track portion in peak hours, which means long WT for passengers in the other direction.
- Network effects and opportunities may not be properly acknowledged. Predefined strategies never highlight the possibility for a capacity shift, allowed by the structure of the network (see Figure 4-1. There are two ways to go from Tussenwater to Beurs: via Slinge or via Schiedam).

4.2.4. Conclusion on the disruption management in the metro of Rotterdam

The two main conclusions of this short analysis of the disruption management in the metro of Rotterdam are that:

- Although the RET has data to analyse disruptions in a passenger-oriented way, no metric using them is defined. Frequency and duration are not enough to assess how impacted passengers are.
- The predefined strategies used in case of disruptions on the infrastructure are an important first step toward being more passenger-oriented but they present shortcomings.

4.3. Presentation of the selected disrupted situation

In this section, the disruption that will be analysed is introduced. The types of measures that will be investigated as part of alternative strategies are then presented. The end of the section focuses on the setups for local- and global-scale assessments.

4.3.1. Overview of the selected disrupted situation

So far, this chapter showed that the morning peak is a particularly sensitive period: these are approximately two hours when a lot of people travel, disruptions are likely to start right before this peak time yet predefined strategies are simply not adapted to peak hours. This is why a disruption occurring during the morning peak is one of the criteria for the in-depth case study selection. Multiple other criteria were selected, including where and for how long it happened, but also how the disruption was registered. The selected case study is presented in Table 4-2. A reference day was also selected and seasonality effects were corrected for (see Appendix E for more details on the selections and seasonality effects).

Table 4-2: Main characteristics of the selected disrupted situation.

<table>
<tr><td rowspan="3">
</td><td>Location of the partial blockage and type of disruption</td><td>Day & time of start</td><td>Adopted service control strategy</td><td>Duration of the incident phase</td><td>Duration of the recovery phase</td></tr>
<tr><td rowspan="2">Maashaven (Mhv) northbound, equipment failure.</td><td rowspan="2">Wed., May 18th 2016, 07:50 AM</td><td rowspan="2">Single-track operations in Mhv + short-turnings in Rcs (Rotterdam Centraal Station) and Slg (Slinge).</td><td colspan="2">According to the Incident Registration Management System used at the RET</td></tr>
<tr><td>55 minutes</td><td>105 minutes</td></tr>
</table>

AVL data allows to draw a time-space diagram of the operations on May 18th, during the incident phase. It can be found in Figure 4-10. It allows to better understand the disruption and the strategy implemented by dispatchers. Figure 4-9 presents the infrastructure layout in the disrupted area.

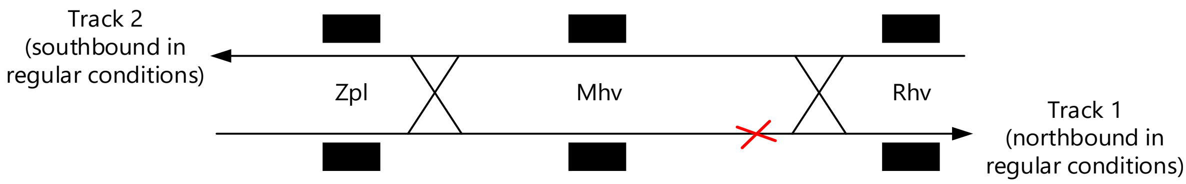


Figure 4-9: Layout of the tracks in the disrupted area (RET, 2015).

The red cross in Figure 4-10 indicates the time and location (between Maashaven and Rijnhaven, before the switch; see Figure 4-9) where the unplanned event occurred. The exact start of the disruption can be estimated between 07:47 and 07:50. Thus, the decision-making process started at least at 07:50, but it was already enough to have train 57 blocked behind, in Mhv. The start of the strategy application phase is probably the moment when dispatchers decided to allow for single-track operations on track 2, i.e. when they decided to delay train 39 southbound in Rhv to let train 61 northbound go first on track 2 in Mhv, around 07:53. The end time of the incident and strategy application phases corresponds to the moment when track 1 was re-opened, between the arrival of train 47 northbound on track 2 and train 56 northbound on track 1, i.e. between 08:40 and 08:44. Therefore the strategy application phase lasted around 50 minutes.

Table 4-3 compares the reference day with the actual strategy used by dispatchers and the predefined strategy corresponding to this partial blockage, on a 50-minute basis. The actual strategy is not equal to the predefined strategy. 13 trains crossed the bottleneck in 50 minutes, as opposed to the 20 planned trains. In particular, only half of the planned trains crossed the bottleneck southbound. Given the calculations carried out in Appendix D , this is not surprising: the predefined strategy was found to be unfeasible. This raises the following questions: ***Is the dispatchers' strategy the best feasible strategy that can be applied for passengers?*** *And whatever the answer to this question is, how can the predefined strategy be adapted?*

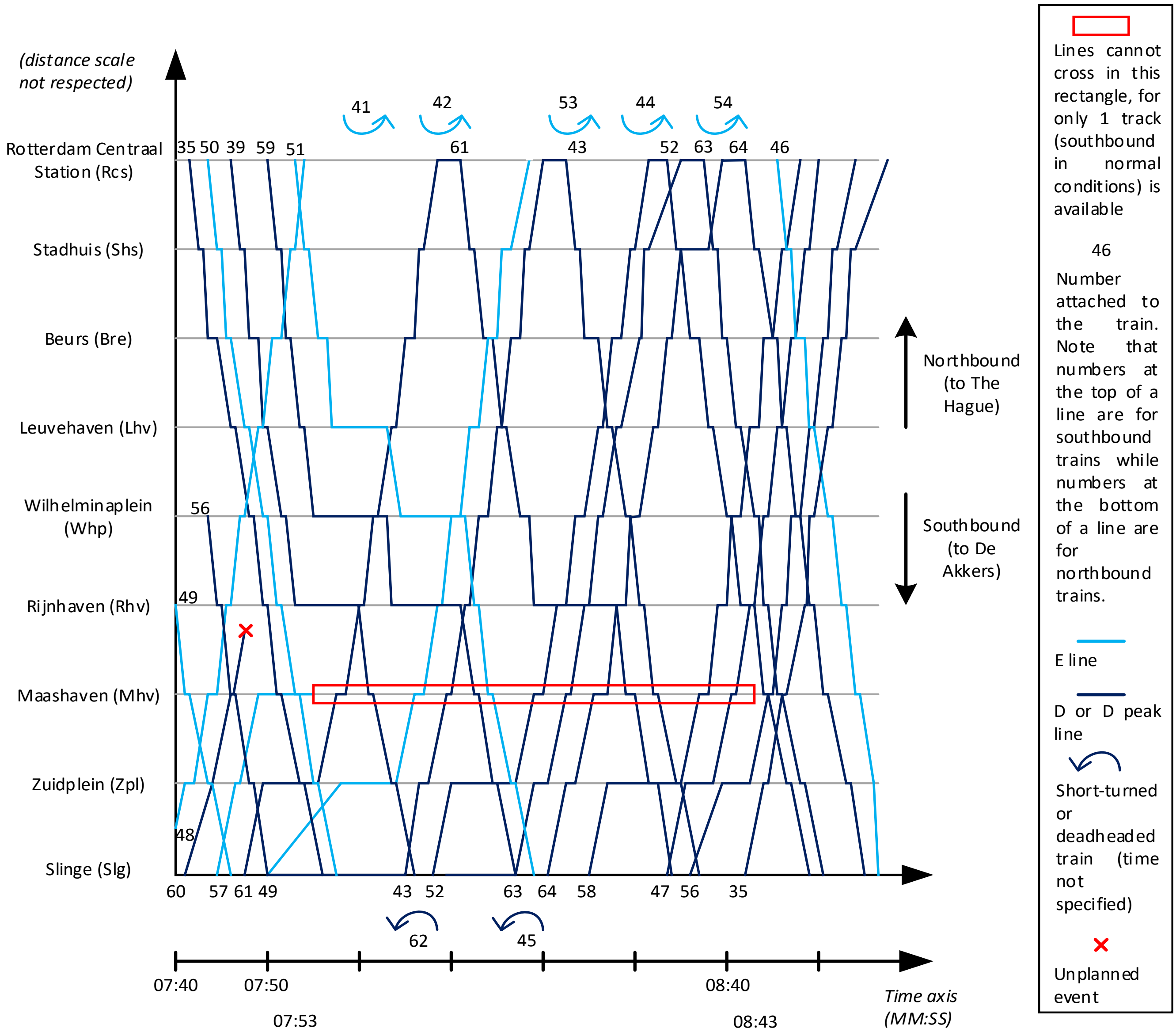


Figure 4-10: Time-space diagram between Slg and Rcs on May 18th, from 07:40 AM until 08:50 AM.

Table 4-3: Comparison of the reference day, the actual strategy used by dispatchers and the predefined strategy, basis of 50 min.

Reference day	**Actual strategy**	**Predefined strategy**
No strategy (no disruption); 15 trains in each direction	Single-track operations, sequence in Mhv track 2: ↑ ↓ ↑↑ ↓↓ ↑↑↑ ↓↓ ↑↑. 8 trains NB, 5 trains SB. Short-turnings: 5 E line trains in Rcs, 2 D line trains in Slg E line trains in Slg stay in Slg.	Single-track operations, sequence in Mhv track 2: ↑↑ ↓↓ ↑↑ ↓↓ ↑↑ ↓↓ ↑↑ ↓↓ ↑↑ ↓↓. 10 trains NB, 10 trains SB. Short-turnings: 5 E line trains in Rcs, 0 D line trains in Slg + E line trains in Slg stay in Slg.

4.3.2. Setup of the assessments

This sub-section details the setups of the assessments. Only highlights are given here; all details can be found in Appendix G . The detailed setup of the model in ARENA can be found in Appendix H .

Local-scale assessment: Spatial and time scopes

Figure 4-11 illustrates the chosen set of stations, between terminal stations Slg and Rcs, on the trunk section of lines D and E. This is motivated by the fact that Slg and Rcs both offer the possibility for trains to short-turn relatively easily since they have at least one track more than the two regular ones. Besides, the predefined strategy is focused on this trunk section (see Table 4-3). It is assumed that passengers outside of this trunk are not affected.

Figure 4-11: Set of selected stations.

In line with the presentation of the global-scale assessment last chapter, instead of two lines, it is assumed that there is one line. In recurrent conditions, it has a frequency of 18 vehicles per hour, with seating and crush capacities determined based on the mix of trains taken into account in the assessment.

The dummy stations are at the outer edges of the selected set, called S (for South) and N (for North), respectively for the outer edge near Slinge and near Rotterdam Centraal. The section from Blijdorp to Den Haag Centraal is called the *E line branch* and the one from Slinge to De Akkers the *D line branch*. Time windows are determined based on the data from May 18th and are applied for the evaluation of all related scenarios. All time windows have the same length, one hour.

Local-scale assessment: Passenger data

To find the adequate s2s matrix for the scope S, OV-Lite is used. It can be found in Appendix G . The main highlights are:

- 38% of passengers from the line E branch (Blijdorp – Den Haag Centraal) alight or transfer in Bre.
- 32% of the passengers who boarded in Zuidplein alight or transfer in Beurs. This group of passengers is particularly interesting because they need to go through Maashaven.
- 28% of the passengers reaching Wilhelminaplein, the third busiest station in terms of alighting passengers, come from Beurs.
- There are 6783 northbound passengers and 5211 southbound passengers.

Global-scale assessment

Lines and line characteristics in OV-Lite are adjusted to model various scenarios. The new configuration was tested and verified.

Service control measures used in the generation of alternatives

Single-track operations, holding for regularity purposes, holding upstream of the bottleneck (for single-track operations) and short-turning are the investigated measures, due to their relevance for the incident phase and for the case study.

Model in ARENA

An overview of the model in ARENA is shown in Figure 4-12. It specifies the schematic overview displayed in Figure 3-14. There is one path for each direction. Each path is made up of a set of stops to visit in a predefined order. At the beginning of the simulation, at 07:53 AM (start of single-track operations), some trains are already present in the trunk section. They are therefore injected in the simulation before it starts running. A schedule for incoming trains is also provided. Holding times are directly added within paths. Blocks in red represent inputs.

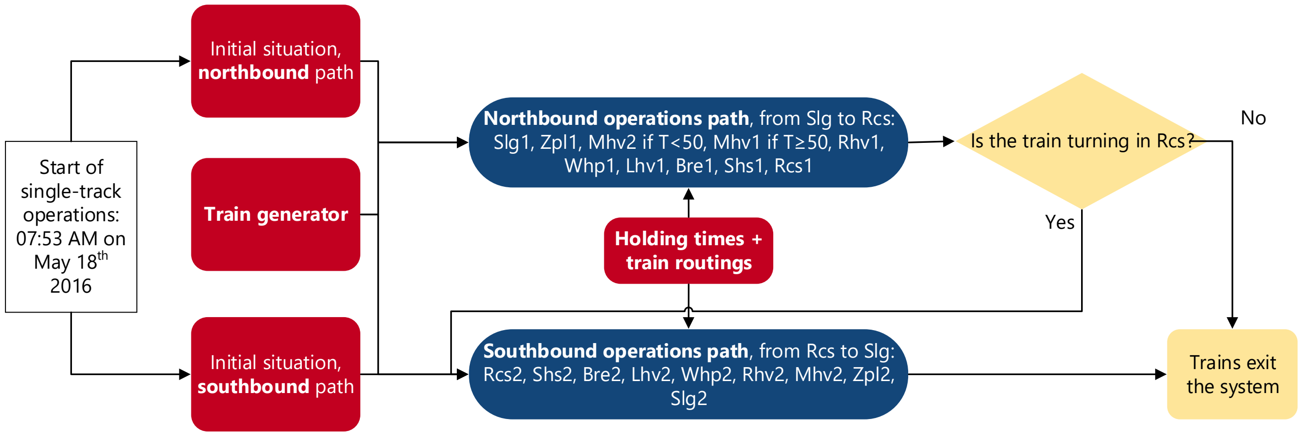


Figure 4-12: Schematic overview of the model in ARENA.

4.4. Conclusion of the presentation of the case study

First, this chapter presented the case study, i.e. the metro of Rotterdam operated by the RET. Sub-sections 4.1 and 4.2 answered the sub-question presented at the beginning of the chapter:

> **B1.** How are operations and disruption management currently organised for the metro of Rotterdam?

The metro system of Rotterdam is made up of five lines, which all share tracks with at least one other line at some point. This means that a disruption, particularly on a shared infrastructure portion, can have significant network-wide effects.
An investigation on metrics used to analyse disruptions shows that the RET does not analyse disruptions in a passenger-oriented way, which may be misleading on the actions to take to mitigate these disruptions. This highlights the relevance of the passenger impacts defined in Chapter 3.
At the operational level, having predefined strategies is already a first step towards being passenger-oriented but benefits gained from the standardisation in responses may be overshadowed by the shortcomings of these strategies. Indeed, they were qualitatively designed by metro dispatchers, often former drivers, who did not explicitly formulate design objectives. Service control interventions were chosen according to what seems logical and manageable to dispatchers, people who are often well-aware of rolling stock and crew rescheduling issues, with two strong focus areas: first, limiting the deviation of crews from their original duty and second, returning to the regular timetable as soon as possible. In addition, the lack of precision of certain elements, like distinctions between different times of day, pushes dispatchers to use rules which may not be the most advantageous for passengers. In that sense, the predefined strategies at the RET could be seen more like guidelines than pre-planned strategies, using the terminology of Moore (2003) (see section 2.2 page 15). Yet in non-recurrent rail blockages, pre-plans rather than guidelines are advised.

A disruption on which the assessment framework will be applied in next chapter was then chosen based on multiple criteria and the measures to investigate in alternative strategies were selected. On May 18th 2016, dispatchers used short-turnings and single-track operations associated with holding upstream of the bottleneck to address the incident phase of the blockage in Maashaven. These measures will be investigated, as well as holding for regularity purposes.

Chapter 5 Application of the assessment framework

In this chapter, the methodology developed in Chapter 3 is applied on the case presented in the second part of Chapter 4. The aim is therefore, as explained at the beginning of Chapter 3, to test the assessment framework. This chapter will answer the two following sub-questions:

B2. For the selected case, how does the current predefined service control strategy perform?

B3. Which new strategies could be developed and how do they perform when assessed by the developed framework?

The first section presents the local-scale assessment results, intertwined with the procedure to generate alternative strategies. Next, the global-scale assessment is performed in section 5.2. In section 5.3, the validation phase of the assessment framework is discussed. Then, in section 5.4 some complementary analyses are conducted, as already suggested in the previous chapters (sensitivity analysis, long-term impacts, etc.). Finally, conclusions are formulated in section 5.5.

5.1. Generation of alternative strategies and local-scale assessment results

First, the Base Scenario – i.e. what happened on May 18th 2016 – is assessed. Then, the heuristic procedure is applied and alternative scenarios are generated. Next, the results of the local-scale assessment are discussed per impact, and then per OD pair.

5.1.1. Base Scenario performance

The results of the assessment of the Base Scenario, depicted in Figure 5-1, show that the impacts that incorporate waiting time (WT at first stop, denied boarding, transfers) are dominating.

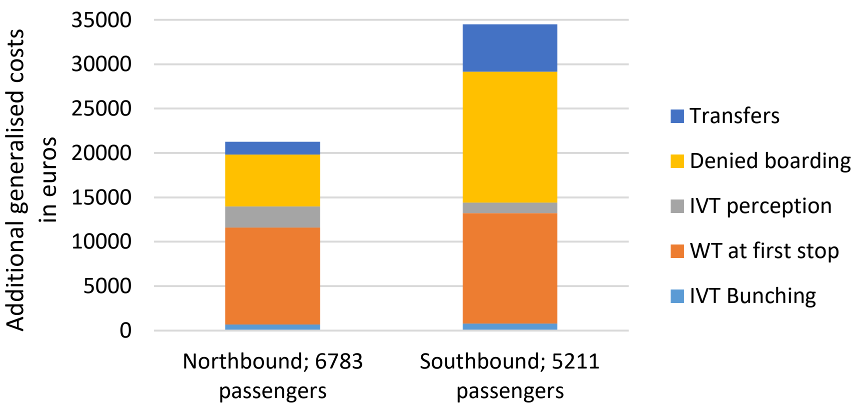


Figure 5-1: Local-scale assessment of the Base Scenario, one hour of the morning peak (strategy applied by dispatchers on May 18th 2016); passenger impacts translated into monetary costs and divided per direction.

There are 30% more passengers travelling northbound than southbound. Yet the latter suffer on average from a larger inconvenience, especially in terms of denied boarding. The Balance Index of the Base Scenario is rather low, 0.63. The observed imbalance is probably due to the significant gap in service in Rcs, 18 minutes between two southbound train departures. This gap highlights that it is not beneficial to implement a strategy early without anticipating the consequences: if E line train 51 (see Figure 4-10 page 62) had been short-turned, the 18-minute gap would have been even larger. This gap is caused by the combination of two events:

- The breakdown of a D line train, which will therefore not turn back in Rcs,
- The short-turning of E line trains in Rcs. When the disrupted operations plan is up and running, no significant gap in service in Rcs SB is expected because the D line should have a rather regular pattern. However, at the start of the short-turnings, during the *transition phase*, a gap is created. The operations plan is indeed designed in such a way that *E line trains usually cross paths around*

Rcs, i.e. when an E line train in Rcs is heading to Slg, another one is heading to Den Haag. Therefore, each can be called the *counter-train* of the other one. On May 18th, a train and its counter-train both headed towards Den Haag at the beginning of the disruption.

5.1.2. Results of the generation of alternative strategies procedure

The flowchart of the procedure is shown in Figure 5-3 (it needs to be read starting at Scenario 2, then 3, 4, etc.), and the results in AGC stand in Figure 5-4, page 67. The text in the remainder of this section accompanies these figures. Details on the generated scenarios can be found in Appendix I .
Three main categories of strategies were investigated, as shown in Figure 5-2. They are:

- Single-track operations with short-turnings where a third track is available, like in the Base Scenario (left in Figure 5-2),
- Short-turnings where a third track is available *and* in the trunk section: in the bottleneck or elsewhere (right in Figure 5-2). More explanations come in the paragraphs below.

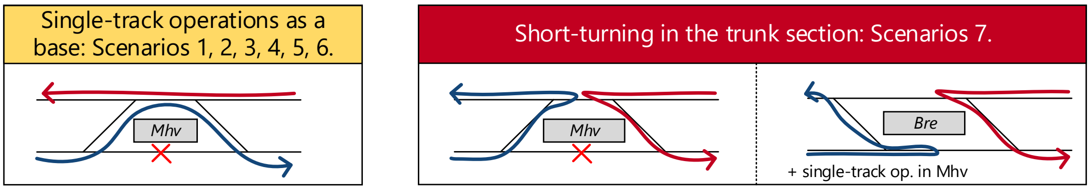


Figure 5-2: Two categories of strategies investigated.

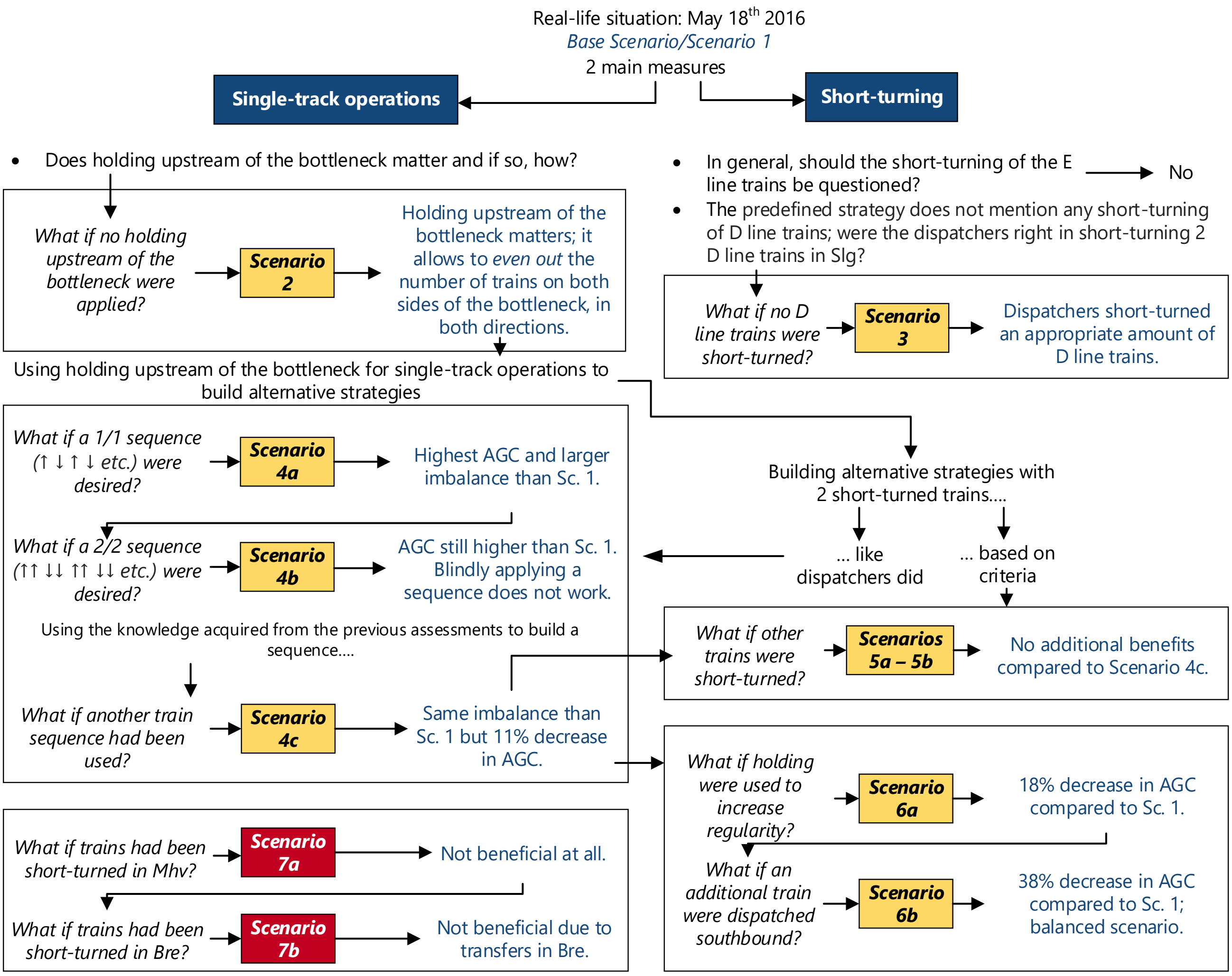


Figure 5-3: Flowchart for the procedure to derive an ideal service control strategy. It needs to be read starting at Scenario 2, then 3, 4, etc.

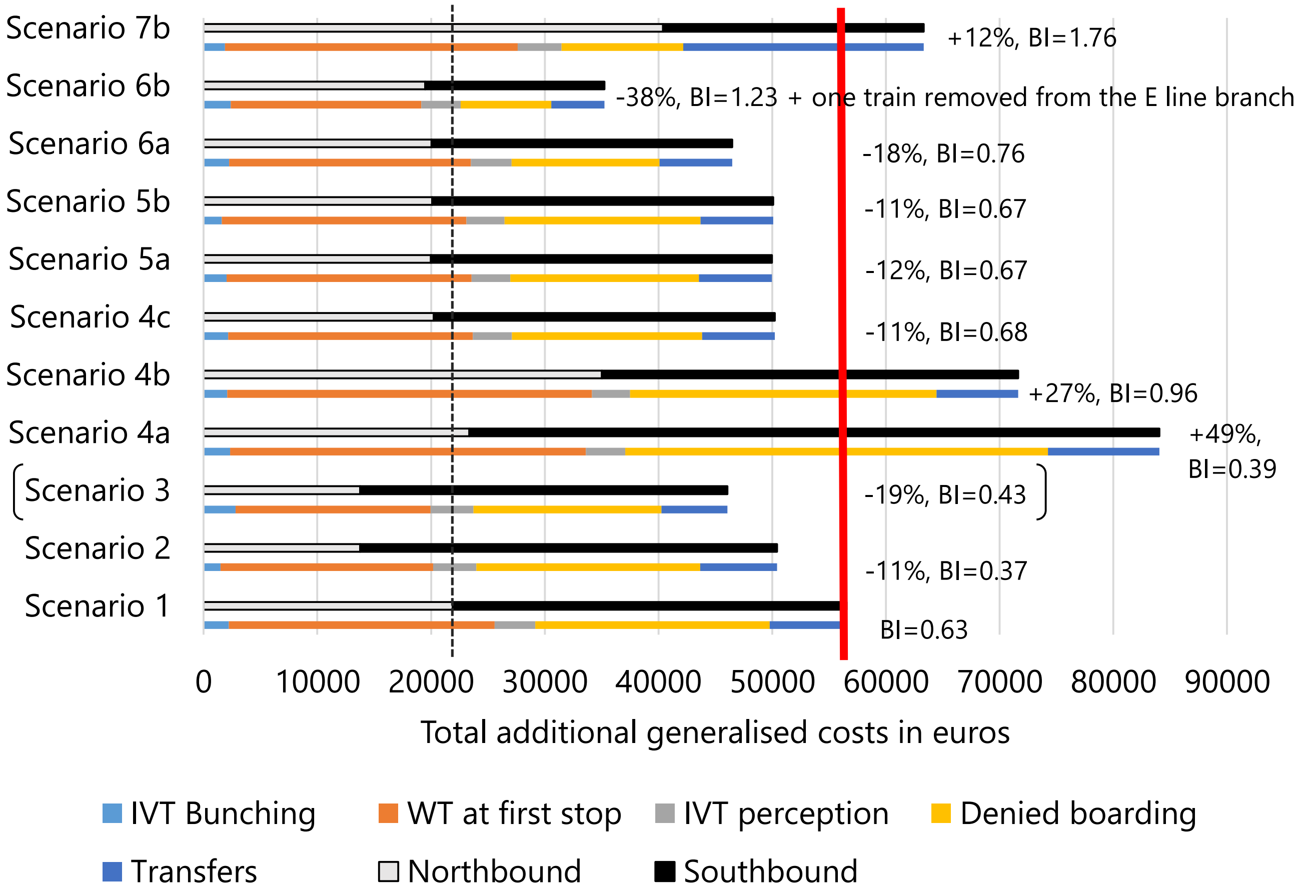


Figure 5-4: Inconvenience experienced for all passengers, translated in AGC, for Scenarios 1 to 7b, for a disruption in Mhv on May 18th 2016, 1 hour in the morning peak. Scenario 3 is within brackets because it is not a realistic option. Scenario 7a was only roughly estimated, hence it does not show here. The black dashed line is based on the total NB AGC for Scenario 1.

In general, should the short-turning of the E line trains in Rcs be questioned?

There is already not enough capacity to accommodate all D line trains during one hour on track 2 of Mhv. Not short-turning E line trains in Rcs is risky, since it might create large gaps in headways on the E line branch. Therefore, short-turning the E line trains in Rcs is deemed to be a logical decision. Yet it does not prevent to examine what would happen if *one* of them would not short-turn; see Sc. 6b.

Does holding upstream of the bottleneck matter?

In **Scenario 2**, no holding upstream of the bottleneck is applied. The BI of Scenario 2 is equal to 0.37 therefore holding upstream of the bottleneck is probably beneficial for passengers. Here, SB passengers experience a disproportionate inconvenience compared to NB ones. Holding upstream of the bottleneck allows to give or remove priority to trains and thus to even out the number of trains circulating on both sides of the bottleneck, in both directions. In Scenario 2, the gap in Rcs has increased from 18 to 21 minutes because a train was not held in Rhv SB.

Before testing if various ways to hold upstream of the bottleneck can lead to an improvement compared to the Base Scenario, the strict application of the predefined strategy is investigated.

Were dispatchers right in short-turning 2 D line trains in Slg?

The answer is yes. In real-life, there can only be 2 passenger trains heading NB in Slg, but when no D line trains are short-turned like in **Scenario 3**, the simulation shows that up to 3 trains may queue at some point in Slg. Besides, at the end of the strategy application phase, only 9 trains have left from

Slg, like on May 18th. Thus dispatchers were right in short-turning 2 D line trains in Slg. Short-turning more would probably not be beneficial though, since capacity is still needed. Therefore, *how* the capacity is used needs to be investigated.

What would be an ideal sequence of trains in Mhv?
Scenarios 4a and 4b were built in an attempt to answer this question with basic sequences of trains in the bottleneck: respectively 1/1 (↑ ↓ ↑ ↓ etc.) and 2/2 (↑↑ ↓↓ ↑↑ ↓↓ etc.). The same short-turning strategy than dispatchers on May 18th is assumed. A 1/1 sequence does not work for more than a few minutes because of the large gaps created southbound: after 35 minutes of 1/1 sequence, 3 NB trains must be sent in a row to avoid a 12-minute hold in Zpl NB, but this creates a 14-minute gap in Rhv SB. **Scenario 4a** performs poorly, both in terms of AGC and balance. The results of **Scenario 4b** prove that forcing a 2/2 sequence, often advocated by dispatchers, is more beneficial than a 1/1 sequence, *but* still worse than the sequence used by dispatchers. As a conclusion, there is a need to *acknowledge* the transition phase rather than forcing a sequence straightaway.

What would be an ideal sequence to best deal with the transition phase?
Scenario 4c is built based on the knowledge acquired so far:

- To properly accommodate the transition phase, more trains should cross the bottleneck NB than SB in the first few minutes of the strategy application phase, to allow for as fewer and shorter headway gaps in Rcs SB as possible.
- To preserve balance and make the recovery phase easier, a balanced sequence is probably better once the transition phase is over (like 1/1, 2/2 or 3/3). A 1/1 strategy is not time-effective (occupation times for following trains are lower than first trains, see Appendix D) and a 3/3 strategy may leave large headway gaps. A 2/2 sequence is probably adequate.

Figure 5-5 illustrates the train sequence in Mhv2 during the strategy application phase, both in the Base Scenario and in Scenario 4c. The main difference is that in Scenario 4c, at the start, the NB direction is prioritised. Scenario 4c presents an 11% decrease in AGC compared to the Base Scenario, with a similar degree of imbalance though. So far, it is the first scenario to present a real improvement compared to the Base Scenario.

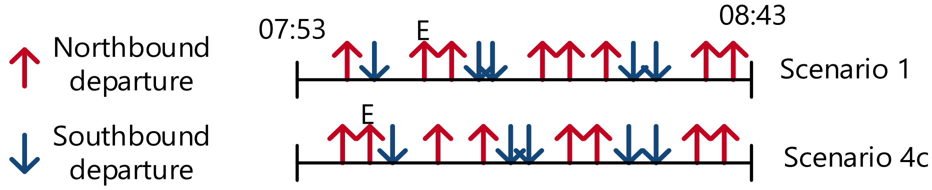


Figure 5-5: Sequences of trains in the bottleneck (Mhv2) during the strategy application phase, with indication of the E line.

What if different D line trains had been short-turned in Slinge?
In Scenarios 5, various short-turnings are investigated. The train sequences in Mhv2 of these scenarios are in line with the remarks used for Scenario 4c. **Scenario 5a** was built by short-turning the two trains that would leave gaps in headways in Slg as small as possible during the disruption. **Scenario 5b** was built with a goal to minimise bunching in Slg. More details can be found in Appendix I .
Despite the careful selection of trains to short-turn, little to no difference between the AGC of Scenario 4c, 5a and 5b is observed. This can be explained by:

- The fact that the same train sequence was used; the trial-and-error approach showed that the sequence depicted in Figure 5-5 for Scenario 4c was also the best option for Scenarios 5.
- The location of the partial blockage, close to Slinge, where trains are short-turned.

Therefore in general, the train sequence during single-track operations may matter more than which train is short-turned, but it would not be advised to short-turn trains that leave large gaps in headways.

Does holding for regularity purposes bring a significant improvement?
To design Scenarios 6, it is chosen to build upon Scenario 4c, since 5a and 5b do not offer significant improvements. Holding for regularity purposes can be added (exact times in Appendix I):

- At departing terminals, i.e. Rcs SB and Slg NB. Large headways in both of these stops creates denied boarding (see sub-section 5.1.3).
- In stations upstream of the bottleneck. Instead of holding trains at stops right upstream of the blockage (here, either Rhv SB or Zpl NB), holding can be spread in other stops.

Scenario 6a performs better than the Base Scenario, with an 18% reduction in AGC: a 9% decrease northbound and a 24% decrease southbound. Still, in this scenario, only one train (train 61) leaves from Rcs southbound within 23 minutes, meaning still high waiting times. To improve Scenario 6a, it is proposed to let an E line train drive to Slg, in Scenario 6b.

What if there is an additional southbound train?
Scenario 6b is in fact the best one, with a decrease in AGC by 38% and a Balance Index indicating a relatively balanced scenario. Denied boarding SB is reduced by 40% compared to Scenario 6a in terms of AGC. The downside is that a train from the E line branch has been removed, but since there were eight trains on the E line branch at that moment and seven are deemed enough, it could have been possible to do it without majorly impacting E line branch passengers[2]. The situation modelled could have been either train 49 short-turning in Rcs or train 41/42 heading to Slg.

Would short-turning trains between Slg and Rcs yield significant additional benefits?
Scenarios 7 investigate short-turning in the bottleneck and in a strategic location on the network. The knowledge acquired from the assessment of Scenarios 1 to 6 can already provide a good idea on how Scenarios 7 might perform. Scenarios with a capacity of 8 trains either NB (Scenario 4b) or SB (Scenario 4a) perform poorly. Fewer than 8 trains is therefore not reasonable from the passengers' perspective. On a 50-minute basis, the threshold is 7 trains.
The same technique than developed in Appendix D is used to estimate capacity on a 50-minute basis, the duration of the strategy application phase. If at least 8 trains can fit in, the scenario will be assessed. For both scenarios, additional details are provided in Appendix I .

First, **Scenario 7a** investigates the short-turning of trains in Mhv. 7 trains in each direction would yield an occupancy rate of 140%; therefore, Scenario 7a is not a viable option. This is mostly due to the amount of time needed to turn a vehicle and all of the related safety procedures.
Second, **Scenario 7b** investigates the short-turning of trains in Beurs instead of Rotterdam Centraal. Beurs is chosen following the determination of the s2s matrix and the subsequent remarks page 63: this is the station with the largest share of origins and destinations, therefore it is expected that the short-turning of trains will inconvenience a relatively small amount of travellers. Furthermore, the track layout is favourable to such types of operations; there is a scissor switch on each side of Bre. Note that in this scenario, single-track operations still take place in Mhv. An acceptable occupancy rate is found when 8 trains are sent from Slg and 9 from Rcs.
The model developed in ARENA does not seamlessly extend to short-turning in the trunk section. However, from the previously assessed scenarios, what matters for passengers is already clear, namely regularity. Thus based on the insights gained from previous assessments, a manual optimisation using

[2] Since September 2016, there are two additional trains during the morning peak on the E line, therefore this measure – not short-turning an E line train to bridge a gap in headways – would be more realistic now. Dispatchers tend to protect the E line branch because its users have very few alternative options to reach either Rotterdam or The Hague in case of a reduced service in the metro.

a time-space diagram is used for Scenario 7b. The proposed strategy is not beneficial since AGC have increased by 12% compared to Scenario 1. Therefore it is better not to shift the short-turning point from Rcs to Bre, which can be explained by the fact that despite a high share of origins and destinations, more passengers need to go *through* Bre than *through* Rcs (resp. 3,760 and 1,480), meaning high transfer costs.

Conclusion of the procedure

Figure 5-6 shows the progression that led to Scenario 6b. The scenarios that perform best are the ones based on single-track operations with holding upstream of the bottleneck, short-turnings in stations with a third track (Slg, Rcs) and holding for regularity purposes.

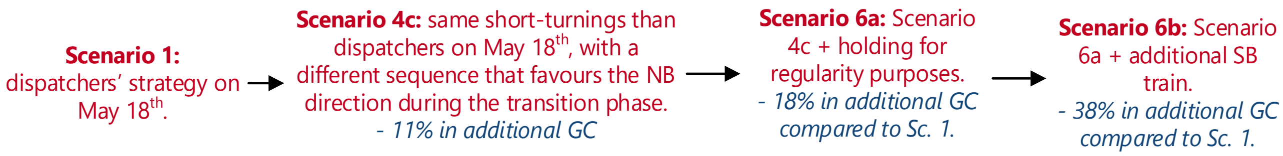


Figure 5-6: Progression from Scenario 1 to Scenario 6b.

A decrease in AGC by up to 38% can be achieved, with an increase in cost balance between both directions. The way the transition phase is handled plays a significant role in the amount of inconvenience experienced by passengers. Next sub-section details the results per impact.

5.1.3. Results of the local-scale assessment per impact

Waiting time components bring the largest contribution to the overall inconvenience experienced by passengers in all scenarios. In Scenarios 1, 6a and 6b, the combination of transfers, additional waiting time at the first stop and waiting time extension due to denied boarding form respectively 90%, 93% and 83% of the AGC. The division of AGC is displayed in Figure 5-7 for these scenarios. Other scenarios are not shown because they do not perform as well as 6a and 6b but may still be used for comparison purposes in this sub-section. Figure 5-4 showed, with the black dashed line, that Scenarios 6a and 6b perform better than Scenario 1 mainly because of the decrease in southbound AGC.

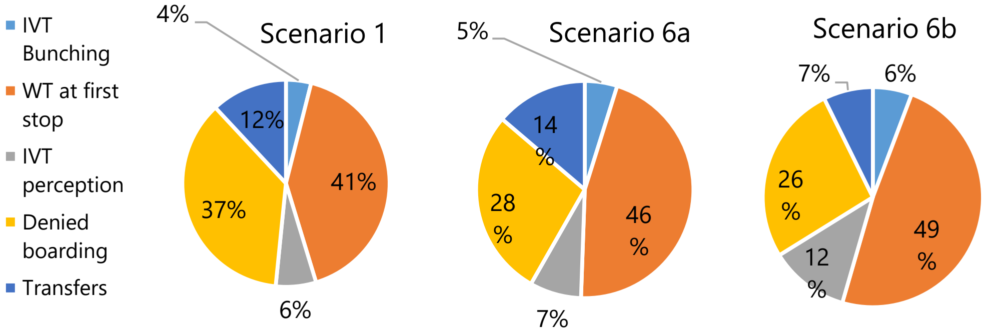


Figure 5-7: Pie charts of the additional generalised costs for Scenario 1, 6a and 6b.

Impact (a): Bunching at stops

As can be seen in Figure 5-7, bunching at stops is the smallest component in terms of AGC in all scenarios, and its share only slightly increases when holding for regularity purposes is used. Indeed, holding adds up some bunching time but only to a minor extent since not all vehicles are being held at the same stop.

Bunching may arguably cause more inconvenience than found here though. Indeed, when a full vehicle is stationed at a stop, whether voluntarily held or not, some passengers may still attempt to get in, which might in turn cause stress to passengers inside the vehicle, as it gets more crowded but the vehicle is not moving. However, even if bunching times were weighed with the Value of Waiting Time instead of the Value of Time, this component would still be a minor one because bunching time ranges from 0 to 3.6 additional minutes per passenger and stop.

Additional waiting time (AWT) at each stop

The AWT at each stop is a value used to compute impacts (b), (d) and (e). Figure 5-8 shows the AWTs in minutes for Scenarios 1, 6a, 6b and 7b. Scenario 7b is here to show the effect of short-turning the E line in Bre: since the E line frequency is around 6 vehicles per hour only, the average headway and the PRDM in Bre NB are high, yielding an AWT of 36.2 minutes.

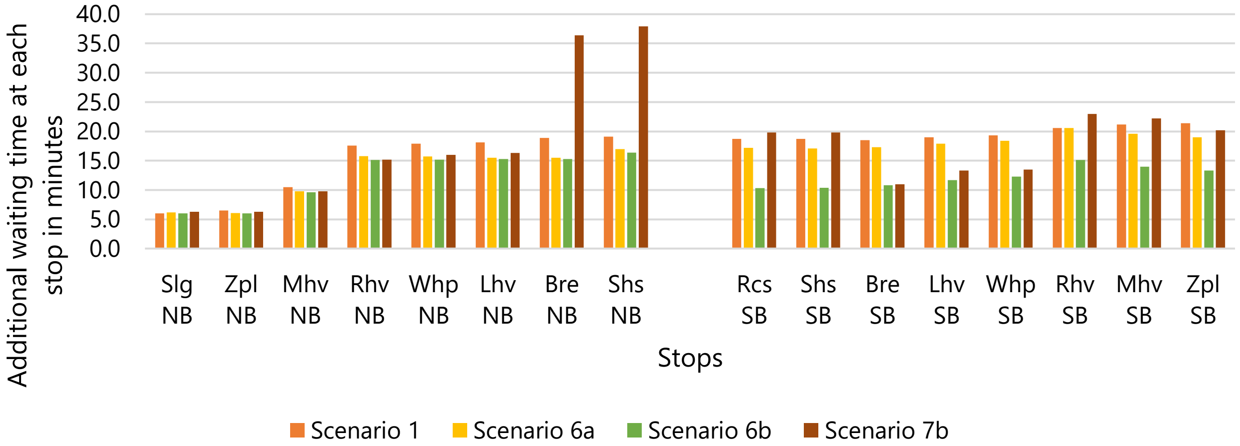


Figure 5-8: Additional waiting time at each stop in the trunk section for Sc. 1, 6a, 6b and 7b, used for impacts (b), (d) and (e).

In general, average headways range from 5 to 8.5 minutes. If only half of these values were taken into account to compute waiting time, little difference between scenarios would be observed, and **WT of many passengers would be severely underestimated**. A good example of that is waiting time in Rcs SB in the Base Scenario (recall the 18-minute gap): $\frac{average\ headway}{2} = \frac{7.2}{2} = 3.6\ minutes$ seems like an optimistic value for waiting time in Rcs SB.

PRDM values all range between 120% and 280% for non-recurrent conditions. In recurrent conditions, a PRDM above 100% is interpreted as bunching: twice the capacity of one vehicle arrives at a certain time. In non-recurrent conditions, it can also be seen as a form of bunching, where the capacity of only one vehicle arrives after a large headway.

Average WTs calculated via the PRDM take into account the fact that more passengers will arrive during large headways than small ones and reflect the irregularity perceived by passengers. 18.7 minutes (WT in Rcs SB) is probably above the *actual* average AWT of passengers but it is more realistic than 3.6 minutes. Thus **the computed WT value is a good proxy for *perceived* average additional waiting time, probably not too far-fetched compared to an actual value and therefore a relevant metric for a passenger-oriented study**. In addition, WTs are slightly underestimated due to the overestimation of the PRDM for the reference day (see page 41), which makes the computed additional waiting time values even closer to actual additional waiting times.

Furthermore, a correlation was found between the number of vehicles circulating during the incident phase, the level of control of dispatchers and the additional waiting time at stops.

Figure 5-9 shows that when only 8 vehicles drive southbound (Scenario 4a), the amount of AWT is 10 to 15 minutes higher than with 9 vehicles. When 9 vehicles are used, favouring the NB direction in Mhv during the transition phase (Scenario 4c) provides more benefits than the strategy used by dispatchers on May 18th (Scenario 1). Scenario 4c can be seen as having a high level of control because it anticipates the consequences of a gap in headway. Not using any form of control (thus no holding upstream of the bottleneck) increases values of AWT (Scenario 2). Therefore, for the same amount of trains, more anticipation, thus a tighter control of the sequence in the bottleneck, means lower AWT. Finally, AWT can be further reduced by letting an additional train drive southbound while applying a high level of control (Scenario 6b).

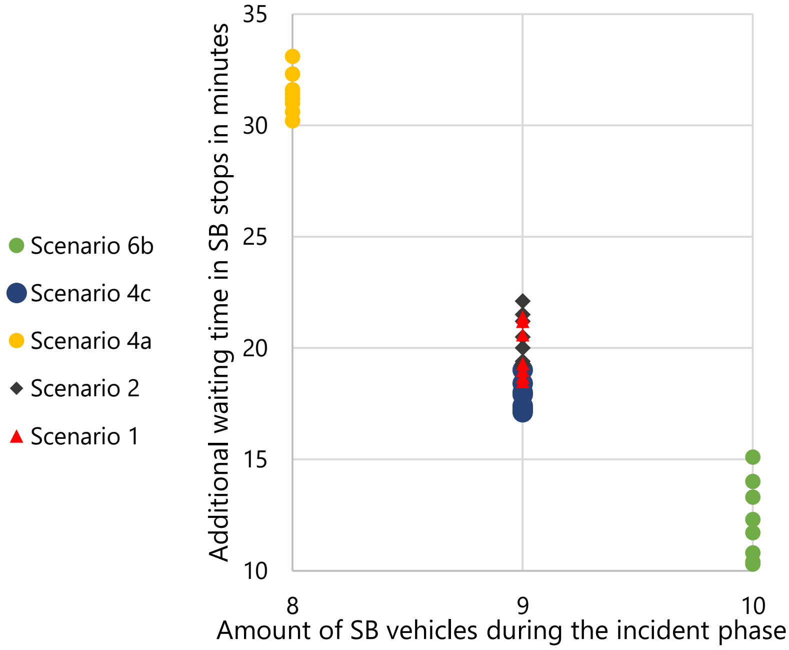


Figure 5-9: Additional waiting time in southbound stops in function of the amount of vehicles for Scenarios 1, 2, 4a, 4c and 6b.

Impact (b): Additional waiting time at the first stop

AWT at the first stop is the largest contribution to the AGC, as seen in Figure 5-7, except in Scenarios 2 and 4a, where denied boarding prevails. 12%, 10% and 10% of the passengers using this trunk section during one hour of the morning peak come respectively from Zpl NB, Bre NB and Bre SB, hence the value of AWT at these stops is important.

Impact (c): Average additional perceived in-vehicle time between stops

Just like for impact (a), the contribution of impact (d) to the AGC is relatively low. For the reference day, the additional perceived IVT never exceeds 0.4 minutes, with values often close to zero; a figure is displayed in Appendix J . The calculation of this impact clearly highlights the fact that contrary to what many dispatchers think, *flows of passengers are not just mainly northbound*. The values of impact (c) do not significantly differ across scenarios, but they demonstrate that the portion between Rcs SB and Whp SB is a busy one, hence the southbound direction ought not to be neglected.
Regarding impact (c), Scenario 6b does not perform significantly better than Scenario 1.

Impact (d): Denied boarding (DB)

There are two components for denied boarding: denied boarding occurrence and the extended waiting time it generates. Across all scenarios, denied boarding occurs systematically at the same stops, indicated in Figure 5-10, except for Scenarios 5b, 6a, 6b and 7b where there is no denied boarding in Slg NB. The other exception is denied boarding in Bre NB in Scenario 7b.
From Figure 5-4, it can be seen that most of the difference between Scenario 4c and Scenario 6a stems from DB. Therefore, *by holding trains*, especially trunk-bound trains in Slg and Rcs, the AGC of denied boarding decreases by 25% and denied boarding in Slg can be eliminated.
Figure 5-11 presents the average boarding demand at stops over one hour of the AM peak in function of denied boarding occurrences. Dots above the $x = y$ line mean that for the given scenario and the

Figure 5-10: Stops where denied boarding occurs.

given stop, boarding passengers are likely to be denied boarding on average each at least once. This is an *average* value though: in reality, some passengers will never be denied boarding while others will be denied boarding once, twice or more. However it gives a good idea of the probability to be denied boarding as a passenger. Scenario 6b performs better than all other scenarios, except in Rhv NB and Mhv NB. The somewhat superior performance of Scenario 1 in Mhv NB and Rhv NB can be attributed to the fact that dispatchers sent 3 trains NB in a row through Mhv at some point. However, this has consequences for SB passengers, notably in Bre and Rcs where boarding demands are high.

By looking at the differences across scenarios between NB and SB stops in Figure 5-11, it can be concluded that using an appropriate service control strategy does not necessarily make significant changes in the close surroundings of the disruption (here Zpl, Mhv, Rhv) but can significantly reduce the probability to be denied boarding in other places in the network (here southbound).

Denied boarding may be overestimated for two reasons: first, because of the crush capacities provided by OV-Lite. Since the latter is normally used at the strategic level, capacities are voluntarily slightly underestimated. Here, the crush capacity is based on an occupation of 2 people per m^2 of available floor. This is why a sensitivity analysis is conducted on the value of the crush capacity; see sub-section 5.4.1 page 81. Second, the calibration of ARENA in Appendix H shows that data stemming from the simulation may lead to a slight overestimation of denied boarding.

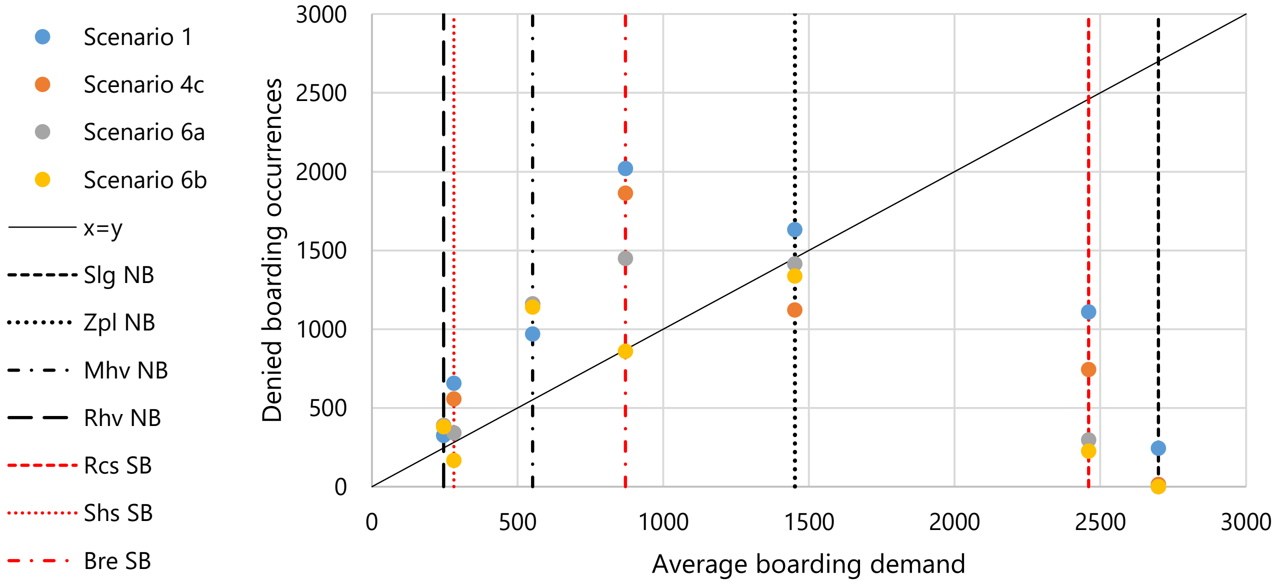


Figure 5-11: Denied boarding occurrences in function of the average boarding demand at stops over one hour of the AM peak. Average boarding demands in Slg NB and Rcs SB are computed by taking into account occupancy rates of vehicles coming from respectively the D and the E line branches.

Impact (e): Unplanned transfers

Monetary impacts for transfers are relatively stable across alternative scenarios with the same basis (1, 2, 3, 4, 5 and 6). In Scenario 6b, if the additional southbound train would come from the E line branch, transfer AGC compared to Scenario 1 may decrease around 30%. In Scenario 7b, transfer costs have increased by more than 300% compared to Scenario 1 while the amount of people having to transfer only rose by 25%. The explanation comes from the high AWT value in Bre NB.

5.1.4. Comparison of performances at the OD pair level

The results from the assessment allow to investigate what is happening at an OD pair level.
Table 5-1 shows the AGC per OD pair and per passenger in Scenario 1. Contrary to what could be expected, passengers crossing the bottleneck NB (figures in italic), i.e. the ones for which the inconvenience sounds the most obvious, are not necessarily the ones suffering the heaviest impacts. Going from N to S (e.g. Blijdorp – Rhoon) is more than twice as costly than S to N (e.g. Rhoon – Blijdorp). The most impacted passengers are the ones boarding in Rhv NB, Bre SB and Shs SB, where situations are relatively similar: a combination of relatively high AWT and vehicles almost full.
Table 5-2 shows AGC per OD pair, taking passenger demand into account. Bre-Whp is the fourth busiest OD pair yet the most impacted one in Scenario 1, in spite of being **in the opposite direction and upstream of the disruption**. An interestig statistic is that 39% of the passengers travelling through at least one of the stops of the scope start their journey either on the E line branch SB or between Rcs SB, Shs SB and Brs SB, yet they represent 57% of the AGC for Scenario 1.
An interesting comparison is the results for Zpl-Brs versus Brs-Whp (in bold in Table 5-2): there are only 8% more passengers travelling on the second OD pair (resp. 510 and 551 passengers) yet AGC are 240% higher. They are still 58% higher in Scenario 6b (see Table 5-4).

	S	Slg	Zpl	Mhv	Rhv	Whp	Lhv	Bre	Shs	Rcs	N
S	0,0	0,0	0,9	*1,3*	*1,4*	*1,5*	*1,6*	*1,7*	*1,7*	*1,8*	*3,0*
Slg	0,0	0,0	1,5	*1,9*	*2,0*	*2,0*	*2,2*	*2,2*	*2,3*	*2,3*	*3,6*
Zpl	4,5	4,5	0,0	*3,0*	*3,1*	*3,2*	*3,3*	*3,4*	*3,4*	*3,5*	*4,7*
Mhv	4,5	4,5	4,5	0,0	*6,1*	*6,2*	*6,3*	*6,4*	*6,5*	*6,5*	*7,8*
Rhv	4,4	4,4	4,4	4,3	0,0	8,6	8,7	8,8	8,9	8,9	10,2
Whp	4,5	4,5	4,4	4,4	4,1	0,0	3,9	3,9	4,0	4,0	5,3
Lhv	4,7	4,7	4,6	4,6	4,3	4,1	0,0	3,9	3,9	4,0	5,2
Bre	11,2	11,2	11,1	11,1	10,8	10,6	10,4	0,0	4,0	4,1	5,3
Shs	11,2	11,2	11,2	11,1	10,8	10,6	10,4	10,4	0,0	4,0	5,3
Rcs	6,7	6,7	6,7	6,7	6,4	6,2	6,0	5,9	5,8	0,0	0,0
N	6,7	6,7	6,7	6,6	6,3	6,1	5,9	5,9	5,7	0,0	0,0

Table 5-1: Additional generalised costs in euros in Scenario 1 per OD pair and per passenger.

	S	Slg	Zpl	Mhv	Rhv	Whp	Lhv	Bre	Shs	Rcs	N
S	0	0	275	59	60	381	185	578	413	557	226
Slg	0	0	66	33	22	166	126	629	207	360	186
Zpl	498	54	0	48	115	532	433	**1718**	615	1023	586
Mhv	127	136	143	0	61	274	165	1339	504	893	404
Rhv	66	133	315	65	0	112	140	951	248	526	234
Whp	89	45	102	35	8	0	54	335	96	405	206
Lhv	33	37	60	23	4	94	0	23	23	83	52
Bre	569	1440	3471	898	366	**5830**	603	0	1525	1866	1580
Shs	347	314	648	200	87	1456	219	1089	0	73	132
Rcs	337	451	911	280	114	2844	328	1197	127	0	0
N	181	294	626	146	88	1418	533	4454	695	0	0

Table 5-2: Additional generalised costs in euros in Scenario 1 per OD pair.

Appendix J provides tables similar to Table 5-1 and Table 5-2 but for Scenarios 4c and 6a. The main conclusions are that AGC steadily decrease from Scenario 1 to 4c and then slightly from Scenario 4c to 6a for almost all OD pairs in a rather uniform way. Only passengers leaving from Mhv NB or Rhv NB do not experience any improvement. A more drastic change happens with Scenario 6b, as shown in Table 5-3 and Table 5-4. The same conditional formatting is used to allow for changes to be clearly visible. In Scenario 6b, southbound passengers all benefit considerably from an additional train, and, most importantly, **this is not detrimental for northbound passengers** – unlike Scenario 7b. In Scenario 6b, southbound OD pairs that do not cross the bottleneck show a significant decrease in AGC compared with Scenario 1.

	S	Slg	Zpl	Mhv	Rhv	Whp	Lhv	Bre	Shs	Rcs	N
S	0,0	0,0	0,7	0,9	1,0	1,1	1,2	1,3	1,4	1,5	2,7
Slg	0,0	0,0	1,3	1,6	1,7	1,8	1,9	2,0	2,1	2,1	3,4
Zpl	2,8	2,8	0,0	2,5	2,6	2,7	2,8	2,9	3,0	3,1	4,3
Mhv	3,0	3,0	3,0	0,0	6,2	6,3	6,4	6,5	6,6	6,7	7,9
Rhv	3,3	3,3	3,3	3,2	0,0	8,1	8,2	8,3	8,4	8,5	9,7
Whp	3,1	3,1	3,0	2,9	2,6	0,0	3,3	3,4	3,5	3,6	4,8
Lhv	3,3	3,3	3,2	3,2	2,8	2,6	0,0	3,3	3,4	3,5	4,7
Bre	4,9	4,9	4,9	4,8	4,5	4,2	4,0	0,0	3,3	3,4	4,6
Shs	4,3	4,3	4,2	4,1	3,8	3,6	3,3	3,2	0,0	3,5	4,7
Rcs	3,7	3,7	3,6	3,6	3,2	3,0	2,7	2,6	2,4	0,0	0,0
N	3,8	3,8	3,8	3,7	3,4	3,1	2,9	2,7	2,6	0,0	0,0

Table 5-3: Additional generalised costs in euros in Scenario 6b per OD pair and per passenger.

	S	Slg	Zpl	Mhv	Rhv	Whp	Lhv	Bre	Shs	Rcs	N
S	0	0	208	42	43	283	142	454	339	468	205
Slg	0	0	60	28	18	142	109	553	187	330	176
Zpl	311	34	0	40	96	448	369	**1475**	538	905	536
Mhv	85	91	96	0	62	278	168	1362	516	918	413
Rhv	50	99	236	48	0	105	132	897	235	501	224
Whp	61	31	70	24	5	0	46	288	84	357	188
Lhv	23	26	42	16	3	60	0	20	20	73	47
Bre	251	634	1521	389	152	**2333**	229	0	1252	1548	1374
Shs	132	119	245	75	30	490	69	332	0	63	118
Rcs	183	245	493	149	58	1379	149	521	53	0	0
N	103	168	356	82	47	731	258	2078	314	0	0

Table 5-4: Additional generalised costs in euros in Scenario 6b per OD pair.

5.1.5. Conclusion from the local-scale assessment results

The predefined strategy used at the RET for the studied disruption has a sound basis. Yet, it is possible to do better for passengers, with a combination of holding for regularity purposes, holding certain trains in front of the bottleneck and adding a southbound train. Blindly applying the predefined strategy led to high AGC while a more anticipatory implementation of the predefined strategy led to a 38% reduction in AGC compared to May 18th. The RET would therefore need to work both on predefined strategies and the real-time decision-making part.

5.2. Global-scale assessment results

The bus, tram and metro networks of the RET are represented in OV-Lite. The train network or the network of other bus operators is not comprised in the model. First, the transition from the local-scale assessment to the global-scale assessment is done in sub-section 5.2.1. Then, the Base Scenario is assessed. Next, other scenarios are assessed and their performance is compared to the Base Scenario.

5.2.1. From the local-scale assessment to the global-scale assessment

The global-scale assessment is as a complementary approach to the local-scale assessment, therefore not all scenarios are assessed: only Scenarios 1, 6a and 6b. Frequencies are summarised in Table 5-5. One can see that there are few differences between Scenarios 1, 6a and 6b, therefore few changes are expected in the results. In addition to these scenarios, a variant to Scenario 6b, Scenario 6b *bis*, is also modelled: a decrease of the E line frequency on the E line branch. As explained in section 5.1, on May 18th, sending an E line train southbound from Rcs would most likely not have been detrimental to passengers – at least during the incident phase – since 7 vehicles are needed on this branch and there were 8 of them. Still, it could be interesting to model the alternative situation where there is a drop in frequency on the E line branch. Instead of 6 trains per hour and per direction, the frequency will be set at 5. No distinction is made between average and perceived frequency.

Table 5-5: Average and perceived frequencies (NB frequency; SB frequency) for the assessed scenarios.

	Scenario 0			**Scenario 1**			**Scenario 6a**			**Scenario 6b**		
Line(s)	*All*	*D*	*E*	*All*	*D*	*E*	*All*	*D*	*E*	*All*	*D*	*E*
Average frequencies	18; 18	12; 12	6; 6	9.6; 9	7.5; 7	2.1; 2	9.6; 9	7.5; 7	2.1; 2	9.6; 10	7.5; 7	2.1; 3
Perceived frequencies	16.8; 18.3	11.2; 12.2	5.6; 6.1	2.2; 1.4	1.7; 1.1	0.5; 0.3	2.3; 1.5	1.8; 1.2	0.5; 0.3	2.3; 1.5	1.8; 1.1	0.5; 0.4

5.2.2. Base Scenario performance

To locate the mentioned stations, the reader can refer to the map with abbreviations page 55. A map of the high-frequency network of the RET is provided in Appendix K , plus a zoom on the tram network.

Average versus perceived frequencies
The assignment with perceived frequencies yields more realistic results than the one with average frequencies because the effects of irregularity are completely neglected with average frequencies. Yet even with perceived frequencies, AGC are low compared to the AGC values for the local-scale assessment, whereas more passengers are taken into account in the global-scale assessment. This may be due, amongst others, to comfort and crowding not being taken into account. More justifications and the full analysis can be found in Appendix J . The remainder of this section uses results from the assignment with **perceived frequencies**. Results are displayed in Table 5-7, page 79.

Re-routing of passengers over the network

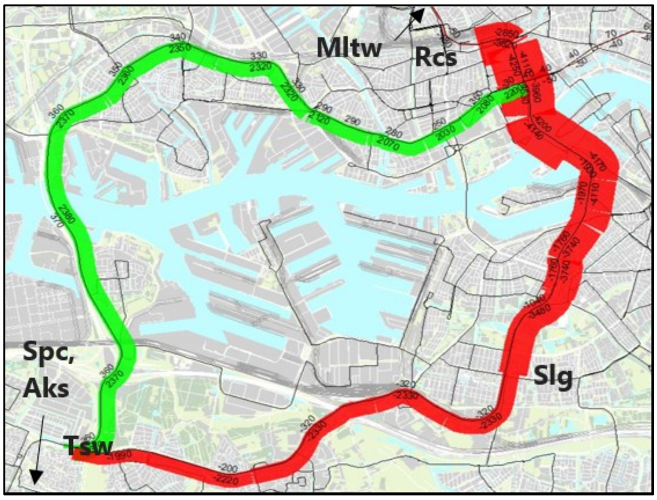


Figure 5-12 shows the difference in metro passengers in the Base Scenario compared to the reference day. Red indicates a drop in passengers in the Base Scenario compared to the reference day while green means an increase (also valid for Figure 5-13 and Figure 5-14).

Figure 5-12: Difference in passengers in the metro between the reference day and May 18th, for one hour of the morning peak.

As predicted by metro planners in the questionnaire, a decrease in service between Slg and Rcs means that passengers will switch to the C line: in Tussenwater (Tsw) or De Akkers (Aks), passengers heading northbound choose line C instead of line D because the drop in frequency in Slg no longer makes the D line an attractive option. This observation is illustrated by looking at an OD pair that goes through both Tsw and Rcs: Spijkenisse Centrum (Spc) - Melanchtonweg (Mltw). Table

5-6 shows that in Scenario 1, all passengers coming from Spc (and thus from stops between Aks and Tsw) take the C line at Tsw to reach the city centre (around Bre, where metro lines cross). The analysis of this OD pair also shows that trams are used in the city centre as an alternative to the metro. Figure 5-13 and Figure 5-14 reveal that the amount of passengers increase respectively in the tram and in the bus compared to the reference day. This is especially the case for lines that drive parallel to the D and E line, crossing the river and in the city centre.

Table 5-6: Analysis of the route choice of the OD pair Spijkenisse Centrum – Melanchtonweg.

	Reference day	**Base Scenario**
Choice in Spc	24% C line, 76% D line.	80% C line, 20% D line.
Choice in Tsw	No transfer.	Transfer to C line for those who took the D line in Aks.
Choice in city centre (around Bre)	Transfer in Bre to E line for those who took the C line.	Transfer in Bre to a tram to reach Rcs.
Choice in Rcs	Transfer to E line for those who took the D line.	Transfer to E line.
Travel time	42 min	53 min
Generalised cost	5.3 €	7 €

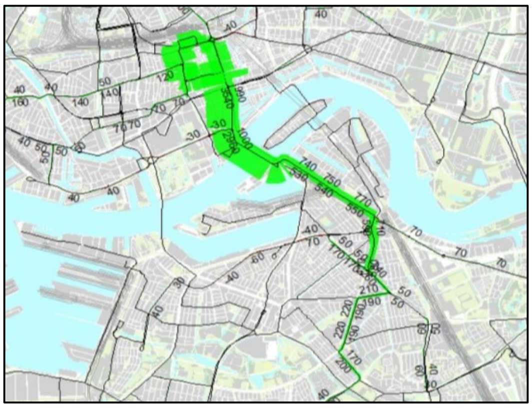


Figure 5-13: (Left) Difference in passengers in the tram between the reference day and Scenario 1.

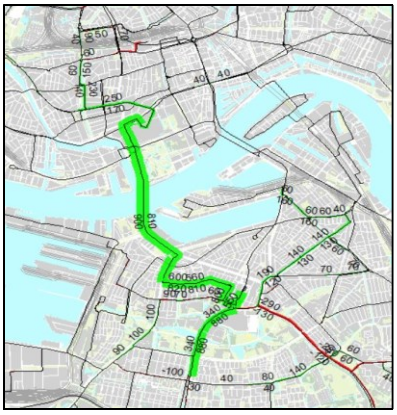


Figure 5-14: (Right) Difference in passengers in the bus between the reference day and Sc. 1.

Given these changes, one may wonder: *would the C line and/or the tram lines be overcrowded?* Figure 5-15 to Figure 5-20 show how I/C (intensity versus capacity) ratio vary per mode from the reference day to the Base Scenario. Only I/C ratios higher than 0.9 are displayed. Recall that OV-Lite does not take comfort or crowding into account in the assignment and thus in the GC computation.

In spite of the decrease in passengers between Slg and Rcs observed in the metro in Figure 5-12, Figure 5-16 shows that lines D and E would be overcrowded between these stations. This is misleading since capacity with perceived frequencies is underestimated compared to the actual offered capacity. Therefore, the I/C ratios between Slg and Rcs in Figure 5-16 should be interpreted with caution. For the busiest link (Whp-Rhv), with a capacity of 9.6 vehicles per hour (average frequency NB) instead of 2.2 (perceived frequency NB), the I/C ratio would drop from 2.5 to 0.7. A value of 0.7 may be underestimated though because irregularity is not taken into account. For the other lines and modes, the figures page 78 give a more realistic idea of expected levels of crowding.

- <u>Metro:</u> the C line between Vijfsluizen and Schiedam Centrum is expected to be overcrowded. Therefore it would make sense to **redirect a few D line vehicles towards the C line**.
- <u>Tram:</u> Figure 5-18 compared with Figure 5-17 highlights increases in I/C ratios, but not to the point where overcrowding is expected.

- Bus: Figure 5-20 compared with Figure 5-19 also underlines a growth in I/C ratios, especially for line 44 which provides a service between Zuidplein, Dijkzigt and Rotterdam Centraal.

Reference day | **Scenario 1**

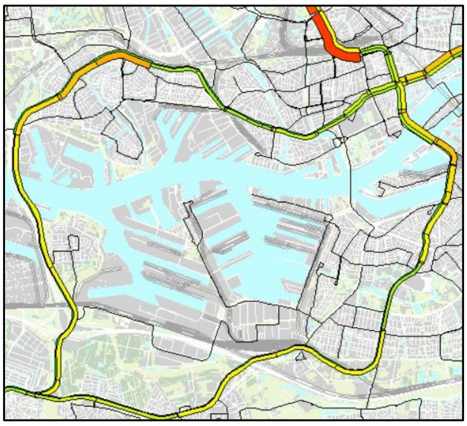


Figure 5-15: (Left) I/C ratio for the metro, reference day.

Figure 5-16: (Right) I/C ratio for the metro, Scenario 1.

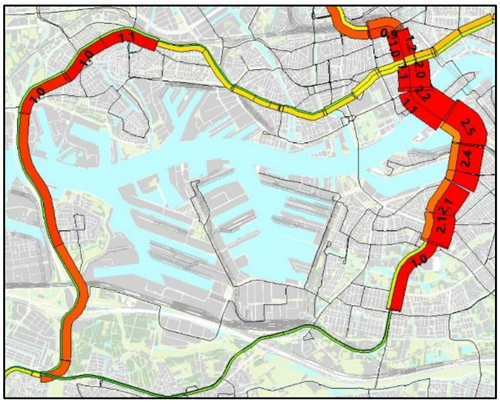
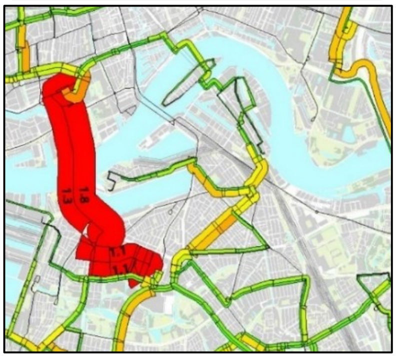


Figure 5-17: (Left) I/C ratio for the tram, reference day.

Figure 5-18: (Right) I/C ratio for the tram, Scenario 1.

Figure 5-19: (Left) I/C ratio for the bus, reference day.

Figure 5-20: (Right) I/C ratio for the bus, Scenario 1.



Interestingly enough, the assignment in OV-Lite shows a relative low popularity of tram lines that run parallel of lines D and E compared to bus line 44 and metro lines. It may be due to the fact that tramways start being an alternative option for NB passengers from Whp only, at which point it is more advantageous for passengers within the metro not to transfer (transfer costs + additional IVT of the tram) or to board the metro despite the low frequency. In reality, since not all passengers would be able to board bus line 44 (crush capacity of 50, 8 vehicles per hour), even more passengers are expected between Zpl and Rcs in the metro, which is why, provided that the model is representative of the reality, it could be useful in a real-life situation **to re-direct metro passengers travelling within the city centre to switch to a tram line.** Here, the city centre is considered to be between stop Whp, Lhv, Bre, Shs and Rcs. That way, metro capacity could be left for people who travel further. Similarly, E line branch passengers heading to the city centre and dropped in Rcs due to a short-

turning **need to be informed that they may switch to a tram** if they want to go up until Whp, prior being dropped or on platforms in Rcs. This is currently *not* a common practice at the RET (Roukema, 2016). It is not expected that all passengers would switch anyway, but at least they would know their options. **The full potential of the network should be used**: passengers coming from stations eastern of Voorschoterlaan and heading to Rcs could be encouraged to switch to tram line 7, those western of Marconiplein and heading to Rcs could be directed to trams 8 and 23, etc. From the author's observations, this is also not currently done: passengers on the A-B-C lines may be informed of a disruption on the D and E lines but not of their alternative options.
In OV-Lite, passengers have full information about the decrease in service and their options, which is arguably more realistic during the morning of a working day than during a summer weekend for instance. Indeed, there is a high share of commuters during the morning of a week day (see Figure 4-4 page 56). They can be expected to represent a smaller proportion during a summer weekend, where more leisure passengers are expected. On the one hand, commuters have a better knowledge of the transport system they use than leisure passengers, because the former use the system on a more regular basis. But on the other hand, they might be used to taking the same route every day and therefore lack awareness about other routes. Still, this is the group of passengers who is most likely to know how to navigate in the network when conditions are degraded. It can be argued that the higher the share of commuters, the closer to a real possibility the outcome of the transit assignment in OV-Lite is.

Estimates of lateness
In Scenario 1, with perceived frequencies, it is estimated that 256 people would miss their train connection in Rcs (against 0 with the assignment with average frequencies). Only 4% of all people heading to school/work would be late, but that still represents about 1620 people. Assumptions to compute these figures can be found in Appendix J .

5.2.3. Comparison of the performance of the Base Scenario with other scenarios

Table 5-7 confirms what was expected from analysing Table 5-5: there is little to no change across alternative scenarios, due to frequencies on a line level not varying much. ATT slightly decrease from Scenario 1 to Scenarios 6a and 6b but not significantly, especially when translated into AGC. Lowering the frequency on the E line branch (Scenario 6b *bis*) creates slight increases compared to Scenario 1.

Table 5-7: Comparison of impact (f), additional generalised costs and estimates of lateness for Scenarios 1, 6a, 6b and 6b bis.

	Scenario 1	**Scenario 6a/6b**	**Scenario 6b *bis***
ATT (impact (f))	1160 hours	1150 hours	1220 hours (+0.5%)
AGC	11,380 €	11,310 € (-0.5%)	12,070 € (+6%)
# pass. missing train connection	256	Same than Scenario 1	
# pass. late at work/school	1620	1615	1680 (+4%)

Regarding the re-routing of passengers in the network, the results of Scenarios 6a and 6b are once again identical to that of Scenario 1.
As for Scenario 6b *bis*, the decrease in frequency on the E line translates into raised WT in Rcs NB. Overall, there is a 13% increase in AWT in Scenario 6b *bis* compared to the Base Scenario. No meaningful changes at the network level are observed. Most interestingly, a drop in frequency from 6 to 5 vehicles per hour and per direction creates overcrowding from Blijdorp to Rcs, where the link has an I/C ratio of 1. This crowding could be even more important in reality since OV-Lite assumes a

regular service, which is never strictly the case in reality. Therefore, it makes sense that dispatchers are willing to preserve a minimum amount of E line vehicles on the E line branch, since "losing" one vehicle by sending it to the disrupted area creates overcrowding.

5.2.4. Conclusion of the global-scale assessment

The global-scale assessment gives an idea on one additional measure that could be included in a predefined service control strategy: shifting capacity from the D line branch to the C line, which can be seen as a form of diversion. However, this assessment lacks information on passenger behaviour in non-recurrent conditions in general, making results somehow delicate to interpret. Arguably, the assessment indicates that the tram is not as popular as expected. This is why actively re-directing metro passengers with an origin and a destination within the city centre to the tram could potentially alleviate crowding in the metro, which is not clearly shown by the assignment but reasonably expected. Passengers are not necessarily aware of their options, hence the need to inform them.
On a methodological level, differences across alternative scenarios are too subtle to be captured by the model.

5.3. Validation of the assessment framework

As evoked in Chapter 3, the last phase of the assessment framework is a validation of the results of the in-depth case study via interviews.
The developed simulation model seems to point in the right direction, since moderate changes in strategy lead to moderate – yet non-negligible – improvements, and measures improving regularity have already been found to be beneficial to passengers (Schmöcker et al., 2005).
None of the interviewed employees at the RET found the qualitative and the quantitative results to be exaggerated. In fact, proposed changes in strategy are rather moderate and are seen by most as feasible. Only some traffic controllers show some resistance, which will be discussed in Chapter 6. The list of interviewees can be found in Appendix K .
Almost all interviewees state that the conclusions of the assessment come as a confirmation, backed by a scientific approach, of the intuition that the RET could do more to be passenger-oriented. Interest was shown for quantitative results, although the notion of perceived travel time and how it relates to actual travel time is not always straightforward to understand (see discussion page 71). The interviews were also useful to enlighten the interpretation of the global-scale assessment results. As mentioned in sub-section 5.2.4, the lack of information of travellers' behaviour in non-recurrent conditions and the use of an assignment model calibrated for recurrent conditions only makes the interpretation of the results of the model thorny. This is why expert interviews can be interesting complements; the insights gained from these interviews is already integrated in section 5.2. Some interviewees were curious about additional service control measures; these are discussed in section 5.4.

5.4. Complementary analyses

First, a sensitivity analysis on the crush capacity is conducted. Second, the potential use of other service control measures during the incident phase is discussed. Finally, the third part of this section is dedicated to an analysis of long-term impacts of a disruption on passengers.

5.4.1. Sensitivity analysis: crush capacity for denied boarding calculations

As mentioned in sub-section 3.3.3 page 44, crush capacity is not a value that is well-known in general in public transport studies. In both the local- and the global-scale assessments, the original crush capacities from OV-Lite were used. They assume that there can be up to 2 people standing in one square metre of available floor in a vehicle. According to the Strategic Rail Authority in Great Britain, as long as each standing passenger has 0.55 square metres of space, the train is not overcrowded (House of Commons Transport Committee, 2002). Therefore 2 people standing per m^2 is probably a lower bound for crowding (0.55 m^2 for 1 person means 1.8 people standing per m^2). According to the manufacturer of the RET trains, the vehicles are designed to contain up to 4 people per m^2. However, in practice, this is an optimistic value since a study conducted at HTM shows that it is more 3 or 3.5 (Yap, 2016). These two numbers are therefore used for the sensitivity analysis. A value of 3 was already determined for the metro of Singapore (Tirachini et al., 2016). *What if 3 or 3.5 people could stand per square metre of available floor?*
The reader can refer to Appendix N for the full analysis. Let cc_2 be the crush capacity with 2 standing people per m^2 of available floor and cc_3 with 3 and $cc_{3.5}$ with 3.5.

Three main conclusions can be formulated:

- Even with increased crush capacities, trends remain the same for the case study. There is still a decrease by around 35% in additional generalised costs for the ideal strategy (Sc. 6b) compared with the one applied by dispatchers on May 18th. Denied boarding still occurs in all scenarios. Carrel, Halvorsen & Walker (2013) showed that denied boarding is one of the most significant negative experience driving a decrease in public transport use, therefore it would be advantageous to use the strategy that limits denied boarding occurrences.
- Capacity is a major variable in PT studies, especially if one is looking for quantitative results. More research would be needed to better be able to determine crush capacities.
- Therefore, this sensitivity analysis allows to derive *bandwidths* for the results. Depending on many factors (the vehicle, its layout, stops on the line, interpersonal distance in culture, age, time of day, day or year, etc.), a crowded vehicle could mean anywhere above 2 people standing per m^2. The bandwidths are determined for 2 to 3.5 people standing per m^2.
  These bandwidths are all the more so relevant as data stemming from the simulation were shown to slightly overestimate AGC. Therefore lower bounds for AGC of crafted scenarios were rounded down. Table 5-8 displays these bandwidths.

Table 5-8: Bandwidth for additional generalised costs for Scenarios 1, 4c, 6a and 6b.

Scenario	Scenario 1	Scenario 4c	Scenario 6a	Scenario 6b
Short description of the scenario	*Dispatchers' strategy: short-turning + single-track operations*	*Sc.1 with a different sequence in the bottleneck.*	*Sc. 4c with holding for regularity purposes.*	*Sc. 6a with an additional southbound train.*
Bandwidth for AGC / Societal costs per disruption	43 – 57 K€	37 – 50 K€	35 – 47 K€	28 – 35 K€

With such bandwidths, it is possible to compute **a rough estimate of savings in societal costs on a yearly basis**, when a passenger focus is applied to the rescheduling process during the incident phase. From mid-January 2016 until mid-January 2017, approximately 60 disruptions at least as long as the case study or in a similar range and leading to a partial blockage during a peak hour of a working day occurred in the RET metro network (source: internal database). It means around once every 6 days. Assuming around 15,000 € of savings in societal costs for passengers per incident, savings could amount to approximately **900 K€ of societal costs, if every disruption similar to the case study is handled like in the best case scenario**. To give an order of magnitude, saving 1€ of societal costs means reducing the waiting time of one passenger by five minutes.

5.4.2. Additional service control measures

After gaining insights from the "what-if" procedure, some small analyses can be conducted on the use of other measures. Both of the measures discussed here were suggested by either dispatchers.

Expressing
Given how critical the use of the bottleneck is, one may wonder whether expressing (see page 17) might be a good idea. First, this measure would have to be communicated clearly enough to passengers to be considered for use. Therefore only one stop could be skipped; if the pattern is more complex (like skip every other stop), it becomes too difficult for passengers to follow. Maashaven could be an interesting candidate, because the time when track 2 of Mhv is used is "precious" time (bottleneck). However, if a passenger is skipped by a train, she/he does not have any other direct option. It is possible to walk (0.7 km to Rhv, 1.3 km to Zpl, i.e. between 10 and 15 minutes with a normal pace), or take the tram with 1 change (around 20 extra mins). Neither option is optimal. Besides, skipping Mhv NB is probably not a good option because of the relatively high boarding demand rate (9 passengers per minute – they could not all fit in the tram and few are probably willing to walk). Mhv SB would be a better option since it has low alighting and boarding demand rates (resp. 3.2 passengers/min and 1.7 passengers/min). But since alternative options are lacking, it would be advised to have only one or two trains skipping this one. In addition, passengers would need to be properly informed, preferably with personnel at stops where they alight. Around one minute could be saved for each time Mhv SB is skipped. Given the small amount of saved time and the effort it requires to do it well (extra personnel, announcements on the train), it is probably not worth it.

Gap train/spare vehicle addition
Ideally, the RET would have extra vehicles ready to dispatch if an incident occurs. However, this is a costly option: not only does the vehicle needs to be ready at the right place in a reasonable amount of time, but there also needs to be spare drivers. When disruptions like the case study do not happen every day, this is expensive. This is why Fang and Zeng (2015) suggest to form long-term partnerships with taxi companies for instance, as already implemented in Munich and Berlin. They claim that these are more advantageous than spare crew/vehicles. Another solution, proposed by Jin et al. (2014), is to use buses that are already in the network. They showed that the resilience of a metro system during disruptions could be improved by leveraging on local bus integration, i.e. with a modified design of the bus network. Both of these solutions require long-term thinking though.

5.4.3. Long-term impacts of a disruption

In sub-section 3.2.1, the RBT (Reliability Buffer Time) metric was introduced. It was suggested to use it to estimate long-term impacts of a disruption. Uniman (2009) defines **the RBT as the difference between the 95th percentile travel time and the 50th percentile travel time**. For example, a RBT of 5 minutes means that if a commuter plans 5 minutes of buffer time for her/his journey, she/he will be on time at their destination 95% of the time, thus late at work once per month on average. A high RBT in non-recurrent conditions might lead passengers to readjust their departure time, extending the impacts of the disruption up to multiple days or even weeks after the disruption. A long-term, societal impact of a disruption can thus be computed.

The full analysis with justifications can be found in Appendix O . To sum up, the focus is placed on the WT component of travel time and thus denied boarding is also taken into account. One stop is investigated only, Brs SB. A manual estimation of the waiting time that each passenger waits can be done, based on the outcomes of the denied boarding module. The crush capacity corresponding to 3 people per m^2 is chosen, since 2 people per m^2 were probably more of a lower bound.
RBT and a waiting time distribution for each investigated scenario (reference, 1, 4c, 6, and 6b here) can then be derived: see Figure 5-21 (assuming normal distributions here; see Appendix O). Table 5-9 shows the DB occurrences, the RBT, the shift in departure time per passenger during the following days and the long-term societal impacts in euros for each scenario.
Although the average waiting time in Scenario 4c is inferior to the average waiting time in Scenario 1 in the local-scale assessment, the spread is larger and thus so is the RBT. This shows that averages do not show the full picture (note that 50th percentiles do not represent averages but medians). Only in Scenario 6b is the RBT lower than in Scenario 1.

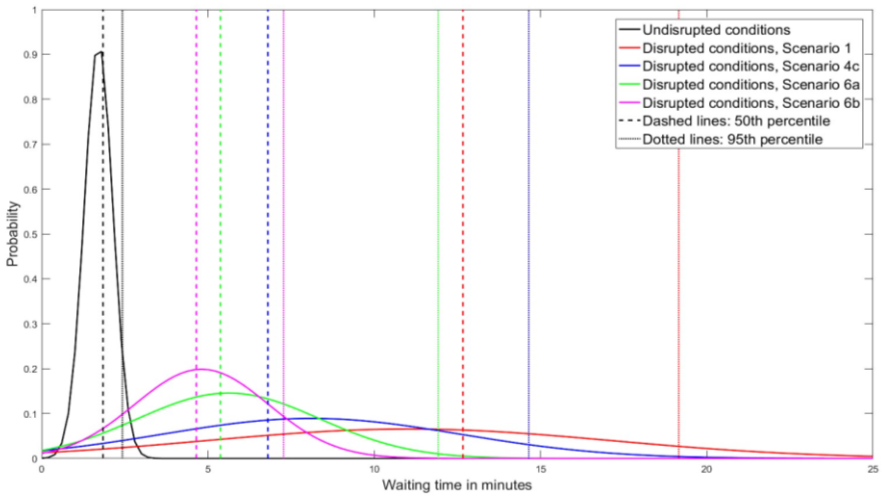


Figure 5-21: Waiting time distributions in Beurs, during one hour of the morning peak under different scenarios and visualisation of the percentiles used to compute the reliability buffer time metric.

The shift in departure time is based on the reference day. Arguably, not all passengers will shift their departure times, and these time shifts are likely to differ depending on the experience of each user. Here, it is assumed that half of the passengers will shift their departure time, i.e. 435 passengers. Since the disruption took place on a Wednesday, it is assumed that they will shift departure times for 7 days: on working days until the end of the week and all of the following week. Minutes are then transformed into a monetary impact with the Value of Time (see sub-section 3.2.3 page 34).

Table 5-9: RBT in Scenarios 1, 4c, 6a and 6b for Beurs SB, 1 hour of the morning peak, and corresponding long-term societal impacts. Denied boarding occurrences are calculated with the local-scale assessment framework, with 3 people per m^2.

Scenario	**DB occ. in Bre SB**	**RBT in minutes**	**Shift in departure time per passenger during the following days**	**Total societal impact for 7 days in €**
Ref. day	-	0.6	-	-
Scenario 1	1099	6.5	5.9 minutes earlier	2,400
Scenario 4c	859	7.8	7.2 minutes earlier	2,900
Scenario 6a	354	6.5	5.9 minutes earlier	2,400
Scenario 6b	208	2.6	2 minutes earlier	1,000

In Scenario 1, there are at least 2,400 € of long-term societal impacts of the disruption. Given that Beurs SB is only one stop, long-term societal costs could amount to multiple thousands of euros. In order to reach a significant improvement, a strategy such as the one suggested in Scenario 6b is needed. Adding a southbound train can make a significant difference: regularity is improved, and thus not only is the average AWT significantly lower (from the local-scale assessment: -6.5 min in Scenario 6b compared to Scenario 6a), but the spread is also much narrower, making all the difference. Column 2 of Table 5-9 also shows that there is no link between DB occurrences and long-term societal impacts. Therefore, this analysis shows not only that long-term impacts can be non-negligible, but also that using metrics based on extreme values can provide new insights on the performance of strategies.

5.4.4. Conclusion of the additional analyses

The analyses conducted in this section complement the assessment framework.
First, the sensitivity analysis allowed to discuss the value chosen for crush capacity and led to derive a bandwidth for the AGC of the local-scale assessment. It was also found that capacity is a major variable of the model and, by extension, of PT studies.
Second, short analyses on the implementation of two additional service control measures were conducted, expressing and gap train/spare vehicle addition. None of these is deemed to be particularly interesting to apply for the case study, but given the performance of Scenario 6b where an additional train is sent southbound, it would be recommended for the RET to study two alternatives suggested for the measure "gap train/spare vehicle addition", which require long-term thinking.
Third, the long-term impact of the disruption was quantified, under the form of a societal cost. In this analysis, extreme values – as opposed to average values – were used via the reliability buffer time metric. Firstly, long-term impacts were found to be non-negligible, and secondly, using metrics based on extreme values was found to provide new insights on the performance of strategies.

5.5. Conclusion on the application of the assessment framework

This chapter allowed to test the framework theoretically developed in Chapter 3 through an in-depth case study. Service control strategies for a partial blockage in the metro of Rotterdam were generated and assessed. The framework was then validated with interviews, thereby completing the development of the assessment framework. Then, a section was dedicated to complementary analyses.

This section answers the two sub-questions mentioned at the beginning of this chapter.

B2. For the selected case, how does the current predefined service control strategy perform?

In essence, the predefined service control strategy of the studied disruption is a sound basis. Infrastructure is a major limiting factor anyway. However, it could be refined:

- By making a distinction between peak and off-peak hours:
  - Not all trains should be sent for single-track operations if the incident phase takes place during peak hours. The risk in omitting to short-turn trains is that an imbalance be created between directions.
  - In peak hours, for a disruption on the D line, predefined strategies could suggest to shift a few vehicles from the D line to the C line in order to prevent crowding on the latter.
- By mentioning the sequence of trains to use during the steady operations phase. A 2/2 sequence (↑↑ ↓↓ ↑↑ ↓↓ etc.) is reasonable. However, dispatchers need to know that the transition phase may need to be handled differently.

The assessment framework has indeed highlighted the importance of the transition phase. More than the predefined service control strategy, real-time decisions, i.e. the way the predefined strategy is implemented, are just as important as the pre-plan. By keeping the same short-turning pattern than dispatchers but by handling the transition phase in a way that anticipates gaps in service created by the unplanned event, additional generalised costs can be reduced by around 12%.

B3. Which new strategies could be developed and how do they perform when assessed by the developed framework?

First, in the local-scale assessment, alternative scenarios were generated in an iterative way, based on a “what-if” approach. This assessment revealed multiple facts about service control measures:
- In the studied case, the train sequence through the bottleneck matters more than which train is short-turned. Yet in general, it is not advised to short-turn a train leaving a large headway gap.
- In addition to an appropriate sequence in the bottleneck, using holding for regularity purposes led to a total decrease in additional generalised costs by around 18%. Spreading holding times at different stops allows to further reduce the components that weigh the most in passengers' inconvenience, waiting time and denied boarding.
- On top of these measures, the addition of a southbound train, taken from the E line branch, allows for the gap created by the blockage to be further reduced and leads to a total decrease in additional generalised costs by around 35%. Most benefits went to OD pairs upstream of the bottleneck. In a complementary analysis on long-term impacts of the disruption, adding a southbound train was found to be particularly efficient to limit extreme values of waiting time. This is why analysing solutions to be able to implement extra capacity along metro lines regardless of whether it influences other lines would be useful; these solutions require long-term thinking.

The global-scale assessment does not allow to distinguish between the performances of alternative scenarios but it offers insights on where passengers might decide to re-route. Arguably, the assessment indicates that the tram is not as popular as expected. This is why actively re-directing metro passengers with an origin and a destination within the city centre to the tram could potentially alleviate crowding in the metro, which is reasonably expected. Passengers are not necessarily aware of their options, hence the need to inform them.

Therefore, the assessment framework was successfully tested. It shows that there is room for improvement to take the passenger perspective into account at the traffic control centre of the RET. On a yearly basis, it is estimated that savings in terms of societal costs could amount to approximately 900 K€, if every disruption similar to the case study is handled like in the best case scenario. To give an order of magnitude, saving 1€ of societal costs means reducing the waiting time of one passenger by five minutes. This assessment framework also gave unexpected yet relevant insights, such as the fact that the most impacted OD pairs are not necessarily the ones that one may think of prior to the assessment, due to passenger patterns and the ripple effects created by the unplanned event. Waiting time was found to impact passengers in a major way, thus the efforts that the RET puts into enhancing the experience of passengers while they are waiting is worthwhile (the so-called “wait softeners”: music, scents, etc.) (Peters, 2016).

Next chapter moves away from the case study and discusses the generalisation of the results as well as the assessment framework approach.

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Chapter 6 Discussions beyond the assessment framework

This chapter presents a series of reflections beyond the assessment framework. First, the results of the assessment from previous chapter are generalised in section 6.1. Second, section 6.2 seeks to draw conclusions on service control measures, also based on the insights gained from Chapter 5. Lastly, to allow for the results of this study to have a real-life application, it is necessary to discuss what they would imply for other stakeholders in public transport. Section 6.3 thus goes beyond the framework's passenger perspective and aims at answering the following sub-question:

> **B4.** What are the challenges for the implementation of passenger-oriented service control measures?

The chapter ends with a conclusion.

6.1. Generalisation of the results of the studied disruption

By using the insights gained from Chapter 5, generalisations to other partial blockages in the network of the RET can be done. Because of time constraints, the generalisation is done for partial blockages between Slinge and Rotterdam Centraal only. The results of the global-scale assessment were already coarse enough to allow for a generalisation, but those of the local-scale assessment were not. No consideration on power groups is made in this section and partial blockages in terminal stations (Rcs and Slg) are not investigated. This section is divided into three parts: predefined strategies adaptations, real-time decisions and a short part on passengers' information. A generic conclusion closes the section.

6.1.1. Predefined strategies adaptations

All of the predefined strategies for partial blockages between Slg and Rcs are similar to the one used for the blockage of Mhv northbound:

- D line trains can drive as usual,
- E line trains are either short-turned in Rcs or must remain in Slg.

From the answer to sub-question B2 in previous chapter, there are three main takeaways for predefined strategy adaptations: the short-turning of D line trains and a capacity shift from the D line to the C line in peak hours, and the sequence of trains in the bottleneck.

Short-turning of D line trains in (or ahead of) Slinge in peak hours

One may wonder: *Why is it important to mention short-tunings in predefined strategies, as dispatchers seem to already short-turn the right amount of trains thanks to their experience, like on May 18th?*

To better understand this, an analogy with road traffic can be used. When a partial blockage happens between Rotterdam Centraal and Slinge, the first response is to short-turn southbound E line trains in Rotterdam Centraal. Therefore the situation on the trunk section can be represented with an analogy with road traffic, as depicted in Figure 6-1. Vehicles come from Slinge, turn in Rotterdam Centraal and head back to Slinge. At some point, they have to share a track because of a defect train. In the bottleneck, only one direction can go at a time.

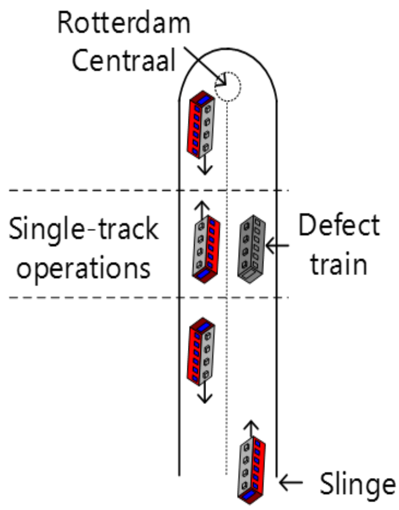

Figure 6-1: Analogy with road traffic.

If too many vehicles come from Slinge, there is a risk to create a gridlock situation but, most importantly from a passenger perspective, the northbound direction would be favoured over the southbound one in a first phase, which would require, in a second phase, to favour the southbound direction in the bottleneck. By doing so, large gaps in headways are created on both sides. Therefore it is important to dose the amount of vehicles sent northbound.
Furthermore, none of the respondents from the questionnaire (see Appendix C) mentioned the need to short-turn D line trains in Slg for a partial blockage in Mhv during the morning peak, even for a 90-minute blockage, while in reality, they obviously make adaptations. But it means that the short-turnings they carry out may be more of the **reactive kind than the pro-active one**. Yet as mentioned in the local-scale assessment, anticipation is paramount, especially for passenger-oriented strategies. When specifically asked, face-to-face asked about short-turning, there were three different answers: 1. Some dispatchers say they would short-turn all D peak line trains (the 6 trains added during peak time on the D line), 2. some say they would follow the predefined strategy literally, 3. some try to anticipate which D line trains absolutely need to be short-turned.

Even though it cannot be pinpointed in a standard way which trains will need to be short-turned exactly, having an idea about the amount of trains to short-turn for each partial blockage could help dispatchers to be more passenger-oriented. Ultimately, the type and the number of crossovers influence the amount of trains that can be sent though the bottleneck. The reader can refer to Appendix M for track layout structures between Slg and Rcs. Table 6-1 gives an estimate of the amount of D line trains that would need to be short-turned during a peak hour for various partial blockages. This estimate is based on the same methodology and sources than Appendix D . Besides, a 2/2 sequence is assumed and trains may wait in front of crossovers instead of at stops if crossovers are located more than 500 metres from a stop.

Stop and track	**Length of disrupted section**	**Amount of stops**	**Estimated amount of D line trains to short-turn**
Shs tr. 2	0.9 km	1	2
Bre, tr. 1 or 2	0.5 km	1	2
Whp or Lhv, tr. 1	1.4 km	2	5 to 6 (D line peak trains)
Whp or Lhv, tr. 2	1.3 km	3	6 to 7 (D line peak trains)
Rhv, tr. 1	1.3 km	3	
Rhv tr. 2	0.6 km	1	2
Mhv, tr. 1 or 2	1.6 km	1	3
Zpl, tr. 1 or 2	0.5 km	1	1

Table 6-1: Estimated amount of D line trains to short-turn for various partial blockages between Slg and Rcs during one hour of single-track operations of the morning or evening peak (lengths from internal documents of the RET). Tr. 1: NB operations, 2: SB.

Logically, the longer the disrupted section and the more stops, the more trains would need to be short-turned. There is not one partial blockage where all D line trains could be sent as stated in the current predefined strategies.

Capacity shift from the D line to the C line in peak hours/Diversion
The more short-turned D line trains there are, the more relevant capacity shift becomes. However, it would not be recommended to send all short-turned D line trains on the C line since it may disrupt operations on the C line and then impact the A and B lines. Reasonably, a couple of D line trains could be sent, which is already an option that a dispatcher evoked in the questionnaire, but does not apply because it is not common practice.

Train sequences in the bottleneck
The predefined strategies do not mention train sequences in the bottleneck (↑ ↓ or ↑↑ ↓↓, etc.). The author has seen, in some VKL files, cases where four or up to five trains were sent in a row per direction in peak hours. This means that large gaps in headways were created.
In the local-scale assessment, it is argued that a 2/2 strategy **during the steady operations** (not the transition phase) of the predefined strategy is favourable. During peak hours and when 3 stations are in the disrupted section, one may argue that a 3/3 sequence could be more interesting. It would make a better use of the single track **if** the 3 trains follow each other closely. However, this still means large headway gaps (around 14 minutes) on both sides of the disrupted section, which may lead to denied boarding (see below). This is when actively re-directing passengers towards the tram network would be particularly important. No decision is arguably better than the other.

6.1.2. Real-time decisions

It is **not** possible to fully standardise how a disruption should be handled. As mentioned in the literature review page 15, non-recurrent disruptions in railways should be addressed with a predefined strategy *and* real-time decisions, the latter being the added value of dispatchers. The extent to which the initial situation is taken into account (notably the anticipation of where headway gaps are/will be) has a major influence on passenger impacts, but it is difficult to standardise a response for the large spectrum of initial situations. Still, this sub-section aims at giving insights on the effects of partial blockages between Slg and Rcs on passengers in three ways:

- By shedding light on passenger demand patterns in the network.
- By giving indications on how large gaps in headway may be at the beginning of a disruption.
- By providing estimates about the gaps in headways above which denied boarding is likely to occur.

Passenger demand patterns
Participatory observations conducted at the traffic control centre have revealed that dispatchers lack knowledge of where passengers go to/come from throughout the day, i.e. flows of passengers. **Their knowledge is often biased by their own experience.** In particular, between Rcs and Slg, most think that morning peak equals to a large majority of passengers northbound (inbound) and evening peak southbound (outbound). Yet the section between Rcs and Whp is busy in the morning peak southbound and in the evening peak northbound. Justifications can be found in Appendix P .

Headway gaps during the transition phase, AM and PM peak
Based on the knowledge of the amount of trains blocked and their nature, it is possible to roughly predict how large gaps in headway will be right after the unplanned event occurs, as shown in Table 6-2. Such information can be used by dispatchers to better anticipate the consequences of partial blockages. Table 6-2 is determined based on the assumption that a partial blockage occurs either northbound or southbound, with one or two blocked trains. It is assumed that the predefined strategy is enforced as soon as possible and that **all** southbound E line trains are short-turned in Rotterdam Centraal, as stated by current predefined strategies. In peak hours, one gap in headway corresponds to approximately 6.5 minutes and two gaps to approximately 10 minutes. They may be even longer due to single-track operations. Table 6-2 shows that partial blockages happening NB can be particularly difficult to tackle because of the gaps they create in both directions. To prevent this, if sending an additional train SB like in Scenario 6b is not possible, dispatchers also have the option to short-turn a train without a third track. It is not ideal in general, but it may be advantageous in some situations.

Table 6-2: Amount of gaps in headways during the transition phase between Rcs and Slg during the transition phase caused by various partial blockages on the trunk section.

	Northbound	**Southbound**
E line	1 gap in headway northbound, downstream + 1 gap in headway southbound caused by the counter-train being short-turned.	1 gap in headway southbound, downstream and possibly one northbound because the blocked train does not turn in Slg.
D line	1 gap in headway northbound, downstream and 2 gaps in headway southbound (from the blocked train + a short-turned E line train).	1 gap in headway southbound, downstream (the gap in headway northbound comes a long time later since the D line runs until Aks).
E line + D line	*(Like on May 18th)* 2 gaps in headway northbound, downstream and 2 gaps in headways southbound.	2 gaps in headways southbound, downstream, 1 gap northbound.
2 D lines	2 gaps in headways northbound, downstream and around 3 gaps in headways southbound (counter-trains of the E line turning in Rcs).	2 gaps in headways southbound, downstream.

Headway gaps have an impact on denied boarding. One can look at boarding, alighting and occupation rates at various stops to estimate whether or not denied boarding could occur for any disruption affecting the E and D lines, and if so, for which headway gap. Denied boarding is deemed likely to happen when the boarding rate at a stop is larger than the alighting rate. The estimates and calculation details can be found in Appendix P . The main remarks are:

- In the morning peak, the maximum headway gap for Rhv NB is rather low, such that with the cancellation of one train only, combined with a few irregularities, denied boarding may occur at this stop. The same remarks goes for Mhv NB. In general, DB is likely to happen at the same stop than the studied case, plus Rhv SB (but it would take a gap in headway of around 20 minutes).
- In the evening peak, demand is more spread and thus larger gaps are needed for DB to occur. Yet if the same disruption than on May 18th had happened during the evening peak, with the same strategy than dispatchers, there would have been denied boarding occurrences in Whp NB and consequently in Lhv and Bre.

A short analysis for in-between peak hours can be found in Appendix P .

6.1.3. Passengers' information

Informing passengers that a disruption is occurring is not enough: they need to be told, preferably before they are confronted with the direct consequences of the disruption, what their alternatives are. It is recommended not to assume that passengers know their way in the network. Similar to predefined strategies used by dispatchers, pre-plans – or simpler, guidelines – for the travellers' informer(s) could be established in advance. In the case of a disruption between Slg and Rcs, guidelines would include not only advice for passengers travelling on the D and E lines, but also for passengers travelling on the A, B and C lines. The suggestions mentioned page 78 remain valid for any disruption occurring between Slinge and Rotterdam Centraal.

6.1.4. Conclusion of the generalisation

In general, predefined service control strategies in high-frequency, rail-bound urban public transport need to make a distinction between peak and off-peak hours so as to avoid the use of rules of thumb by dispatchers, which can have a negative impact on passengers. For peak hours, they could mention, for instance, an estimate of vehicles to short-turn. However, it remains difficult to standardise responses to be passenger-oriented because a lot depends on the situation at the beginning of the blockage and thus on real-time decisions. Still, knowing passenger demand patterns and being able to anticipate headway gaps and their consequences are undeniably relevant elements for the traffic control centre. They may allow for more passenger-oriented decisions to be taken. Additionally, it would be advised to prepare some guidelines to be able to inform passengers all over the network of their alternative options as soon as possible, especially if the disruption impacts a major corridor.

6.2. Impacts of service control measures on passengers

At the beginning of this research, one of the deliverables of this study was defined to be a literature review of service control measures, with a special focus on the impacts of each of these measures on passengers. Yet the literature review has revealed that studies on the appropriate strategies to adopt for high-frequency rail-bound urban public transport systems, particularly during the incident phase, are scarce. This section therefore summarises the insights gained on different service control measures throughout this study.

6.2.1. Holding

The impacts of holding (for regularity purposes) on passengers were found to be the same than defined by Schmöcker et al. (2005). However, on-board passengers were not found to be at a significant disadvantage, due to the fact that they are waiting on-board of a vehicle and do not perceive time like people waiting on platform. Therefore as a contrast, a (+) was added to downstream passengers in Table 6-3.

6.2.2. Single-track operations and short-turning

Three main types of strategies were investigated in the case study, as depicted in Figure 6-2. They could arguably be applied in a wide range of metro systems, since the infrastructure remains generic.

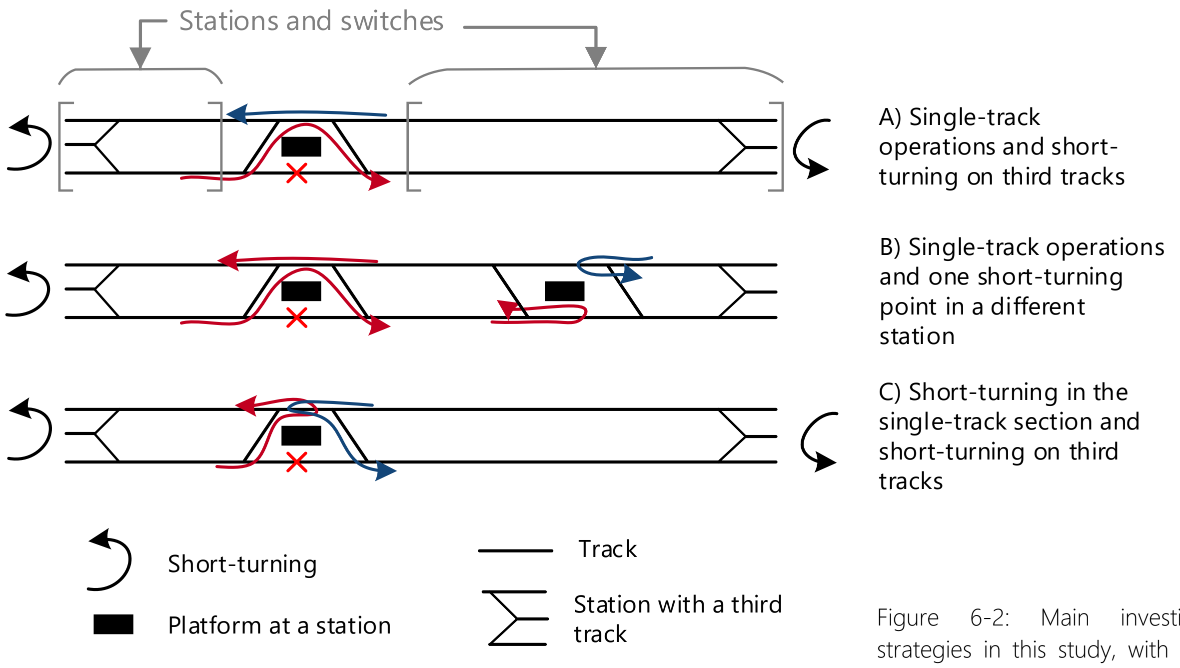

Figure 6-2: Main investigated strategies in this study, with short-turning and single-track operations.

From the application of the assessment framework, three major elements about short-turning in non-recurrent conditions in high-frequency rail-bound systems can be noted:

- This measure forms the basis of strategies, especially during peak hours. Trying to fit all of the available capacity in the disrupted corridor is likely to lead to a deadlock and/or balance issues. The latter can have particularly negative impacts on passengers, even on OD pairs which do not even need to go through the bottleneck.
- The infrastructure is a major constraint in the application of short-turning. A third track has undeniable advantages. With two tracks, switches' layout needs to be adapted for short-turning to be an attractive option but safety procedures can still lead to long occupation times. Short-turning with a single track would not be recommended, especially with a long single-track section length. As a consequence, short-turning within the disrupted section like in configuration C in Figure 6-2 would only be recommended if a third track is available within the disrupted section.
- The lower the ratio "passengers who need to transfer due to the short-turn" versus "passengers who alight at the short-turn point" at a given station, the better it is as a short-turn point. This ratio is more important than the share of origins and destinations at the short-turned point. If this ratio is high, then at least frequencies on both sides of the short-turning point need to be similar to allow for passengers to flow.

This research also brought new insights on single-track operations.

- It needs to be associated with holding upstream of the bottleneck, otherwise it is likely not to benefit passengers.
- The sequence of trains sent through the bottleneck is probably the most important variable:
    - In the case study, it was found to be more important than which trains are short-turned.
    - The chosen sequence reflects a trade-off between the use of the bottleneck capacity and headway gaps on both sides of the bottleneck. The larger the batches of vehicles sent in a row (e.g. 4 trains), the better the bottleneck capacity is used but the larger the headway gaps in the other direction.
    - Imbalances can easily be created. For instance, when a train is sent in one direction, either it or its counter-train must come back within a reasonable time frame to avoid imbalances (it should not "disappear", otherwise the other direction is at a disadvantage). The longer the single-track portion, the more crucial the sequence of trains.

No group of passenger is arguably positively impacted by single-track operations since it means a reduction in service. However, it remains probably better than a replacement service (which takes time to arrive at the disruption location) or short-turning without a third track or with two tracks but unequal frequencies on both sides of the short-turn point.

6.2.3. Conclusion

Table 6-3 summarises passenger impacts, by using the same format than Table 2-4 displayed in page 23. The application of the assessment framework thus allowed to gain new insights on measures used in non-recurrent conditions in a high-frequency, rail-bound urban public transport system.
In the application of the assessment framework, the addition of a vehicle (or rather, the fact that this vehicle was not short-turned to stay on a branch – see Scenario 6b) was assumed to be mostly positive since enough vehicles were already on the branch to serve passengers as usual. Still, more research would be needed on "replacement measures" (see page 20) in order to be able to make a generalisation, therefore it is not displayed in Table 6-3.

Table 6-3: Inventory of service control measures for which new insights on their impact on passengers were gained during this study (holding and short-turning based on the work of Schmöcker et al. (2005) and Wilson et al. (1992)).

Type of measure	Measure	Groups of impacted passengers	Type of impact
Speed control	Holding for regularity purposes	Downstream passengers on platforms	(+) (+)
		On-board passengers	(-)
Station-skipping	Short-turning	Reverse direction passengers	(+)
		Short-turn point boarders Skipped segment boarders Skipped segment alighters	(-)
		If frequency of the service to continue the trip is lower than original service	(-) (-)
Other	Single-track operations associated with holding upstream of the bottleneck	All passengers	(-) but better than a replacement service or short-turning without 3rd track

6.3. Further impacts

Moving away from the assessment framework, to allow for the results of this study to have a real-life application, it is necessary to discuss what the considered measures would imply for other stakeholders involved in the disruption management process. The strategies developed in Chapter 5 were developed taking into account constraints such as safety and infrastructure, are not radically different from strategies used by dispatchers and yet they are not being applied at the moment at the RET for operations rescheduling. Therefore these new strategies undeniably present challenges in practice.

6.3.1. Dispatchers' considerations during the disruption management process

In order to understand what these challenges are, it is first essential to understand what dispatchers need to consider when applying rescheduling measures. Even when using predefined strategies, they are the ones who eventually allow a pre-planned set of measures to be implemented in any given situation. Carrel (2009) highlighted the factors and principles that influence and govern the decision-making process of dispatchers. These are summarised here.

- **Safety**. Pre-planning certainly already takes safety into account and safety systems protect trains in the network without the need for dispatchers' intervention. However, in some cases dispatchers may have to switch to a manual mode and intervene, but safety remains their top priority.
- **Time of day**. Although pre-planning can make a distinction between different periods, such as peak and off-peak hours, subtleties are left to the care of dispatchers. For instance, decisions can be different depending on whether the blockage occurs at the beginning, the middle or the end of the morning/evening peak.
- **Rolling stock**. The location and characteristics (number of wagons, length of vehicles, etc.) of each vehicle has to be taken into account by dispatchers. For instance, it may be ideal to short-turn a certain vehicle that would leave a small gap in headways as advocated by the pre-plan but if this vehicle has three times more capacity than the following one, dispatchers may choose to short-turn the train that has less capacity instead.

- **Crew.** There are a few situations that dispatchers try to avoid regarding crews: a vehicle stationing at a given stop without driver, a driver needing to work overtime to take a vehicle to a certain location, or drivers not getting their breaks. Any action influencing a vehicle's trip also has repercussions on drivers. All of these situations are likely to happen when using measures such as short-turning and diversion. As mentioned in the section on disruption management in the metro of Rotterdam, page 59, the crew schedule is in fact one of the most important considerations for dispatchers' real-time decisions. Carrel (2009) made the same observation for the London Underground.
- **Timetable.** It may change across days because of planned construction works or maintenance for instance. Pre-planning cannot anticipate that, unless the planned disruption is long enough, therefore dispatchers' work is paramount.
  Rolling stock, crew and timetable considerations are intricately linked and can be grouped together as "operations plan" considerations.
- **Workload management and robustness of intervention.** Carrel (2009) specifically introduced these principles, often embedded in dispatchers' work; they are not necessarily aware of them. Management of workload means that dispatchers will opt for a decision that is compatible with their current and forecasted levels of workload. Robustness of intervention means that they implicitly take into account the fact that there is a chance that their decision might be misunderstood or not implemented as planned, especially since dispatchers have to communicate with a wide range of actors. Consequently, they may prefer to opt for simpler or usual strategies rather than more optimal but more complex ones.

6.3.2. Challenges for the implementation of passenger-oriented service control measures at the traffic control centre

The operations plan, workload management and robustness of intervention are further discussed here in relation to the implementation of the service control measures discussed in Chapter 5. The discussion is based on participatory observations at the traffic control centre of the RET. The metro of Rotterdam is still used as an example but comments can apply to other modes and PTOs.

Operations plan

The operations plan is punctuality-based. Yet a measure like holding for regularity purposes is by definition regularity-based. Holding often involve voluntarily delaying trains, something dispatchers usually try to avoid because of the issues it creates with drivers, notably lateness for the rest of their shift. This is why, at the moment, some dispatchers choose to hold trains upstream of the bottleneck to give priority to late trains (i.e. so that they can be on time at their terminals), which is not necessarily what is best for passengers.

In practice, short-turning is also sometimes based on delay considerations instead of headway gaps. For blockages that are not forecasted to be too long, dispatchers usually try to make sure that short-turned trains can be renumbered to ensure little delays. However, this does not prevent drivers to be "on the wrong train", which is why, for some dispatchers, there is a resistance in short-turning trains unless it is absolutely necessary, i.e. quite some time after the start of the disruption. As seen in Chapter 5, the transition phase is crucial and the aftermath may be serious for passengers.

Shifting capacity/diversion also further disrupts the operations plan because it means letting trains drive on a line where they are not scheduled to. This is particularly likely to create problems with drivers' shifts.

Dispatchers are therefore prone to favour measures that do not disrupt the operations plan too much. Furthermore, at the RET, the habit to focus on the timetable is reinforced by the work environment (screens only display timetable-related figures, like train delays) and by the punctuality-based fine system imposed by the authority from which the RET can operate the metro concession, the MRDH (Authority of the Metropolitan Region Rotterdam – The Hague).

Workload management of dispatchers

The farthest away current operations are from the operations plan, the heavier the levels of current and forecasted workloads are (forecasted workload for the recovery phase). In addition, even relatively small service control measures like holding for regularity purposes would increase dispatchers' workload because they are required to anticipate which vehicles need to be held. Anticipation is paramount for a passenger-oriented implementation of service control measures, starting with the question "Where are large gaps in headways expected?". Based on the answer, the sequence for single-track operations can be adjusted, vehicles can be held, etc. It could be expected that the more such a passenger-oriented anticipation is applied, the less heavy the workload, because dispatchers would get used to thinking in a certain way, adopt a new habit. Still, there is a non-negligible resistance barrier to cross.

Robustness of intervention

Multiple measures may be problematic to implement because they are not expected by other stakeholders, at least not for the first times they are being applied. For instance, holding for regularity purposes requires drivers to be informed and to understand why they must wait, so that they can communicate it to passengers in a clear way. Short-turning in other places than the usual ones would also take some extra effort to ensure that drivers and passengers (and other dispatchers) understand why the vehicle has to turn. It may be particularly beneficial for passengers, to fill a gap for instance, but if it is too much of a hassle for dispatchers, it will not be implemented. The same goes for diversion.

Measures that can be beneficial for passengers during the incident phase are therefore challenging. The major reason is because they are regularity- and not punctuality-based, therefore requiring changes in dispatchers' work habits. Now one may wonder: *what could facilitate the implementation of passenger-oriented real-time decisions at the traffic control centre?*

6.3.3. Improvement ideas for passenger-oriented real-time decisions

Three ideas are developed in this sub-section to bring improvements.

First, in general, an emphasis on **the importance of regularity** and the small actions to take to improve it could already be beneficial. For instance, holding for regularity purposes, even if applied to only one or two trains, can already be valuable. By using the generalisation provided page 89, dispatchers can also know how large gaps in headways are expected to be and which stops are most likely to cause denied boarding than others. Furthermore, passengers most probably prefer to wait inside a train than on a platform: when inside the train, the uncertainty factor typical of waiting time and the associated anxiety are reduced (Van Hagen, 2011).

Second, altering **the work environment** could be useful. At the moment, dispatchers are only able to see timetable-related figures on their screens, such as train delays. It is suggested that an additional layer, which could be displayed at dispatchers' convenience, be added to the screens. This layer would

show, for each stop, *the time elapsed since the latest train*. This time is therefore directly linked to passengers' waiting time, which weighs the heaviest in passengers' inconvenience. Based on this information, dispatchers may be able to take appropriate actions. At the moment, some dispatchers claim they can see gaps from looking at train positions on the screen; however, with the time pressure and the mental workload that brings a disruption, it is unlikely that dispatchers manage to keep track of all gaps at all stops. It is estimated that 10 to 20 days would be needed to implement such a layer, with an estimated cost of 15,000 € (Van der Veen, 2016).
A second piece of information that could be useful to implement in this layer is the *time estimate until next train at each stop*. However, it is not recommended to implement this without the time elapsed since the latest train, since this second piece of information is an estimate and may therefore fluctuate depending on the actions taken by dispatchers.

Third, it would be recommended to correct dispatchers' gaps in knowledge.

- The first gap in knowledge is about **passenger demand patterns** and generally, how busy stations are at various times of day. A first attempt to bridge this gap in knowledge can be found in the generalisation section of this chapter but this should be generalised to the rest of the network.
- The second gap in knowledge concerns the **fines imposed by the authority**, the MRDH. As in every concession, the authority sets goals with bonuses or maluses depending on the performance of the entrusted entity. Metro dispatchers at the RET often justify their focus on the punctuality of trains, especially in non-recurrent conditions, based on the fact that they know that the MRDH fines the RET for unmet punctuality goals. However, interestingly enough, the management of the traffic control centre has never received any guidelines or any detailed official notice regarding the rail concession fine system (at least in 2016 – fines were officially implemented in December 2016). An investigation into the problem shows that although dispatchers are right – there are punctuality-based fines – they clearly miss sizeable pieces of information. Two important remarks are worth making:
    1. The contract does offer some freedom to control **regularity** without the risk of fines, provided that the operations' plan modifications are well-registered (source: see Appendix Q). A clause states that in case of cancelled trip(s), the RET may adapt the departure of future trips for the benefit of regularity, on the condition that headways be inferior to 10 minutes. The punctuality requirements are then effective relative to the adapted departure times. In addition, departing early from a stop is also allowed, contrary to dispatchers' beliefs, on the condition that departing on time raises an issue infrastructure-wise (this could be useful for single-track operations). Therefore in order to be able to apply some more passenger-focused measures, the RET needs to find a way to properly register carried out adaptations.
    2. The contract also states goals based on the results of the yearly survey of public transport users' satisfaction. This survey contains multiple quality aspects and answers can be expected to be influenced by the way disruptions are handled. The RET may get maluses for not reaching certain targets. There is therefore an additional motivation to focus on the passenger perspective when tackling disruptions.

6.3.4. Conclusion

The assessment framework has considered the passenger perspective only and does not include any impacts related to the vehicle and crew schedules or to the level of adaptation that each measure may require from dispatchers. Most of the measures that would benefit passengers during the incident phase are regularity-oriented and since dispatchers are used to focus on punctuality for multiple reasons, the strategies proposed in this research may be somewhat challenging to apply. Still, satisfied customers are also desirable for any PTO. This is why, as another extension of this research, it would be recommended to conduct a cost-benefit analysis, taking into account short- and long-term passenger- and operator-related impacts, to be able to estimate what is most worthwhile.

6.4. Conclusion of the discussion on the assessment framework

The first section of this chapter has presented a generalisation of the results from Chapter 5 focused on predefined strategies, real-time decisions, passengers' information and service control measures. The second section sought to gather the insights gained on the measures used during the application of the assessment framework and their impacts on passengers.

The third section shed light on the impacts not considered by the assessment framework yet important in order to consider the implementation of passenger-oriented strategies. It allows to answer the last sub-question. Note that although this answer is formulated through the analysis of the practices at the RET, some items may apply for other public transport operators.

> **B4.** What are the challenges for the implementation of passenger-oriented service control measures?

Recurrent conditions are based on the respect of the operations plan, its punctuality guaranteeing regularity, and both benefit passengers. However, this is also what makes the interfaces between recurrent conditions and a disruption difficult to address, especially during the recovery phase, because disrupted operations need to be taken back to normal operations at some point. The incident phase needs a different treatment though, because of the reduction in capacity it typically involves. However, the punctuality paradigm tends to stay present during the incident phase among traffic controllers, while a regularity paradigm – with regularity-based measures and the anticipation of gaps in headways – would be more beneficial to passengers. This shift in paradigm is the main challenge and is multifaceted:

- The work environment in which dispatchers operate is conducive to a punctuality focus, like the display of delays. Real-time display of passenger-focused indicators could make it easier to take passenger-oriented decisions. This can be done on a short-term basis (scale of weeks).
- Dispatchers are humans and thus logically seek to manage their workload level. Heavy changes in the operations plan may mean too much workload. Even for smaller changes, a shift in paradigm means using approaches that may disrupt habits and thus lead in the early stages to an elevated workload. This may explain a certain resistance to change. On a long-term basis (at the scale of months), it could be expected that some new habits be integrated. It may be shorter for some dispatchers.
- Multiple actors are part of the disruption management system and thus a shift in the rescheduling approach needs to be understood by all. This could be established on the long term.
- The lack of information regarding the fine system established by the authority leads to the spread of the belief that there is no freedom in how disruptions can be handled, other than respecting punctuality. Even when the information is spread, the system will need to be adapted so that the clauses that allow a focus on regularity can be applied. This could be achieved on the long term.

Chapter 7 Conclusions and recommendations

In the first section of this chapter, the main conclusions of this study are formulated, by answering the main research question. Next, the practical implications of the results for PTOs are presented, followed by some recommendations tailored for the RET. The chapter ends with recommendations for further improvement of the assessment framework and for further research.

7.1. Main conclusion

The following main research question was formulated at the beginning of this research:

Research question
How can service control strategies used in non-recurrent conditions in a public transport system be improved and developed when the passenger perspective is taken into account?

Service control strategies for non-recurrent conditions can be developed and improved for the benefit of passengers via the use of an assessment framework, as developed in this thesis. In this framework, multiple passenger impacts due to disruptions can be assessed. By using the framework, the decision-maker can then compare the performance of various service control strategies in response to one specific disruption. This makes this assessment framework unique. It was tested on a case study, to demonstrate its applicability and to show the kind of insights that could be gained from it. The assessment framework was found to shed light on several matters, from predefined strategies to real-time decisions. In order to be more comprehensive, the next step could be to integrate some non-passenger-related impacts.

The rest of this section details the development of the assessment framework and the main findings. The incident phase – from the start of the incident until the cause of the disruption is resolved – was the main focus of this study but the framework lays the foundations for an extension with a wider focus. The assessment framework was developed in four phases.

First, a literature review was used to define key elements of the framework such as data needs and structure, and to get a good understanding of the meaning of "taking the passenger perspective in non-recurrent conditions": it starts with using impacts that directly relate to passenger needs, and to measure these impacts with recurrent conditions as a reference. These impacts were defined and divided into two scales of assessment:

- At a local scale, for a few stops:
    - Bunching, which translates into an additional effective in-vehicle time at stops.
    - Crowding and comfort aspects, assessed in two complementary ways:
        - Via additional perceived in-vehicle time between stations; the more crowded a vehicle, the longer in-vehicle time is perceived to be,
        - Via denied boarding, which causes an extension of waiting time.
    - Unplanned transfers, which translates into a penalty and additional waiting time.
    - Additional waiting time at the first stop.
- At a global scale, on a network level:
    - Additional travel time.

These impacts were embedded into a three-step methodology aiming at using them to assess disruptions. It is based on Van Oort et al. (2015). Firstly, vehicle data are used to compute supply-side impacts. Secondly, these impacts are translated into the previously defined passenger impacts, via the use of passenger data. Thirdly, passenger impacts are aggregated into an additional generalised costs (AGC) value that allows for various scenarios to be easily compared, including at the OD-pair level. The methodology is used separately for the local and the global scales.

So far, only the disruption to be investigated has vehicle data (AVL data). This is why, in a second step of the framework development, a method was selected to be able to generate vehicle data for alternative strategies, so that different strategies can be compared for the same disruption. Discrete-event simulation is chosen to model various scenarios, given an initial situation. Once the list of measures to include in the assessment is established, alternative strategies are generated in the simulation model based on a "what-if" approach, a heuristic optimisation procedure. Each modification corresponds to a different combination or implementation of service control measures and thus to a different strategy. For each modification, the variable inputs of the model are thus incrementally modified, based on the results from the local-scale assessment of previous strategies. The local-scale assessment is the one that allows to craft new strategies because of its focus on the microscopic level (track, road, etc.). This is therefore how service control strategies are developed. The generation of alternative stops when enough combinations of measures have been tested.

In the third phase, the assessment framework was applied on an in-depth case study, a partial blockage during the morning peak in the metro of Rotterdam, operated by the RET. This application was meant to both test the framework and to measure the nature of the improvements it could achieve.

The application of the assessment framework allowed to transform intuitions from observations into facts backed by a scientific approach: although predefined strategies at the RET are a good basis, there is still room for improvement to take the passenger perspective into account at the traffic control centre. For this specific case study, additional generalised costs were reduced by around 35% by implementing the three following changes:

- By modifying the sequence of trains for single-track operations during the transition phase, in a way that anticipates gaps in headway created by the unplanned event.
- By implementing holding for regularity purposes.
- And by not short-turning (or redirecting) one train, so that it can fill the gap in headway created by the unplanned event.

Implementing the first one only already led to approximately 12% of reduction in AGC and when the second one was added, an 18% reduction was achieved.

In a fourth phase, the assessment framework was validated through interviews. The assessment framework was therefore successfully developed.

The main takeaways are that service control strategies used in non-recurrent conditions can be improved in two main ways:

- Via refined pre-planned service control strategies. In particular, predefined strategies for high-frequency, rail-bound partial blockages need to have a variant for peak hours.
- Via real-time decisions that would anticipate better the occurrence of headway gaps caused by the unplanned event. In particular, the transition phase is crucial and decisions should be taken early enough to prevent these gaps from widening.

Overall, the application of the framework shows that passenger-oriented strategies for the incident phase are based on a regularity paradigm while current rescheduling practices are still mostly carried out with a punctuality paradigm. This difference in paradigm is arguably the main reason why the passenger perspective is thorny to take into account at the traffic control centre: any change comes at a cost. Such a shift would impact vehicle and crew schedules and thus dispatchers' work habits, hence a resistance to change. In order to be more comprehensive, the next step to improve the assessment framework could be to integrate some non-passenger-related impacts to be able to suggest more explicitly trade-offs between passengers and the operations plan for instance.

7.2. Practical implications

This section discusses the practical implications of this study for other transport operators, especially when operating rail-bound urban public transport systems. Since the case study was conducted at the RET, next section, section 7.3, specifies these implications into recommendations for the RET.

7.2.1. Service control strategies

In every service control strategy, there is a pre-planning component and a real-time decision-making component. In the case of disruptions in high-frequency, rail-bound urban public transport systems, the pre-planning component is recommended to be a partial pre-plan, i.e. it should contain:

- The service control measures to use: short-turning and holding for regularity purposes are the most basic ones for the incident phase in high-frequency, rail-bound systems.
- Variants between peak and off-peak hours,
- In peak hours, for partial blockages, an estimation of the maximum capacity that can be sent in a certain corridor and the most suitable short-turning points.

In general, it would be advised that pre-plans be not only designed by traffic controllers. Planners can also offer valuable insights.

During the real-time decision-making phase, passengers will benefit from a focus on regularity. This means anticipating gaps in headways, particularly at the very beginning of the disruption. Besides, dispatchers should have a good knowledge of passenger demand patterns.

7.2.2. The case of partial blockages in high-frequency rail-bound urban public transport systems

As highlighted by the literature review, disruptions causing partial blockages in high-frequency rail-bound public transport systems have received little attention so far. The application of the assessment framework shed light on two measures in particular: short-turning and single-track operations.

For both measures, two essential prerequisites are:

- The infrastructure (presence of crossover tracks),
- A safety system that allows trains to drive in another direction than the usual one on a given track and to drive through crossovers relatively seamlessly.

Short-turning should occur:

- In priority, where a third track is available,
- And ideally, at stations where the ratio $\frac{passengers\ who\ need\ to\ transfer\ due\ to\ the\ short{-}turn}{passengers\ who\ alight\ at\ the\ short{-}turn\ point}$ is relatively low. In order to determine this ratio, passenger data is required.

However, these are just guidelines for a systematic short-turning pattern, since it might be beneficial, during the transition phase for instance, to short-turn one train on a section with one of two tracks only, in order to bridge a gap in headways for instance.

When applying single-track operations, there is a trade-off between **regularity** and **bottleneck capacity**. In general, if the bottleneck is of moderate length, without third track and has one stop, a balanced sequence with small batches is recommended and is likely to prevent high passenger inconveniences. Figure 7-1 shows other options and trade-offs. The longer the single-track length and/or the more stations – which could due to a lack of switches – the more inconvenienced passengers are likely to be. The balance between using bottleneck capacity efficiently and focusing on regularity would become more and more difficult to achieve and capacity may be lacking. This is why in (sections of) network lacking crossovers, PTOs are advised to look at **long-term solutions** to be able to dispatch extra capacity within a reasonable amount of time, which could be done, for instance, through partnerships with taxi companies or, for PTO who also operate buses, a better integration of the bus network.

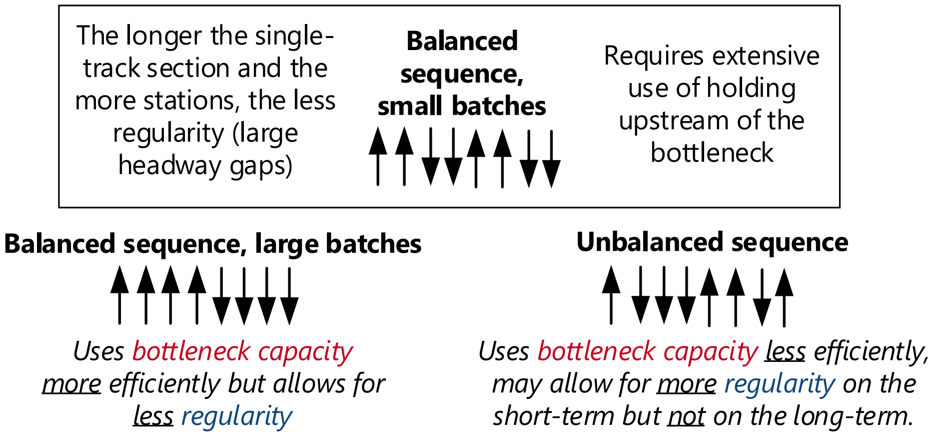

Figure 7-1: Single-track operations during steady operations in non-recurrent conditions in a rail-bound urban public transport system; regularity/bottleneck capacity use trade-off.

7.2.3. Investigating rescheduling measures

A last yet essential implication of this study is that when investigating rescheduling measures in general, it is strongly advised to spend some time to get to know the system as a whole, and not only at the traffic control centre. Dispatchers often have reasons to act in a certain way that can only be explained when one has the bigger picture in mind, meaning that multiple viewpoints are often needed to understand a phenomenon. A good example in this study, specific to the RET, is how a lack of information about the fine system influence traffic controllers' actions.

7.3. Recommendations for the RET

The application of the framework on a case study at the RET allows to give some tailor-made recommendations to the public transport operator. The disruption management system at the RET has a solid basis with plenty of good practices, such as using predefined strategies and promoting their use in the organisation, putting effort into the development of the registration system of disruptions and their strategies, and using "wait softeners" (Peters, 2016) to improve the waiting experience, since waiting time has the most negative impact on passengers.

Still, there is room for improvement. On a yearly basis, it is estimated that savings in terms of societal costs could amount to approximately 900 K€, if every disruption similar to the case study – occurring slightly more than once a week – is handled like in the best case scenario. To give an order of magnitude, saving 1€ of societal costs means reducing the waiting time of one passenger by five minutes.

7.3.1. Predefined service control strategies and passenger demand patterns

At the moment, predefined service control strategies in the metro of Rotterdam are guidelines with a solid basis, but still leave substantial room for freedom. For instance, partial blockages with very different characteristics in terms of single-track section length and amount of stations currently have the same predefined strategy. It would be recommended to highlight capacity issues in the predefined strategy itself, **to encourage pro-activity instead of reactivity**. The current "guideline" format of predefined strategies can have a serious impact on passengers during peak hours. One of the main outcomes of this study is that **predefined strategies need to incorporate a variant for peak hours**. Furthermore, it could be recommended to include a few metro planners in the design process of the predefined strategies, since they are often more aware of passenger demand patterns and thus potential capacity issues. Besides, it is recommended for the traffic control centre to help dispatchers build a better knowledge of these demand patterns, as they are useful to be able to take passenger-oriented real-time decisions.

Similarly to predefined service control strategies, it could be suggested for the RET to create some instructions for passengers' informers, so that they can announce re-routing alternatives at all stations that offer alternatives.

7.3.2. Shift from a punctuality to a regularity paradigm during the incident phase

During the incident phase, passengers would benefit from a shift from a punctuality to a regularity paradigm, with a focus on preventing headway gaps from widening. Even though the strategies developed within the assessment framework are not radically different from the ones currently used, this shift in paradigm remains challenging. It is recommended for the RET to take two main actions to allow for the focus to shift towards regularity:

- First, to adapt the work environment of dispatchers. An example is to display on traffic controllers' screens the time elapsed since the latest train at each station. It would make regularity-based decisions easier to take than when delays only are displayed.
- Second, to emphasize the importance of regularity in the organisation:
    - In spite of a certain resistance to change, dispatchers need to be aware of the importance of regularity during the incident phase. To begin with, it could be suggested to highlight **the positive effects of seemingly small actions**, such as holding for regularity purposes. On a medium- to long-term basis, it would be expected that dispatchers get used to implementing measures with a regularity focus in mind. This process could be supported by them being informed of the clauses defined by the authority that directly relate to their actions, i.e. the passenger-focused goals and the freedom to control regularity without the risk of being fined. The latter will also need an adaptation of the work environment, since operations plan adaptations need to be properly registered. The RET needs to create **conditions in which dispatchers are given the opportunity to focus on passengers**.
    - However, the rest of the organisation also needs to understand the regularity focus, from drivers to managers who set targets and define indicators for the analysis of disruptions.

Obviously, all disruptions are different and there is no standard response. A disruption forecasted to be short would call for less focus on regularity than a long one. All changes come at a cost that the assessment framework did not include, even if these changes are relatively small ones. Ideally, it would be interesting to balance demand- and supply-oriented impacts. It would be recommended for the RET to perform **a cost-benefit analysis**, with short- and long-term, demand- and supply-oriented impacts to be able to estimate to what extent being passenger-oriented is worthwhile.

7.3.3. Long-term solutions for disruptions

Capacity was shown to be a major variable during disruptions. Extra capacity (re-directed capacity in the case study) allowed for a substantial generalised costs reduction. Having extra capacity ready at all times is a costly option but long-term solutions could be investigated – again, by using a cost-benefit analysis – such as long-term partnerships with taxi companies or leveraging on local bus integration.

7.3.4. Further use of the developed assessment framework

The results of the first application of the assessment framework can thus be used to conduct a cost-benefit analysis. What about the **use** of the assessment framework itself at the RET?
Realistically, the assessment framework developed here could not be part of a real-time decision support system yet. It needs further improvements (see next section). However, it can still be used by the RET for a posteriori analysis purposes.
For instance, another disruption could be selected and analysed with the framework, preferably a relatively recurrent one. A case on the portion of shared infrastructure for lines A, B and C (between Schiedam Centrum and Capelsebrug) would be particularly interesting, since the frequency is the same from 7 AM to 7 PM but predefined strategies do not take into account passenger flows. If there is no possibility for the RET to access a discrete-event simulation tool, generating AVL data for alternative strategies can be done in multiple other ways, from open source tools to even simpler methods, such as directly modifying AVL files or by drawing time-space diagrams, the method used to assess Scenario 7b.
Yet even without generating new strategies, this study can still be used by the RET in multiple ways. First, the framework can be used to simply quantify passenger impacts for any given historical disruption. A software such as Microsoft Excel is enough. The in-depth case study conducted in this thesis can then serve as a reference point, especially for societal costs per disruption. Second, this study provides a method to estimate capacity in single-track operations, detailed in Appendix D . The RET has all the necessary tools to apply this method. Indicating capacity issues in predefined strategies would be highly valuable and was deemed useful by multiple dispatchers. Third, the framework of application of OV-Lite to analyse passenger impacts in non-recurrent conditions was set up and can be used, although an upgrade to a capacity-constrained assignment first would be welcome.

7.4. Further research

In this section, suggestions for further research are formulated, starting with suggestions for the improvement of the assessment framework. In a second part, suggestions for further research linked to the themes covered in this thesis are made.

7.4.1. Suggestions for the assessment framework improvement

Short-term improvements
It would be advised to use multiple reference days instead of one. It would give a more solid reference and would thus enhance the accuracy and the reliability of the quantitative results.
Another short-term improvement concerns passenger data. This framework currently relies on static passenger data: a fixed demand matrix for each period of day and fixed occupation/boarding/alighting rates. Ideally, time-dependent data would be used: for instance, boarding rates that vary within the studied period. A related area of improvement would be to make use of the latest data available, in order to avoid assumptions like in this study (see Appendix E).

Assessed impacts
Multiple improvements regarding the assessed impacts can be done.
First, it is recommended to include long-term impacts in the assessment framework, as briefly addressed in Chapter 5. The analysis on the use of the Reliability Buffer Time metric showed that an indicator based on extreme values provides valuable insights into the performance of strategies.
Second, denied boarding is currently computed in such a way that only a few sets of headways at some stops are taken into account. Therefore, the effect of holding for regularity purposes was probably underestimated, since headways were made to vary from stop to stop. In addition, the calibration of the discrete-event model shows that data generated with the model lead to a probable overestimation of denied boarding costs. Therefore, denied boarding costs may have been slightly overestimated for all crafted scenarios. The denied boarding module could be improved by taking into account all of the headways at each stop, by implementing a share of passengers who would renounce to queue and by taking into account the fact that being denied boarding multiple times leads to an increased marginal inconvenience.
Third, the transfer penalty was always quantified with the same constant while transferring is probably more energy- and time-consuming at certain stations than other: making a distinction could further improve the ability of the assessment framework to evaluate passenger inconvenience.

Generation of alternative strategies
The discrete-event simulation could use some improvements. It could be made more flexible, so that short-turning at non-terminal stops could be more seamless to implement. An immediate improvement would be to add stochasticity to dwell times or/and travel times between stops. A step further would be to make dwell times dependent on the amount of passengers alighting and boarding (or wanting to board, in the case of denied boarding). This would avoid the assumptions to compute additional in-vehicle time at stops.
Long-term impacts, denied boarding calculations and passenger-dependant dwell times: all of these improvements could be implemented through a significant upgrade of the simulation model used to generate alternative strategies. It would be suggested to make use of an agent-based simulation (ABS). Although Discrete-Event Simulation (DES) offers the advantage of having benefitted from years of research, ABS is the most recent form of modelling in operations research and is suited to model agents individually, each having their own goals and behaviours. Behaviours in DES are more passive, determined by the system. An interesting option would be to use a hybrid version and to model vehicles with DES and passengers with ABS. It would also allow for behaviours such as reneging (leaving the queue after entering) or balking (renouncing to enter the queue) to be modelled more realistically than by simply defining a share of people who would renounce to queue. ABS would also allow for a better quantification of waiting time inconvenience, since it would be possible to know

how long each agent has queued. Such a simulation could allow for impacts based on extreme values to be computed with more accuracy.

Global-scale assessment
The global-scale assessment could be improved in two main ways:

- By using a capacity-constrained transit assignment model, as it would give more realistic insights on re-routings and could take into account crowding and thus comfort. AGC would then be probably higher than the ones found in this research.
- By comparing the results of the transit assignment (using the recurrent-conditions logit scale parameters) with the OD matrix of passengers over the full network during the studied disruption, to see how many people would have re-routed to other modes, etc. It would also allow for a calibration of parameters in non-recurrent conditions (for a certain situation). Logit scale parameters are not the only ones that may be different: the willingness to walk to go to the first stop, controlled by the *loopradius* (walking radius) parameter in OV-Lite, might also change.

Even with these two improvements, the transit assignment model may not allow to distinguish between various service control measures. However, it can still be used as a valuable complementary analysis, especially if the two previously suggested improvements are implemented. The global-scale assessment could prove particularly important in case the assessment framework is extended to complete blockages, which were not considered in this study.

Real-time decisions and recovery phase
Although the assessment framework does allow to predict the consequences of the use of certain strategies, it is not possible yet to use it for real-time operations. An extension of this study would therefore be to implement it as part of a predictive tool for strategies in a traffic control centre. The definition of timetable-focused indicators would then be essential, in order to allow the predictive tool to present trade-offs to traffic controllers. Therefore, the assessment framework would need to be extended to the recovery phase. The passenger perspective is arguably even trickier to take into account during this phase. Timetable-focused impacts and objective would then need to be considered since the recovery phase ends when the operations plan is restored.

7.4.2. Recommendation for further research

This section presents recommendations for further research, on the topic of passenger-oriented disruption management in public transport systems.

First, it is recommended to get more insights on the behaviour of urban public transport passengers during non-recurrent conditions, particularly for unplanned events. This could prevent the use of multiple assumptions and significantly improve the quality of the results, for the transit assignment model but also for the quantification of impacts at the local scale. It is a vast theme that will not be covered within one study. It would be useful to know under which conditions passengers usually give up on their trips, where passenger re-route, etc. It is arguably a research topic which attracts more and more attention; during the course of this study, three studies have been conducted on this topic. Nesheli et al. (2016) investigated users' perceptions and decision tendencies due to holding and station skipping. Papangelis et al. (2016) studied the decision-making processes of passengers in rural areas in response to disruptions. Finally, Yap et al. (2016) investigated the passenger impacts of planned disturbances on a public transport network.

Second, by using smart card and GPS data or a survey, it would be interesting to investigate the behaviour of passengers in relation to how they have been informed over the disruption. This would be particularly useful for public transport operators, who could adapt their communication strategies for disruptions.

Third, it could be interesting to explore how footages from security surveillance cameras could be used to estimate denied boarding occurrences. Indeed, even with smart card and GPS data, denied boarding occurrences remain difficult to estimate.

Fourth, it is recommended to perform more research on in-vehicle crowding. As discussed at the beginning of the sensitivity analysis, the crush capacity is particularly difficult to determine. It would be interesting to know by which factors exactly and how it is influenced. Indeed, it was found to be a major variable of the assessment and thus deserves attention.

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Appendix A Generalised costs function constants

1. Values of travel time components

To transform travel time components into monetary values, it is common practice to use values of time.

Without taking crowding into account, in-vehicle time (IVT) is often found to be valued at 1.0 (Bovy & Hoogendoorn-Lanser, 2005; Van der Waard, 1988), meaning that on-board passengers have an exact perception of time. Although variations can be found across modes and purposes (Wardman, 2004), the value of 1.0 is kept for this study for the sake of simplicity.
Another important component for this study is waiting time. An old and widespread convention in transport planning is to set waiting time valuation as twice the value of IVT (Wardman, 2004). Appendix Table 1 is a brief summary of studies that investigated waiting time valuation: except for Bovy & Hoogendoorn-Lanser (2005) whose main focus were heavy railways, all values are below 2.0. For this thesis, it was decided to choose only one value of waiting time (and not one for the first stop plus one for transfers) for convenience purposes. Besides, a trade-off had to be made between a value from a Dutch study, a value determined for urban public transport, and a value determined with commuters in the sample, since they are the largest group of people in the morning peak in the metro of Rotterdam (this value was thus determined when the disruption to investigate was selected). Wardman (2004) found a value of 1.77 for urban public transport in the UK and both Van der Waard (1988) and Wardman (1998) found values ranging below this number; therefore a value of 1.7 can be considered as a good compromise.

Appendix Table 1: Summary of studies that investigated the weight of the waiting time component

Study	Value	Country	Mode	Comments
Van der Waard (1988)	1.5 – 1.8	The Netherlands	Heavy railways and urban public transport	Value for the first stop wait time. Morning peak data.
Wardman (1998)	1.53 – 1.71	United Kingdom	Heavy railways and urban public transport	Meta-study. Value for wait time and not for wait + walk, therefore likely to be compatible with the metro.
Wardman (2004)	1.77	United Kingdom	Urban public transport	Meta-study.
Bovy & Hoogendoorn-Lanser (2005)	2.2	The Netherlands	Heavy railways	Same value for both the first wait time and wait time at transfers.
Arentze & Molin (2013)	1.23 – 1.5	The Netherlands	Heavy railways and urban public transport	Respective values for short- and medium-distance trips; no commuting trip purpose.

Appendix Table 2 summarises the travel time components taken into account in this study and their respective weights. The transfer component corresponds to the high-frequency transfer component determined by Bovy & Hoogendoorn-Lanser (2005).

Appendix Table 2: Overview of travel time component weights (Bovy & Hoogendoorn-Lanser, 2005; Van der Waard, 1988; Wardman, 1998, 2004).

Travel time component	Weight
In-vehicle time	1.0
Waiting time	1.7
Transfer	5.1 (minutes)

Appendix Table 3 gives the translation into constants with the unit €/hour. For this purpose, a value of time was used; it comes from Kouwenhoven et al. (2014). Since it stems from data from 2010, it was first corrected for inflation for 2016.

Appendix Table 3: Values of monetary constants used for in the AGC function, corrected for the 2016 inflation. Value of Time from Kouwenhoven et al. (2014).

Name of the constant	Value
Value of in-vehicle time (VoT)	7.4 €/hour
Value of waiting time (VoWT)	12.6 €/hour
Transfer penalty	0.6 €/transfer

2. Crowding multipliers

The average perceived IVT can be assessed by multiplying IVT by factors that depend on the level of crowding. Wardman & Whelan (2011) determined different multipliers for commuters and leisure passengers, in columns 2, 3, 4 and 5 of Appendix Table 4. They did so by gathering the findings of 17 British studies on the valuation of rail crowding over 20 years. Note that the load factor LF is defined as the ratio in a vehicle of seating passengers per total amount of passengers. Besides, the multiplier for standing passengers only becomes relevant once the load factor exceeds 1 since it is assumed that each passenger takes a seat when there is one available.
When the trip purpose distribution commuters/leisure passengers is known, it is possible to determine multipliers with a weighted average, as done in the last two columns of Appendix Table 4. In this case, they were determined given the trip purpose distribution in the metro of Rotterdam during the morning as shown in Figure 4-4, page 56. The morning period was chosen *a posteriori*, after the case to investigate was selected.

Appendix Table 4: In-vehicle time multipliers (2nd, 3rd, 4th and 5th columns based on Wardman & Whelan (2011)).

	Seating multipliers		Standing multipliers		Seating multipliers	Standing multipliers
LF	**Commute**	**Leisure**	**Commute**	**Leisure**		
0.5	0.86	1.04			0.91	
0.75	0.95	1.14			0.98	
1	1.05	1.26	1.62	1.94	1.09	1.68
1.25	1.16	1.39	1.79	2.15	1.20	1.85
1.5	1.27	1.53	1.99	2.39	1.32	2.06
1.75	1.40	1.69	2.20	2.64	1.45	2.28
2	1.55	1.86	2.40	2.93	1.61	2.53

Appendix B Passenger-oriented disruption metrics

Barron and his team (2013) provided very specific definitions for each data item to the 22 metro authorities they surveyed but these are not available in their paper. Consequently the data analyst at the RET was asked to understand each data item in a broad sense, within the following limits:

- The mean distance between failures is the ratio of total train kilometres to the number of failures. In this context, a failure is defined as a defect that requires the vehicle to be removed from service.
- Service is degraded when it is slowed during a disruption or because of congestion following disruption resolution. Service is stopped when some trains are completely stopped due to a disruption.
- Number of trains affected means the initial train affected, plus any others cancelled or late as a result of the incident.
- The total train delay time is defined as the sum of all delay time caused to all trains affected by the incident.
- The total affected passengers is an estimation of the number of passengers who have been affected by the incident, including those on the initial train affected and those on subsequent trains that were delayed.
- The total passenger delay is the sum of all delay time caused to all passengers affected by the incident.

Appendix Table 5 shows how the RET performs compared to the metro systems investigated by Barron and his colleagues.

Appendix Table 5: Comparison of the incident-related metrics used at the RET in April 2016 for the metro vs. the metrics required in the study of Barron et al. (2013).

Data Item	**Amount of metro systems that report it in Barron et al. (2013)**	**Is it reported at the RET?**	**If yes, details if needed. If no, is there another measure close to it?**
Number of incidents	22/22	**Yes**	
Mean distance between failures	22/22	No	Planned to be implemented in a couple of months at the RET.
Incident cause	21/22	**Yes**	
Incident date	12/22	**Yes**	
Incident start date	11/22	**Yes**	Two types of measures are registered: • Starting time of the incident. • Starting time of the information to passengers. Usually there is only a marginal difference between them.
Duration of degraded service	5/22	-	
• Until problem is identified	1/22	No	
• Until normal service is restored	4/22	**Yes**	Ending time of the incident minus starting time of the incident, the ending time being when the timetable is restored.
Duration of stopped service	4/22	-	
• Until problem is identified	2/22	No	
• Until normal service is restored	3/22	**Yes**	Since April 2016. From the start of the incident until the cause of the disruption is resolved.
Total impact on trains	3/22	-	
• Number of trains affected	3/22	No	
• Total train delay time	3/22	No	
Total impact on passengers	2/22	-	
• Total passengers affected	2/22	No	
• Total passenger delay	1/22	No	The travellers' informer provides a rough estimation to passengers.

Appendix C Questionnaire

The questionnaire was sent around mid-July 2016 and replies were collected until mid-August 2016. 7 out of 24 dispatchers answered, a relatively low response rate that may be explained by holidays – less staff was present at the traffic control centre – yet a workload that remained substantial due to construction works on the network. With hindsight, it may also be attributed to the length of the questionnaire, although the repetition of the same pattern was meant to lower complexity.

Zoals een aantal van jullie waarschijnlijk al weten, ik ben de Franse jonge vrouw die bij de RET bezig is met haar afstudeer traject. Ik doe onderzoek naar de mogelijkheden om scenario's meer passagier georiënteerd te maken. Om de resultaten betekenisvol en toepasbaar te krijgen heb ik jullie input nodig. Alles wat jullie mij toesturen is **geheel vertrouwelijk** en wordt alleen gebruikt voor mijn persoonlijke research. Dat betekent dat ik aan niemand zal laten weten wie wat doet, wie wat zegt of wie graag wat doet. Ook niet als er naar gevraagd wordt.
Het zijn vijftien vragen welke maximaal 20 minuten van jullie tijd kosten. Ik zou het fijn vinden als jullie me willen helpen.
De antwoorden kunnen natuurlijk in het Nederlands gegeven worden en ik hoop ze **voor vrijdag 12 augustus** te mogen ontvangen. Mocht je nog vragen hebben stuur dan een mail, daarnaast ben ik af en toe ook op de centrale verkeersleiding te vinden.

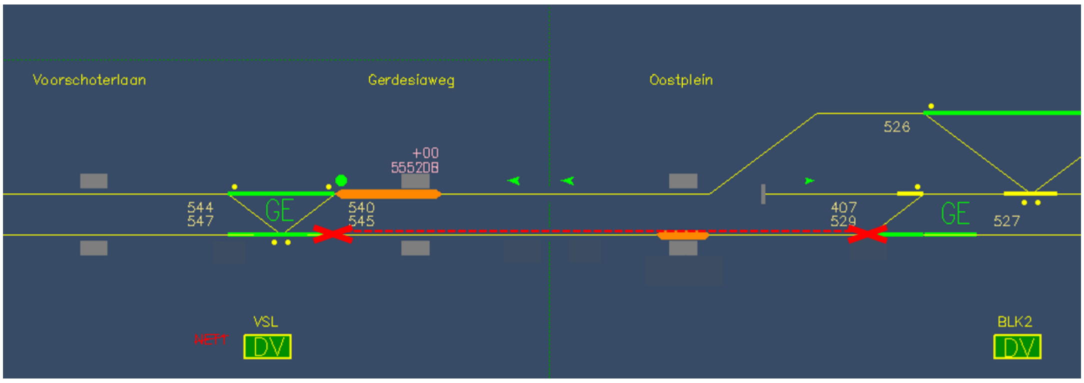
Uitleg

Je krijgt een aantal potentiële cases voorgelegd met daarbij de voorspelde vertraging. Aan jou de vraag wat je gaat doen in deze situaties. Je kunt de scenario's gebruiken of ervoor kiezen dit niet te doen. Er is geen goed of fout antwoord. Vertel gewoon wat jij passend vindt in deze situatie. Bij elke situatie begint de verstoring **om 08.00 uur op een reguliere weekdag**. Voel je vrij om zoveel details te vermelden als je wilt!

De opbouw van de vragen is altijd dezelfde en heeft 5 stappen.

1. Omschrijf stap voor stap welke bijsturingsacties je neemt.
2. Licht toe waarom je deze acties/beslissingen hebt genomen. Leg bijvoorbeeld uit wat de operationele beperkingen waren (dit kan gaan om bestuurders, passagiers, materieel, dienstregeling, je eigen werkdruk). Bijvoorbeeld: *Ik denk, dat passagiers/bestuurders gelukkiger zijn met deze optie want...* of *Ik bestel pendelbussen niet omdat ze ... minuten nodig hebben om te komen en dat is te lang* of *Dit is de makkelijkste manier voor mij*.
3. Leg uit welke uitkomsten je verwacht of graag zou willen zien van jouw bijsturing.
4. Licht toe of je dezelfde bijsturingsacties zou doen wanneer de verstoring/calamiteit van kortere duur zou zijn. Zo ja, waarom? Zo nee, waarom niet?
5. Licht toe of je dezelfde bijsturingsacties zou doen wanneer de verstoring/calamiteit van langere duur zou zijn. Zo ja, waarom? Zo nee, waarom niet?

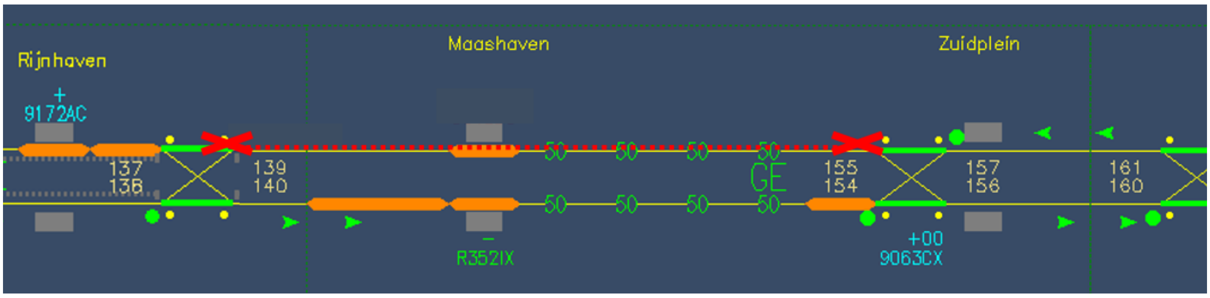
Case 1
Een trein gaat defect in station Oostplein, spoor 1 (richting Blaak).



Bij het begin van de verstoring is de voorspelling dat de trein voor de komende 45 minuten het spoor blokkeert.

1.a. Wat ga je doen, stap voor stap?
1.b. Waarom? Welke beperkende omstandigheden zijn er in de te nemen bijsturingsacties?
1.c. Welk resultaat verwacht je van je bijsturingsacties?
1.d. In hoeverre zou je hetzelfde doen wanneer de verwachte verstoringsduur 15 minuten zou zijn?
1.e. In hoeverre zou je hetzelfde hebben gedaan als de verwachte verstoringsduur 90 minuten zou zijn?

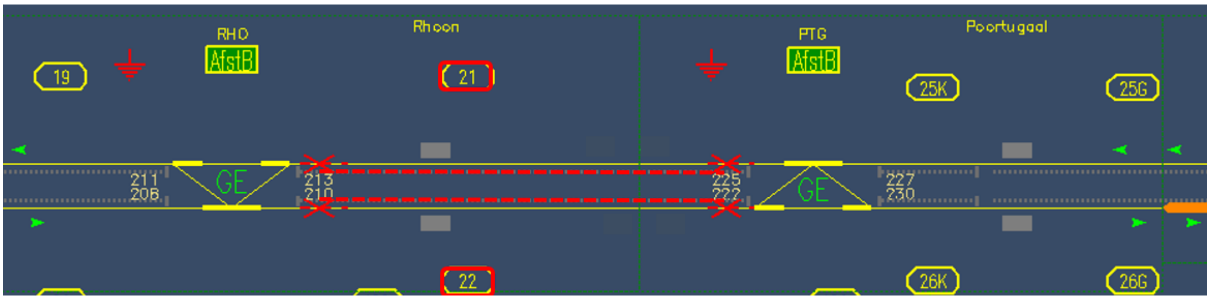
Case 2
Een trein gaat defect in station Maashaven, spoor 1 (richting Beurs).



Bij het begin van de verstoring is de voorspelling dat de trein voor de komende 45 minuten het spoor blokkeert.

2.a. Wat ga je doen, stap voor stap?
2.b. Waarom? Welke beperkende omstandigheden zijn er in de te nemen bijsturingsacties?
2.c. Welk resultaat verwacht je van je bijsturingsacties?
2.d. In hoeverre zou je hetzelfde doen wanneer de verwachte verstoringsduur 15 minuten zou zijn?
2.e. In hoeverre zou je hetzelfde hebben gedaan als de verwachte verstoringsduur 90 minuten zou zijn?

Case 3
Spanningsgroepen 21 en 22 (Rhoon Station) zijn uitgevallen. Er is geen trein in deze secties.



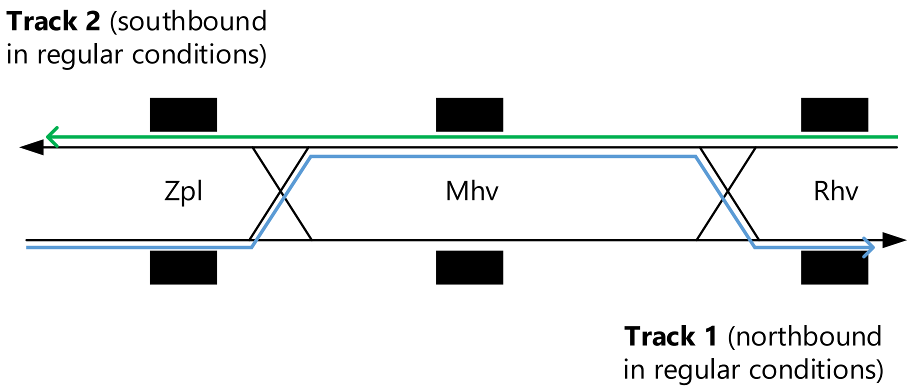
Bij het begin van de verstoring is de voorspelling dat het spoor voor de komende 45 minuten blokkeert wordt.

3.a. Wat ga je doen, stap voor stap?
3.b. Waarom? Welke beperkende omstandigheden zijn er in de te nemen bijsturingsacties?
3.c. Welk resultaat verwacht je van je bijsturingsacties?
3.d. In hoeverre zou je hetzelfde doen wanneer de verwachte verstoringsduur 15 minuten zou zijn?
3.e. In hoeverre zou je hetzelfde hebben gedaan als de verwachte verstoringsduur 90 minuten zou zijn?

Merci beaucoup!
Met vriendlijke groet,
Anne

Appendix D Capacity calculation for single-track operations

Given the track layout depicted in Appendix Figure 1 and AVL data from a disrupted day with single-track operations on track 2 of Maashaven, it is suggested to determine whether 12 vehicles per hour in each direction on track 2 of Mhv is a feasible option.



Appendix Figure 1: Track layout betwen Zuidplein and Rijnhaven.

The method presented by Chu & Oetting (2013) is used. They explain a simple way to compute the occupation rate of a track section where trains can come from and go to different routes. It allows to find whether a certain sequence of trains on this track section is feasible or not.

In the predefined strategy defined at the RET, it is implicitly defined, according to dispatchers, that trains should go in the bottleneck 2 by 2. Therefore, a train going through track 2 in Mhv can be either:

- The first train going southbound,
- Or the second train going southbound,
- Or the first train going northbound,
- Or the second train going northbound.

In this situation, an occupation time is made up of 4 components, columns 2 to 5 of Appendix Table 6. First trains have longer occupation times because switches need to change position and the section needs to be cleared of the previous train, running in the opposite direction. Second trains follow, therefore switches are already in the right position, reducing the occupation time. Furthermore, second trains can depart from the preceding station as soon as the first train has left Maashaven. Therefore, with this method, it is assumed that a second train is always ready to follow after the first train. This is not always the case in reality; consequently, if the calculation is done for one hour, the rule is that this *compressed* occupation time should not exceed 85% of 60 minutes, i.e. 51 minutes. A maximum occupation rate of 85% is the value recommended by the UIC (Union Internationale des Chemins de fer) (2013) and used by Chu & Oetting (2013) as well.

Running times between stations and dwell times can be determined either theoretically or empirically.

- For the running times, it is chosen to use a theoretical approach, based on the simulation developed by Both (2015), because it will allow for this calculation procedure to be easily reproduced at the RET. The running times are provided with a couple of clicks in a simple Java applet. It is assumed that all travel times are similar.
- The dwell times could also be determined from Both (2015) but given that this is a non-recurrent situation, dwell times from recurrent conditions as determined by Both (2015) are likely to underestimate the reality. In case the same calculation procedure needs to be performed again

internally at the RET but for another track section, it could be recommended to take the average dwell time provided by Both (2015), plus a certain percentage between 10 and 50%. Dwell times in Appendix Table 6 come from AVL data and were determined following a procedure described in Appendix H .

Theoretical times and actual running times are not overly different, they usually vary by less than a minute. This can be explained by multiple things:

- Not all drivers drive similarly,
- The travel time in the simulation of Both (2015) are not based on empirical travel times but running time calculations based on speed. He notes in particular that when stations lie on slopes, the calculated running time to and from them may be over- or underestimated. This is not the case in this situation but Both (2015) acknowledges other limitations. For instance, running times also depend on where trains stop at a platform, train length, speed limitations that may be slightly inaccurate in the simulator, etc.

Empirical running and dwell times are not difficult to determine *per se*, but they require some processing of the corresponding AVL data file, which needs to be requested first, etc. In addition, using empirical running times requires to be cautious, since bunching may happen outside of stations. It is not supposed to happen in theory but the time-space diagram in Figure 4-10, page 62, shows that it may occur (train 49).

The time for switches to change position include safety checks. It was determined with the help of a senior planner at the RET (Van Ravels, 2016).
These times are displayed in Appendix Table 6.

Appendix Table 6: Occupation time components.

	First NB train	**Following NB train**	**First SB train**	**Following SB train**
Approach time (from switches to Mhv)	1.7 min	0.4 min (=1.7-1.3)	1 min	0 min
Usual dwell time in Mhv	0.8 min	0.8 min	0.5 min	0.5 min
Time between the departure from Mhv to the arrival at next stop	1.3 min	1.3 min	1.6 min	1.6 min
Switches	0.5 min	0 min	0.5 min	0 min
Total occupation time	**4.3 min**	**2.5 min**	**3.6 min**	**2.1 min**

The predefined strategy states that there should be 6 trains of each type in one hour.
Therefore the (compressed) occupation time of the track 2 in Mhv is equal to:

$$t_{occ,comp} = 6 \times (4.3 + 2.5 + 3.6 + 2.1) = 75\ minutes > 60\ minutes$$

This means an occupation rate of 125%. The predefined strategy is therefore not feasible, and even more so as 75 minutes is the *compressed* occupation time. Indeed, it was obtained assuming that:

- As soon as a first train releases the platform in Mhv, the second train follows,
- And as soon as the second train reaches the station following Mhv, the first train in the other direction occupies the section.

In reality, there is always a bit of slack time during such events. As explained before, the compressed occupation time calculated with this method should not exceed 51 minutes, otherwise the proposed strategy is unfeasible.

Outside of peak hours, the predefined strategy would be feasible, with a compressed occupation rate of 63%.

Therefore, this predefined service control strategy is deemed to be too optimistic and not feasible during peak hours. The questionnaire reveals that dispatchers do not perceive that, while metro planners do. On the contrary, the latter are even too pessimistic. One of them assumes a constant occupation time of 4.7 minutes for each train. This is an overestimation, which, in turns, leads to an underestimation of the available capacity.

A posteriori analysis (after the selection of the disruption to investigate)
Assuming a 4.7-minute occupation time, the actual strategy implemented by dispatchers on May 18th would not be feasible – but since it was used in practice, it undoubtedly is feasible. On May 18th, they were able to send 12 trains through track 2 of Maashaven in 50 minutes but if the occupation time had been 4.7 minutes per train, they could only have sent 10 of them.

Appendix E Selection of the disrupted situation to be investigated

This appendix explains how the disruption on which the methodology will be applied is selected. A reference day needs to be selected.

1. Criteria for selection

In April 2016, a new registration system for disruptions was introduced at the RET, the Incident Registration Management System. The difference with the old logbook system is that dispatchers need to mention the duration of the blockage – and not just the total disruption duration – and the strategy they used. This is therefore the disruption database that will be used for this research. Indeed, although it is recent and therefore limited in content, registrations in the old system are too shallow to allow to investigate them on the given time frame of this research. They are not impossible to investigate though, but they would require operations reconstruction; see Carrel (2009).

The following criteria for selection are used:

- The disruption should have taken place in the metro system and be a partial blockage that lasted at least 10 minutes,
- It should be properly registered, notably without ambiguity regarding the actions taken by dispatchers,
- Given how critical the morning peak of a regular workday in the metro of Rotterdam is (see Chapter 2), it would be preferable to select at least one disruption that occurred during this period,
- The location of the disruption should not present a track layout so particular that the results of the analysis cannot be generalised to other locations in the network. In addition, studying a disruption that occurred on a trunk part, i.e. with more than one line running, is preferable due to the complexity it generates (whereas a 10-minute frequency may not require a specific strategy).

For the reference day, the following criteria are used:

- It should be a day when no disruption happened prior to or during the studied time period,
- Just like the selected disruption events, it should be a weekday outside holidays during the same season, with no structural difference in scheduled timetable.

2. Selection

The selected disrupted situation is presented in sub-section 4.3.1, page 60. The selected reference day is April 12^{th}, 2016. It was tested whether any bunching or denied boarding occurrences were happening on the reference day, but none of these were found.

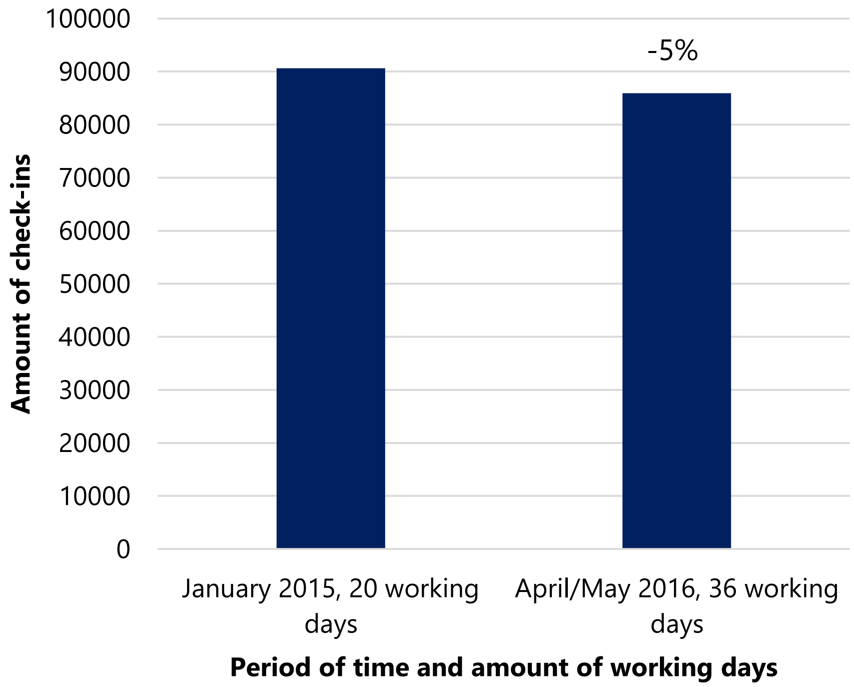
3. Seasonality

Since the OV-Chipcard data in OV-Lite is from working days in January while the reference day and the selected case are respectively in April and May, there may be a need to correct for seasonality effects. Indeed, in the Netherlands, there is a strong correlation between precipitations (but also extreme temperatures) and a modal shift from bicycle to public transport (Sabir et al., 2010). In addition, data in OV-Lite is from 2015 while the cases in this thesis are from 2016. Because of

maintenance and construction works, service supply is different between these two years. In particular, the construction works in Den Haag Centraal between February 2016 and August 2016 are expected to have impacted negatively the average amount of check-ins during the peak hour of a regular working day. The exact figure is relatively difficult to determine though. However, a compensating effect might be the fact that demand has always increased each year with the same structural network, by 1.3% between 2013 and 2014 and by 4.9% between 2014 and 2015 (RET, 2016c).
It is assumed that passenger figures from spring 2016 do not present abnormalities.
The data available to determine the change in demand between January 2015 and April/May 2016 is the number of check-ins for each hour of every day in these months. Two filters were applied:

1. Only check-ins between 7 and 8 AM included (120 minutes) are kept, i.e. passengers who began their journey during the peak hour.
2. Weekends, holidays ("Meivakantie"), public holidays and extra weekend days due to public holidays on a Thursday for instance are filtered out.

Appendix Figure 2 shows the result of this analysis: a decrease in approximately 5% in demand was found and is consequently applied to the input OD-matrix of OV-Lite. This figure was approved by senior planners at the RET (Westerweele & Kranenburg, 2016) as well as an OV-Chipcard data analyst (Man, 2016).



Appendix Figure 2: Average amount of check-ins per working day during the morning peak in the public transport network of Rotterdam.

Appendix F Inventory of service control measures used in the metro of the RET

In total, 208 pre-planned strategies were designed, one for each blocked section. An analysis of them reveals similar patterns. They are listed in Appendix Table 7. Disruptions terminals are not included, since measures depend on the terminal position in the network.

Appendix Table 7: Overview of the general structure of current predefined service control strategies at the RET.

Type of situation	Where?	Type of measures	Comments
Complete blockage	All the network	Short-turning, cancelling, shuttle buses	Shuttle buses implementation is not systematically mentioned.
Partial blockage, one line	Branches	Single-track operations	
Partial blockage, multiple lines, trunks	Capelsebrug – Schiedam Centrum, Rotterdam Centraal – Slinge, Tussenwater – De Akkers	Single-track operations, short-turning, sometimes cancelling	Short-turnings are done where a third track is available (Blaak, Rotterdam Centraal, etc.)
Partial blockage, multiple lines, between two junctions	Capelsebrug – Graskruid	Single-track operations, diversion	Diversion on the C line branch

Appendix G Practical details on the local- and global-scale assessments setups

1. Determination of vehicle capacities

Average capacities were chosen, both for crush and seating capacities.
In OV-Lite, the crush capacities are 438 for the D line (corresponding to 3 wagons) and 374 for the E line and the extra D line vehicles (corresponding to 2 wagons). These crush capacities were determined by the OV-Lite developers based on the assumption that there can be up to 2 people standing in one square metre of available floor of a vehicle. According to Alstom, the manufacturer, the vehicles are designed to contain up to 4 people per square meters. However, in practice, this is an optimistic value since a study conducted at HTM shows that it is more 3 or 3.5 (Yap, 2016). Still, the crush capacities from OV-Lite are likely to be below the real figures; a margin actually exists because of the requirements of the planning phase, where it is common practice to assume a slightly lower capacity than the actual one. Thus *denied boarding is likely to be overestimated*. The average crush and seating capacities were determined by taking into account the capacities of trains in the time windows. How changes in crush capacity affect denied boarding is examined in a sensitivity analysis in Chapter 5.

2. Selection of the time windows

The reasoning behind the choice of time windows as presented in Appendix Table 8 and Appendix Figure 3 follows five steps.

1. All time windows should be of equal lengths, to allow for an easier comparison between stations. Besides, it is suggested that this length can easily relate to 60 minutes (like 30, 40 or 45 minutes). This is because frequencies are usually expressed on an hourly basis.
2. All trains that cross the bottleneck in both direction should be included in the impact set. This means that a rolling time window approach is preferable to a fixed time window approach, even if it means spilling over the recovery phase for a few minutes in downstream stations. A fixed time window approach is too narrow: the last train(s) that pass(es) the bottleneck and drive(s) downstream the blockage may cross the upper boundary of the time window at some point, thereby excluding direct impacts of the chosen control strategy (like a full train).
3. <u>For the direction where the blockage occurs</u>: **downstream** of the blockage, passengers are expected to accumulate on platforms right after the blockage has happened. These passengers need to be taken into account in the assessment. Therefore the last train before the blockage occurs needs to be part of the impact set in downstream stations, so that headway *h* (see Appendix Figure 3) – and therefore demand for boarding – can be computed. For convenience purposes, it is suggested that this train be taken into account at the **bottleneck** station and at **upstream** stations as well. This way, the rolling time windows follow as many identical train lines as possible.
   - ➔ So far, it is possible to determine the time windows and their length in the direction of the disruption. The length is the maximum separation between the last train before the bottleneck and the last train before the recovery phase, rounded up to a duration that can easily relate to 60 minutes.
4. <u>In the other direction</u>, given the remarks mentioned in 1 and 2, two options are possible:
   a. Either the same time windows can be chosen; this is what Carrel (2009) did.

b. Or the same reasoning than the one described in 3 can be applied, i.e. making time windows start when the last undisrupted train drives.

Both options mean that a period of time during which traffic is somehow regular is included, respectively:

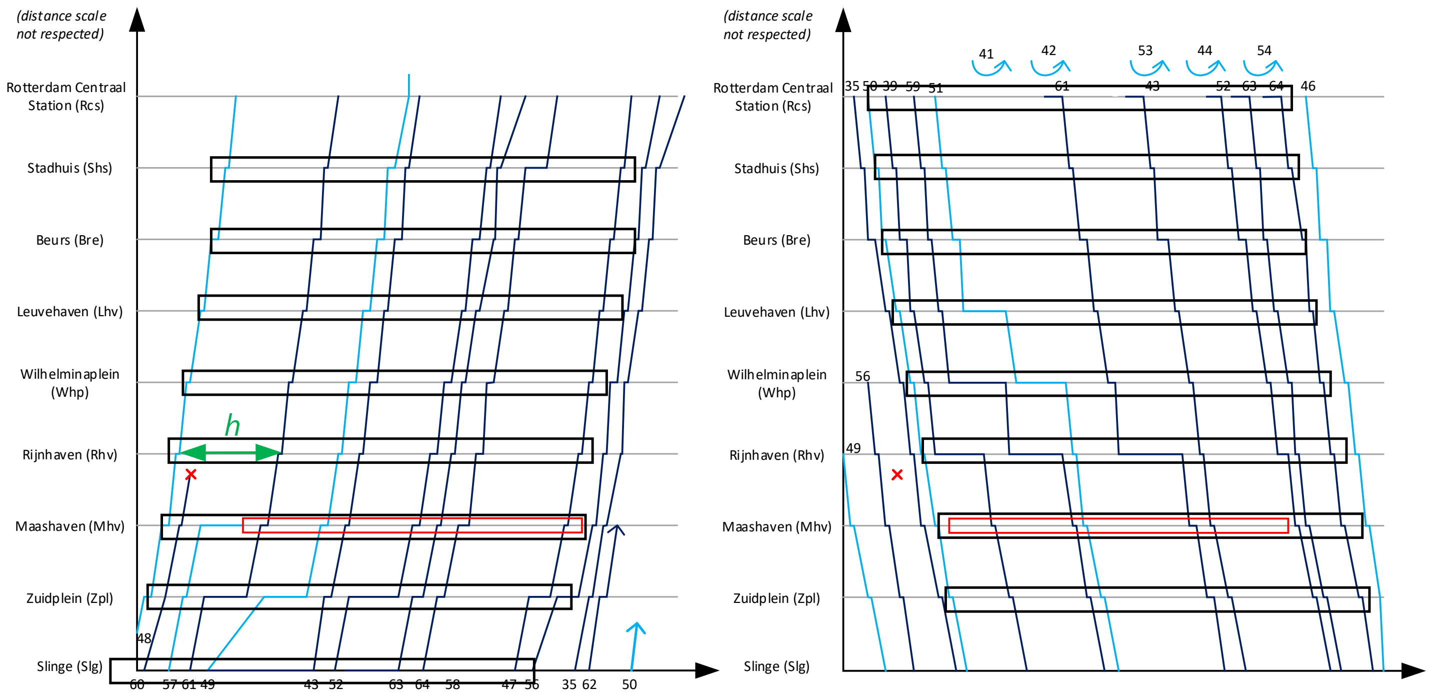
a. Before the strategy application phase (since this phase only affects the other direction),
b. Or the beginning of the recovery phase.

Since following similar trains is easier for the assessment – especially for the denied boarding module, option b. is chosen. However, this means that a few minutes of the recovery phase are taken into account in the assessment.

5. At terminal stations, only departures in direction of the studied trunk are assessed.

Appendix Figure 3 presents the chosen time windows for the case study. It is clearly visible that:

- Northbound, the time windows follow the departure of train 48. 12 to 9 trains are included in time windows depending on the station.
- Southbound, 9 trains are included in the time windows, starting with train 50.



Appendix Figure 3: Chosen time windows (left: northbound, right: southbound)

Note however that when these time windows are used to assess the scenarios, a deviation of one to two minutes is allowed in order to prevent a train from not being taken into account because it is outside one of the "strict" time window by a few seconds. The general idea is that, across one direction, **similar trains should be followed.** For instance, 9 trains in Bre SB, 8 trains in Lhv SB and 9 trains in Whp SB would make the PRDM in Lhv an outlier, which should be avoided.

Appendix Table 8: Selected time windows for the case study.

Northbound		Station	Southbound	
Start	End		Start	End
07:39	08:39	Slg	-	-
07:41	08:41	Zpl	07:55	08:55
07:44	08:44	Mhv	07:53	08:53
07:45	08:45	Rhv	07:51	08:51
07:47	08:47	Whp	07:50	08:50
07:49	08:49	Lhv	07:47	08:47
07:51	08:51	Bre	07:46	08:46
07:52	08:52	Shs	07:45	08:45
-	-	Rcs	07:43	08:43

3. Determination of the s2s matrix

Method

It is not possible to generate $p^{(y,z)}$ for all $(y, z) \in S$ directly from the transit assignment in OV-Lite. Instead, a station-to-station (s2s) matrix for the whole network can be generated. This matrix contains the number of trips identified as going between a set of specified stops, in the case study metro stops, where "going between" encompasses trips that make a transfer between modes. However, the s2s matrix does not include trips that are passing through a stop on a line.

For instance, a passenger taking the tram in A, transferring to the metro in B to reach their destination C will be counted in the A – C cell of the OD matrix but in the B – C cell of the metro s2s matrix. Note however that transfers within a same mode do not appear: if the passenger transfers in metro station T on their way from B to C, they will only appear in the B – C cell and not in B – T and T – C.

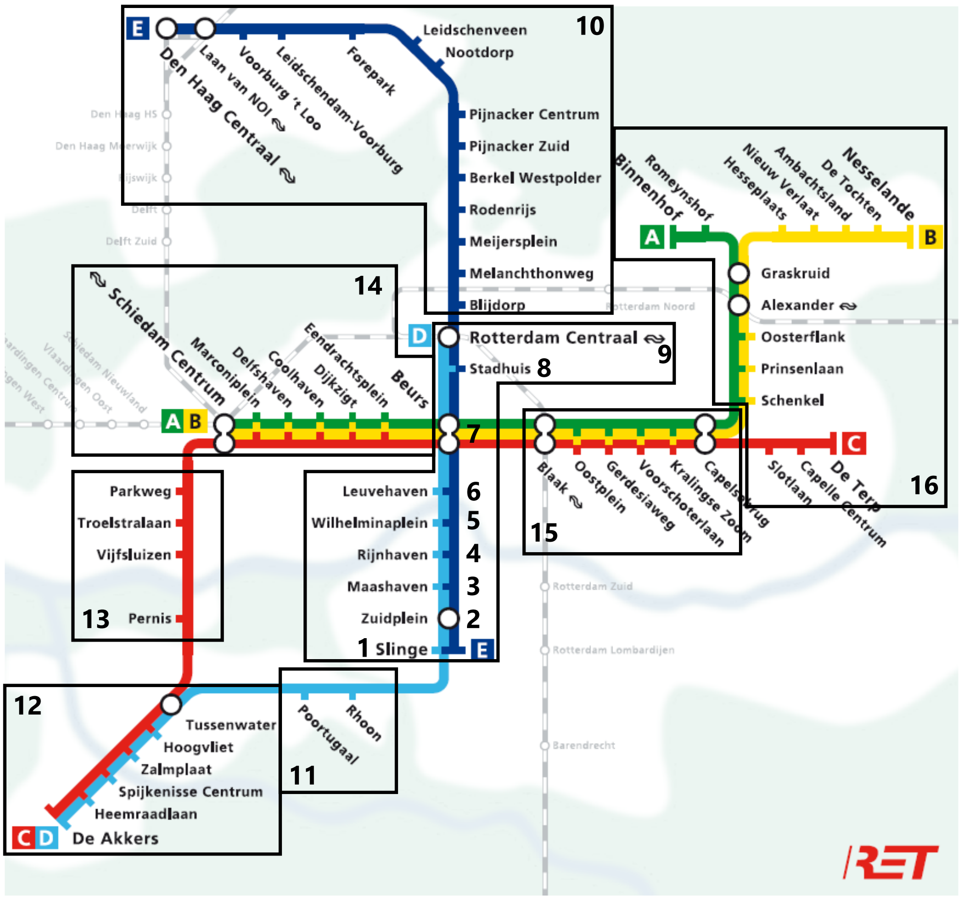
To get $p^{(y,z)}$ for all $(y, z) \in S$, a s2s matrix *for the stations in S only* needs to be generated. Since S contains two dummy stations, the s2s matrix of the network needs to be processed. To obtain the right s2s matrix, the three following steps are suggested:

- Make sure that a $r \times r$ s2s matrix is available, r being the number of stations of the investigated mode in the network. In the case illustrated in Figure 3-9 page 38, one would need an 8×8 s2s matrix.
- Determine which stations outside of the set can be aggregated. Ideally, this step would not exist but it is meant to keep the amount of OD pairs manageable. With the example in Figure 3-9, it is possible to aggregate stations A and B into one, and stations G and H together. The s2s matrix becomes a 6×6 s2s matrix.
- The process therefore stops when rows and columns of the s2s matrix labelled as "A-B" and "G-H" can be respectively renamed α and β, the dummy stations. A representation of the network would then be Figure 3-10. However, if more groups are created at step 2 (δ, ε, etc.), another aggregation step is needed, so that in the end, the s2s matrix has the same size than the number of stops within the scope S.

In this s2s matrix, all passenger trips that use at some point at least one of the selected stops are included. Trips that originate and/or terminate outside of the set of selected stops are seen as coming from or going to the dummy stations α or β. Note that assumptions may be needed if, for instance, passengers from A to H (see Figure 3-9) have the option to choose another route with the same mode in the studied network. The shortest path tool in OV-Lite may then be used.

Application

Stations are first aggregated, before determining the 11 × 11 s2s matrix required for the calculation of additional generalised costs. The groups that were created are displayed in Appendix Figure 4. To make the task manageable, a limited amount of groups had to be formed, but enough to allow the 11 × 11 s2s matrix to be filled with a few assumptions as possible.



Appendix Figure 4: Aggregated stations.

Instead of a 62 × 62 s2s matrix (3,844 cells), using these groups allows to get a 16 × 16 s2s matrix (256 cells). The 11 × 11 s2s matrix required for the assessment (and shown in Appendix Table 9) was then filled in by determining whether or not passengers in each cell of the 16 × 16 s2s matrix would make a part of their trip within the set of selected stations and if yes, which stations they would use. Some cases were non-ambiguous: passengers who board in the group of stations 15 and alight in the group of stations 14 will most likely not use the segment between Slinge and Rotterdam Centraal. However, some cases were more delicate. For instance, do passengers travelling between Parkweg (group 13) and Zuidplein travel through Tussenwater, or through Schiedam Centrum and Beurs? To solve this kind of dilemma, the shortest path engine of OV-Lite was used and trips were divided between the cells of the new s2s matrix accordingly. In this case, assuming an uniform distribution of passengers in Parkweg 16% board the C line southbound and will therefore be counted in the cell with coordinates "S - Zuidplein" of the s2s matrix, while 84% board the C line northbound and will therefore be counted in the "Beurs - Zuidplein" matrix.

According to this method, there are approximately 12,000 passengers who use this trunk line between Slinge and Rotterdam Centraal at some point in their journey during 1 hour of the morning peak. This figure was validated by an OV-Chipcard data analyst (Man, 2016).

In Appendix Table 9, a conditional formatting is applied, so that the busiest pairs are visible in red or dark orange.

	S	Slg	Zpl	Mhv	Rhv	Whp	Lhv	Bre	Shs	Rcs	N
S	0	237	309	46	43	259	116	349	242	315	75
Slg	73	0	45	18	11	81	58	282	91	154	52
Zpl	110	12	0	16	37	167	131	510	180	294	124
Mhv	28	30	32	0	10	44	26	209	78	137	52
Rhv	15	30	72	15	0	13	16	108	28	59	23
Whp	20	10	23	8	2	0	14	85	24	100	39
Lhv	7	8	13	5	1	23	0	6	6	21	10
Bre	51	129	312	81	34	551	58	0	380	458	297
Shs	31	28	58	18	8	137	21	105	0	18	25
Rcs	50	67	136	42	18	462	55	203	22	0	255
N	27	44	94	22	14	232	90	761	121	592	0

Appendix Table 9: s2s matrix for 1 hour in the morning peak on the trunk section of the D and E lines. S: outer edge near Slinge, N: outer edge near Rotterdam Centraal.

4. Selection of service control measures that will be used in the assessment framework application

Before the application of the assessment framework, the list of service control measures that will be used in alternative strategies must be established. In the conclusion on the inventory of service control measures, a list of the most suitable implementation phases for each measure is defined in Table 2-3 (page 23). In this study, the focus is placed on the incident phase. Appendix Table 10 lists these measures and whether or not:

- They are already used in the predefined strategies of the RET (based on the inventory presented in Appendix F),
- They will be used in this study to build alternative strategies.

Explanations are provided below Appendix Table 10.

Appendix Table 10: Inventory of the incident-phase service control measures used at the RET and in this study.

#	Measures that can potentially be implemented during the incident phase	Measures in the predefined strategies at the RET	Measures used in this study
1	Holding	X (implicitly, type a. only)	X (a. and b.)
2	Short-turning	X	X
3	Diversion	X	
4	Cancelling	X	
5	Non-rail-bound shuttle service implementation	X	
6	Single-track operations	X	X

1. Holding can be understood in two ways:
    a. Holding upstream of the bottleneck when single-track operations are used, to prioritise trains. It is not explicitly mentioned in the predefined strategies, yet used by dispatchers who believe that some sequences should be respected (e.g. ↓↓ ↑↑), which makes it interesting to investigate: does it really bring any benefit and if so, under which conditions?

   b. Holding as a measure to increase regularity, as described in the literature review page 16.
2. Short-turning is one of the main measures used in case of disruptions at the RET. But as explained in the example in sub-section 4.2.3, predefined strategies underestimate short-turning. Thus it ought to be investigated.
3. Diversion can only happen in some specific cases in the metro network of Rotterdam, when there is a junction. There is no junction nearby the selected disruption, thus it will not be investigated.
4. Cancelling may be used in alternative strategies yet it will not be investigated since, at a local-scale, it will not be distinguishable from short-turning.
5. The RET only implements non-rail-bound shuttle service implementation for complete blockages. Besides, the questionnaire and the participative observations have revealed that this measure is challenging, since it is based on an estimation of the duration of the incident. Therefore, it is unlikely that it be adopted by dispatchers for partial blockages and thus not investigated.
6. Single-track operations are used in every predefined strategy for partial blockages at the RET, this measure ought to be investigated by this framework.

5. Setup of the global-scale assessment

Since the scope of the local-scale assessment is limited to stops between Rcs and Slg, only the lines between these stations need to be modified (with one exception; see page 75). The method is as follows:

- First, existing lines are all duplicated to easily replicate existing lines' routes and characteristics.
- Second, duplicated lines are shortened, so that the duplicated D and E lines only run between Rcs and Slg. Their frequencies are adjusted according to the local-scale assessment results.
- Third, the original D and E lines are also shortened, so that their new routes correspond respectively to De Akkers (Aks) – Slg and Den Haag Centraal – Rcs.

In recurrent conditions, the wait time and penalty constants within each line in Slg (for the D line) and Rcs (for the E line) are set to zero, so that for each line and in each direction, the two sections of line only form one. This configuration was tested by comparing the skim matrices with and without the modifications described above. Once the largest amount of transfers was raised, the sum of the generalised costs matrix with the dummy lines was found to be insignificantly (10^{-7}%) higher than the sum of the generalised costs matrix without the dummy lines. The largest difference in the skim matrix does not exceed 1%. These slight differences are probably due to the number of maximum transfers allowed being raised, creating new but unattractive route choices on multiple various OD pairs. Thus, the new configuration is considered to be verified.

In non-recurrent conditions, passengers may or may not need to transfer but OV-Lite does not allow to set a certain transfer probability. Setting the transfer constants to zero like for recurrent conditions would severely underestimate AGC because the discontinuity in frequencies would not be acknowledged. Therefore it is assumed that all passengers travelling through the metro stations Rcs and Slg will have to transfer. The local-scale assessment will show that this is relatively valid for Rcs but less for Slg. However, this overestimation could compensate to some extent for the impacts that OV-Lite does not take into account, such as denied boarding and additional perceived in-vehicle time.

Appendix H Specification of the model in ARENA

In this appendix, station names are most of the time abbreviated; the reader can refer to the list of abbreviations page XVII. When the number 1 is coupled to the station abbreviation, it refers to the direction normally used for northbound operations, while 2 is for southbound operations.
The model in ARENA was built once the disruption to analyse was chosen.

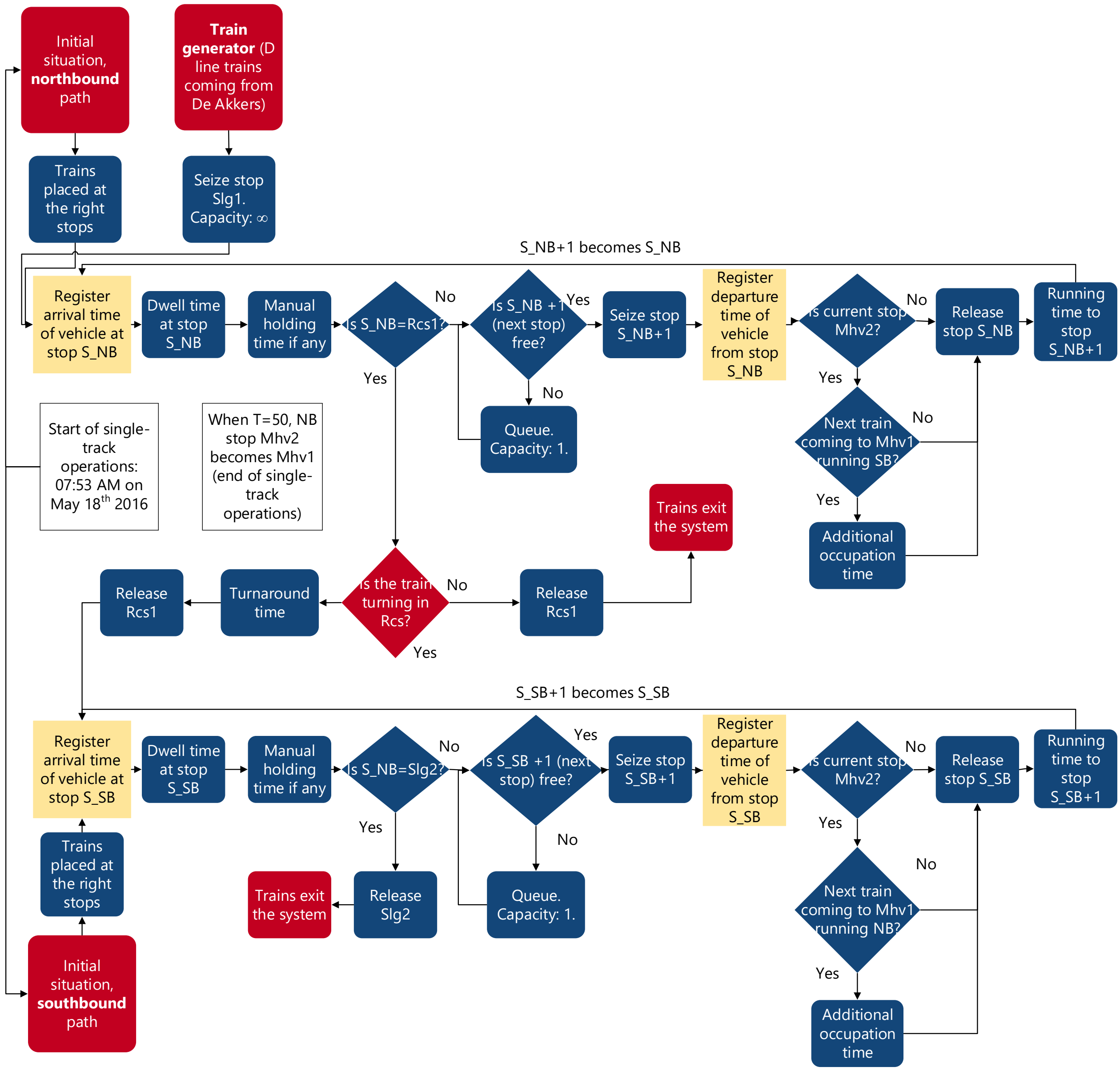
1. Setup of the model

Appendix Figure 5 next page specifies Figure 4-12 from page 64 and details the building blocks of the model, specifically of the two paths. Each stop is represented as a resource. A path is therefore a set of resources that an entity (a train) will seize and release in a successive way. An entity can only seize a resource if it is available: this represents the track safety system. The time during which each resource is seized has a fixed component (dwell time plus dwell time extension due to crowding) and a variable one, bunching time, that depends on when the next resource is available to seize. By registering the total amount of time spent at a stop, as shown by the yellow boxes in Appendix Figure 5, it is possible to know the bunching time of each train. Once a resource is released, the entity goes to next stop with a fixed running times. Dwell and running times are explained respectively in page 134 and 135 of this Appendix. The choice of the turnaround time in Rotterdam Centraal is also explained, page 135.
A specific case is that of a train leaving Mhv. If the next vehicle to seize Mhv comes in the opposite direction of the one leaving, an additional occupation times needs to be added to take into account the fact that switches need to change position and safety checks need to be done. This is further explained in page 136 of this Appendix.
When single-track operations are over, the simulation comes back to normal operations by replacing Mhv2 in the northbound path by Mhv1.
The output of the simulation is a text file comparable to an AVL data file. It is then processed in Matlab: first, train data between 07:39 (beginning of the first time window, see Appendix Table 8 page 129) and 07:53 are manually added and then **the file is processed like an AVL data file**. Trains that left the analysed system short after the beginning of the disruption were also manually added.

Initial situation
The occupation of the selected stops at 07:53 AM is shown in Appendix Table 11 and derived from the time-space diagram in Figure 4-10 page 62. A limitation of the model is that trains from the initial situation that are injected in the model can only be injected as *arriving* in a station.

Appendix Table 11: Occupation of the stops at the beginning of the simulation, i.e. at 07:53 AM.

Northbound	**Is there a train? (1=Yes, 0=No)**	**Southbound**	**Is there a train? (1=Yes, 0=No)**
Slg	1	Rcs	1
Zpl	1	Shs	0
Mhv	0	Bre	0
Rhv	0	Lhv	1
Whp	0	Whp	0
Lhv	0	Rhv	1
Bre	0	Mhv	1
Shs	0	Zpl	0



Appendix Figure 5: Building blocks of the model in ARENA.

Dwell times

As mentioned in the description of impact (a) in sub-section 3.3.3 page 40, dwell time in non-recurrent conditions may contain an extension due to crowding or bunching or both. Due to the absence of passenger interaction in the model, it is not possible to determine the dwell time extension caused by crowding. It must then be estimated. This is done through Formula 26. The same method than explained for impact (a) is used.

$$t^{s,n}_{fixed\ dwell} = \min\left(\widetilde{t^{s,1}_{dwell}}, 2 \times \overline{t^{s}_{dwell}}\right) \quad 26$$

With:

$t^{s,n}_{fixed\ dwell}$	$fixed\ dwell\ time\ component\ implemented\ in\ the\ model, n > 1$
$\widetilde{t^{s,1}_{dwell}}$	$dwell\ time\ observed\ at\ stop\ s\ in\ Scenario\ 1$
$\overline{t^{s}_{dwell}}$	$average\ dwell\ time\ at\ stop\ s\ in\ recurrent\ conditions$

Appendix Table 12: Dwell time at stops, as implemented in the model.

NB	Average dwell times, recurrent conditions	Average dwell times on May 18th 2016	Average dwell times in the model (contains the extension due to crowding)	SB	Average dwell times, recurrent conditions	Average dwell times on May 18th 2016	Average dwell times in the model (contains the extension due to crowding)
Zpl1	32 s	203 s	1.1 min	Shs2	26 s	30 s	0.5 min
Mhv1/2	31 s	48 s	0.8 min	Bre2	39 s	55 s	0.9 min
Rhv1	30 s	39 s	0.7 min	Lhv2	28 s	70 s	0.9 min
Whp1	33 s	46 s	0.8 min	Whp2	32 s	131 s	1.1 min
Lhv1	31 s	40 s	0.7 min	Rhv2	27 s	181 s	0.9 min
Bre1	37 s	48 s	0.8 min	Mhv2	28 s	32 s	0.5 min
Shs1	31 s	57 s	1 min	Zpl2	30 s	36 s	0.6 min
Rcs1	-	-	0.5 min	Slg2	-	-	0.5 min

If the dwell time on May 18th (Scenario 1) at stop s is inferior or equal to twice the dwell time in recurrent conditions at stop s, then this dwell time is used as the fixed dwell time component at stop s. If it is not the case, then twice the dwell time during recurrent conditions is used. It is important not to use a dwell time already too large, otherwise it could already contain bunching. The average dwell times in recurrent conditions are obtained from Both (2015). Dwell times for entities leaving the system, in Rcs1 and Slg, are assumed to be 0.5 minutes.

Running times

The travel times between stops can be found in Appendix Table 13. They also come from the work of Both (2015). The limitations of the running times determined by Both (2015) are already mentioned in Appendix D but overall, differences with empirical running times were found to be low.

Appendix Table 13: Travel times between stops, as implemented in the model (Both, 2015).

Northbound	Travel time (excl. dwell time) in minutes	Southbound	Travel time (excl. dwell time) in minutes
Slg1 – Zpl1	2.0	Rcs2 – Shs2	1.2
Zpl1 – Mhv2 Zpl1 – Mhv1	1.7 1.6	Shs2 – Bre2	0.8
Mhv2 – Rhv1 Mhv1 – Rhv1	1.3 1.0	Bre2 – Lhv2	0.9
Rhv1 – Whp1	0.9	Lhv2 – Whp2	1.4
Whp1 – Lhv1	1.5	Whp2 – Rhv2	0.9
Lhv1 – Bre1	0.9	Rhv2 – Mhv2	1.0
Bre1 – Shs1	0.8	Mhv2 – Zpl2	1.6
Shs1 – Rcs1	1.2	Zpl2 – Slg2	1.9

Turnaround time

The turn-around time in Rcs was set at 2.5 minutes, a value derived from AVL data. It is neither the average nor the planned value of turn-around in Rotterdam Centraal Station, but a *minimum* value found via the AVL file of the disruption of May 18th. In times of disruption, in the studied trunk, where the amount of trains riding southbound depends mostly on the amount of trains riding northbound, this assumption makes sense.

Additional occupation time
In the model, a stop can be seized as soon as the previous train has let the stop. This is not true for the bottleneck stop, Mhv2, where, for instance, trains running northbound cannot even cross the switch (as shown in Appendix Figure 1 in Appendix D) as long as a train going southbound has not crossed it. Therefore, some additional occupation times are implemented in the model. They are based on the difference between the occupations times shown in Appendix Table 6: 1.8 minutes northbound and 1.5 minutes southbound.

2. <u>Verification and validation of the model</u>

Before implementing alternative scenarios, it is necessary to know:

- If the model meets the specifications, i.e. if it does indeed simulate AVL data. The **verification** step is meant to see if the model is built in the right way.
- If the model is an accurate representation of the real system, and, if not, how it behaves and distorts reality. The **validation** step is usually achieved through the calibration of the model, an iterative process where discrepancies between the actual system behaviour and the model outputs provide insights on how to improve the model. This process ends when accuracy is judged to be acceptable.

To verify and validate the model, Scenario 1, i.e. the situation on May 18th, is implemented in ARENA.

Verification of the model
This step is rather straightforward; a first run of the model shows that the right kind of data is simulated, that every train follows the path it has been set to follow and that no stop – or resource – is used by more than one train at a time. As expected, Mhv2 is the busiest resource.

Validation of the model
It is suggested that the accuracy of the model is deemed acceptable once the sequence and the amount of trains passing through the bottleneck (at stop Mhv2) between 07:53 and 08:43, is similar to what happened on May 18th in the same time frame.

First, the situation that happened on May 18th was implemented without any holding measure, since it was barely mentioned by dispatchers in the questionnaire and barely seen by author during the time spent at the traffic control centre. Therefore, in the model, the first train that would claim the bottleneck stop, Mhv2, would always go first. The desired sequence was not obtained though.

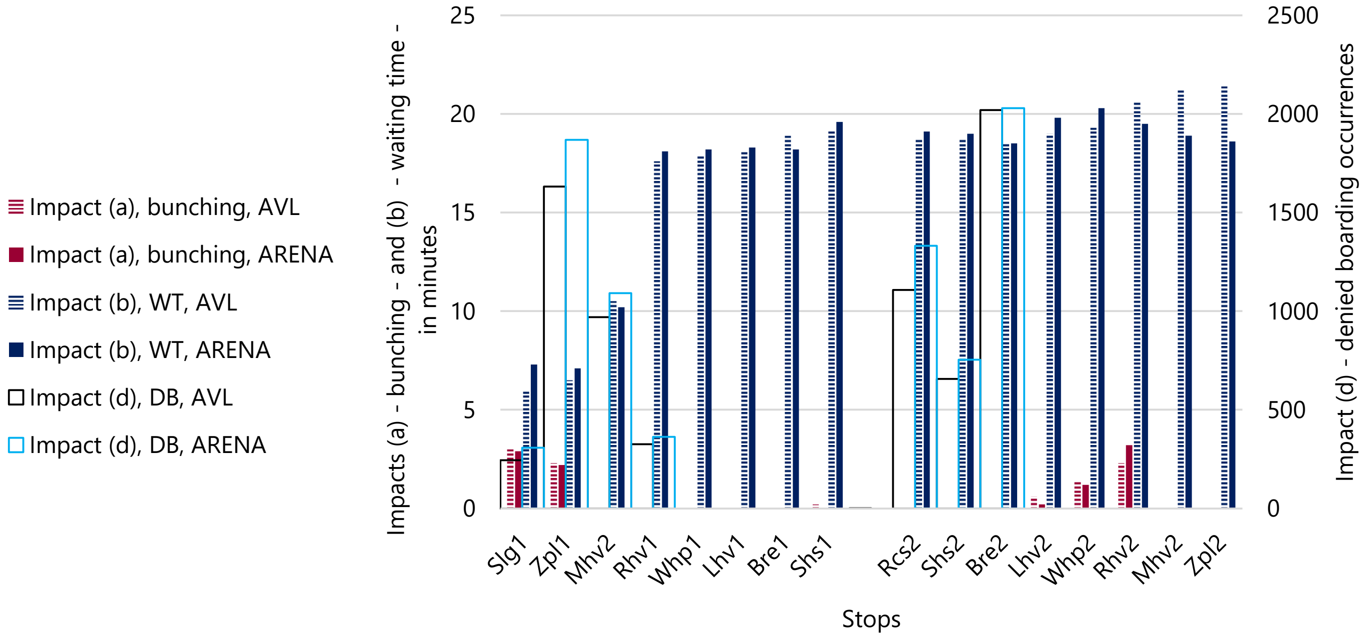
Then, holding was implemented on a few trains. The model does not allow for any kind of optimisation, therefore it was first necessary to determine which trains were held, and then to implement holding times for each specific train at each specific stop manually. With the time-space diagram in Figure 4-10 page 62 a few candidates were selected in stops upstream of the bottleneck. After a few trials, it became clear that holding is in fact only applied in Zpl1 and Rhv2, i.e. the stops right upstream of the bottleneck. The dwell time extensions in Whp2 and Lhv2 are due to bunching, that results partly from the holding applied in Rhv2. With the holding times shown in Appendix Table 14, the desired accuracy was reached: the model is able to simulate the same sequence of trains than

May 18th. There is a 1.5-minute offset in the end but the last train still fits in the single-track operations time window and for a 62-minute simulation, it is not deemed too severe.

Appendix Table 14: Holding times & corresponding stops and trains.

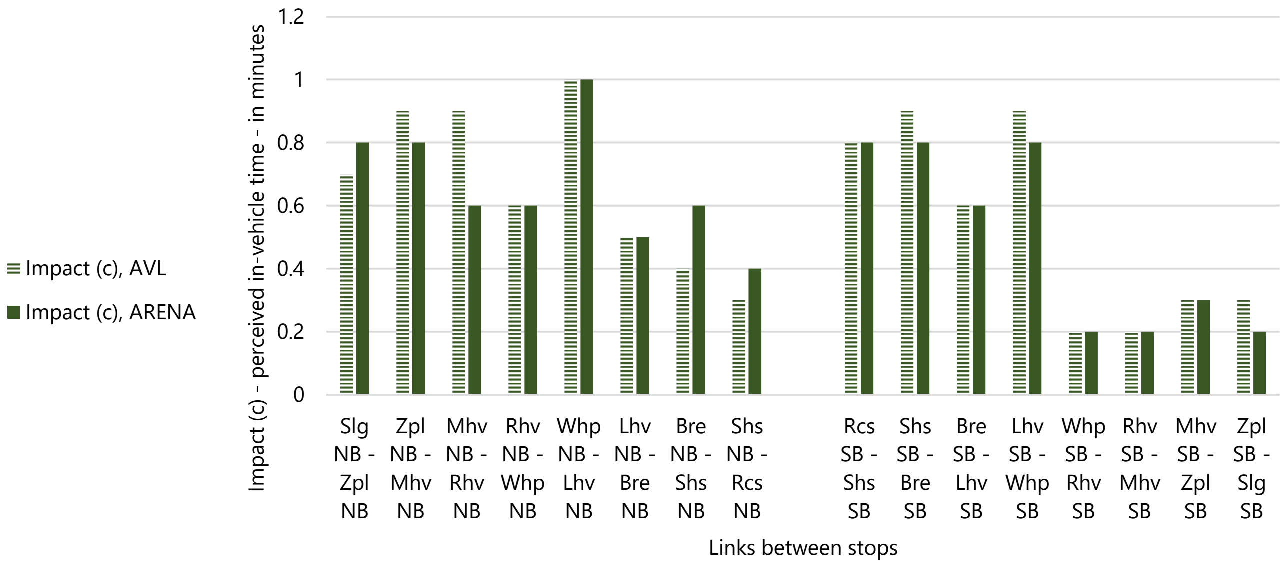
Train number	Stop	Holding time (in minutes)
52	Zpl NB	3.5
58		4
39	Rhv SB	3.5
59		5
61		5

Now that the desired accuracy is reached, the model is validated. However, a missing piece of information is the behaviour of the model in general: what does it over- or underestimate? To obtain this, the simulated AVL dataset is assessed through the local-scale assessment framework developed in Chapter 3 and results are compared with the ones of Scenario 1.
Appendix Figure 6 compares impacts (a), (b) and (d) per stop while Appendix Figure 7 compares impact (c). Impact (e) remains relatively unchanged in terms of impact per passenger, hence it is not displayed here. Appendix Table 15 summarises the additional generalised costs (AGC).



Appendix Figure 6: Comparison of additional bunching times, additional waiting times and denied boarding occurrences as derived from AVL data of May 18th and simulated AVL data, for model validation purposes.

Overall, results are satisfying. Impact (a) is comparable and differences are smaller than a minute. The model was not able to reproduce the bunching effect in Shs NB, but it was only 0.2 minutes per vehicle. The variations observed for impact (b) can be attributed to headway distributions that vary. Denied boarding occurrences are systematically overestimated though. Impact (c), in Appendix Figure 7, is comparable. This can be explained by the fact that it is based on the load factor, and that the highest load factors are often reached between certain stops, both in the model and in reality.



Appendix Figure 7: Comparison of additional perceived in-vehicle time between stops, as derived from AVL data of May 18th and simulated AVL data, for model validation purposes.

Appendix Table 15 shows that the simulation overestimates AGC. This is mostly due to the overestimation in denied boarding.

Appendix Table 15: Comparison of the local-scale assessment final results – additional generalised costs (AGC) – between the reality and the implementation in the model.

	AGC in K€ for Scenario 1, with AVL data from May 18th	**AGC in K€ for Scenario 1, with simulated data, to replicate operations of May 18th**
Northbound	21.9	23.2
Southbound	34.6	35.9
AGC	56.5	59.1

In addition, recall that in the simulation, initial trains can only be injected as arriving at a stop. Yet, train 59 is between Bre2 and Lhv2 at 07:53 (see the time-space diagram in in Figure 4-10 page 62). As mentioned in Appendix Table 11, it was implemented by default as arriving in Brs2. It was decided to see whether results would vary, should train 59 start at Lhv2 instead. No change was found, both when holding was not and was implemented. Since there was not any other ambiguous situation, no other check was conducted.

As a conclusion, the simulation developed in ARENA reproduces reality rather accurately. Still, it is recommended to interpret simulation results with caution, keeping in mind that denied boarding costs in particular may be slightly overestimated.

Appendix I Details on the generated scenarios

This appendix gives some additional details on the generated scenarios.

1. Scenario 3

The assumptions for **Scenario 3** in ARENA are:

- No holding upstream of the bottleneck,
- D line trains coming from Aks have a minimum dwell time of 1 minute in Slg.

2. Scenarios 5: determination of trains to short-turn

In Scenarios 5, various short-turnings are investigated.
Recall that in Scenario 3, no train was short-turned, creating queues of three vehicles in Slinge – which is unrealistic. Therefore, it is argued that the two trains that should be selected for short-turning should be part of a 3-vehicle queue and leave relatively small gaps in headways. The gap in headway can be calculated by adding up two headways: the on with the preceding train and the one with the following train. Appendix Table 16 shows each of these trains with the headway gap they would leave if they were short-turned.

Appendix Table 16: Candidate vehicles for short-turning.

First 3-vehicle queue in Slg			
Train number	49	43	62
Hypothetical gap in headway	5.4 min, but too early to be short-turned on time	3.9 min	14.6 min
Second 3-vehicle queue in Slg			
Train number	62	52	63
Hypothetical gap in headway	14.6 min	13.7 min	8.8 min
Third 3-vehicle queue in Slg			
Train number	64	58	47
Hypothetical gap in headway	8.7 min	8.3 min	8.2 min

Dispatchers decided to short-turn trains 62 and 45. The latter is not displayed in Appendix Table 16 because it was not part of a 3-vehicle queue in Scenario 3, but short-turning it left a headway gap of 9.8 min. Train 45 arrived in Slg between train 63 and train 64.
In **Scenario 5a**, the two trains from Appendix Table 16 that would leave the smallest gaps in headways in Slg are short-turned: train 43 and train 47.
In **Scenario 5b**, the same criteria than for Scenario 5a is applied, but this time considering the two first queues only. This is therefore an "early short-turnings" strategy. Trains 43 and 63 are short-turned.

3. Scenario 6: holding times

In **Scenario 6a**, holding for regularity purposes is applied. The holding times are given in Appendix Table 17. Explanations are also provided.

- Train 61 starts at Zpl NB at the beginning of the simulation. It is not being held northbound because it needs to fill the gap created by the blockage as soon as possible. However, it is held southbound one minute from Rcs SB to Rhv SB to avoid the long bunching in Rhv SB.
- In Scenario 6a, train 49 is the train that directly follows train 61. Therefore, it should follow it relatively closely until it has crossed the bottleneck, so that capacity in the bottleneck is used efficiently. After the bottleneck, holding this train is beneficial because **the next train to come in this direction will be relatively long after since the single track in the bottleneck will first be used in the other direction**. Once train 49 heads southbound, it is not held since it needs to follow train 61 close enough to, again, use bottleneck capacity efficiently.
- Train 43 is held for 3 minutes in Slinge and no longer like dispatchers did on May 18th.
- Train 52 directly follows train 43. This time, the choice was made to hold it when it heads southbound.
- Since trains 63 and 58 have to wait to cross the bottleneck, **their waiting time is spread** between Slg and Zpl.
- Trains 39, 59 and 51 are heading southbound at the beginning of the blockage. Instead of letting them bunching in Rhv or upfront, their bunching time is spread. This is particularly important for train 51 since next train heading southbound comes long after. In real-time, this could have been forecasted: two trains are blocked and E line trains are short-turned in Rcs, therefore a large gap in headway can be expected at southbound stops at the beginning of the blockage.

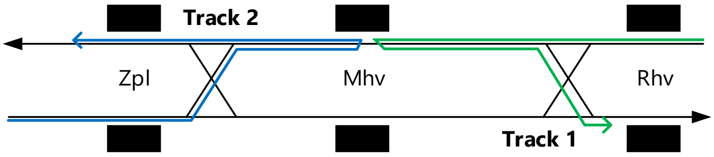
Stop	**Train number**								
	61	**49**	**43**	**52**	**63**	**58**	**39**	**59**	**51**
Slg NB	-		3		3	1.5	-	-	-
Zpl NB					0.5	1.5	-	-	-
Mhv NB							-	-	-
Rhv NB		1		1			-	-	-
Whp NB		1					-	-	-
Lhv NB		1					-	-	-
Bre NB		1					-	-	-
Shs NB		1					-	-	-
Rcs SB	1			1			-	-	4.5
Shs SB	1			0.5			-	-	2.5
Bre SB	1			0.5			-	-	2.5
Lhv SB	1			0.5			-	5.5	2.5
Whp SB	1			0.5			-	5.5	
Rhv SB	1						5	4	
Mhv SB									
Zpl SB									

Appendix Table 17: Holding times for trains in Scenario 6a. Holding times in Scenario 6b are based on the same reasoning and are therefore relatively similar.

4. <u>Scenarios 7</u>

Two scenarios with short-turning as the only measure are investigated, as alternatives to the scenarios based on single-track operations and short-turning where a third track is available **only**. As mentioned page 69, the same technique than developed in Appendix D is used to estimate capacity on a 50-minute basis first and, if capacity reaches at least 7 trains, a manual optimisation using a time-space diagram can be used.

First, **Scenario 7a** investigates the short-turning of trains in Mhv2, i.e. the undisrupted track in station Mhv; see Appendix Figure 8. The occupation times displayed in Appendix Table 18 are used to compute the maximum capacity.



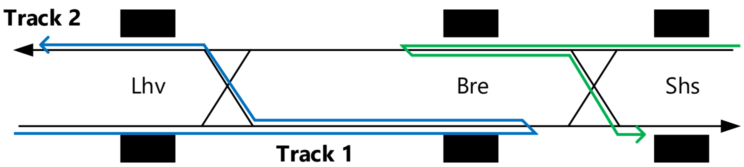
Appendix Figure 8: Short-turning of trains in Mhv, track 2.

7 trains in each direction would yield an occupancy rate of 140%; therefore, Scenario 7a is not a viable option. This is mostly due to the amount of time needed to turn a vehicle: the passengers need to be informed, track safety needs to be activated, the driver needs to leave his/her cabin and go to the other side of the train, and once he/she is in position to drive in the opposite direction, he/she needs to make sure that all passengers in the train have the right destination.

Appendix Table 18: Occupation times for short-turned trains in Mhv2 (Scenario 7a) (Both, 2015; Van Ravels, 2016).

	Rcs – Mhv2 – Rcs loop	**Slg – Mhv2 – Slg loop**
Switches	0.5 min	-
Approach time (from switches to Mhv2)	1.7 min	1 min
Usual dwell time in Mhv	0.8 min	0.5 min
Additional dwell time (to turn the train)	1.5 min	1.5 min
Switches	-	0.5 min
Total occupation time	**5 min**	**4 min**

Scenario 7b investigates the short-turning of trains in Bre, as displayed in Appendix Figure 9. The occupation times are shown in Appendix Table 19. This time, since track are only shared between trains that share a similar route, there are two occupation rates. 9 trains on both sides would yield an occupation rate of 86% for loop 1 (coming from Lhv) and 83% for loop 2 (coming from Shs). Since the trains coming from Slg also need to cross the bottleneck in Mhv2, it is reasonable to assume that 8 trains would be enough in that direction.

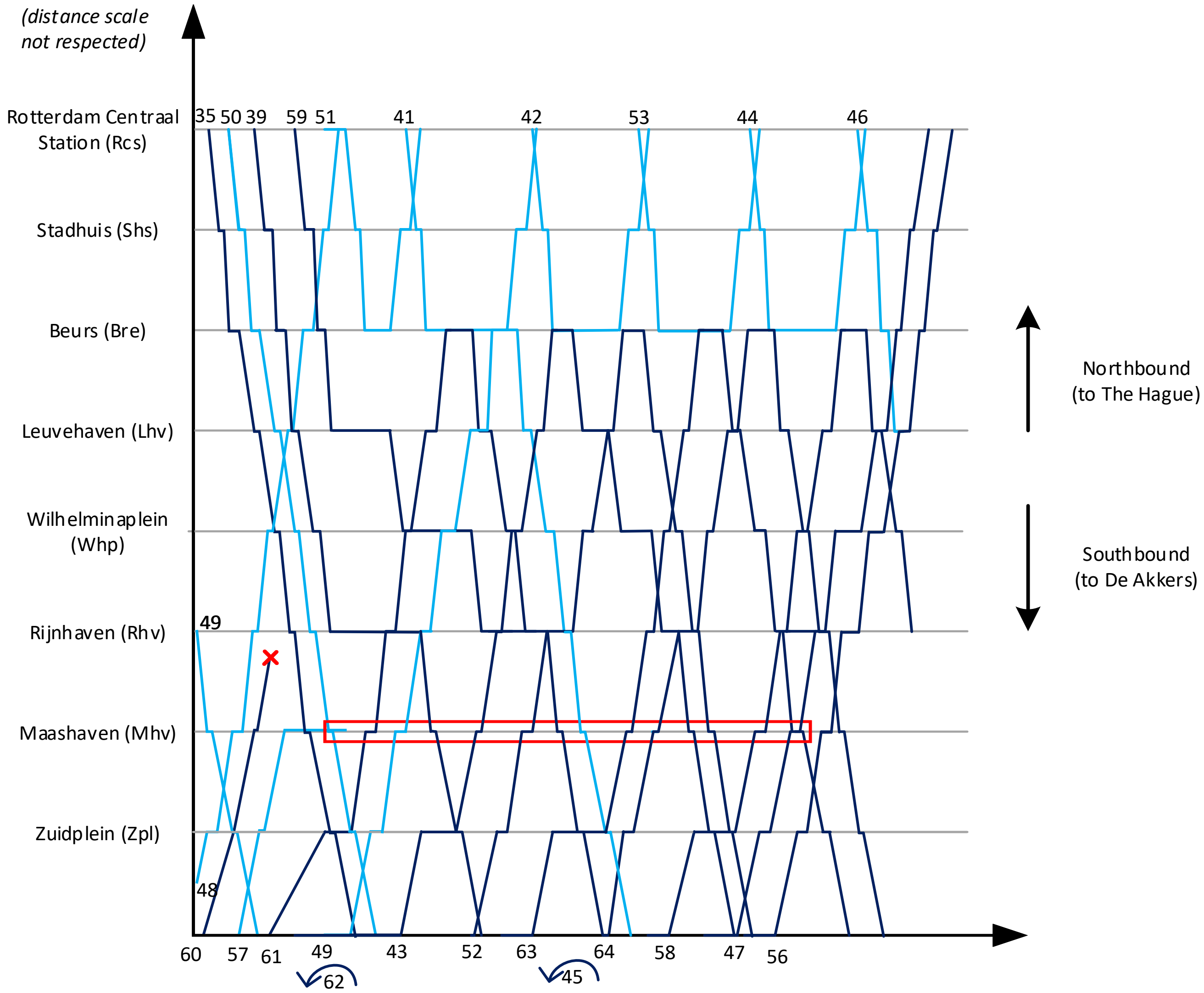


Appendix Figure 9: Short-turning of trains in Bre.

Appendix Table 19: Occupation times for short-turned trains in Bre (Scenario 7b) (Both, 2015; Van Ravels, 2016).

	Loop 1: Lhv – Bre1 – Lhv loop	**Loop 2: Shs – Bre – Shs loop**
Approach time (from switches to Bre)	0.9 min	0.8 min
Usual dwell time in Bre	0.8 min	0.9 min
Additional dwell time (to turn the train)	1.5 min	1.5 min
Switches	0.5 min	0.5 min
Departure	1 min	0.9 min
Total occupation time	**4.8 min**	**4.6 min**

A time-space diagram is then manually built; it stands in Appendix Figure 10. The regular headway pattern of line E coming from the E line branch (northern of Rcs) is clearly visible. These trains are being held longer than needed in Bre to allow for as many passengers as possible to board, however, there is just not enough capacity on this side. The same sequence of trains in Mhv than the one used for Scenarios 4c, 6a and 6b is used.



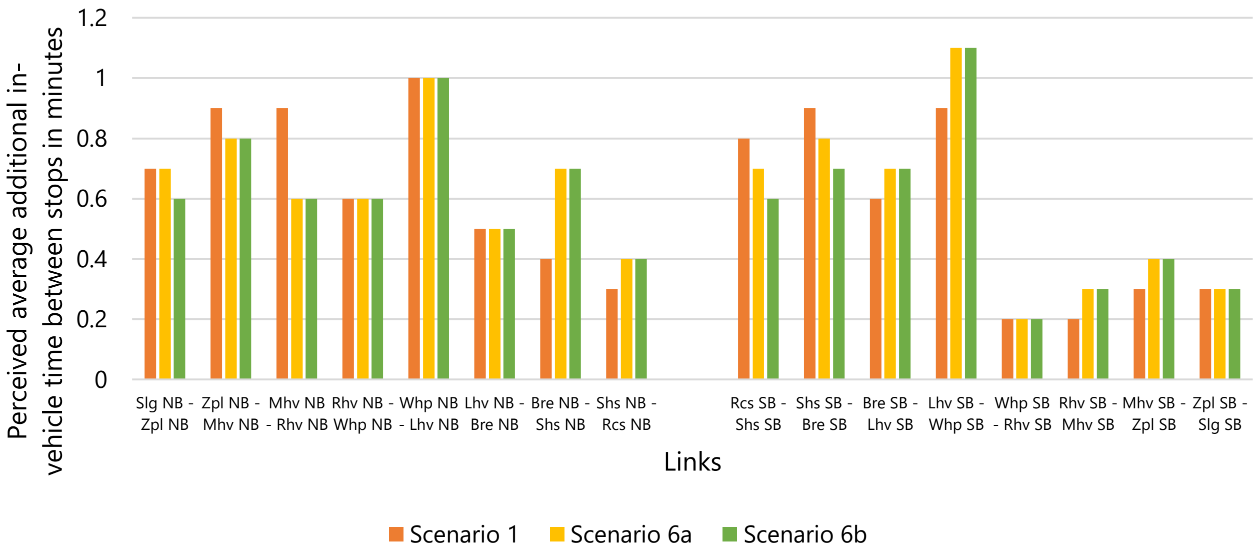
Appendix Figure 10: Time-space diagram of Scenario 7b.

Appendix J Results of the assessment

This appendix provides some material that comes as an illustration/justifications of multiple texts in Chapter 5.

1. Local-scale assessment: Additional perceived in-vehicle time

Appendix Figure 11 shows the average additional perceived in-vehicle time between stops for Scenarios 1, 6a and 6b compared to the reference day. As discussed page 72 , the values of impact (c) do not significantly differ across scenarios, but they demonstrate that the portion between Rcs SB and Whp SB is a busy one, hence the southbound direction ought not to be neglected.



Appendix Figure 11: Average additional perceived in-vehicle time between stops compared to the reference day, for Scenarios 1, 6a and 6b.

2. Local-scale assessment: comparison of performances at the OD-pair level

The tables in this section accompany the text in sub-section 5.1.4, page 74. Some of the tables in page 74 are also here, to allow the reader to easily compare different scenarios. The same conditional formatting is applied for all tables.

	S	Slg	Zpl	Mhv	Rhv	Whp	Lhv	Bre	Shs	Rcs	N
S	0,0	0,0	0,9	*1,3*	*1,4*	*1,5*	*1,6*	*1,7*	*1,7*	*1,8*	*3,0*
Slg	0,0	0,0	1,5	*1,9*	*2,0*	*2,0*	*2,2*	*2,2*	*2,3*	*2,3*	*3,6*
Zpl	4,5	4,5	0,0	*3,0*	*3,1*	*3,2*	*3,3*	*3,4*	*3,4*	*3,5*	*4,7*
Mhv	4,5	4,5	4,5	0,0	*6,1*	*6,2*	*6,3*	*6,4*	*6,5*	*6,5*	*7,8*
Rhv	4,4	4,4	4,4	4,3	0,0	8,6	8,7	8,8	8,9	8,9	10,2
Whp	4,5	4,5	4,4	4,4	4,1	0,0	3,9	3,9	4,0	4,0	5,3
Lhv	4,7	4,7	4,6	4,6	4,3	4,1	0,0	3,9	3,9	4,0	5,2
Bre	11,2	11,2	11,1	11,1	10,8	10,6	10,4	0,0	4,0	4,1	5,3
Shs	11,2	11,2	11,2	11,1	10,8	10,6	10,4	10,4	0,0	4,0	5,3
Rcs	6,7	6,7	6,7	6,7	6,4	6,2	6,0	5,9	5,8	0,0	0,0
N	6,7	6,7	6,7	6,6	6,3	6,1	5,9	5,9	5,7	0,0	0,0

Appendix Table 20: Additional generalised costs in euros in Scenario 1 per OD pair.

Appendix Table 21: Additional generalised costs in euros in Scenario 1 per OD pair.

	S	Slg	Zpl	Mhv	Rhv	Whp	Lhv	Bre	Shs	Rcs	N
S	0	0	275	59	60	381	185	578	413	557	226
Slg	0	0	66	33	22	166	126	629	207	360	186
Zpl	498	54	0	48	115	532	433	**1718**	615	1023	586
Mhv	127	136	143	0	61	274	165	1339	504	893	404
Rhv	66	133	315	65	0	112	140	951	248	526	234
Whp	89	45	102	35	8	0	54	335	96	405	206
Lhv	33	37	60	23	4	94	0	23	23	83	52
Bre	569	1440	3471	898	366	**5830**	603	0	1525	1866	1580
Shs	347	314	648	200	87	1456	219	1089	0	73	132
Rcs	337	451	911	280	114	2844	328	1197	127	0	0
N	181	294	626	146	88	1418	533	4454	695	0	0

	S	Slg	Zpl	Mhv	Rhv	Whp	Lhv	Bre	Shs	Rcs	N
S	0.0	0.0	0.8	1.1	1.2	1.2	1.4	1.4	1.5	1.6	2.8
Slg	0.0	0.0	1.5	1.8	1.8	1.9	2.0	2.1	2.2	2.2	3.5
Zpl	3.7	3.7	0.0	2.5	2.5	2.6	2.7	2.8	2.9	3.0	4.2
Mhv	3.8	3.8	3.8	0.0	6.7	6.7	6.9	6.9	7.0	7.1	8.3
Rhv	4.1	4.1	4.1	4.0	0.0	8.7	8.8	8.9	9.0	9.0	10.3
Whp	4.4	4.4	4.4	4.4	3.9	0.0	3.5	3.6	3.6	3.7	5.0
Lhv	4.7	4.7	4.6	4.6	4.1	3.9	0.0	3.5	3.5	3.6	4.9
Bre	10.2	10.2	10.2	10.1	9.7	9.4	9.3	0.0	3.5	3.5	4.8
Shs	9.6	9.6	9.6	9.6	9.1	8.8	8.7	8.6	0.0	3.7	4.9
Rcs	5.9	5.9	5.9	5.8	5.4	5.1	5.0	4.9	4.8	0.0	0.0
N	5.8	5.8	5.8	5.8	5.3	5.1	4.9	4.8	4.7	0.0	0.0

Appendix Table 22: Additional generalised costs in euros in Scenario 4c per OD pair and per passenger.

Appendix Table 23: Additional generalised costs in euros in Scenario 4c per OD pair

	S	Slg	Zpl	Mhv	Rhv	Whp	Lhv	Bre	Shs	Rcs	N
S	0	0	242	50	50	321	158	497	366	495	211
Slg	0	0	66	32	20	155	118	592	199	346	182
Zpl	404	44	0	40	94	438	359	1431	521	868	521
Mhv	107	115	122	0	67	297	179	1448	547	970	433
Rhv	61	122	292	60	0	113	141	958	251	532	236
Whp	89	44	101	35	8	0	49	303	88	371	193
Lhv	33	37	60	23	4	89	0	21	21	76	49
Bre	521	1318	3181	822	329	5197	537	0	1316	1614	1416
Shs	299	270	557	172	73	1211	182	902	0	67	124
Rcs	296	396	801	245	97	2369	272	991	105	0	0
N	158	257	547	127	74	1172	439	3656	569	0	0

	S	Slg	Zpl	Mhv	Rhv	Whp	Lhv	Bre	Shs	Rcs	N
S	0.0	0.0	0.7	1.0	1.0	1.1	1.3	1.3	1.4	1.5	2.8
Slg	0.0	0.0	1.4	1.6	1.7	1.8	2.0	2.0	2.1	2.2	3.4
Zpl	4.0	4.0	0.0	2.6	2.7	2.8	2.9	3.0	3.1	3.2	4.4
Mhv	4.2	4.2	4.2	0.0	6.4	6.5	6.6	6.7	6.8	6.9	8.1
Rhv	4.5	4.5	4.4	4.4	0.0	8.6	8.7	8.8	8.9	9.0	10.2
Whp	4.3	4.3	4.3	4.2	3.9	0.0	3.4	3.5	3.6	3.7	4.9
Lhv	4.5	4.5	4.4	4.4	4.0	3.9	0.0	3.3	3.4	3.5	4.7
Bre	8.9	8.9	8.9	8.8	8.5	8.3	8.0	0.0	3.3	3.4	4.7
Shs	7.7	7.7	7.7	7.6	7.3	7.1	6.8	6.7	0.0	3.6	4.9
Rcs	5.3	5.3	5.2	5.2	4.8	4.7	4.4	4.3	4.1	0.0	0.0
N	5.2	5.2	5.2	5.1	4.8	4.6	4.3	4.2	4.0	0.0	0.0

Appendix Table 24: Additional generalised costs in euros in Scenario 6a per OD pair.

Appendix Table 25: Additional generalised costs in euros in Scenario 6a per OD pair.

	S	Slg	Zpl	Mhv	Rhv	Whp	Lhv	Bre	Shs	Rcs	N
S	0	0	214	44	44	291	146	465	346	474	206
Slg	0	0	62	30	19	147	113	572	193	339	179
Zpl	442	48	0	42	100	466	383	1530	558	933	548
Mhv	117	126	133	0	64	286	173	1405	532	944	423
Rhv	67	134	318	65	0	112	139	949	249	529	235
Whp	87	43	99	34	8	0	48	297	86	366	191
Lhv	31	36	58	22	4	89	0	20	20	73	47
Bre	454	1148	2764	713	287	4576	466	0	1268	1562	1383
Shs	239	215	444	137	58	973	143	703	0	65	121
Rcs	264	353	712	217	87	2163	243	868	91	0	0
N	140	229	485	112	67	1068	390	3194	490	0	0

	S	Slg	Zpl	Mhv	Rhv	Whp	Lhv	Bre	Shs	Rcs	N
S	0,0	0,0	0,7	0,9	1,0	1,1	1,2	1,3	1,4	1,5	2,7
Slg	0,0	0,0	1,3	1,6	1,7	1,8	1,9	2,0	2,1	2,1	3,4
Zpl	2,8	2,8	0,0	2,5	2,6	2,7	2,8	2,9	3,0	3,1	4,3
Mhv	3,0	3,0	3,0	0,0	6,2	6,3	6,4	6,5	6,6	6,7	7,9
Rhv	3,3	3,3	3,3	3,2	0,0	8,1	8,2	8,3	8,4	8,5	9,7
Whp	3,1	3,1	3,0	2,9	2,6	0,0	3,3	3,4	3,5	3,6	4,8
Lhv	3,3	3,3	3,2	3,2	2,8	2,6	0,0	3,3	3,4	3,5	4,7
Bre	4,9	4,9	4,9	4,8	4,5	4,2	4,0	0,0	3,3	3,4	4,6
Shs	4,3	4,3	4,2	4,1	3,8	3,6	3,3	3,2	0,0	3,5	4,7
Rcs	3,7	3,7	3,6	3,6	3,2	3,0	2,7	2,6	2,4	0,0	0,0
N	3,8	3,8	3,8	3,7	3,4	3,1	2,9	2,7	2,6	0,0	0,0

Appendix Table 26: Additional generalised costs in euros in Scenario 6b per OD pair and per passenger.

Appendix Table 27: Additional generalised costs in euros in Scenario 6b per OD pair

	S	Slg	Zpl	Mhv	Rhv	Whp	Lhv	Bre	Shs	Rcs	N
S	0	0	208	42	43	283	142	454	339	468	205
Slg	0	0	60	28	18	142	109	553	187	330	176
Zpl	311	34	0	40	96	448	369	**1475**	538	905	536
Mhv	85	91	96	0	62	278	168	1362	516	918	413
Rhv	50	99	236	48	0	105	132	897	235	501	224
Whp	61	31	70	24	5	0	46	288	84	357	188
Lhv	23	26	42	16	3	60	0	20	20	73	47
Bre	251	634	1521	389	152	**2333**	229	0	1252	1548	1374
Shs	132	119	245	75	30	490	69	332	0	63	118
Rcs	183	245	493	149	58	1379	149	521	53	0	0
N	103	168	356	82	47	731	258	2078	314	0	0

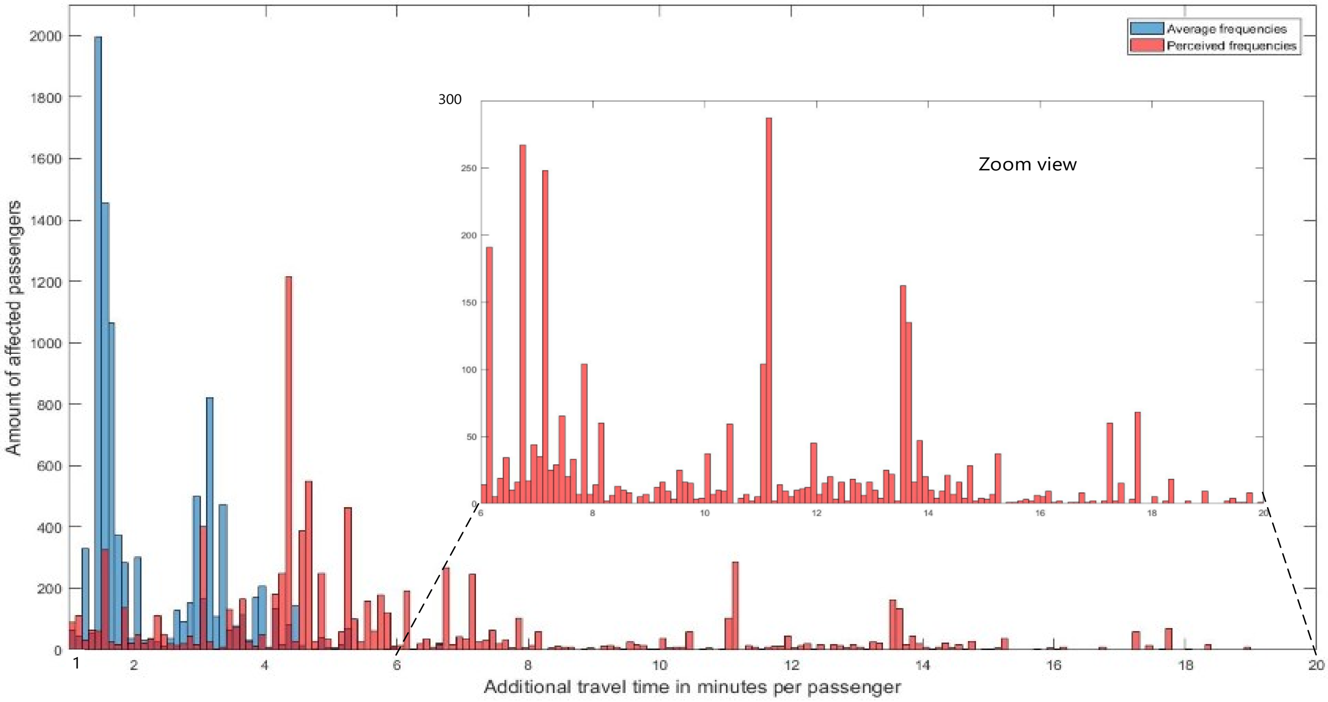
3. **<u>Global-scale assessment: average versus perceived frequencies</u>**

Appendix Table 28 and Appendix Figure 12 compare the results of the global-scale assessment with average frequencies and with perceived frequencies. A few remarks can be made:

- The assignment with *average* frequencies yields questionable ATTs. This is partly caused by OV-Lite not taking into account irregularities, i.e. the existence of large headways during which a large amount of passengers will have to wait for a long time. This leads to a probable underestimation of ATTs: for instance, 1.4 minutes for Zpl-Rcs is low with regards to the local-scale assessment, where an AWT of 6.5 minutes was found in Zpl NB in Scenario 1. In addition, given the time-space diagram in Figure 4-10 page 62 and the assumption of uniform distribution of passengers, 1.4 min seem low while 4.3 min (see Appendix Table 28), seem more realistic.
- In both cases, around 30% of all passengers on the RET network during 1 hour of the AM peak are affected with at least one minute of ATT. This is why the x-axis of Appendix Figure 12 starts at 1 minute: in both cases, a large share of passengers experience less than 1 minute of ATT. Thus, the same amount of passengers experience a greatest inconvenience when perceived frequencies are used. The ATT of passengers with perceived frequencies is spread up until 28.4 minutes (see Appendix Table 28) with a peak around 4.5 minutes (see Appendix Figure 12) while, for average frequencies, the peak is around 1.5 minutes and the maximum ATT is 7.5 minutes.
- Yet even with perceived frequencies, the AGC are low compared to the AGC values for the local-scale assessment, whereas more passengers are taken into account in the global-scale assessment and transfer penalties are probably overestimated (see Appendix G). This may be due to:
    - Comfort and crowding not being taken into account. It means no bunching, no denied boarding, no additional perceived in-vehicle time. Together, they account for 47% of AGC in Scenario 1 for the local-scale assessment.
    - The values of time, the waiting time weight and transfer penalties were kept unchanged in OV-Lite because the model was calibrated with them, but the ones chosen for the local-scale assessment are systematically higher (e.g. 6€/h for the VoT in OV-Lite versus 7.4 €/h).
    - Passengers may re-route in the global-scale assessment: they may have found a cheaper way to reach their destination than travelling with the metro between Slg and Rcs.

Appendix Table 28: Comparison between the results of the global-scale assessment with average and perceived frequencies.

<table>
<tr><th></th><th colspan="4">Average frequencies</th><th colspan="4">Perceived frequencies</th></tr>
<tr><th rowspan="2">OD pair with max ATT per passenger</th><th>OD pair</th><th># pass.</th><th colspan="2">Add. TT</th><th>OD pair</th><th># pass.</th><th colspan="2">Add. TT</th></tr>
<tr><td>Mltw-Ald</td><td>1</td><td colspan="2">7.5 min</td><td>Mltw-Zpl</td><td>6</td><td colspan="2">28.4 min</td></tr>
<tr><th rowspan="4">Top 3 OD pair with <u>max</u> total ATT</th><th>OD pair</th><th># pass</th><th>Total ATT</th><th>ATT per pass.</th><th>OD pair</th><th># pass</th><th>Total ATT</th><th>ATT per pass.</th></tr>
<tr><td>Rcs-Whp</td><td>538</td><td>14 hours</td><td>1.6 min</td><td>Rcs-Whp</td><td>538</td><td>39 hours</td><td>4.3 min</td></tr>
<tr><td>Spc-Rcs</td><td>108</td><td>5.3 hours</td><td>3 min</td><td>Spc-Rcs</td><td>108</td><td>19.9 hours</td><td>11.1 min</td></tr>
<tr><td>Zpl-Rcs</td><td>208</td><td>5 hours</td><td>1.4 min</td><td>Spc-Whp</td><td>69</td><td>15.6 hours</td><td>13.5 min</td></tr>
<tr><th>ATT (impact (f))</th><td colspan="4">439 hours</td><td colspan="4">1160 hours</td></tr>
<tr><th>AGC</th><td colspan="4">€4,630</td><td colspan="4">€11,380</td></tr>
</table>



Appendix Figure 12: Affected passengers and additional travel time per passenger in the Base Scenario compared to the reference day

4. Global-scale assessment: Assumptions to compute estimates of lateness

The analysis of global-scale assessments results follows the structure suggested in sub-section 3.4.4, page 51. The estimates of lateness are computed with the following assumptions:

- For missed train connections in Rotterdam Centraal: 62% of people alighting from the RET network in Rcs have a train connection. This was found by comparing the numbers of alightings in Rcs to the ones at a comparable station with no train transfer (Stadhuis), and attributing the difference to train connection (Yap, 2016). They plan on average 8 minutes of buffer time, i.e. above 8 minutes of delay in the RET network, they miss their train connection (Schakenbos et al., 2016).
- For late arrivals at work/school: 82% of the morning peak passengers go to work/school (see Figure 4-4 page 56, assuming the same trip purpose distribution for tram and bus). They plan on average 8 minutes of buffer time (educated guess, based on the transfer time mentioned above).

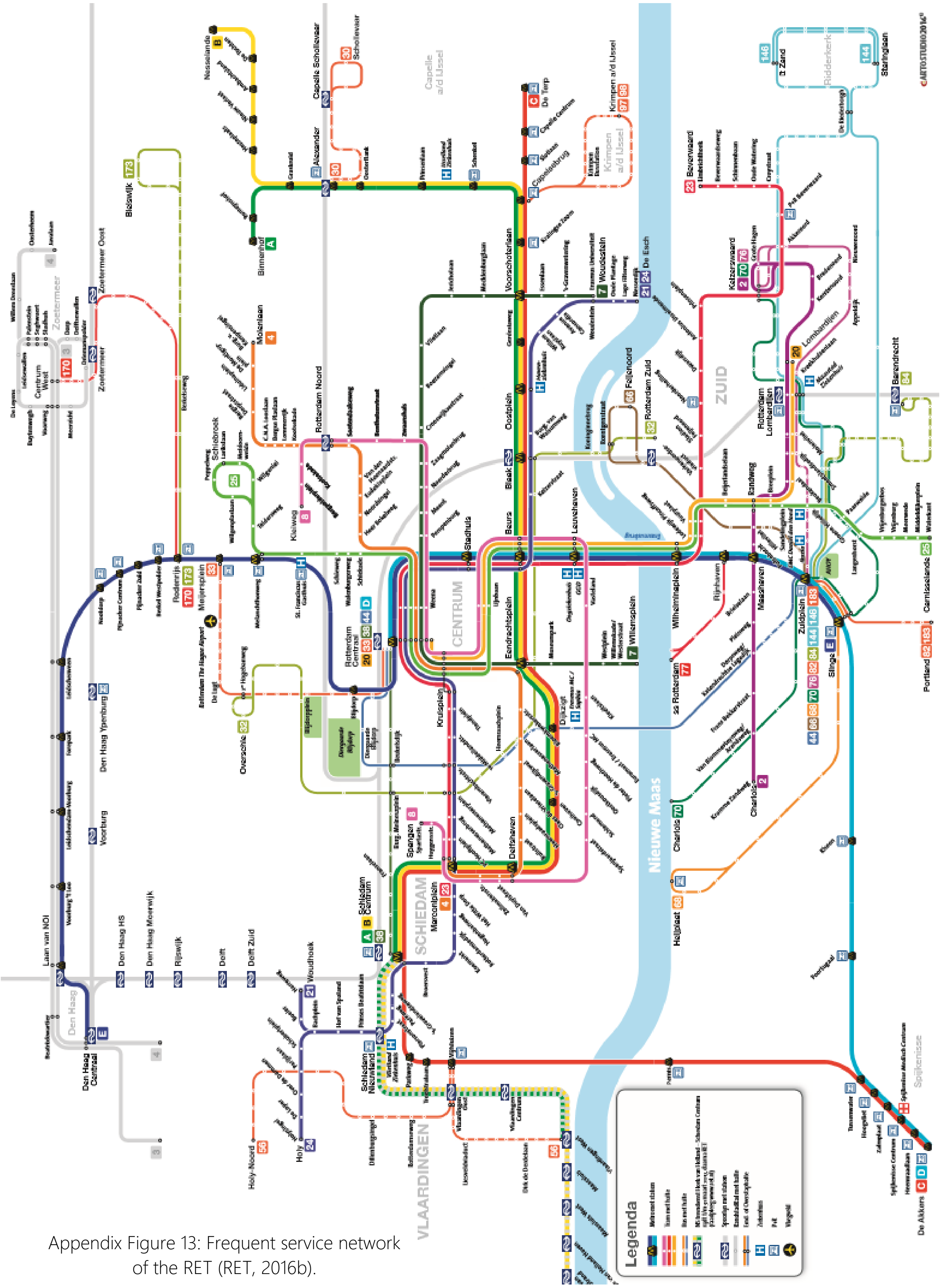
Appendix K List of interviewees for the validation of the results

This appendix provides the list of the RET employees who commented on the results of the model.

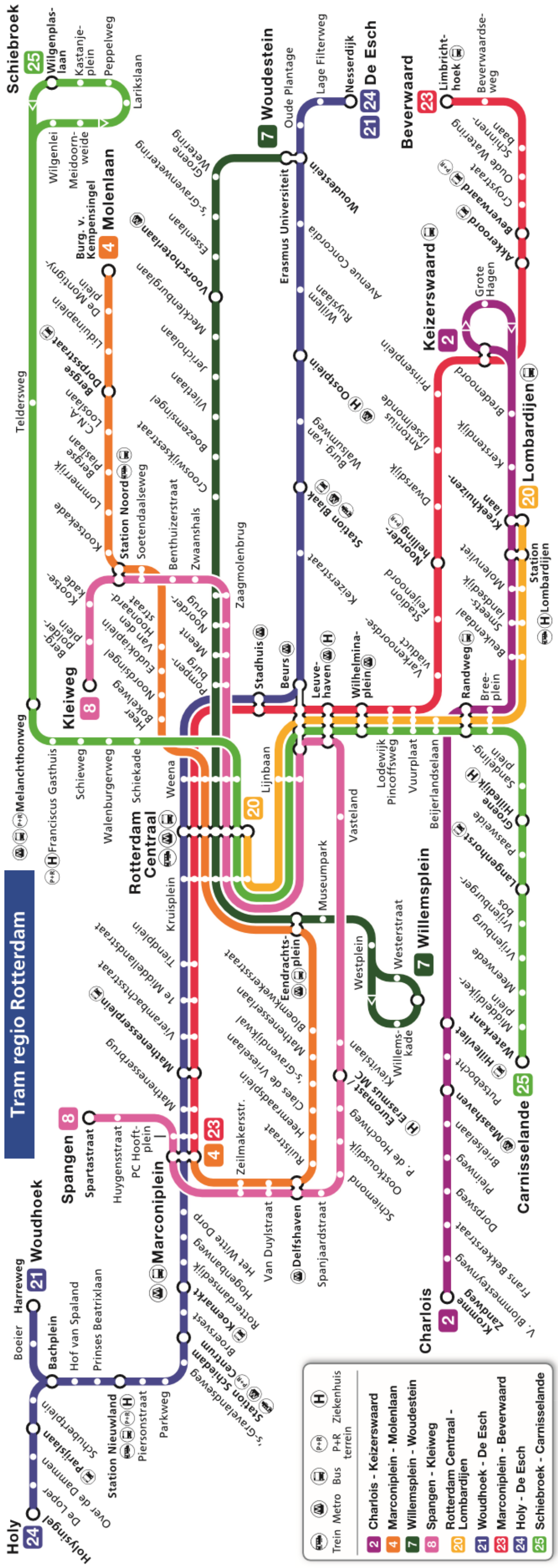
- E. Roukema, process manager in charge of disruptions.
- M. Westerweele, metro planner.
- R. Both, data analyst.
- J. Henstra, senior strategic planner.
- T. Deijl, metro traffic controller.
- K. Franken, metro traffic controller.
- M. Oerlemans, metro traffic controller.

Note that the interviewed traffic controllers were the ones with whom the communication in English was the easiest, which may lead to a bias; all of them have been working at the RET for less than 10 years, while some dispatchers have been working at the RET for more than 30 years. However, they managed to give insights on how their colleagues might react to the results of the assessment framework and their consequences.

Appendix L Frequent service network of the RET

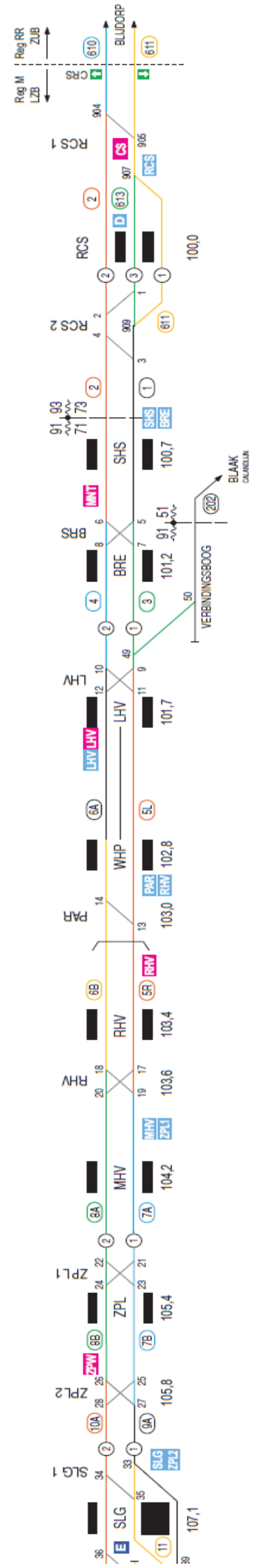


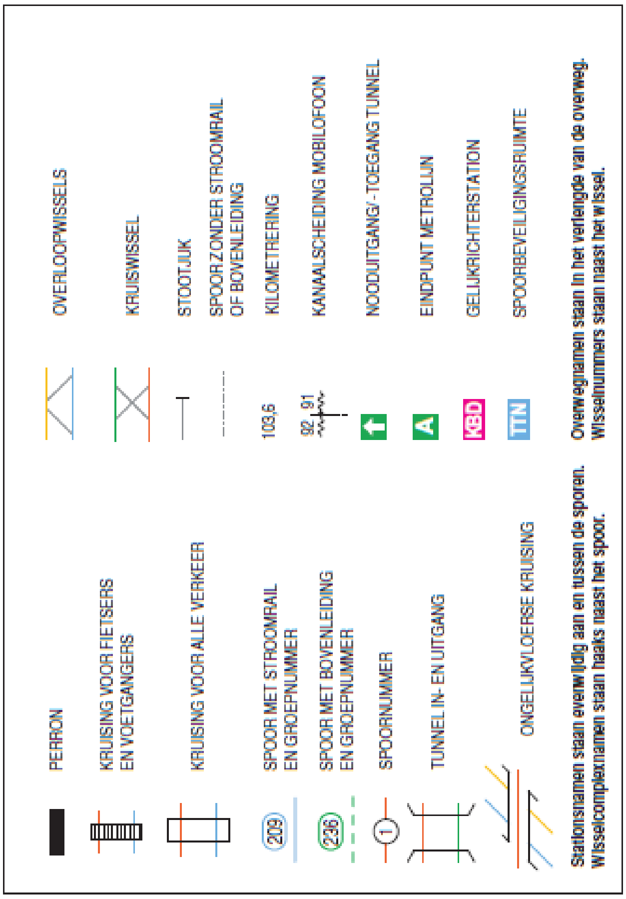
Appendix Figure 13: Frequent service network of the RET (RET, 2016b).



Appendix Figure 14: Tram network of the RET (RET, 2016b).

Appendix M Track layout structure on the trunk section of the D and E lines





Appendix Figure 15: Track layout between Slinge and Rotterdam Centraal (RET, 2015).

Appendix N Results of the sensitivity analysis on the crush capacity values

Let cc_2 be the crush capacity with 2 standing people per square metre of available floor and cc_3 the same but with 3 standing people. Let cs be the seating capacity. These three variables are linked by Formula 27:

$$cc_3 = \left(\frac{cc_2 - cs}{2} \times 3\right) + cs \quad (27)$$

$cc_{3.5}$ can be found simply by replacing 3 by 3.5 in Formula 27.

1. **Local-scale assessment**

Appendix Table 29 provides some of the values of cc_2, cc_3 and $cc_{3.5}$ for the case study. Recall that the values of the crush capacities were determined based on the mix of E and D line vehicles, and taking into account the amount of wagons (see Appendix G). Some scenarios appear twice because there is a distinction between NB and SB crush capacities.

Appendix Table 29: Crush capacities of scenarios with 2 or 3 people standing per square metre of available floor.

Scenario	cc_2	cs	cc_3	$cc_{3.5}$
Reference	396	207	490	538
7b	406	206	506	556
1, 2, 3, 4c, 6a, 6b	424	205	533	538
1, 2, 3, 4a, 4b, 4c, 5a, 5b, 6a	431	204	544	601

For 3 people per m^2, crush capacities increase by about one hundred, i.e. around 25%.
The local-scale assessment was conducted with the new crush capacities. Modifying crush capacities impacts denied boarding occurrences (impact (d)) and additional perceived in-vehicle times (impact (c)), which in turn impact the AGC. Since impact (c) has a minor incidence on the total AGC, it is deemed sufficient to focus on denied boarding, which has a more significant impact. The results stand in Appendix Table 30 to Appendix Table 34 for total AGC and denied boarding occurrences. Appendix Figure 16 and Appendix Figure 17 show how Figure 5-4 (page 67) changes when the crush capacities are increased.
With 3 people per m^2, although crush capacities increased by around 25%, denied boarding occurrences were cut by 2 up to 4 times. Absolute values decrease again with 3.5 people per m^2. However **the increase in crush capacities did not influence the trends observed in section 5.1**. There is still an 18% decrease in the AGC of Scenario 6a compared to Scenario 1 and a decrease around 35% for Scenario 6b compared to Scenario 1. Balance indexes remain comparable as well. Between 3 and 3.5 people per m^2, changes are rather slim for scenarios which already perform well enough (-5 % for Scenario 6b) but more significant for scenarios which do not perform well (-9 % for Scenario 4a). However, none of the worst-performing scenarios improves in such a way that it gets better than Scenario 4c, 6a, 6b or even 1. It is also interesting to note that Scenario 7b does not improve much; this is because it already has the lowest amount of denied boarding occurrences with cc_2.
Thus the values of crush capacities matter when one wants to get quantitative results but are less important when a more qualitative output is desired. Since the assessment framework aims at getting

both, bandwidths for the AGC values for the local-scale assessment are derived thanks to this sensitivity analysis. They can be found in Table 5-8, page 81.

Appendix Table 30: Comparison of results for denied boarding occurrences (DB occ.), balance index and total additional generalised costs with different crush capacities; Scenarios 1-2-3.

	Scenario 1			**Scenario 2**				**Scenario 3**			
	AGC in K€	**BI**	**DB occ.**	**AGC in K€**	**BI**	**DB occ.**	**Difference with Sc. 1 (AGC)**	**AGC in K€**	**BI**	**DB occ.**	**Difference with Sc. 1 (AGC)**
With cc_2	56.5	0.63	6955	50.4	0.37	6682	-11%	46	0.43	6098	-19%
With cc_3	46.3	0.64	3123	40.9	0.37	3189	-12%	38.6	0.45	3130	-17%
With $cc_{3.5}$	43	0.68	2117	38	0.39	2347	-12%	36	0.49	2347	-16%

Appendix Table 31: Comparison of results for DB occurrences, BI and total AGC with different crush capacities; Scenarios 4a-4b.

	Scenario 4a				**Scenario 4b**			
	AGC in K€	**BI**	**DB occ.**	**Difference with Sc. 1 (AGC)**	**AGC in K€**	**BI**	**DB occ.**	**Difference with Sc. 1 (AGC)**
With cc_2	84	0.39	8428	+49%	71.6	0.96	6640	+27%
With cc_3	69.2	0.40	4535	+50%	55.7	0.95	2718	+20%
With $cc_{3.5}$	62.3	0.41	3036	+45%	51.5	0.94	1714	+20%

Appendix Table 32: Comparison of results for DB occurrences, BI and total AGC with different crush capacities; Scenarios 4c-5a.

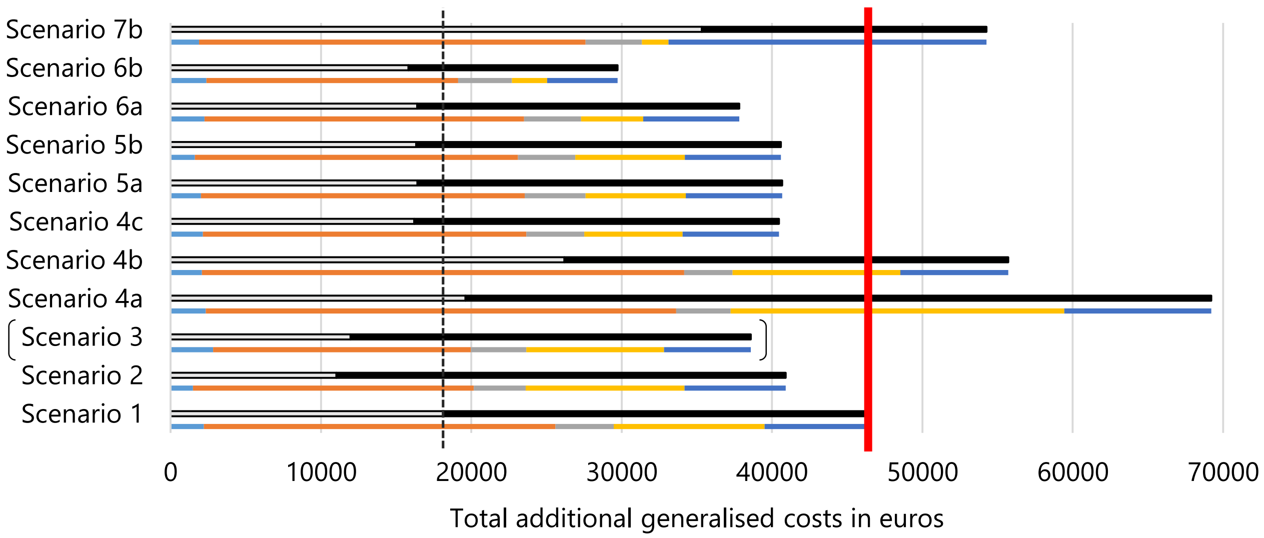
	Scenario 4c				**Scenario 5a**			
	AGC in K€	**BI**	**DB occ.**	**Difference with Sc. 1 (AGC)**	**AGC in K€**	**BI**	**DB occ.**	**Difference with Sc. 1 (AGC)**
With cc_2	50.2	0.68	5844	-11%	50	0.67	5743	-12%
With cc_3	40.5	0.68	2038	-13%	40.7	0.68	2141	-12%
With $cc_{3.5}$	37.7	0.70	1193	-12%	37.9	0.71	1296	-12%

Appendix Table 33: Comparison of results for DB occurrences, BI and total AGC with different crush capacities; Scenarios 5b-6a.

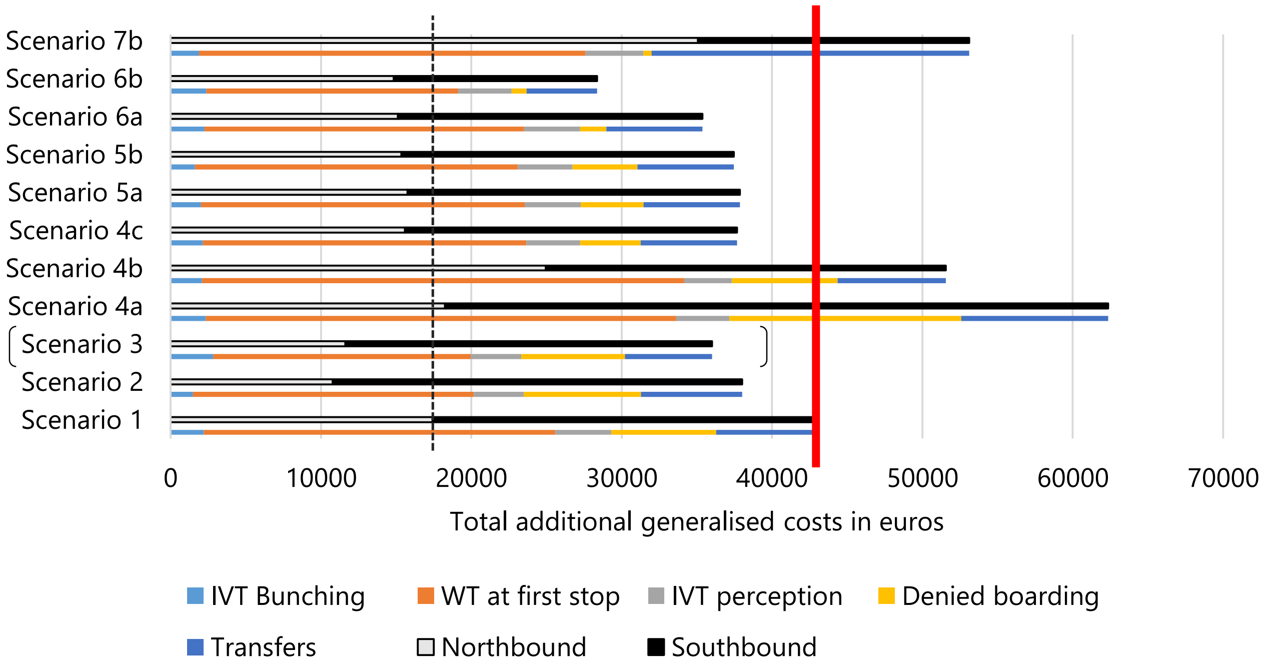
	Scenario 5b				**Scenario 6a**			
	AGC in K€	**BI**	**DB occ.**	**Difference with Sc. 1 (AGC)**	**AGC in K€**	**BI**	**DB occ.**	**Difference with Sc. 1 (AGC)**
With cc_2	50	0.67	6210	-11%	46.5	0.75	5045	-18%
With cc_3	40.6	0.67	2324	-12%	37.8	0.75	1328	-18%
With $cc_{3.5}$	37.4	0.69	1290	-13%	35.4	0.75	515	-18%

Appendix Table 34: Comparison of results for DB occurrences, BI and total AGC with different crush capacities; Scenarios 6b-7b.

	Scenario 6b				Scenario 7b			
	AGC in K€	BI	DB occ.	Difference with Sc. 1 (AGC)	AGC in K€	BI	DB occ.	Difference with Sc. 1 (AGC)
With cc_2	35.2	1.23	4104	-38%	63.3	1.76	3245	+12%
With cc_3	29.7	1.14	1021	-36%	54.2	1.87	597	+17%
With $cc_{3.5}$	28.3	1.10	431	-34%	53.1	1.94	217	+23%



Appendix Figure 16: Inconvenience experienced for all passengers, crush capacity assuming 3 standing people per square metre. The equivalent for 2 standing people per square metre can be found in Figure 5-4. Chart legend in Appendix Figure 17.



Appendix Figure 17: Inconvenience experienced for all passengers, crush capacity assuming 3.5 standing people per square metre.

2. Global-scale assessment

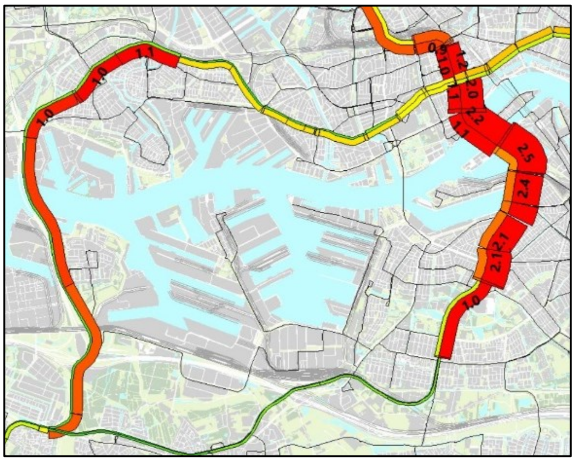
There is no impact on the AGC values of the global-scale assessment since the assignment performed in OV-Lite is not capacity constrained. However, differences lie in I/C ratios, which are to decrease with increased crush capacities. Since this is a relatively minor change – I/C ratios are to be interpreted with caution anyway, as discussed in sub-section 5.2.2 – crush capacities will only be increased from 2 to 3 people per square metre. The modified crush capacities of the metro vehicles can be found in Appendix Table 35. In the global-scale assessment, the "one line" assumption is relaxed and therefore the D and the E line are represented as separate lines between Rotterdam Centraal Station and Slinge. No change in crush capacities of other modes was investigated.

Appendix Table 35: Crush capacities of lines in OV-Lite with 2 or 3 people standing per square metre of available floor.

Line	cc_2	cs	cc_3
A	409	206	510
B, E and D peak (branch only)	374	208	457
C and D (branch only)	438	204	555
D trunk (Rcs-Slg), reference day	406	206	506

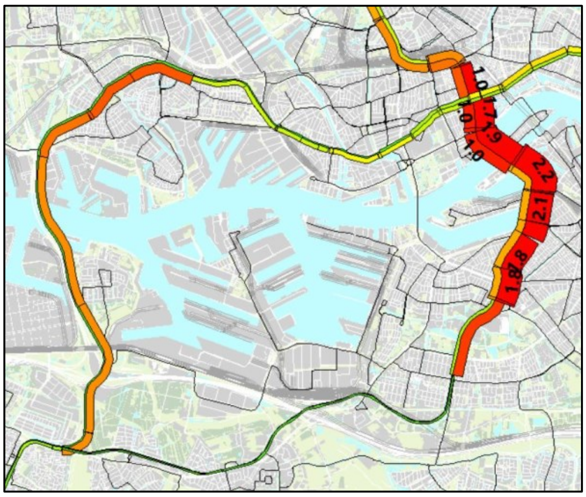
Appendix Figure 18 and Appendix Figure 19 show that if crush capacities are indeed closer to 3 people per square metre than 2, then the I/C ratios with cc_2 were overestimated. In particular the C line would not be as crowded as shown in Appendix Figure 18: in theory, with cc_3, it could still accommodate some passengers. The I/C ratios in Figure 5-16 were not illogical or impossible though, since OV-Lite does not take into account irregularities.
Appendix Figure 20 and Appendix Figure 21 show the I/C ratios for Scenario 6b *bis*, i.e. Scenario 6b, plus a decrease in frequency on the E line. The E line would also not be as crowded as with cc_2 but like the remark with the C line, it does not mean that no vehicle can be crowded. Besides, the I/C ratio from Blijdorp to Rotterdam Centraal remains relatively high, 0.85 (like between Troelstralaan and Schiedam Centrum, on the C line).
Had the transit assignment been capacity constrained, more insight would have been gained from this sensitivity analysis at the global scale.

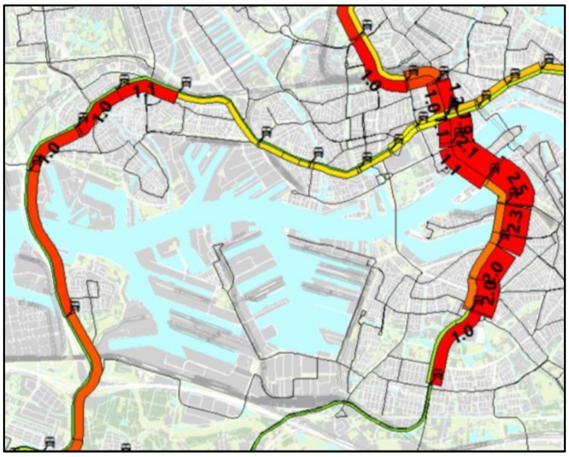
With cc_2 **With cc_3**



Appendix Figure 18: (Left) I/C ratio for the metro, Scenario 1, $\boldsymbol{cc_2}$.

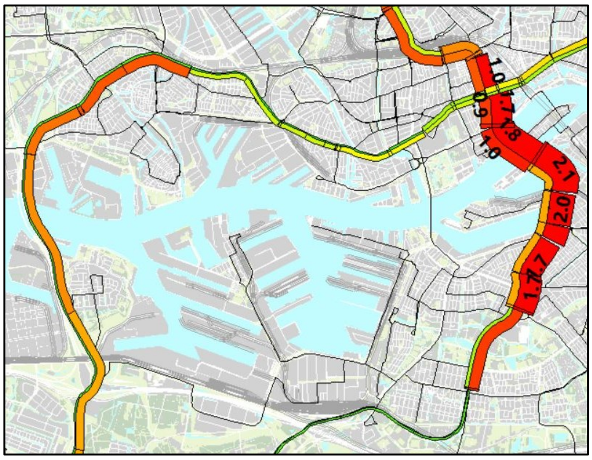
Appendix Figure 19: (Right) I/C ratio for the metro, Scenario 1, $\boldsymbol{cc_3}$.





Appendix Figure 20: (Left) I/C ratio for the metro, Scenario 6b *bis*, $\boldsymbol{cc_2}$.

Appendix Figure 21: (Right) I/C ratio for the metro, Scenario 6b bis, $\boldsymbol{cc_3}$.



Appendix O Waiting time distributions and waiting time reliability buffer time estimation

To be able to estimate long-term impacts, the RBT measure is needed. The reference day, Scenarios 1, 4c, 6a and 6b are analysed. Besides, to keep the task manageable in terms of time, only one stop is analysed, the stop with the highest amount of denied boarding occurrences and AGC: Beurs southbound. To find the RBT, one needs to plot waiting time distributions corresponding to a certain stop for a certain time window (see Appendix Table 8 in Appendix G), while taking denied boarding into account. This appendix details how the waiting time distribution for Beurs SB in Scenario 1 is plotted. A crush capacity assuming 3 people standing per square metre is assumed. A uniform distribution of passengers is assumed. The boarding demand rate in Bre SB from OV-Lite, 14.5 people per minute, is multiplied with headways to estimate boarding demand.
Thanks to the denied boarding module, Appendix Table 36 is obtained.

Appendix Table 36: Detail of the denied boarding occurrences in Scenario 1 in Bre SB from 07:46 to 08:46 AM, with a crush capacity assuming 3 people per square metre.

Train #	Demand, without taking into account denied boarding	Demand, with denied boarding	Amount of boarding passengers	Total amount of passengers left behind (denied boarding)
1	21	21	21	0
2	32	32	32	0
3	53	53	53	0
4	137	137	32	105
5	188	293	44	249
6	164	413	38	375
7	159	534	191	343
8	44	387	360	27

In Appendix Table 37, waiting times are estimated for each group of passengers boarding each vehicle. For instance, "WT train s4+5" line 5 means that the 44 passengers who boarded train 5 waited for train 4 first, have been denied boarding, waited for train 5 and boarded train 5.

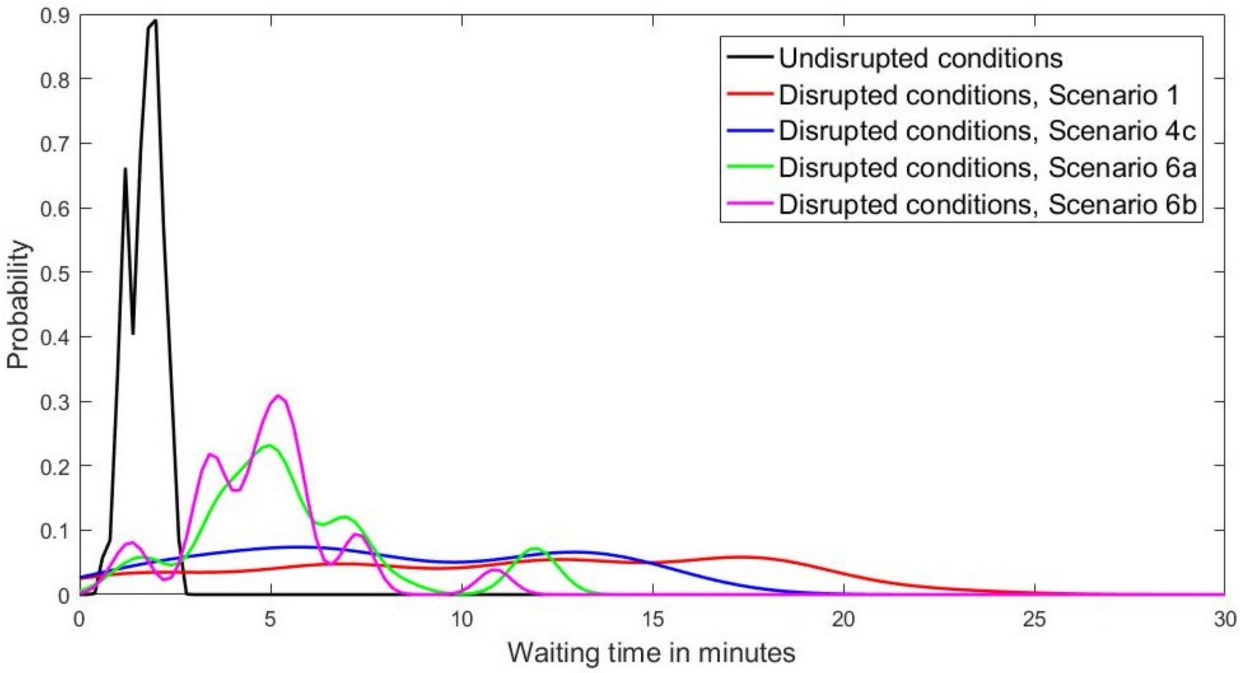
Appendix Table 37: Estimated waiting times for each group of passengers boarding each train.

Amount of boarding passengers	Estimated waiting times
21	WT train 1
32	WT train 2
53	WT train 3
32	WT train 4
44	WT trains 4+5
38	WT trains 4+5+6
191	23 passengers: WT trains 4+5+6+7 168 passengers: WT trains 5+6+7
360	20 passengers: WT trains 5+6+7+8 164 passengers: WT trains 6+7+8 159 passengers : WT trains 7+8 17 passengers : WT train 8

The two main assumptions are:

- No one leaves the queue or refuses to enter the queue.
- Queues are FIFO, i.e. First-In, First-Out. It means that the users who have priority for boarding are the ones who have been waiting for the longest time. This is of course not the case in reality, especially if people are in a rush, where people usually jostle each other more or less nicely.

Thanks to Appendix Table 37, a waiting time distribution in Bre SB during one hour of the morning peak of May 18th 2016 can be plotted. Data is fitted to a kernel probability distribution because kernel density estimates are closely linked to histograms, but with smoothness and continuity properties when the right kernel is used. Matlab is used to plot the distribution. This distribution, along with that of the reference day, Scenario 4c, 6a and 6b can be seen in Appendix Figure 22. Note that ideally, multiple reference days would have been used for the waiting time distribution in recurrent conditions but this was not done due to time constraints.



Appendix Figure 22: Waiting time distributions in Beurs SB during one hour of the morning peak for different scenarios; data fitted to kernel distributions.

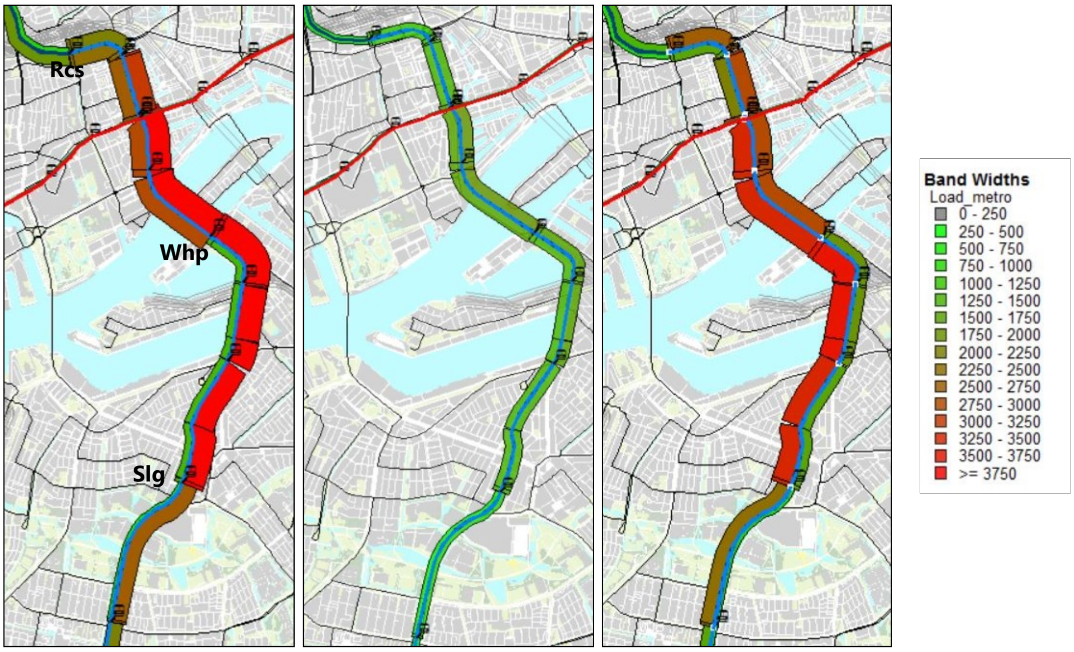
It is already clear that in Scenario 1, i.e. on May 18th 2016, some passengers experienced very long waiting times while this was more moderate for the scenarios crafted with the assessment framework in Chapter 5. The more spread the distribution is, the more likely passengers are to experience extreme waiting times. In Scenario 6b for instance, no one has experienced more than 12 minutes of waiting time. In the main text in Chapter 5, data is fitted to normal probability distributions because it is easier to visualise the spread of data with this type of distribution.

The RBT values can then be deduced (note that they simply depend on data, and not on plotted distributions). They can be found in sub-section 5.4.3.

Appendix P Generalisation of the results to other disruptions on the trunk section of the D and E lines

1. Passenger demand patterns

As evoked in the analysis of impact (c) in Chapter 5, there are some misconceptions among dispatchers of where passenger flows are. Besides, many dispatchers are surprised to learn that there are approximately the same amount of passengers going from Zpl to Brs (NB) than from Brs to Whp (SB) and these are respectively the fourth and the third busiest OD pairs (see Appendix G). The s2s matrix for the evening peak and off-peak hours could be computed in a similar way than the one in Appendix G , but it is a relatively time-consuming process. Therefore OV-Lite is used to get an insight on where passengers come from and go to. Appendix Figure 23 shows the passenger loads the trunk section between Slg and Rcs for one hour of the morning and evening peak as well as in-between peaks, to allow to draw a comparison between situations. It is clear that the section between Rcs and Whp is busy in the morning peak southbound and in the evening peak northbound. Therefore no direction ought to be neglected.



AM peak | In-between peaks | PM peak

Appendix Figure 23: Link loads from OV-Lite between Slg and Rcs during one hour of the morning peak (left), one hour of the in-between peak time (middle) and one hour of the evening peak (right), with OD matrix for spring season.

2. Headway gaps in relation to denied boarding, AM and PM peak

When the boarding rate is larger than the alighting rate, there is a chance for denied boarding to happen. Based on occupation, alighting and boarding rates from OV-Lite, an estimate for the maximum headway gap before denied boarding is computed: see Appendix Table 38 for the morning peak and Appendix Table 39 for the evening peak. These estimates are based on the following assumptions:

- There is an uniform distribution of passengers during the AM peak,
- There is one line running between Slg and Rcs with a frequency of 18 vehicles per hour (see "one line" assumption described page 38),

- The first train to come after the headway gap is train with 3 wagons and with a "normal" load of passengers, i.e. as in recurrent conditions. In Appendix Table 38 and Appendix Table 39, different crush capacities are used: assuming 2 and 3 people standing per square metre of available floor.
- The fact that some additional passengers may need to board at a station because of the disruption itself (their train is defect) is not taken into account.

The load of a train is computed as shown in Formula 28.

$$load = headway \times (occupation\ rate + boarding\ rate - alighting\ rate) \quad (28)$$

The $headway$ value for which the $load$ is just below the crush capacity of the train is the maximum headway gap before denied boarding.

In the morning peak, the maximum headway gap for Rhv NB is rather low. Thus if a disruption happens in Zpl NB for instance, it could be wise to hold a train in Rhv NB so that it can be as full as possible and thus prevent high amounts of denied boarding occurrences later on.

Appendix Table 38: Average occupation, boarding and alighting rates in the AM peak, possibility for denied boarding to occur and maximum headway for different crush capacities.

Stop	Average occupation rate of an arriving vehicle (pass/min)	Average boarding rate (pass/min)	Average alighting rate (pass/min)	Possibility for DB to occur? (0=no, 1=yes)	With cc_2		With cc_3	
					If yes, maximum headway (min):	The load of the train would then be:	If yes, maximum headway (min):	The load of the train would then be:
Slg NB	36	13,3	4	1	9,5	430	12	544
Zpl NB	45	24,2	5,8	1	6,5	412	8.5	539
Mhv NB	62	9,2	1,2	1	6	420	7.5	525
Rhv NB	71	4,1	1,6	1	5,5	404	7	515
Whp NB	74	4,3	9	0				
Lhv NB	69	0,7	6	0				
Bre NB	63	19,1	29,3	0				
Shs NB	54	0,7	17,2	0				
Rcs SB	33	18	10	1	10,5	431	13	533
Shs SB	41	4,7	0,2	1	9,5	432	11.5	523
Bre SB	45	14,5	3,4	1	7,5	421	9.5	533
Lhv SB	49	0,7	3,8	0				
Whp SB	46	1	23,6	0				
Rhv SB	23	1,8	1,3	1	18,5	435	23	541
Mhv SB	24	1,7	3,2	0				
Zpl SB	22	2,2	12,2	0				

Appendix Table 39: Average occupation, boarding and alighting rates in the PM peak, possibility for denied boarding to occur and maximum headway for different crush capacities.

Stop	Average occupation rate of an arriving vehicle (pass/min)	Average boarding rate (pass/min)	Average alighting rate (pass/min)	Possibility for DB to occur? (0=no, 1=yes)	With cc_2		With cc_3	
					If yes, maximum headway	The load of the train would then be:	If yes, maximum headway	The load of the train would then be:
Slg NB	8,7	5,0	1	1	34	431	43	545
Zpl NB	13	16,6	3,1	1	16,5	438	20.5	544
Mhv NB	26	5,0	1,9	1	15	436	18.5	537
Rhv NB	29	2,3	2,1	1	15	438	18.5	540
Whp NB	29	18,4	1,9	1	9,5	433	11.5	524
Lhv NB	46	2,3	1,4	1	9	422	11.5	539
Bre NB	47	21,0	20,6	1	9	426	11.5	545
Shs NB	47	2,6	7,6	0				
Rcs SB	16	15	4	1	16	432	20	540
Shs SB	27	10,9	0,9	1	11,5	424	14.5	535
Bre SB	36	29,3	10,9	1	8	435	10	544
Lhv SB	55	3,8	1,1	1	7,5	433	9	520
Whp SB	58	8,7	4,9	1	7	433	8.5	525
Rhv SB	61	2,5	4,6	0				
Mhv SB	59	2,2	7,4	0				
Zpl SB	54	6,9	23,1	0				

3. Headway gaps during in-between peak hours

In non-peak hours, the frequency between Rcs and Slg is 12 trains per hour and passenger loads are significantly lower in non-peak hours (see Appendix Figure 23). The largest load of passengers is approximately 1900 passengers between Whp and Lhv. Therefore if each train has a crush capacity of at least 320, a frequency of 6 vehicles (instead of 12) per hour could, on average, be enough to serve all demand during a disruption.

Wilhelminaplein NB is likely to be one of the "busiest" stops during the in-between peak time period, yet even with a train with a minimum capacity, a 25- to 30-minute headway gap would be needed for denied boarding to happen. However, the D line frequency is lower during off-peak and thus one gap in headway means almost 12 minutes without a vehicle. Consequently, waiting times could be rather large. Therefore, if there are not more than 2 stops on the single-track operations section, it would be advised to let a few E line trains drive and then turn in Slg. For instance, in case of a partial blockage like the one on May 18th, every other E line train could drive to (and then turn in) Slg.

Appendix Q Clauses belonging to the "Fines, bonuses and maluses" part of the rail concession contract of the RET

The rail concession officially started in December 2016. These clauses stem from the final version of the contract, from 2016.
Translation: J. Henstra.

Aanpassen vertrektijden Ritten bij Rituitval (ID-0140)

Indien een Rit van een Lijn gedeeltelijk of volledig uitvalt, mag de Concessiehouder de in de Geldende Dienstregeling vermelde vertrektijden van voorafgaande en eerstvolgende Ritten van de betreffende Lijn aanpassen ten behoeve van de regelmaat, onder de voorwaarde dat het Interval tussen opeenvolgende Ritten van de desbetreffende Lijn niet meer dan 10 minuten bedraagt.
When a trip is cancelled, the RET is allowed to adapt the departure times of the previous and next trips of this line for the benefit of regularity, under the condition that the [planned] interval of successive trips on this line does not exceed 10 minutes.

Punctualiteit Metro: Te vroeg vertrekken Metrostations (ID-0152)

De Concessiehouder draagt er zorg voor dat, voor zover de Beschikbare Railinfrastructuur dit toelaat, Ritten van Metrolijnen niet eerder vanaf Metrostations vertrekken dan is vastgelegd in de Geldende Dienstregeling.
The RET takes care that metro trips do not depart from stations earlier than mentioned in the timetable, as long as this is permitted by the available infrastructure.

Punctualiteit algemeen: Normen bij aangepaste vertrektijden (ID-0155)

Wanneer de Concessiehouder in geval van het uitvallen van één of meerdere Ritten de vertrektijden ten behoeve van de regelmaat aanpast, gelden de normen ten aanzien van het op tijd vertrekken ten opzichte van de aangepaste vertrektijden.
When the RET adapts departure times of one or more trips for the benefit of regularity, the punctuality requirements are effective relative to the adapted departure times.

Aangepaste vertrektijden vastleggen en verantwoorden (ID-1312)

Indien de Concessiehouder vertrektijden van Ritten met het oog op de regelmaat aanpast, draagt hij er zorg voor dat de Ritten waarvan de vertrektijden zijn aangepast op eenduidige wijze worden vastgelegd en verantwoord.
When the RET adapts departure times of one or more trips for the benefit of regularity, the RET takes care that these trips are registered and justified in an unambiguous way.